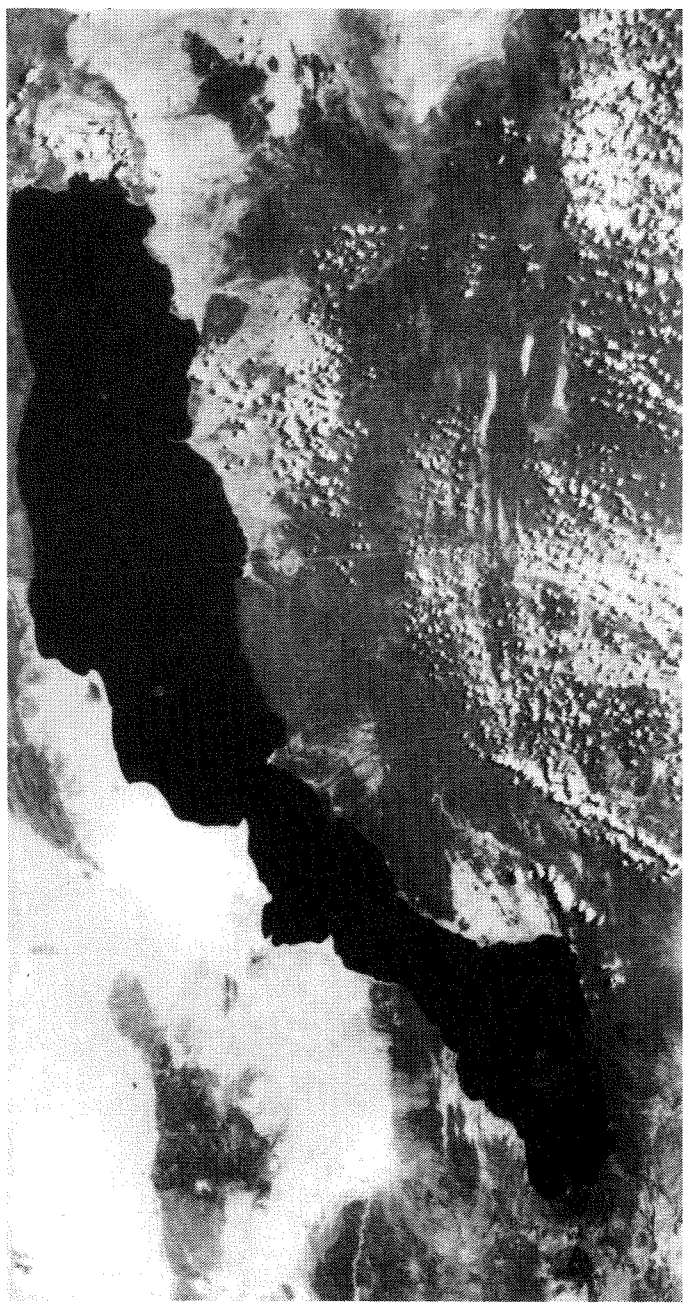
O-85313

Lake Turkana

Limnological study 1985 - 1988



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NIVA – REPORT

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Abstract:
The lake level was declining during the study and reached the lowest level ever recorded in 1988. The salt content was increasing and the conductivity reached ca. 380 mS/m in 1988. Annual temperature variations were small, but sufficient to create thermal stratification in March-May. Low deep water oxygen concentration was observed during stratification, especially in 1988. The development of phytoplankton was limited by the availability of nitrate and light. Light limitation was caused by turbid water and vertical mixing. The gross phytoplankton primary production was 2.4-8.2 g O_2/m^2/day and the estimated total annual production ca. 2 kg O_2/m^2. The total zooplankton production was estimated to approx. 32-80 g dry weight/m^2. Based on these production estimates, the sustainable yield of traditionally exploited fish from the open lake was estimated to roughly 15 000-30 000 tons/year.

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Lake Turkana

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CONTENTS

1. INTRODUCTION

The fish resources in Lake Turkana have traditionally been exploited to a limited extent by the local human population around the lake. Efforts to develop a commercial fishery have been initiated by Kenya Fisheries Department in order to improve the living conditions for the nomadic people who suffer from frequent droughts in the area. NORAD`s assistance to the development of the fishery started in 1971, and has been directed mainly through the Turkana Fishermen's Co-operative Society Ltd.

The commercial fishery has brought about substantial economical and social implications for the local community. In 1982 the number of people in the Turkana District who based their livelihood upon fishery was estimated at 30-40 000 (Watson et al. 1985). However, reduced fish landing in the past decade and marketing problems have made the fisheries much less profitable than was expected during the early development of the commercial fishery. The catch statistics show that the annual fish catch in Lake Turkana peaked in 1976, when 17 000 tons were landed. Since then, the trend has been negative, and the catch in 1984 was only 8 500 tons according to the statistics of Kenya Fisheries Department (Watson et al. 1985).

The main reason for the decline in fish landings was the collapse of the tilapia fishery in the Ferguson`s Gulf area on the western shore of the lake, which in 1976 contributed 16 000 tons of the total 17 000 tons annual catch. The base for this prosperious fishery was reduced after 1976 and, finally destroyed by a decline of the lake level.

The declining yield of the fisheries in Lake Turkana called for a better understanding of the fish resources of the lake and how these should be properly utilized. To provide some of the neccesary information a research project was proposed.

A joint research project for management and strengthening of the fish resources in Lake Turkana was launched by Kenya and Norway in 1984. The project included:

* Stock assessment and trial fishing to obtain information on potential yield and methods to exploit different fish species.

* Study of the tilapia in the Ferguson`s Gulf area to find methods to reinforce the population and restore the fishing potential.

* Evaluation of potential of tilapia aquaculture using locally produced feed.

* Limnological survey of the lake including the Ferguson`s Gulf to provide data which could support the fish resource assessment and development of aquaculture. The limnological study should also provide data on chemical composition of the lake as a basis for evaluation of long-term changes in water chemistry.

This report contains the results of the limnological study. The limnological study was carried out as a joint project by Kenya Marine and Fisheries Research Institute (KMFRI) and Norwegian Institute for Water Research (NIVA). Initially, surveys were conducted from Kalokol on the western shore of the lake. After the construction of a field station at Nataba 23 km SE of Kalokol in 1986, Nataba served as the base for the activities. For this purpose, a small laboratory for water analysis whas set up at Nataba.

A 16.5-foot aluminium boat equipped with an outboard engine was used for surveys of the lake. The lack of a larger vessel has restricted the surveys mainly to the central part of the lake.

Prior to this study, an extensive limnological survey of Lake Turkana was carried out by a British/Kenyan team in 1972-1975. The results, published in a series of reports by Hopson (1982), were invaluable as background to this study. Apart from the survey in 1972-1975 and the Cambridge expedition, which visited the lake in 1930 and 1931 (Beadle 1932), only scattered observations of limnological features of Lake Turkana have been published.

2 SUMMARY

The limnological study of Lake Turkana was carried out in 1985-1988. Most of the observations were made in the central part of the lake in 1987-1988.

The lake level receded during the study and reached the lowest level in 30 years in July 1988. The Ferguson's Gulf dried out completely in 1986. The annual flood in River Omo resulted in a rise in lake level of approximately 0.5, m but this was not sufficient to compensate for the loss by evaporation of 2.3 m on an annual basis. (The lake has no surface outlet).

Recordings of temperature and dissolved oxygen in the central sector of the lake revealed an annual stratification cycle with the most stable stratification between March and May and complete circulation in June-July. During the rest of the year, vertical mixing was partly restricted by a temperature gradient of 1-2 ^{0}C from surface to bottom (70m). The total temperature variation was 27.5-31 ^{0}C at the surface and 25.7-27.0 ^{0}C at 70 m depth.

Afternoon dissolved oxygen concentration is above saturation near the surface, but varies considerably in the deep water depending on the temperature stratification. During periods of stratification, dissolved oxygen at 70 m was reduced to 2.4 mg/l in June 1987 and 0.2 mg/l in May 1988. Such low concentrations of oxygen have not previously been recorded in the lake. The low oxygen concentrations influenced the distribution of fish in the deep water over as much as 20% of the lake area in May 1988.

The water in Lake Turkana is always turbid, because of fine suspended particulate material. This is brought to the lake by the rivers and is resuspended from the bottom sediments by waves and currents. The organic content of the particulate material was 12-46%. The organic content was lowest in the area affected by the River Omo flood.

Due to the turbidity, light extinction is high and transparency low. The Secchi disc transparency in the central part of the lake was 1-4.5 m with the lowest values in October-November and highest in March-April. The euphotic zone (i.e. where light is sufficient for photosynthesis) was estimated to 6 m as an annual average.

The lake water has a high content of dissolved salts, giving a high electrolytic conductivity. Salts brought to the lake by the rivers are

accumulated in the lake as water is lost by evaporation. During the study, the conductivity increased ca. 15% from ca. 330 to 380 mS/m. The increase was caused by the low influx of water.

The accumulation of salts in the lake is counteracted by precipitation of minerals. In particular calcium, magnesium and potassium are lost to the sediments leaving sodium as the dominant cation. Carbonate and bicarbonate are the dominant anions, giving high alkalinity (approx. 24 meq/l).

The concentrations of most heavy metals are low and quite stable, but the levels of aluminium, iron and manganese fluctuate with rather high concentrations in connection with influx of water with high turbidity from River Omo.

The analysis of plant nutrients show very high and stable concentrations of phosphorus ((2.2-2.4 mg P/l, mostly as phosphate), while the total nitrogen concentration is comparatively low (0.5-2.1 mg N/l). Only a small portion of the nitrogen (usually less than 0.1 mg N/l) is in forms readily available as nutrients for algal production (nitrate and ammonia). Very low concentrations of nitrate (< 0.01 mg N/l) are frequently found near the lake surface. The concentration of silicate is high (20-40 mg SiO_2/l).

Algal assays showed nitrogen as the potentially limiting nutrient for production of algal biomass in samples from Lake Turkana. The algal growth potential was higher in the northern part of the lake than in the south.

The chlorophyll-a content in the euphotic zone in the central part of the lake is usually in the range 2-4 µg/l, but occasionally higher values were found in connection with algal blooms. The chlorophyll concentrations indicate a generally low density of phytoplankton. No marked annual variation was observed, but day-to-day fluctuations were sometimes considerable. When the water was stratified the concentration of chlorophyll was low in the deep water, but when vertical mixing was more efficient, chlorophyll was distributed throughout the water column.

The dominant phytoplankton species in net samples are the blue-green alga Microcystis aeruginosa and the green alga Botryococcus braunii. Both these species have buoyancy and sometimes develop blooms at the surface. This property is probably important for the utilization of light in a turbid, mixed water column. Microcystis appeares to be favoured by the more nutrient-rich conditions following the annual

flood of River Omo. A few other species of green algae and diatoms were found on most occasions, but overall the diversity of the phytoplankton community is low.

The photosynthetic planktonic primary production in the central sector was estimated to 2.4-8.2 g $O_2/m^2/day$. There was no pronounced annual variation pattern. The total annual production, estimated from the mean daily gross production was ca. 2 kg $O_2/m^2/year$, corresponding to ca. 0.7-0.8 kg $C/m^2/year$.

The primary production appeared to be slightly lower in 1987-1988 than that reported by Hopson (1982) from observations in 1973-1975.

Observations in the Ferguson's Gulf in 1985 showed an extremely high density of phytoplankton which was an almost monospecific culture of the blue-green alga Anabaenopsis arnoldii. The chlorophyll concentration was 1-2 mg/l. The primary production was also very high, with an estimated daily gross production of 33 g $O_2/m^2/day$.

By experiments in ponds filled with lake water it was shown that a high density of Anabaenopsis arnoldii developed without any additional nutrient input. This indicates that this alga can fix nitrogen and that this process probably contributed to the very high productivity of the Ferguson's Gulf.

Experiments in ponds showed that the conditions at Lake Turkana are favourable for combined algae/tilapia aquaculture based on local resources.

The occurrence of the different zooplankton species and their seasonal fluctuations were very similar in 1973-74 and 1987-88. An annual two-peaked fluctuation of zooplankton biomass was observed. The biomass varied between 0.2 and 5.0 g dry weight per m^2 lake surface. The planktonic crustacean appear to be exposed to a high predation preassure. The total production of zooplankton is estimated to 216 000 - 540 000 tons dry weight per year for the whole lake.

An energy flow diagram for Lake Turkana was constructed based on insolation, measurements of phytoplankton and zooplankton production and conventional efficiency coefficients for fish production (See figure 4.16-1, page 64).

Different approaches have been used to estimate the potential fish yield in Lake Turkana. Based on the measured phytoplankton primary production, an empirical model predicted a total fish yield of 22 000

tons/year in Lake Turkana. Based on zooplankton production, and using the energy flow diagram, a sustainable yield of traditionally exploited fish from offshore areas of the lake was estimated at 15 000-30 000 tons/year. Maximum sustainable yield based on biomass, growth and mortality of the same fish species in the 1970's was estimated at 37 000 tons/year.

Although all three estimates of fish yields are based on different assumptions and approximate figures, the estimated values are rather similar. The estimates indicate that a sustainable yield of approximately 20 000 tons/year could be obtained from the lake.

The dominating influence of the Omo river on the hydrological balance and nutrient budget implies that the production potential is affected by fluctuations in river discharge. Periods of low discharge will decrease the fish production because of reduced input of organic matter and plant nutrients, reduced pelagic primary production and, consequently, reduced zooplankton production. Furthermore, shallow areas flooded during the seasonal rise in lake level may be important for the reproduction of certain fish species (e.g. tilapia).

View of Lake Turkana with Central Island from Nataba on the western shore.

3. DESCRIPTION OF THE LAKE AND CATCHMENT AREA

3.1 Geology

Lake Turkana is situated in the African Rift Valley in the north-western Kenya. The Rift Valley was created by tectonic movements of the earth crust over a period of about 20 million years in the Miocene, Pleistocene and Quaternary times. The valley floor has fallen between series of parallel faults that can be recognized from the Zambesi River to the Red Sea. Many of the largest African lakes and practically all the Kenyan lakes are found within the Rift Valley system.

Volcanic activity was frequent during the creation of the Rift Valley, and lavas from the Quaternary and Tertiary ages cover much of the floor of the valley in Kenya. The lavas are mainly of alkaline type, which has important implications for the chemical composition of lakes in this area. In the Lake Turkana basin, Tertiary volcanic rocks are found in the south and along most of the western side of the lake. A later lava flow (Pleistocene) forms a barrier in the southern end of the lake. Quaternary sediments dominate the western and northern side of the lake.

3.2 History of the lake

The early history of Lake Turkana has been examined by paleolimnological methods by Butzer (1972) and Yuretich (1976) and is summarized by Beadle (1974) and Hopson (1982). The lake basin has existed for about 5 million years. During this time there have been large fluctuations in lake level and, consequently, water chemistry caused by climatic changes. The modern lake has no outlet, but zoogeographical and geological evidence exist that Lake Turkana has been connected to the White Nile in the past. The last period of connection to the Nile occured between 9 500 b.p. and 7 500 b.p, when the lake level was 60-80 m above the present level. The topography suggests that the outflow was to the northwest.

After the connection to the Nile was interrupted, there was a gradual decrease in lake level to the present level about 360 m above sea level. The recent pattern of lake level fluctuation will be discussed later in this report (see section 4.1).

3.3 Climate

Turkana is situated in an arid and hot area. Some climatological data from the meterological station in Lodwar ca. 45 km west of the lake are shown in table 3.3-1. The mean annual rainfall in most of the lake surroundings is less than 250 mm. The occurrence of rainfall is very erratic and unpredictable. The probability of rainfall is highest during the "long rains" in March-May. The air temperature recordings at Lodwar show a seasonal pattern with the lowest temperatures in July-August. There is no meterological station near the lake, but during the Lake Turkana study in 1973-1975, observations were made at Kalokol (Hopson 1982). During this period, air temperatures ranged between 19.5 and 39.9 °C, with a mean daily temperature of 29.26 °C. Mean maximum and minimum values were 26.03 ± 0.19 and 32.49 ± 0.15 °C. The range of annual fluctuations was only 2-3 °C for both maximum and minimum temperatures. As in Lodwar, July and August were the coolest months.

Table 3.3-1. Climatological statistics from Lodwar meterological station (East African Meterological Department 1975).

Month	Temperature °C			Rainfall mm/month		Radiation cal/cm²/d	Evaporation mm/month
	Max.	Min.	Mean	Highest	Lowest	Mean	Mean
Jan.	35.4	22.0	9	111	0	529	311
Feb.	36.2	23.1	7	42	0	535	292
Mar.	36.0	24.2	21	149	0	516	324
Apr.	34.7	24.2	48	186	0	503	275
May	34.8	24.5	25	114	0	544	285
Jun.	34.1	23.9	7	116	0	539	287
Jul.	33.1	23.5	14	132	0	514	283
Aug.	33.3	23.5	10	63	0	543	292
Sep.	34.8	23.9	3	57	0	562	326
Oct.	35.2	24.4	8	89	0	551	343
Nov.	34.5	23.5	13	107	0	516	284
Dec.	34.5	22.4	13	198	0	549	276
Year	34.7	23.6	178	498	19	533	3578

The lake is exposed to frequent strong winds. Recording of wind speed at Longech carried out by Hopson (1982) did not show any pronounced annual variation. The prevailing wind direction was from the south-

east. Concurrent recordings at Loiengalani in the south showed that the wind speeds usually were higher in the southern part than at the western shore of the central section of the lake. Periods of strong winds occur on most days and may develop at any time of the day. Hopson`s observations, however, show that strong winds are most frequent between 9.00 and 11.00 hours.

The windy periods, when the lake becomes quite rough, alternate with calm periods with practically no waves. Calm periods of several hours duration can be observed on most days, but occasionally rather strong winds may prevail for several days.

The daily insolation in the area is rather constant during the year because of the proximity to the equator and the low cloud coverage during all months. The annual mean measured at Lodwar is 512 cals/cm^2/day with a range of monthly means of 456- 528 cals/cm^2/day.

3.4 Morphology and Hydrology

The Lake Turkana basin extends from the coordinates 2°23'- 4°35' North and 35°50'- 36°44' East. The altitude of the lake surface is about 360 m. The main inlet is River Omo, entering the lake from the north, (Figure 3.4-1) which contributes more than 90% of the total water influx. (See figure 3.4.1). Other rivers are temporary, flooding only during the sporadic rains. The second largest river, Turkwel River, is now being dammed for extraction of hydroelectric power at Turkwel Gorge ca. 150 km west of the lake.

Lake Turkana has no outlet, which means that water is lost from the lake mainly by evaporation. The evaporation rate has been estimated to 2.335 m/ year (Hobson 1982).

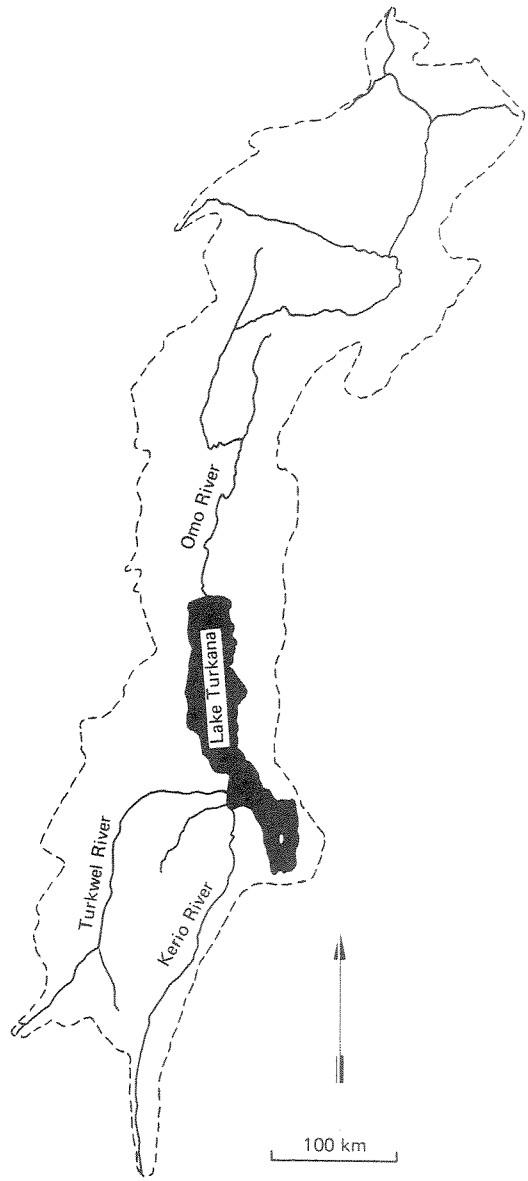


Figure 3.4-1 Catchment area of Lake Turkana. (Reproduced from Hopson 1982).

Morphometric and hydrologic data are given in table 3.4-1. A bathymetric map of the lake is shown in figure 3.4-2 and a hypsographic curve, illustrating the area of different depths is given in figure 3.4-3. The hydrological data presented are all based on the water level recorded on 20 July 1988. This water level was 5.0 m below the reference level used by Hopson (1982), which is the level recorded on 10 September 1972. The water level of Lake Turkana shows marked seasonal fluctuations and also periodical long-term fluctuations. This phenomenon is discussed in detail later (see section 4.1).

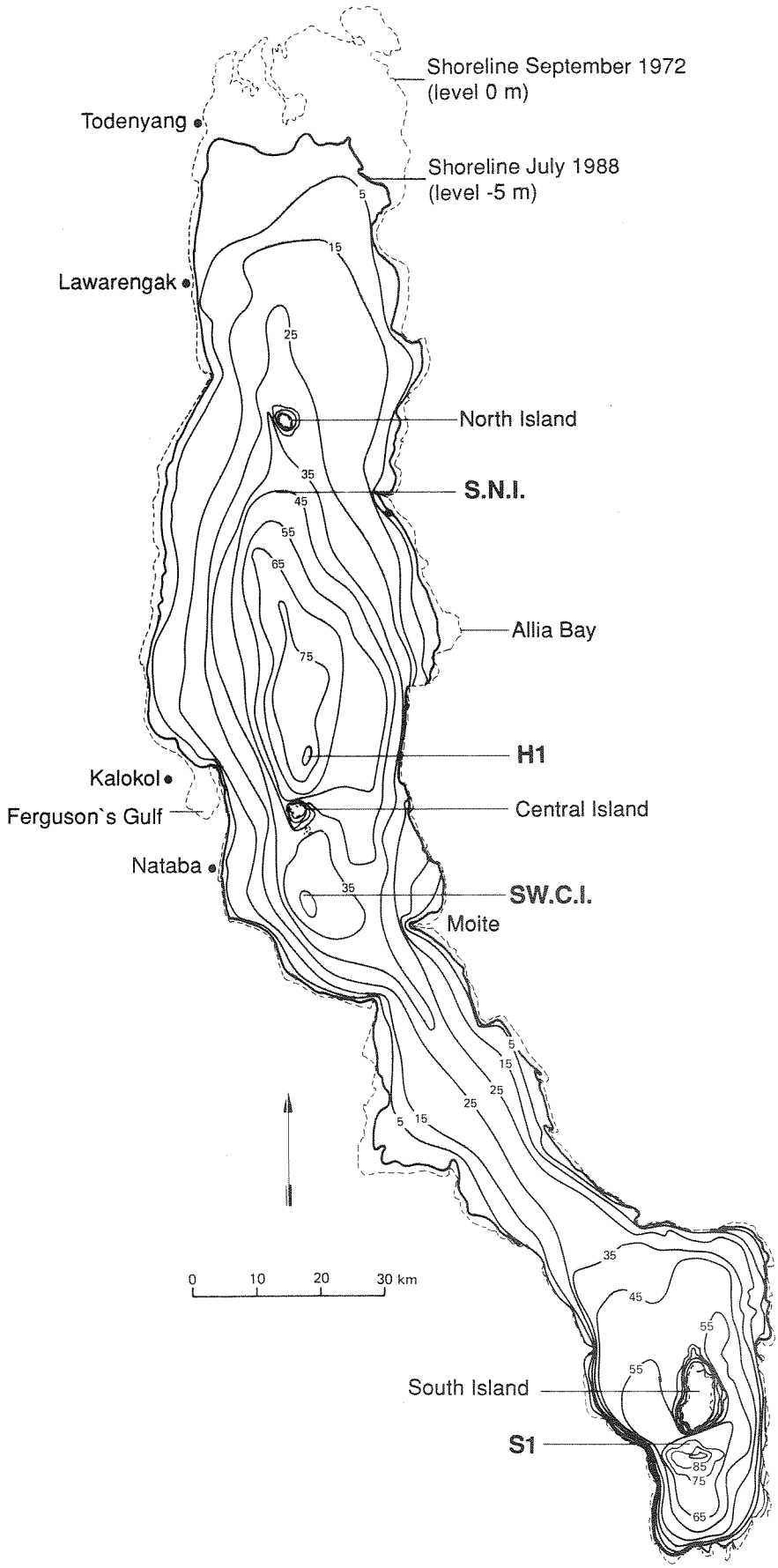


Figure 3.4-2 Bathymetric map of Lake Turkana reconstructed from Hopson (1982). The shoreline in July 1988 has been constructed from a Landsat satellite image. Main sampling stations are also indicated.

Table 3.4-1. Morphometric and hydrologic data of Lake Turkana. The figures are based on the lowest water level recorded on 20 July 1988.

Catchment area	130 860 km²
Lake surface	6 750 km²
Location	2°23'-4°35' north, 35°50'-36°44' east
Altitude above sea level	360.4 +-5 m
Length	ca. 235 km
Maximal breadth	ca. 40 km
Depth maximum	109 m
Depth mean	30.2 m
Volume	203.6 km³
Water influx (steady water level)	500 m³/s
Evaporation (from lake surface)	2.3 m/year

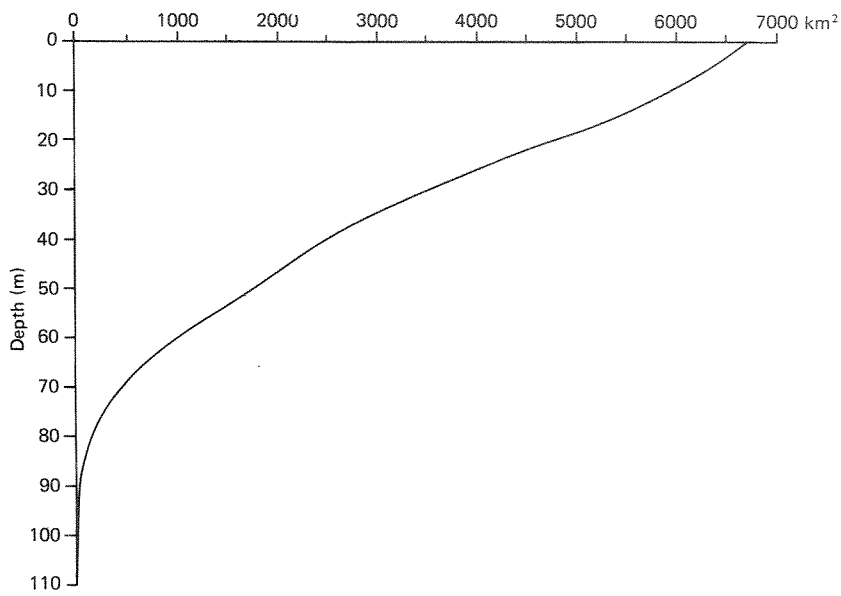


Figure 3.4-3 Hypsographic curve of Lake Turkana, July 1988.

4. RESULTS AND DISCUSSION

4.1 Lake level

As a closed basin lake, the surface level of Lake Turkana is sensitive to climatic variations. The fluctuations are determined by the influx from rivers and groundwater and by evaporation from the lake surface. The annual evaporation rate has been estimated to 2.3 m, (Hopson 1982) which corresponds to 6.4 mm/day. To compensate for the evaporation, an annual influx of 500 m^3 per second is required to keep a stable water level.

Continuous records of the level of Lake Turkana are not available, but the existing scattered information has been compiled by Butzer (1971) and Hopson (1982) who constructed a graph showing the major fluctuation in water level from 1888 to 1975. We have extended the plot by adding our records and information obtained from Arthur Scott and Peter Saina. (See figure 4.1-1).

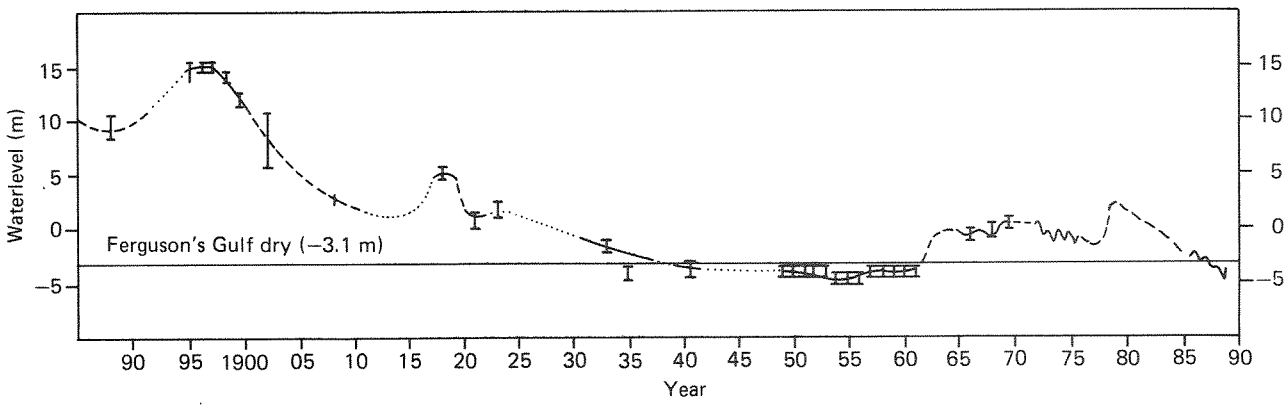


Figure 4.1-1 Water level of Lake Turkana 1888-1988. 0 m = ca. 365 m above sea level. Data from 1888-1970 from Butzer (1971), 1971-1975 from Hopson (1982).

Hopson (1982) used a reference level (zero-level) which was estimated to be 365±5 m above sea level. According to our reconstruction this level is 5.1 m below the floor of the Angling lodge at Kalokol and 2.4 m below the floor at the Nataba field station.

During this study, these buildings were used as fixed points for levelling the water surface. Records of the relative lake level fluctuations at the Angling Lodge between August 1985-January 1986 were submitted by Mr. Hasham. The gauges used during the Hopson study

in 1972-75 had been removed so no definite connection to previous records could be established. A connection, however, was established by comparing the depth of an area in the Ferguson`s Gulf as it was recorded in June 1975 and November 1985. This comparison shows that the water level was 0.9 m lower in November 1985 than in June 1975. The main uncertainty associated with this estimate is the possible change in bottom topography in the Ferguson`s Gulf by erosion and sedimentation.

There was a peak in water level around 1895 when the level was ca. 20 m higher than in 1988, followed by a general decline during the first half of this century (figure 4.1-1). After a minimum in the 1950's, there was a rapid increase in the beginning of the 1960's. Another rapid increase occured in 1978-1979, when the maximum level reached ca. 7.5 m above the level in 1988. The water level below which the Ferguson`s Gulf is dry is indicated in the figure. It is known that the gulf was dry in the 50's as shown by the figure, but it has also been claimed that the gulf was completely dry and the water level almost as low as in July 1988 in 1935 (Arthur Scott pers. comm.). This implies that the level in 1935 was lower than indicated in figure 4.1-1.

The fluctuations in the level of Lake Turkana the last 100 years seem to agree well with the pattern of fluctuation from other nearby African lakes (Lamb 1966, Butzer 1971, Richardson and Richardson 1972, Hopson 1982).

The most recent water-level fluctuations are shown in figure 4.1-2, which is based on Hopson's records from 1972-75 and the records obtained during this study. The two data sets are combined as described earlier, and the estimated peak level in 1979 is included.

Seasonal variation in rainfall in the River Omo catchment area causes high influx of water in July-December. This causes an annual fluctuation pattern in the lake with minimum levels usually occuring in June-July and maximum levels in October-November. The seasonal variations are illustrated in figure 4.1.2. This figure also shows that there has been a general decline in water level in the periods when continuous recordings were made, 1972-1975 (Hopson 1982) and 1985-1988. During these periods, the influx of water, which caused a rise in water level between July and October, was not sufficient to compensate for the annual evaporation. The annual decline of the water level was faster in 1985-88 compared to 1972-75.

Heavy rain in most of the catchment area of the lake in late July and

August 1988 caused a fast rise of the level with a daily mean of 1.5 cm for several weeks.

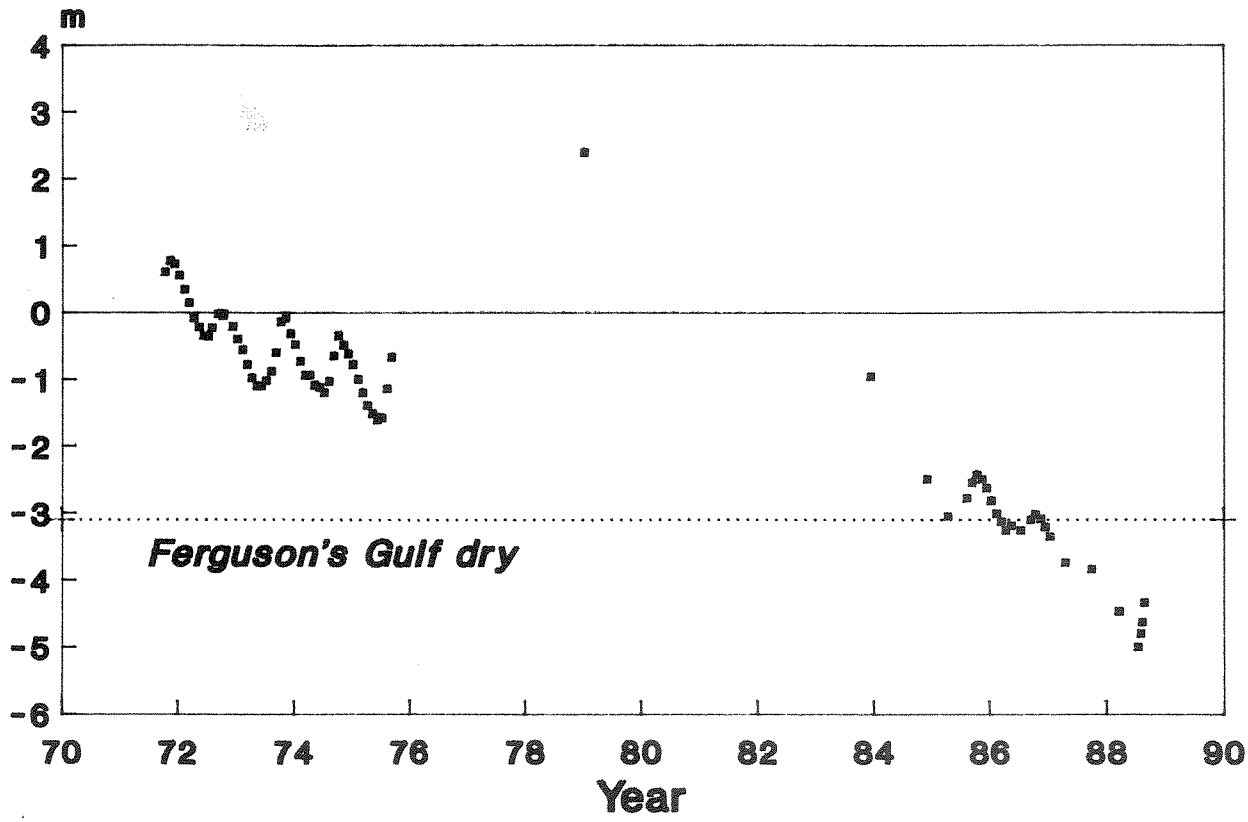


Figure 4.1-2 Water level of Lake Turkana 1971-1988. 0 m = ca. 365 m above sea level. Data for 1971-1975 from Hopson (1982).

4.2 Temperature and stratification

Vertical temperature gradients create physical stability of the water column and reduce vertical mixing. Stratification caused by temperature gradients influences the distribution of dissolved oxygen and regeneration of nutrients as well as the distribution of phytoplankton and potential for primary production.

Temperature profiles were taken at the offshore routine station, H1, in the central part of the lake. The results are compiled in appendix II, and illustrated as isoterms in figure 4.2-1.

Due to the proximity of the equator, the annual temperature variations are low. The subsurface temperatures ranges ranged from 27.5 to 31 ^{0}C

and the bottom temperatures (70 m) were 25.5-27 °C. In spite of the small annual variations and the frequent strong winds, periods of temperature stratification were observed during the first half-years in 1987 and 1988.

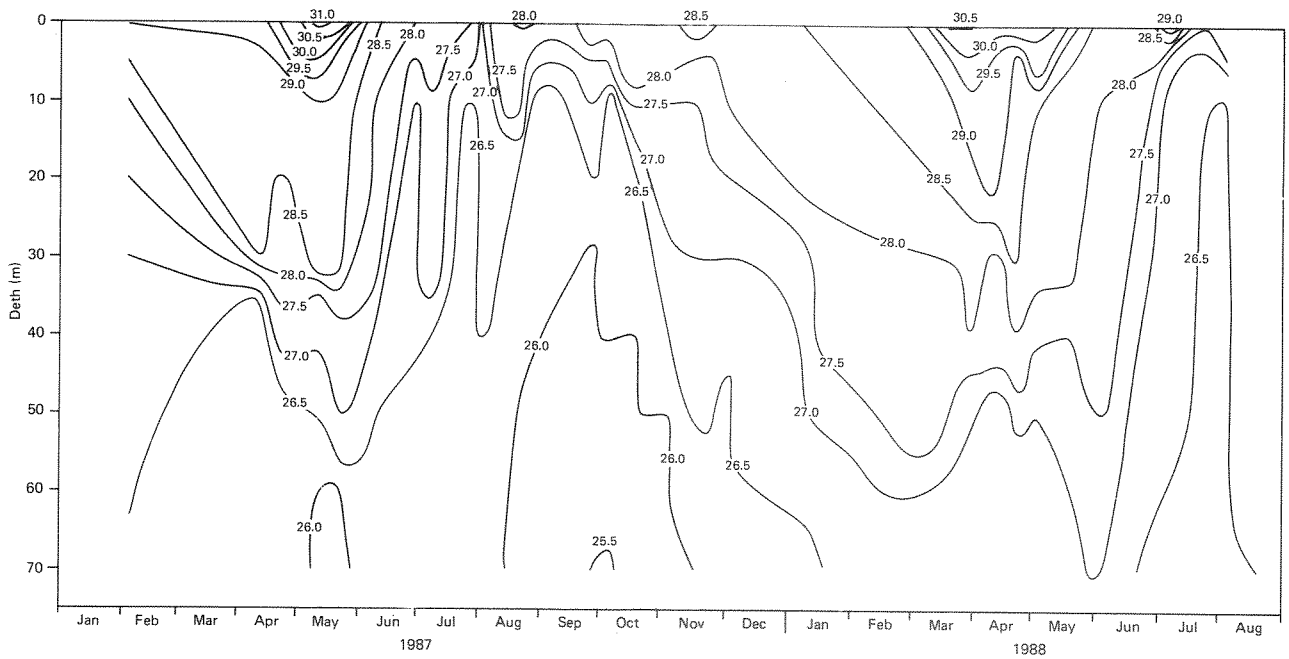


Figure 4.2-1 Isoterm plot for Lake Turkana at H1, 1987-1988. The frequency of observations can be seen in appendix II.

In February 1987 temperature decreased gradually ca. 3 °C from surface to bottom. Later, in March, a pronounced thermocline developed. The thermocline deepened progressively from March to May. During this period, the temperature increased, especially in the surface water, increasing the heat content of the whole water column. Superficial stratification over the major discontinuity layer was usually observed in the afternoon. This was probably broken up during the night after cooling and mixing by either northerly or south-easterly winds.

Cooling of the water column started in June, and in July the whole water column was close to isothermal. Minimum temperatures were reached in September 1987 after which the water column started warming up again until May 1988. During this time the vertical temperature gradient increased gradually, creating a stable stratification in March-May with a thermocline between 20 and 50 m. This stratification was broken up in June 1988, and the whole water column was again close to isothermy.

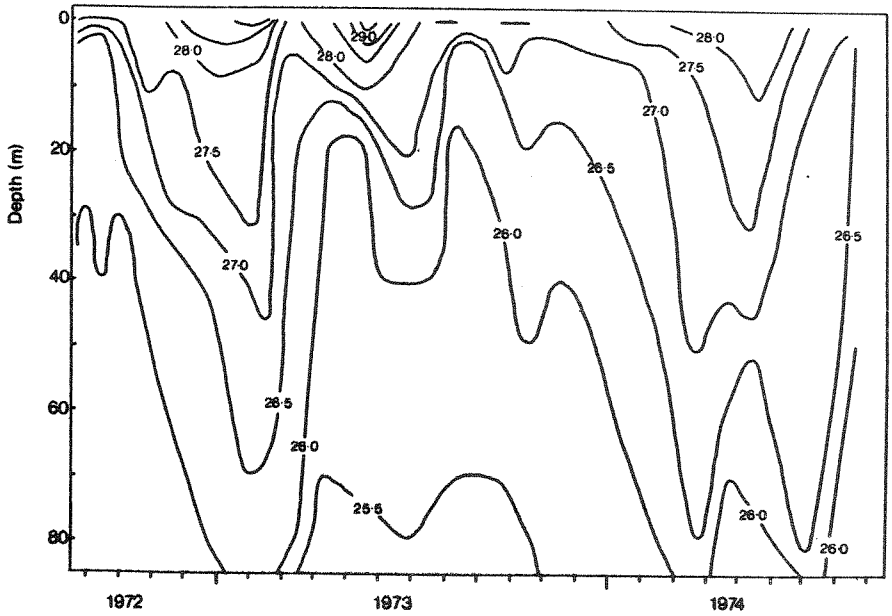


Figure 4.2-2 Isoterm plot for Lake Turkana at H1, 1972-1974. (Reproduced from Hopson (1982)).

In addition to the recordings at H1, some temperature profiles have been taken from other stations. Figure 4.2-3 shows temperature and oxygen profiles from H1 and a station SW of Central Island on two occasions. The profiles from the two locations in the central sector are rather similar, but the thermocline was located slightly deeper at H1 than SW of Central Island in April 1987. This difference in profiles taken on two consecutive days is probably due to internal waves in the thermocline.

In July 1988 a temperature profile was recorded also in the southern basin. The profile showed a weak gradient with 1.2 ^{0} difference from 10 m to 85 m depth. Profiles from the central sector showed almost isothermy in the same period.

The observed seasonal stratification pattern and the temporal daily superficial stratifications in spite of the small annual variations in temperature are accounted for by the fact that there is a rapid alteration of density with temperature at the high temperature range found in tropical lakes (Beadle 1974). A similar annual stratification pattern has been described in Lake Victoria, where a temperature difference of 1.5 ^{0}C, was sufficient to establish a relativly stable functional thermocline (Talling 1966).

The annual stratification in 1987-1988 shows similarities with earlier observations made by Hopson at the same station (Hopson 1982). Figure 4.2-2 shows the temperature variations in 1972-74. Stratification was most pronounced in March-October 1973 with a thermocline above 40 m. In 1974 the temperature gradient was weeker and no typical thermocline was found. The almost isothermal situation that was seen in June 1987 and 1988 occurred also in 1974, but not in 1973.

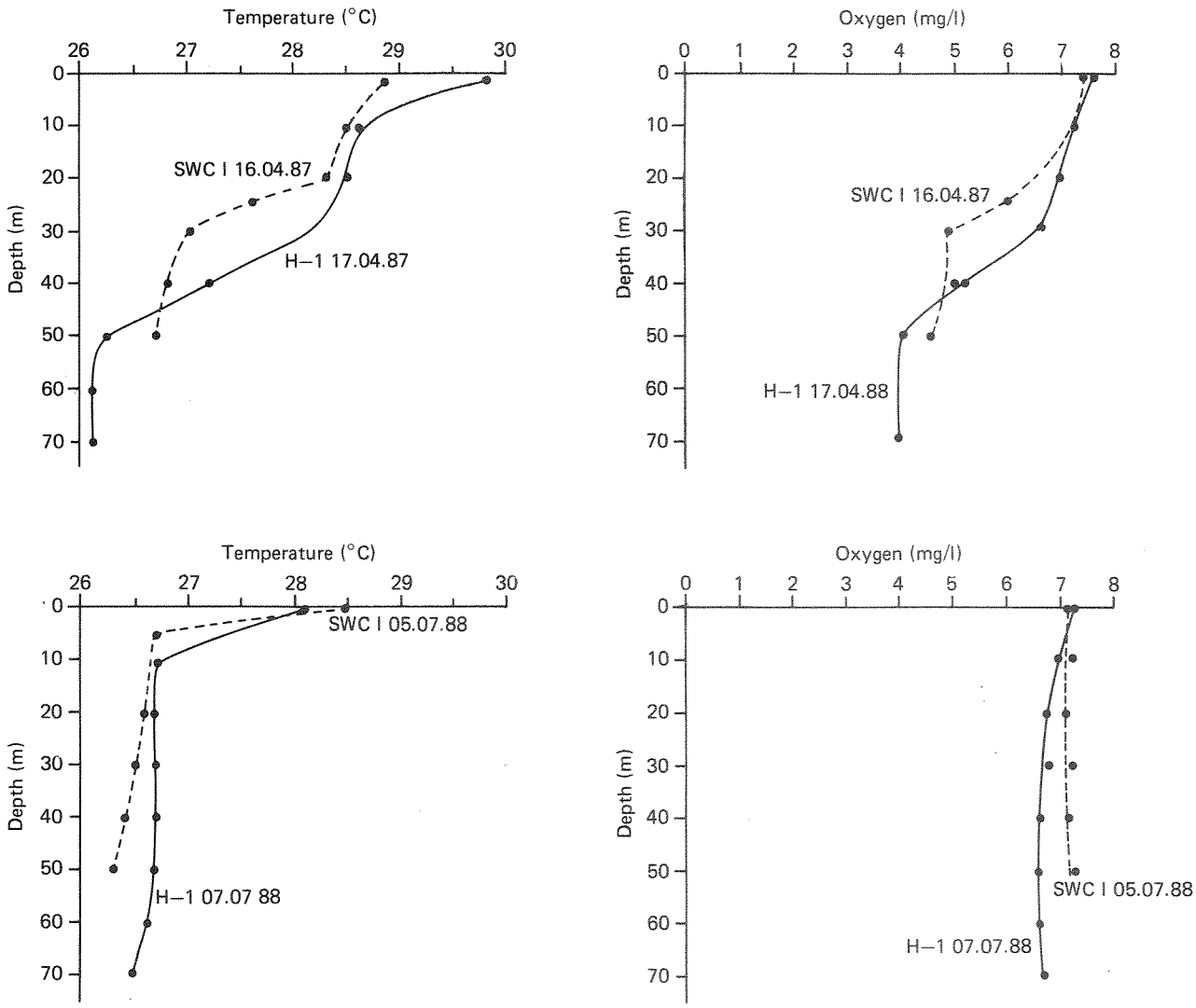


Figure 4.2-3 Temperature and oxygen profiles from the central sector of Lake Turkana (Stations, see figure 3.4.2).

4.3 Dissolved oxygen

The vertical distribution of dissolved oxygen is dependent on the processes which produce and consume oxygen, i.e. photosynthesis and respiration. There is also an exchange of oxygen between water and air across the lake surface. Below the upper water layer where oxygen is produced by phytoplankton and exchanged with the atmosphere, oxygen is continuously consumed for decomposition of organic matter. As a result, oxygen depletion may occur in the deep water if mixing of the water is restricted. Therefore, stratification has a major influence on the vertical distribution of dissolved oxygen.

Results of the oxygen measurements are listed in appendix II and shown as an isoplot in figure 4.3-1. The gradients of dissolved oxygen observed during the periods of thermal stratification in 1987 and particularly 1988 were stronger than those found by Hopson (1982) in 1972-74. The lowest concentrations near the bottom at H1 during that period was 4.96 mg O_2/l, as compared to 2.4 mg/l in June 1987 and 0.2 mg/l in May 1988. These differences can be explained either by different rates of oxygen consumtion or by differences in mixing. The first alternative implies that the load of organic material in the deep water was higher during the present study as compared to the previous one. This does not appear likely since no increase in productivity has been found (See section 4.13). Thus, it must be concluded that the temperature stratification reduced the vertical mixing of the water column more efficiently in 1987 and 1988 than in 1972-74.

The very low oxygen values in the deep water in March - May 1988 probably had concequences for the fish fauna. Fish can not survive when oxygen concentrations approach zero, and most species avoid areas where the concentration is less than 2 mg O_2/l. By the end of May, less than 2 mg O_2/l was found below ca. 55 m in the central basin. This means that fish were restricted over a very large area. If the conditions were similar in the southern basin, the total area affected by O_2 - levels less than 2 mg/l was about 1 300 km^2 or approximately 20 % of the lake area as can be seen from the hypsographic curve in figure 3.4-3.

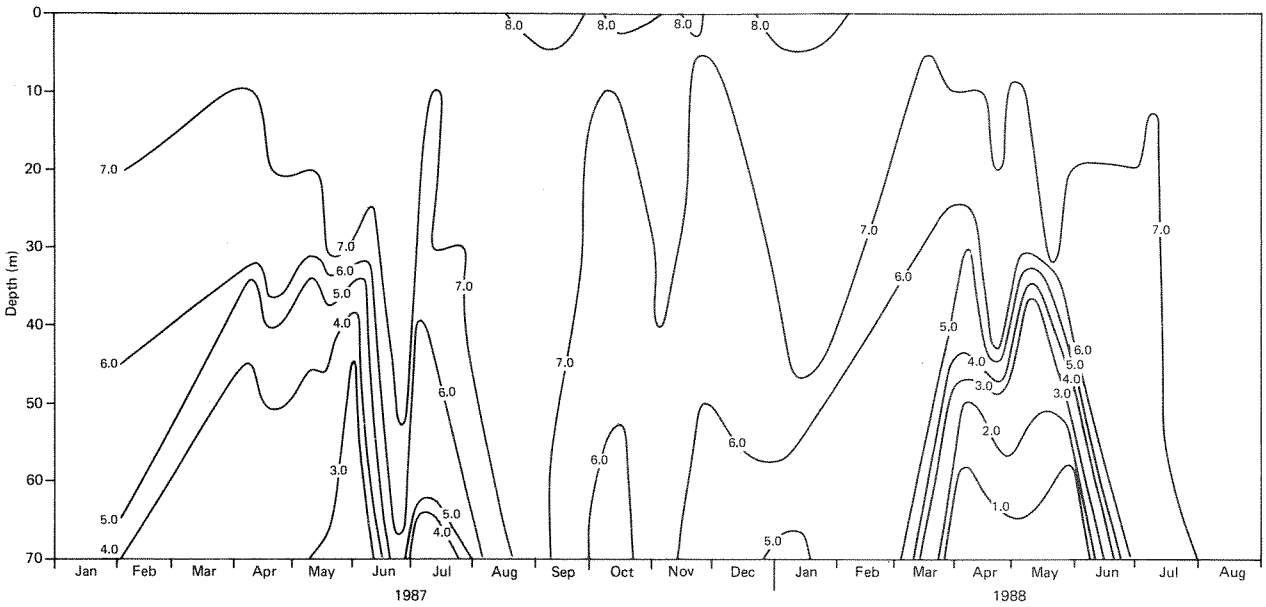


Figure 4.3-1 Iso-plot for oxygen at H1 1987-1988.

4.4 Secchi depth and light extinction

The penetration of light into the water column is important for planktonic photosynthesis (see section 4.13). The rate of extinction of light in the water column depends mainly on the content of particulate material and dissolved coloured compounds. Light penetration can be measured by a light meter, but the visability of a white "Secchi-disc" is also a useful parameter for describing the transparency of the water.

The Secchi depth recordings in the central sector of the lake (H1 and south-west of Central Island) in 1987-1988 are shown in figure 4.4-1. The figure shows an annual variation with the clearest water in March-April, when the Secchi depth was 3 - 4.5 m. The lowest transparency (Secchi depth 1-1.5 m) was recorded in October-November 1987, when the turbid water from the Omo River reached the central part of the lake.

Some observations e.g. in April 1987 show substantial short-term fluctuations in transparency. These are probably caused by resuspension of fine particles by waves and currents from shallow areas. "Clouds" of resuspended material can often be observed from the air and even on satellite images.

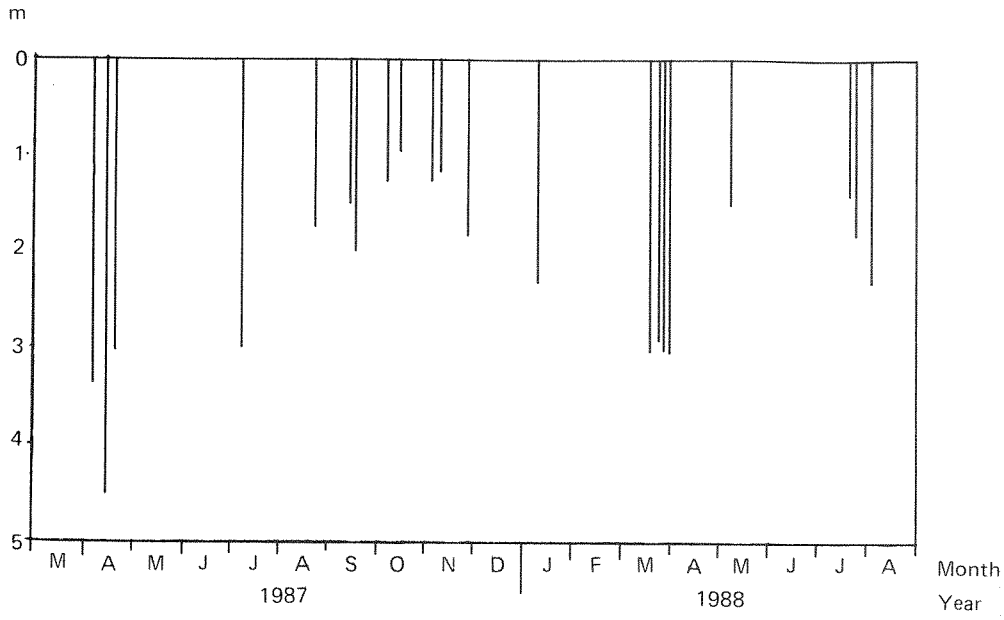


Figure 4.4-1 Secchi depth recordings in the central sector 1987-1988.

The influence on the Omo River on the turbidity is most marked in the northern part of the lake. Secchi depth recordings a few km south of Northern Island showed 3 m in March and 0.4 m in August 1988. On the latter occasion the Secchi depth increased to 2.5 m in the central sector (H1) and 3.0 m in the southern (S1).

Underwater radiation recordings were performed on several occasions in 1987. From the profiles, the depth where the light was reduced to 1% of the subsurface level was calculated by regression analysis. This depth is usually considered as the limit of the euphotic zone, i.e. the zone where photosynthesis may occur. The depth relation between Secchi depth (Sd) and depth of the euphotic zone (Z_{eu}) is shown in figure 4.4-2.

Linear regression of the data gives:

$$Z_{eu} = 0.134 + 2.593 * Sd \quad (r=0.9186)$$

With this relation it is possible to estimate the depth of the euphotic zone from the more frequent Secchi disc readings. The results indicate that the euphotic zone in the central sector of the lake varies between 2.5 and 12 m (mean value 6 m).

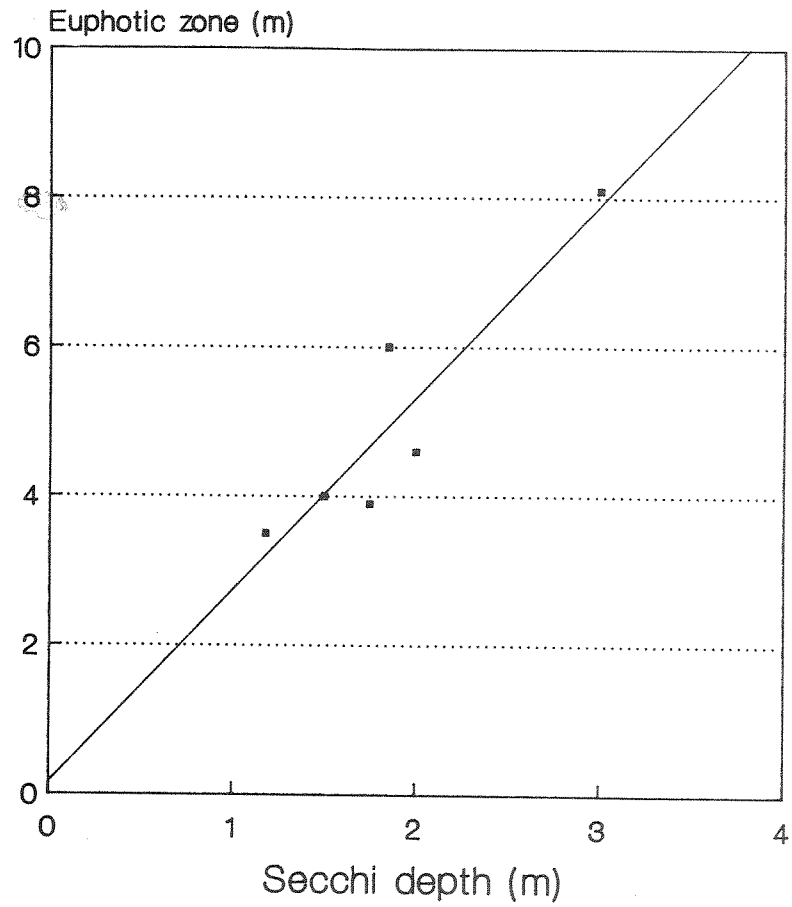


Figure 4.4-2 The relation between Secchi depth and the depth of the euphotic zone, calculated from light extinction measurements.

4.5 Conductivity and major ionic composition

The content of dissolved salts in Lake Turkana is high as a result of evaporative accumulation which has taken place since the lake was disconnected from the Nile 7500 years ago. The total salt concentration can be measured as electrolytical conductivity. Depth profiles of conductivity has been taken on several occasions from 1985-1988 in the central part of the lake. A few observations have been made also in the northern and southern parts of the lake. The data are compiled in appendix II.

The conductivity was, on most occasions, rather uniform from surface to bottom, but sometimes with slightly increasing values with depth. During the period of thermal stratification in April and May 1987, also a stratification of conductivity could be observed. Figure 4.5-1 shows the profiles for temperature and conductivity on 8 May 1987. The conductivity was uniform down to the thermocline at 30 m, but increased by 7 mS/m between 30 and 70 m. The same pattern was not observed during the period of stratification in 1988. Several profiles from March - May 1988 show a rather uniform conductivity with depth. On the other hand, differences in conductivity with depth could be observed at times when the temperature gradient was much smaller e.g. on 21 November 1987.

When the conductivity values are studied over the whole observation period, there seems to have been an increase of about 50 mS/m from 1984-1988 in the central part of the lake. Figure 4.5-2 shows the conductivity measured at 10 m at station H1, north of Central Island from November 1984-August 1988. The observations show an increasing trend over the period, which must be the result of evaporative concentration of salts.

The frequency of observations allows an analysis of the annual variations in conductivity to be made for 1987-1988. The data show that the conductivity increased during the first months of 1987. After a peak between May-August, the conductivity decreased in September-October. A new increase in conductivity occured in the beginning of 1988, and this trend persisted up to August 1988. The annual variation in conductivity reflects the inflow of less saline water during the flood in River Omo, which normally starts in July. The flood water reaches the central part of the lake 2-3 months later.

Recordings of conductivity in March 1988 showed little difference in levels at H1 in the central part of the lake and south of the Northern Island, 55 km to the north. Observations in July-August 1988 in the northern, central and southern part of the lake, however, showed that conductivity increased from north to south. (See figure 4.5-3). The influence of River Omo, which was flooding at that time, is clearly reflected by a drop in conductivity in the surface layer in the north.

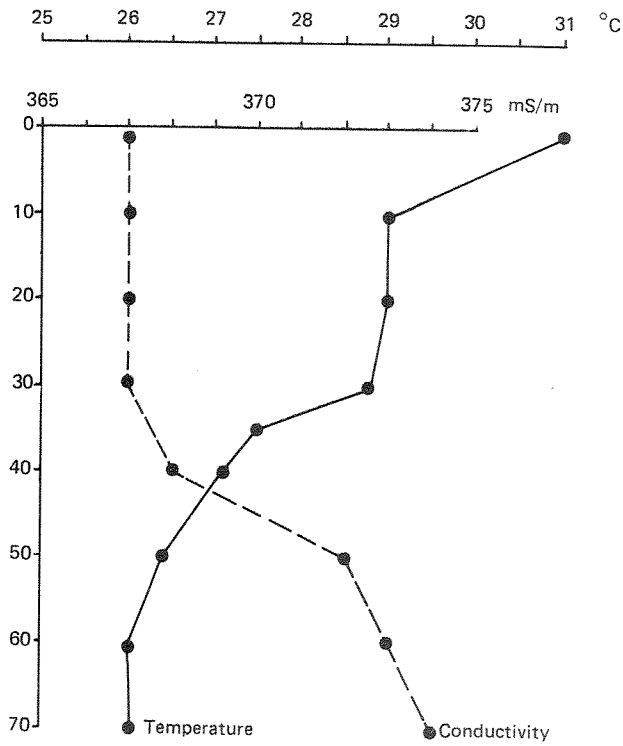


Figure 4.5-1 Temperature and conductivity profiles at H1 on 8.5.1987.

The present level of conductivity in lake Turkana (380 mS/m in August 1988) corresponds to approximately 2.44 g dissolved solids/l according to the relations found by Wood and Talling (1988) for several alkaline Ethiopian lakes. Previous data on conductivity from Lake Turkana include a record from Talling and Talling (1965) of 330 mS/m in 1961, and several data from the Hopson survey in 1973-75 when the level in the central part of the lake was between 340-360 mS/m (Hopson 1982).

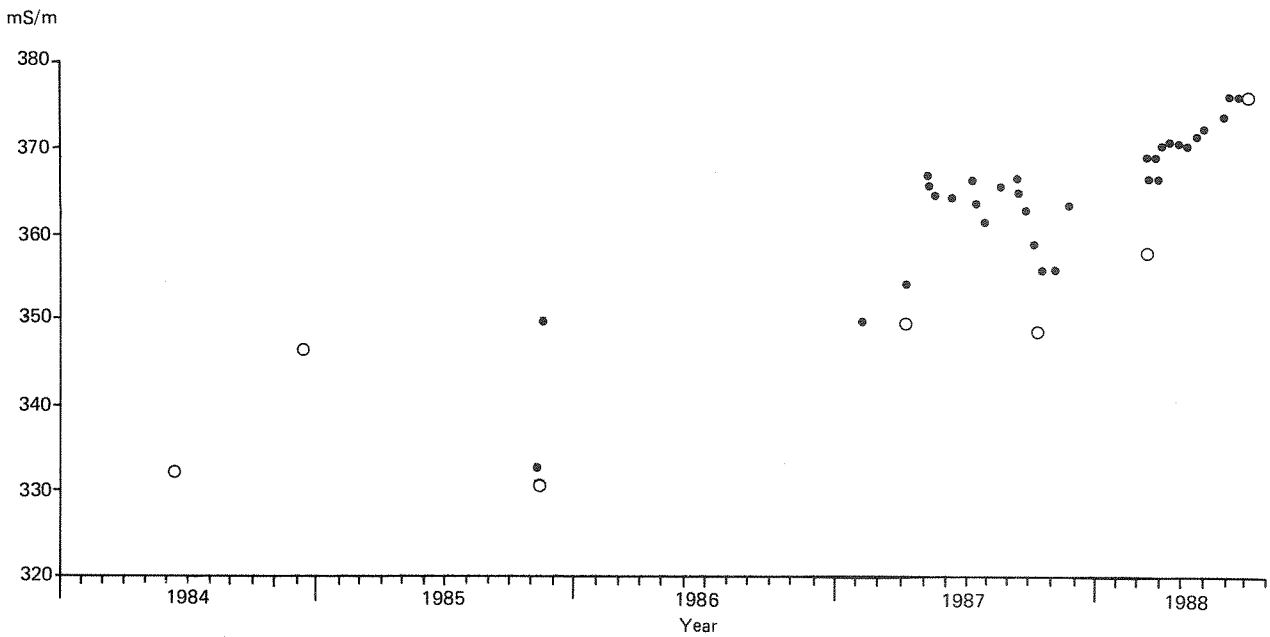


Figure 4.5-2 Conductivity measured at 5-10 m at H1 in 1985-1988. • Recorded in the field. o Measured in the laboratory (NIVA).

4.6 Major ions

The major ionic composition has been examined in several water samples from H1 in the central part of the lake, and samples from the southern and northern parts in July-August 1988. The results are shown in appendix IV.

Sodium is the dominant cation in the lake water, with concentrations ranging from 770 to 930 mg/l in samples from H1 at 0-10 m depth. The corresponding range is 14-21 for potassium, 4.1-4.3 for calcium and 1.8-2.4 for magnesium.

Among the anions, carbonate and bicarbonate (alkalinity) dominate (21-24 meq/l), but also the chloride concentration is high (ca. 440 mg/l or 12 meq/l). Of the other anions, particularly the fluoride concentration is high (10-12 mg/l).

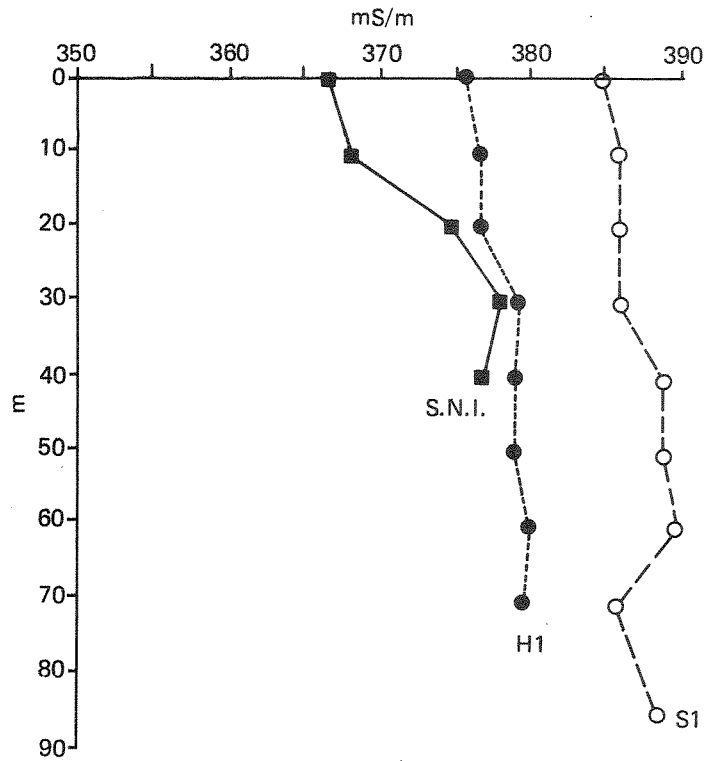


Figure 4.5-3 Conductivity profiles in the southern basin (S1), central basin (H1) and in the northern sector (S. N.I.) in July-August 1988.

The reason for the high ionic strength in Lake Turkana is that salts brought to the lake by the inflowing water are left behind when water is lost by evaporation. Hopson (1982) estimated that if no other process than concentration through evaporation acted, the conductivity should have increased by 0.6 mS/m per year since the time of closure ca. 7500 b.p. The actual increase in conductivity has been much lower (ca. 0.045 mS/m per year). Concequently the salt content of the water must be modified by other factors. This can also be seen by comparing the proportion of different ions in the lake and in the water which enters the lake from River Omo. No samples from River Omo could be obtained during this study, but data from Hopson (1982) show that the proportions of calcium and magnesium, but also potassium is much higher in the river water than in the lake.

The processes causing the loss of some ions from the lake water have been investigated by Yuretich and Cerling (1983) who showed that calcium, magnesium and potassium are lost to the sediments by formation of insoluble minerals. Also some sodium appears to be lost, probably by adsorption to minerals. The most conservative ion is

chloride. Hopson (1982) found that the theoretical concentration factor for this ion since enclosure was very close to the observed value (292 and 330, respectively).

Wood and Talling (1988) compiled data from a number of Ethiopian alkaline lakes and showed that the relative proportions of the major ions are fairly constant over a wide range of salinities. Lake Turkana fits well into this picture. The loss of Mg and Ca by mineralisation seems to occur particularly at conductivities above 100 mS/m and results in a poor correlation between these ions and conductivity for the whole series of lakes studied.

On the other hand sodium, chloride and alkalinity were found to be better correlated with the conductivity, which shows that these ions are more conservative in the alkaline lakes.

The increase of conductivity that was observed in the period 1984-1988 indicates that the processes wich counteract the evaporative concentration of salts are too slow to cope with the rapid reduction of lake volume that took place during these years (see figure 4.5-2).

4.7 Minor ions

Concentrations of different metals were analysed from several localities and depths of the lake. The main motives for these analysis were documentary and also to identify unexpected concentrations. The following metals were analysed: Copper (Cu), zink (Zn), cobalt (Co), lead (Pb), mercury (Hg), manganese (Mn), nickel (Ni), aluminium (Al), iron (Fe), cadmium (Cd) and chromium (Cr). The mean values, together with minimum and maximum figures are given in table 4.7-1, and the data are listed in appendix V.

The concentrations of copper, zink, cobalt, lead, mercury, nickel, cadmium and chromium were fairly low and quite stable.

The values of aluminium, iron and partly manganese fluctuated with some rather high concentrations. These fluctuations could be seen in connection with influx of water from River Omo. The highest concentrations coincide with the most turbid water (lowest transparency and Secchi depth).

Aluminium occurs in different fractions and one group, labile aluminium, is known to have high toxic effect on fish. Three samples with low, medium and high concentrations of total aluminium were

analysed for labile aluminium. The concentrations were all low, less than 38 µg/l, and with no expected effect on fish.

Few analysis of metals in water exist from this part of Rift Valley. Wood and Talling (1988) summarize the figures available from Ethiopian rift lakes. Compared with Lake Turkana, some of these values were slightly higher but within the same order of magnitude.

Table 4.7-1 Concentrations of metals (µg/l) from Lake Turkana 1987-88 given as mean, minimum and maximum values.

	Mean	Min - Max		Mean	Min - Max
Cu	3.6	2.7 - 5	Ni	<5	<5 - <5
Zn	25	<10 - 50	Al	1360	253 - 3750
Co	<5	<5 - <5	Fe	735	86 - 2150
Pb	0.9	0.8 - 1.0	Cd	0.12	<0.1 - 0.16
Hg	<0.5	<0.5 - <0.5	Cr	1.2	<5 - 1.5
Mn	10.8	4.0 - 30.8			

4.8 Plant nutrients

The nutrients that most frequently limit the production of algae in lakes are phosphorus, nitrogen and silicate. In temperate lakes phosphorus is by far the most important element in this respect, and it has been shown that the maximum algal biomass in lakes may be predicted from the load of phosphorus together with some hydrological features (Vollenweider 1976). There are, however, several indications that the situation may be different in tropical lakes. Talling and Talling (1965) who reported chemical data from a great number of African lakes noted that the phosphorus concentrations were generally higher than in temperate lakes and that the often low levels of inorganic nitrogen may imply nitrogen limitation of the algal production. Later Moss (1969) showed experimentally that nitrate or nitrate plus phosphate were potentially limiting to algal growth in several Malawi lakes. A recent review of nutrients in African lake ecosystems (Thornton 1986) strengthens the impression that the nitrate/phosphate ratio in African lakes generally is low, which means that nitrogen may play a more important role as limiting nutrient for algal production. It should be pointed out, however, that nutrient limitation can not be determined by chemical analysis of water alone.

Nutrient limitation must be assessed by physiological examination of the algae or by detailed analysis of the nutrient regeneration prosesses in the lake.

Some organisms such as some blue-green algae (Cyanobacteria) have the ability to assimilate nitrogen in the molecular form (N_2), which occurs dissolved in the water and is supplied by exchange with the atmosphere. Production of nitrogen-fixing blue-green algae can therefore take place without supply of dissolved nitrate and ammonia as long as other nutrients, including phosphorus, are available.

While phosphorus and nitrogen are essential nutrients for all algae, silicate is essential only to algae producing silicate skeletons, mainly the diatoms. Silicate, therefore, does not limit the potential production of algal biomass in a water body, but it may effect the species composition of the algae that develop.

During this study, several analyses of phosphorus and nitrogen compounds and some of silicate were made. (See appendix II, III and IV). For phosphorus and nitrogen, both the total content and the available inorganic components (phosphate, nitrate and ammonia) were analysed. The phosphorus content of all samples from the lake was very high (2.2-2.4 mg P/l). The phosphate-P concentration was in the same range as the total phosphorus, and when both parameters were analysed on the same samples, it was found that practically all the phosphorus was in the phosphate form, and thus readily available for assimilation by algae.

The content of total nitrogen was in the range 0.5-2.1 mg N/l, which is also rather high, but still low when compared to the phosphorus levels. Unlike phosphorus, however, most of the nitrogen was not in a form readily available to the algae. The nitrate concentrations were almost exclusively below 100 µg N/l, and ammonia below 40 µg N/l. The nitrate analysis were carried out with two different methods (see appendix I), and when both methods were applied on the same samples, it was found that the salycilate method, which was used for the majority of the analysis, tended to overestimate nitrate at the lowest concentrations and underestimate it at the highest concentrations when compared to the more recognized Hg/Cu-reduction method. The variations in concentrations that are reported may therefore be underestimated. Obviously the concentrations may fall to very low levels (less than 10 µg N/l) as was found in July and August 1988 (See appendix IV). This indicates that the supply of nitrogen may limit algal production in the surface layer. During the stratification periods, the nitrate concentrations were higher below the thermocline, where nutrients are

released from decaying organic matter, than above, where nitrate is assimilated by the algae. This can be seen in the data from April 1987 and April-May 1988.

The inorganic nitrogen compounds (nitrate and ammonia) usually accounted for less than 20% of the total nitrogen. The nature of the remaining nitrogen is not known. Analysis of samples taken in July-August 1988 showed little difference between filtered and unfiltered samples, which means that most of the nitrogen is in dissolved forms or attached to particles smaller than 1 µm. The content of particulate nitrogen was analysed directly by element analysis of material collected on a glass fibre filter from a sample taken at H1 on 26 March 1987. According to this analysis the content of nitrogen was 90 µg N/l, while the total nitrogen concentration was 570 µg N/l. Thus approx. 16% of the nitrogen was recovered in the particulate fraction. Of the remaining 480 µg N/l in solution, 27 µg was as nitrate. Ammonia was not analysed in this sample, but from previous analyses, it may be assumed that the ammonia concentration was lower than the nitrate concentration. Thus, some 400-450 µg dissolved N/l is not accounted for. The nature and biological significance of this nitrogen fraction remains unknown, but algal assays have shown that it is not readily available for algal production (See section 4.9)

The nutrient concentrations in the central part of the lake do not display any obvious annual variations. Very low concentrations of dissolved inorganic nitrogen may be observed in the surface layer at any time of the year. Probably, rapid fluctuations occur as a result of wind mixing. In periods of little mixing, nitrate near the surface is rapidly depleted by the algae.

Silicate analysis were carried out on samples taken in March and July-August 1988. The results are shown in appendix IV. All values are high, ranging from 21-39 mg/l. Silicate limitation of the growth of diatoms in the lake is therefore unlikely.

Comparison of the nutrient data from this study with data from the Hopson study 1973-1975 shows large deviations in the levels of phosphate. The average phosphate concentration in lake water samples reported by Hopson (1982) was 330 µg/l, while a large number of samples in 1985-1988 showed phosphate concentrations above 2000 µg/l. Morover, there was perfect agreement between values obtained at the field laboratory and at the NIVA laboratory in Norway. The reason for this discrepancy between Hopson's results and the present ones is not known, but changes in phosphate levels of this magnitude seems unlikely. The same method was used for phosphate analysis in both

studies.

Also the nitrate concentrations reported by Hopson (1982) are low, but still in the same order of magnitude as has been found during this study. As discussed earlier, the nitrate determinations made by the salycilate technique may have overestimated the nitrate concentrations in the low range. The results therefore supports the conclusion drawn by Hopson (1982) that nitrates are very rapidly utilized and therefore never are found in high concentrations in the surface waters.

The permanently high concentrations of available phosphorus rules out the possibility of phosphorus limitation of algal producrtion in the lake. The frequently very low concentrations of nitrate indicate that the production of algae may be limited by the supply of nitrogen. However, the recycling of nitrogen may be rapid enough to allow a high rate of primary production. The role of the relatively large pool of dissolved nitrogen compounds is particularly interesting in this connection.

4.9 Algal growth potential

Algal growth potential (AGP) tests, using a green alga (Monoraphidium minutum) isolated from a fish pond in Kalokol, were carried out on samples taken from the lake in March and July-August 1988. All samples were mixed surface layer samples from 1-6 m depth. The cell yield in samples without nutrient addition and with addition of P, N and the two nutrients in combination is shown in table 4.9-1.

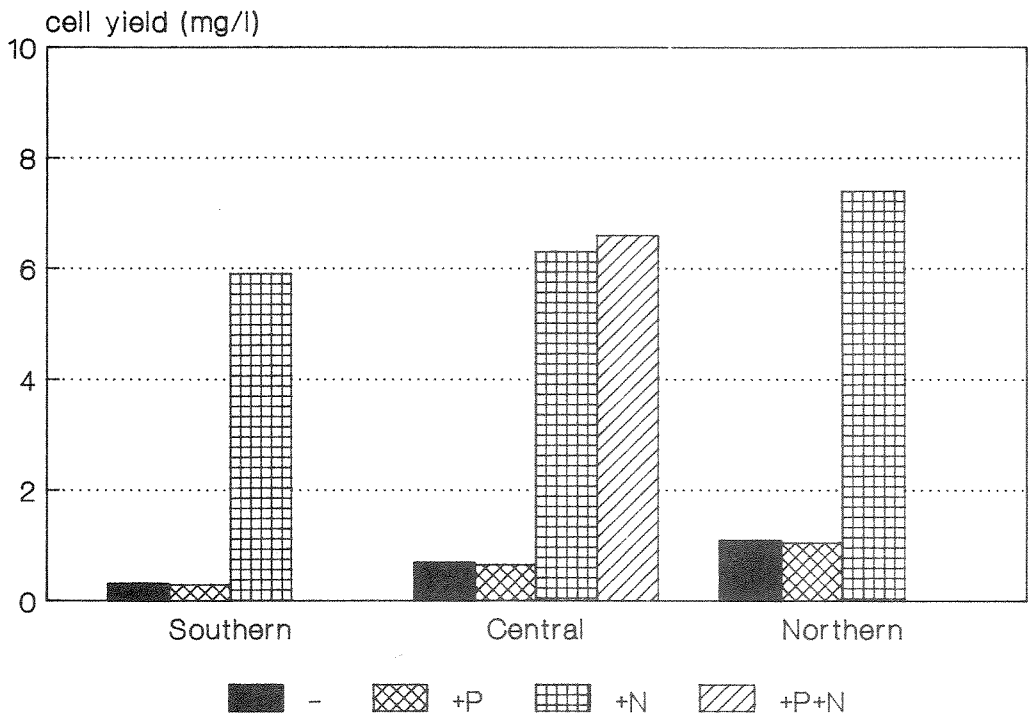
The results show that phosphorus addition had no stimulating effect on the growth of the test alga in any of the samples. When nitrogen was added, the biomass production increased dramatically. Phosphorus and nitrogen in combination gave no further increase compared to nitrogen additions alone.

The AGP-tests confirm the conclusions from chemical analysis that nitrogen is a potential limiting nutrient in Lake Turkana and that phosphorus is available in surplus. This means that the large pool of dissolved nitrogen is not readily available for assimilation by the algae.

The AGP-tests of samples taken in July-August also indicate a gradient in nutrient (nitrogen) avaliability, which increases from the southern to the northern part of the lake.(See figure 4.9-1).

Table 4.9-1 **Result of algal growth potential tests. Final cell yield of test algae (mg/l) without nutrient addition and without addition of 50 µg P/l and 500 µg N/l.**

Sample	Date	Cell yield (mg/l) no nutrients	+P	+N	+P+N
H1 (Central)	26.03.88	1.1	1.0	4.3	4.5
H1 (Central)	11.08.88	0.69	0.65	6.3	6.6
S1 (Southern)	21.07.88	0.31	0.29	5.9	--
North Island	08.08.88	1.09	1.05	7.4	--



Nutrient spikes: 50 ug P/l, 500 ug N/l

Figure 4.9-1 **Algal growth potential in samples from the southern, central and northern sector of Lake Turkana in July-August 1988. The bars illustrate the cell yield in samples without nutrient addition and with addition of 50 µg P/l and 500 µg N/l.**

4.10 Particulate material

Lake Turkana receives large amounts of fine particulate material from the rivers. The finest particles remain in suspension for a long time. Particles are also brought into suspension by erosion of the bottom in shallow areas by waves and currents. As a consequence, the content of particulate material in Lake Turkana is always high, which gives the water a greenish-grey apperance and reduces the transparency (see section 4.4.

The particulate material from different parts of the lake in July-August 1988 was collected on glass fibre filters for inorganic and organic analysis. The results are shown in table 4.10-1.

The particle transport with the River Omo flood caused very high concentrations of suspended solids in the surface water at the North Island 32 mg/l). In the central sector of the lake the levels were between 2.2 and 3.2 mg/l, and even lower in the south (1.4-1.9 mg/l). In the very turbid water in the north, the organic fraction of the suspended matter contributed only 10-15% of the suspended solids. The organic content increased with decreasing content of suspended solids to 20-30% in the central sector and 40-45% in the south. This means that the organic particulate content was more evenly distributed than the inorganic.

Table 4.10-1 Particulate (inorganic and organic) material in water samples July-August 1988).

Station	Date	Depth m	Total mg/l	Inorganic mg/l	%	Organic mg/l	%
South N.I.	8/8	0-3	35.75	31.50	88	4.25	12
South N.I.	8/8	10	20.17	17.17	85	3.00	15
H1	17/7	0-6	2.71	2.05	75	0.66	25
H1	17/7	10	3.56	2.72	77	0.84	23
H1	17/7	40	3.16	2.27	72	0.89	28
West C.I.	4/8	0-6	3.54	2.46	69	1.08	31
East C.I.	4/8	0-6	2.29	1.37	60	0.92	30
S1	21/7	0-6	1.57	0.87	55	0.70	45
S1	21/7	10	1.92	1.04	54	0.88	46
S1	21/7	40	1.39	0.81	58	0.58	42

The concentrations of organic particulate material in the northern part of the lake in August 1988 shows that a considerable amount of allochtonous material is brought to the lake from the catchment area with the Omo River flood. There are no data from the river itself that can be used for calculations of the total load of allochtonous material to the lake. If the concentration found at the Northern Island during the flood (4.25 mg organic dry weight /l) is taken as representative for the water entering the lake, and the mean influx is 500 m^3/s, the annual load of allochtonous organic material would be roughly 10 $g/m^2/year$ or 50 $kcal/m^2/year$. This is less than 1% of the estimated mean phytoplankton gross production (see section 4.13). It appears thus that the allochtonous input of organic material is small compared to the autochtonous (in the lake) production when the whole lake is considered. In the northern part of the lake, where most of the influx takes place, the contribution of organic material from the river may, however, be significant. Analysis of the water entering the lake is needed for a more accurate estimate of this contribution to the energy budget of the lake.

4.11 Chlorophyll

Measurements of the amount of chlorophyll-a in particulate material can be used as an estimate of abundance of phytoplankton in the water. No fixed ratio between chlorophyll and algal biomass can be given, but the normal range of chlorophyll-a content in algae is ca. 1-5 %.

The results of chlorophyll analysis are given in appendix VI. The vertical distribution of chlorophyll was usually rather uniform in the surface layer. Therefore the average chlorophyll in samples from 0-6 m was calculated for each series. Figure 4.11-1 shows the chlorophyll levels measured in the central part of the lake (H1) in 1987-1988. Most observations show concentrations in the range 2-4 µg chl-a/l. One extreme value, ca. 13 µg chl-a/l was found during an algal bloom in November 1987. Unfortunately no further observations were made during this period that could show for how long this situation persisted.

The sampling frequency does not allow an analysis of the annual variations in algal biomass, but the observations indicate that the highest levels occur at the time when the Omo River flood reaches the central part of the lake. This is also the period when algal blooms at the surface are most frequent.

During periods when the frequency of observations was high, as in March-April and July-August 1988, it can be seen that short-term

fluctuations in chlorophyll concentration can be considerable. This is probably a result of wind mixing of the surface water. The frequent strong winds mix and dilute the algae down from the surface layer. During calm periods, algae with buoyancy (eg. Microcystis and Botryococcus) move towards the surface. Thus, the vertical distribution of the algae depends on the weather conditions not only at the time of sampling, but also during several hours prior to the sampling.

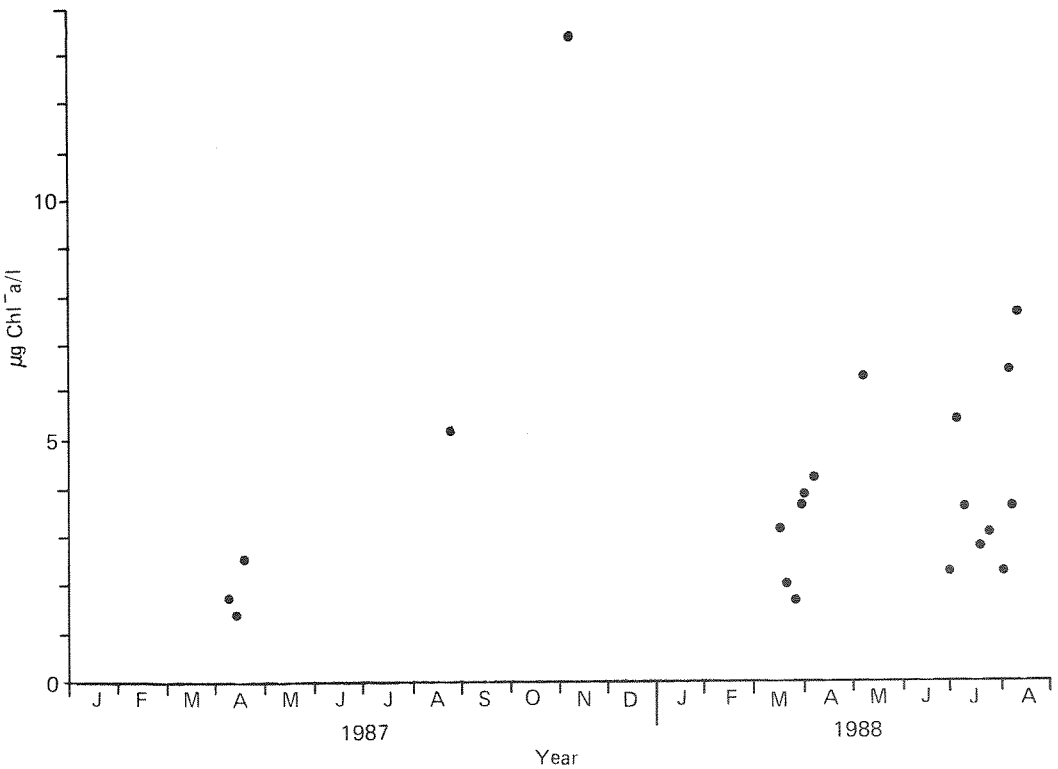


Figure 4.11-1 Chlorophyll-a mean values 0-6 m in the central sector of Lake Turkana 1987-1988.

Since the study concentrated on the central part of the lake, there are little data to describe the horizontal distribution of chlorophyll over the lake. An investigation of transects within the central sector between Nataba and Moite and between Longech spit and Allia Bay 16-17 April 1987 showed a range from 1.7-3.6 µg chl-a/l without any conspicuous general trend. Samples taken in the central section of the lake on 4 August 1988 showed a higher value on the western side (6.4 µg chl-a/l) than on the eastern (3.5 µg chl-a/l).

When chlorophyll was measured near the North Island in March 1988, the concentration was low (2.1 µg/l) and not significantly different from

the levels recorded in the central sector at the same time. In the beginning of August, however, when the River Omo was flooding, chlorophyll concentrations were much higher near the North Island than in the central part of the lake.

Figure 4.11.2 shows profiles of chlorophyll-a in the northern, central and southern part of the lake as observed between 22 July and 8 August 1988. The profile from the northern sector (near the Nothern Island) shows a strong accumulation of algae near the surface. Blooms of Microcystis were observed in the area. The profiles from the central and southern sector show an almost uniform distribution down to 6 m. The maximum concentrations were lower than in the northern sector, but the average concentration over 0-6 m depth at station H1 was not much lower than at the northern station. At S1 in the south, the chlorophyll concentrations were low at all depths. The figure illustrates the effect of nutrient input from the River Omo, which allows development of high algal density in the north. At the time of observation, the flood water was beginning to reach the central part of the lake, where the chlorophyll concentrations were increasing. The southern part of the lake was not affected by the River Omo flood.

Before this study, no data on chlorophyll had been reported from the open lake. Harbott (Hopson 1982) analysed chlorophyll only in the Ferguson's Gulf, and used phytoplankton volume as a measure of biomass for the open lake stations. An approximate conversion factor from cell volume to chlorophyll can be obtained from the data reported by Hopson (1982) from Ferguson's Gulf, which show that chlorophyll-a (µg/l) is approximately 6 times the algal volume (mm^3/l). According to the figures presented by Hopson (1982), the algal volume in the central sector of the lake was between 0.05 and 0.6 mm^3/l (mean values for the whole water column). This corresponds to approximately 0.3-4 µg chl-a/l. Unfortunately, algal biomass in the euphotic zone comparable with the present study was not reported. It was noted, however, that the distribution of phytoplankton was not uniform, often showing accumulation of algae towards the surface.

Profiles of chlorophyll over the whole water column were analysed on four occasions in 1988. In April, when the water was stratified, chlorophyll was very low below the thermocline (0.2-0.6 µg/l), while it was 3-4 µg /l between 0-20 m. Profiles taken after the stratification broke up show much more even distribution of chlorophyll over the whole column, although the concentrations were always highest near the surface. (See figure 4.11-3).

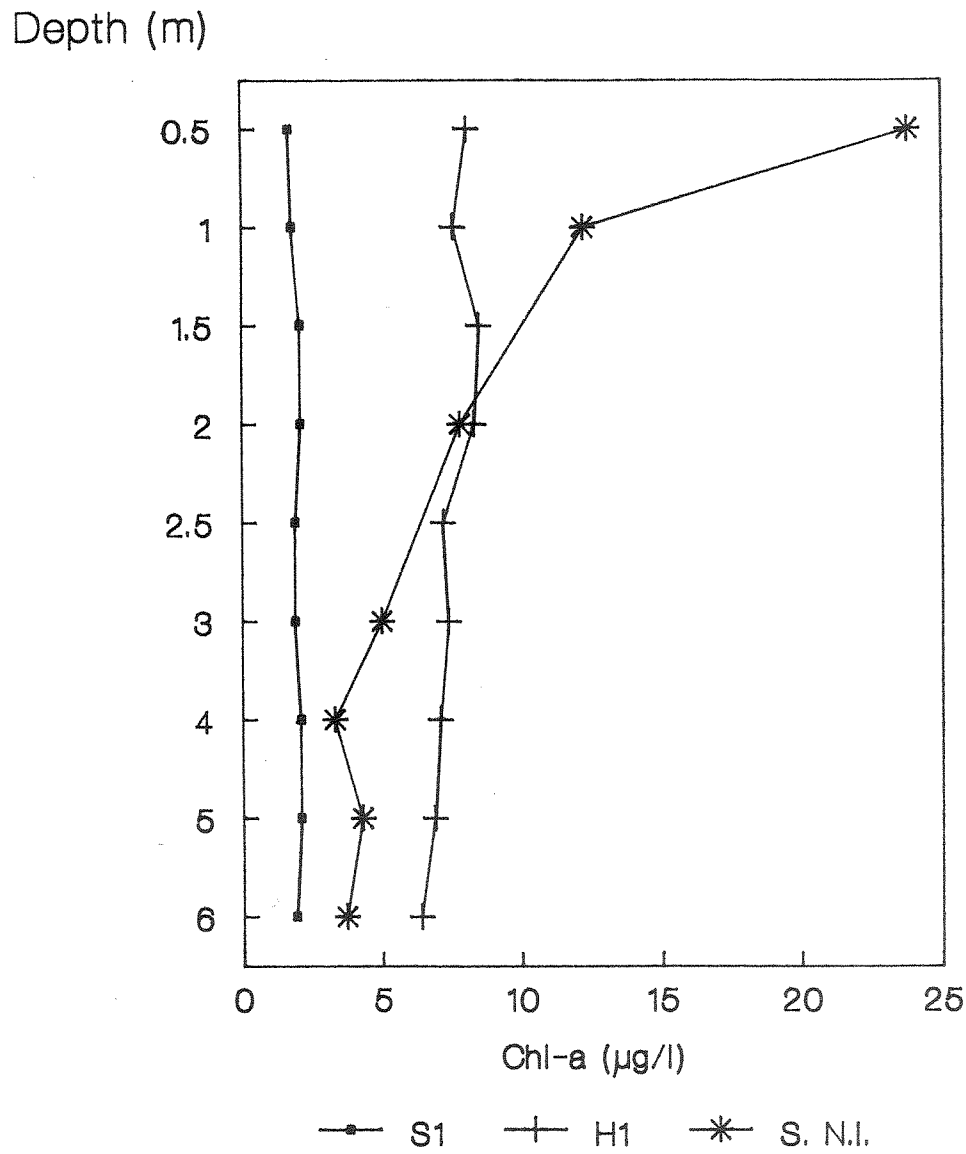


Figure 4.11-2 Chlorophyll-a profiles in the southern (S1), central (H1) and northern (S. N.I.) sector of Lake Turkana in July-August 1988.

The distribution of chlorophyll shows that the phytoplankton is continuously mixed down from the euphotic zone, when the water is not stratified. Degradation of phytoplankton below the euphotic zone causes a decrease of chlorophyll. This is most significant when thermal stratification reduces the transport of phytoplankton to the hypolimnion as in April 1988. Chlorophyll content decreased approx. 50% within one week in water samples from the surface layer stored in the dark at 25-30 ^{0}C.

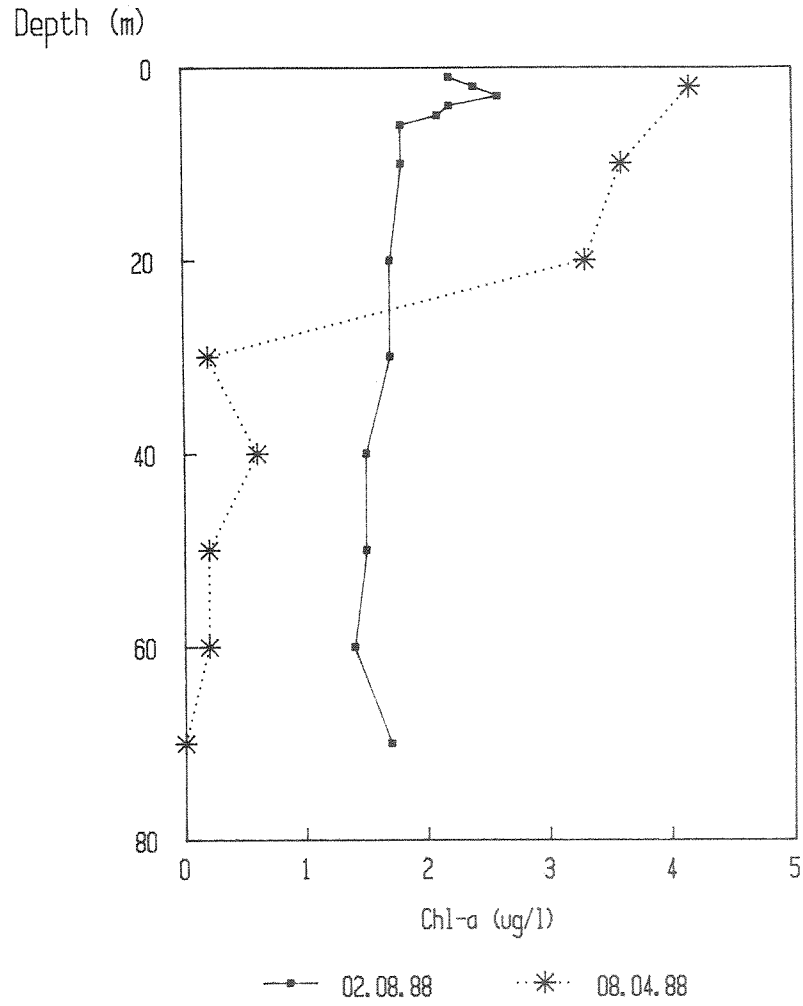


Figure 4.11-3 Chlorophyll-a profiles at H1 in the central basin of Lake Turkana during periods with thermal stratification (8.4.88) and without stratification (2.8.88)

4.12 Phytoplankton

An extensive survey of the plankton flora in Lake Turkana was carried out by Harbott in 1972-1975 (Hopson 1982). During that study, quantitative estimates of different algal species were made in a large number of samples covering all seasons and different parts of the lake. It was not possible to obtain a similar detailed description of the phytoplankton during this study. Samples for identification of the most important species in the euphotic zone were collected with a plankton net (mesh size 25 µm) on several occasions at different times

of the year, mostly in the central sector of the lake in 1984- 1988. The material does not allow quantitative estimates of the phytoplankton density, but may give information on the relative importance of different net plankton species.

The occurence and relative abundance of different algal species in the net samples is indicated in table 4.12-1 and pictures of the most important species are shown in figures 4.12-1-4.

The number of of phytoplankton species found in the net samples was low. The species that most frequently dominated the the plankton were the blue-green alga Microcystis aeruginosa and the green alga Botryococcus braunii. Blooms of Microcystis were sometimes observed, e.g. in the central part of the lake in October 1987 and in the area around the North Island in August 1988. Such events appear to occur in connection with flooding of rivers which brings nutrient-rich water to the lake. Less conspicuous blooms were occasionally formed by Botryococcus, which was concentrated by wind driven currents to form a reddish scum along the western shore e.g. on 11 April 1987.

Usually Botryococcus ans Microcystis occured simultanously in the net samples, but Microcystis appeared to be more abundant in periods with rising lake level and low transparency, while Botryococcus was most abundant in March-June, when the lake level was going down and the water usually was more transparent. This may indicate that Microcystis is favoured by the higher nutrient availability caused by the inflow of nutrient rich water from the rivers. Dominance of Microcystis when the influence of Omo flood water is high was observed also by Harbott (Hopson 1982).

The filamentous green alga, Planctonema lauterbornii was observed in all samples, and was particularly abundant in May 1988. Other important green algae were Oocystis gigas, Oocystis sp. and Spaerocystis schroeterii.

Among the diatoms, the centric, planktonic Coscinodiscus sp (probably C. rudolfii) was usually the most abundant. A large pennate species, Surirella sp. was observed in most samples, and was abundant on several occasions. Surirella sp. is not considered to be a planktonic alga and could be expected to sink rapidly out of the euphotic zone. The fact that this species was found so often in large numbers in the middle of the lake, where the depth is 70 m, and several kilometers from the Central Island is difficult to explain if it should be only of litteral origin, brought out into the pelagic zone by the currents.

Table 4.12-1. Algae found in net samples (25 µm) of plankton from Lake Turkana. The relative abundance is indicated as:

* = sparse
** = common
*** = abundant
**** = dominating

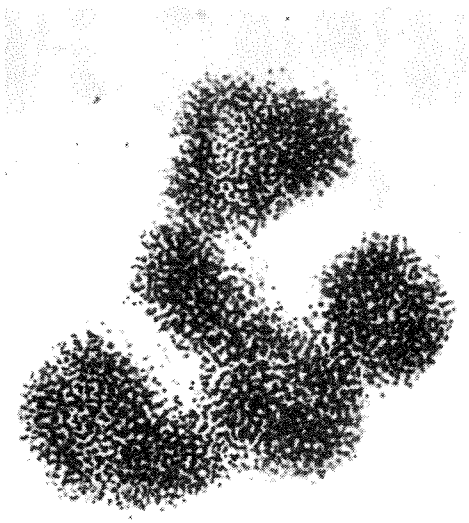
Station:	H1	H1	H1	H1	H1	H1	S1	S. N.I.	H1	H1	H1	H1	H1	S1	S. N.I.
Date:	06.10.87	15.10.87	21.11.87	07.01.88	17.03.88	26.03.88	08.04.88	03.05.88	19.05.88	30.05.88	30.06.88	17.07.88	04.08.88	21.07.88	08.08.88
Blue-green algae															
Microcystis aeruginosa	***	***	**	***	*	**	***	**	**	***	**	***	***	**	***
Anabaena constricta						(*)									
Green algae															
Oocystis gigas	*	*	*	*	*	*	*	**	*	**	***	**	*	*	*
Oocystis sp.	**	**	*	*		*					**	**	**	*	*
Sphaerocystis schroeteri	*			**		*	**	*	*	*	**	**	**	**	*
Planctonema lauterbornii	*	*	*	*	*	**	*	*	***	***	*	**	**	**	*
Botryococcus braunii			*	*	**	**	*	***	***	***	***	**	*	*	*
Diatoms															
Coscinodiscus sp.			*	*	**	**	*	**	*	**	**	***	***	**	*
Surirella sp.	**	**	*		**		*				*	*			
Other, pennate diatoms			*												

Only on one occasion, in November 1987, several other species of littoral diatoms were found in the sample taken at H1, indicating transport of suspended algae, probably from the shores of Central Island.

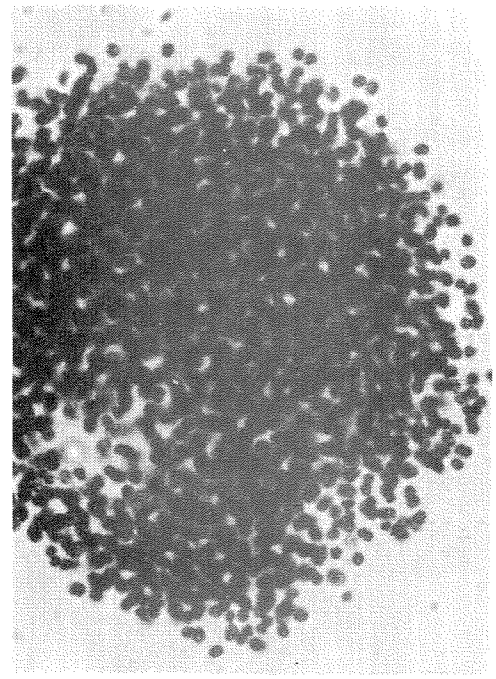
In addition to algae, the net samples taken near the surface often contained large numbers of the ciliate Vaginocola sp. This organism lives inside a cup-shaped house and feeds on small organic particles, eg. bacteria and small algae. Often empty houses were occupied by another ciliate, Vorticella sp. These ciliates were noted also by Beadle (1932) and Hopson (1982). The abundance of planktonic ciliates indicates that these organisms play an important role in the pelagic community.

Many of the phytoplankton species found during this study have been reported also by previous workers. The importance of the blue-green alga Microcystis aeruginosa was noted already by Beadle (1932). Microcystis, Botryococcus, Planctonema and Coscinodiscus were abundant during the study carried out by Harbott in 1973-1975 (Hopson 1982). The green algae Oocystis spp. and Sphaerocystis schroeteri, which were common in the samples in 1987-1988 were, however not included in the list of the most important species by Hopson (1982). This indicates that these species have become more abundant, but differences in sampling technique used during the two studies may have contributed to this apparent difference.

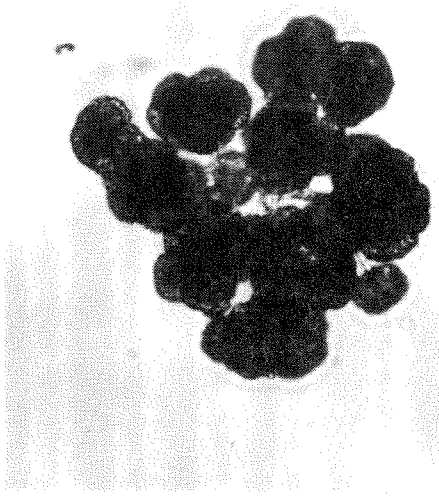
The diversity of the phytoplankton community in Lake Turkana is low compared to the other large East African lakes (Talling 1987, Heckey and Kling 1987). The quantitative dominance of Microcystis and Botryococcus, typical for Lake Turkana, is not found in these lakes. Microcystis aeruginosa is, however dominant in some shallow, turbid lakes in East Africa e. g. Lake George (Ganf 1974) and Lake Baringo (Källqvist 1987).



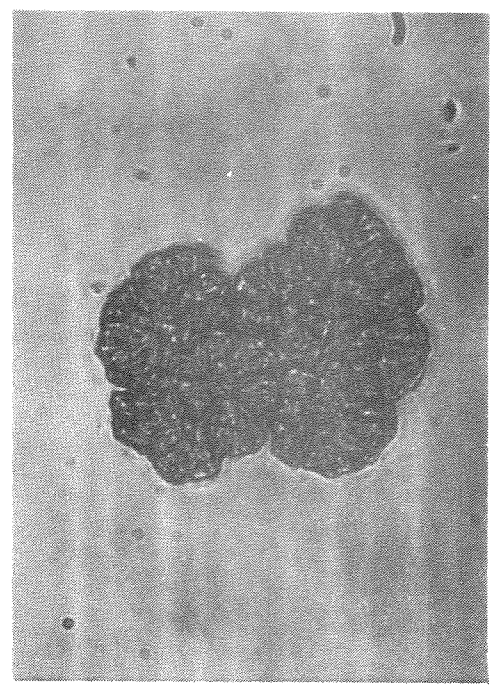
Microcystis aeruginosa



Microcystis aeruginosa

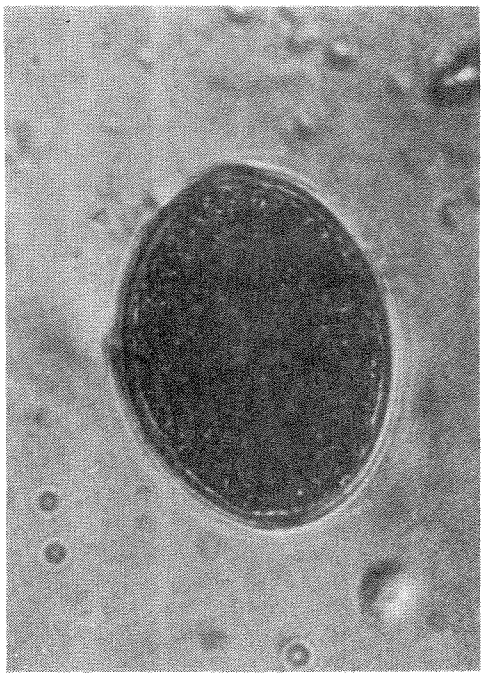


Botryococcus braunii

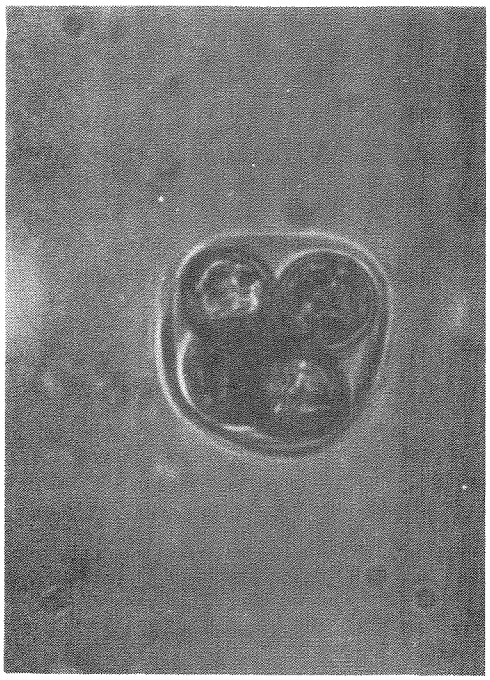


Botryococcus braunii

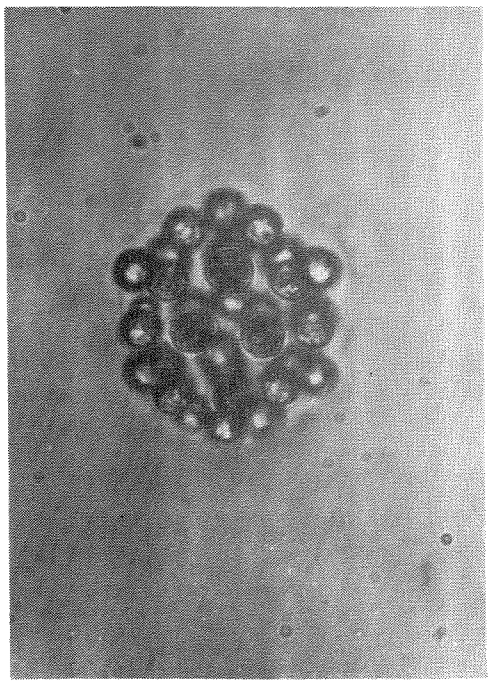
Figure 4.12-1 The most abundant phytoplankton species in net samples from Lake Turkana.



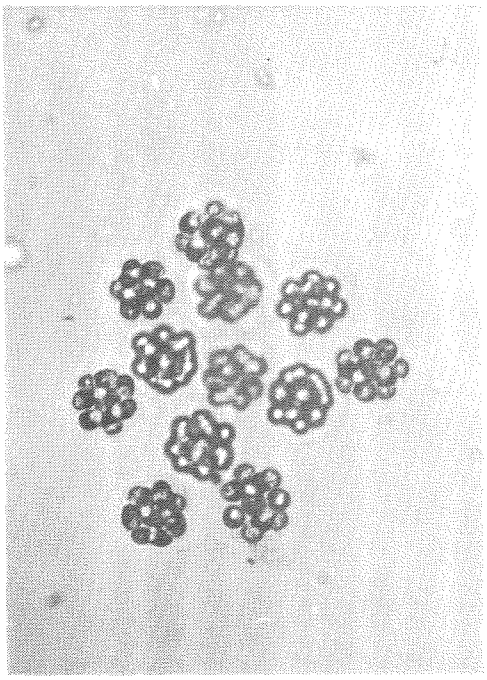
Oocystis gigas



Oocystis sp.

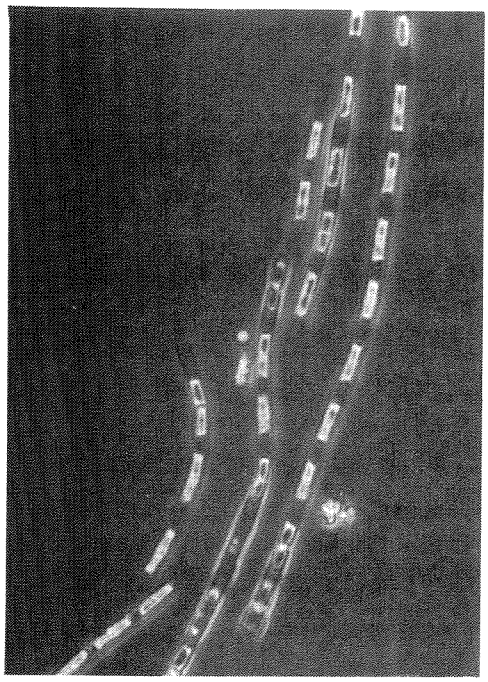


Sphaerocystis schroeteri

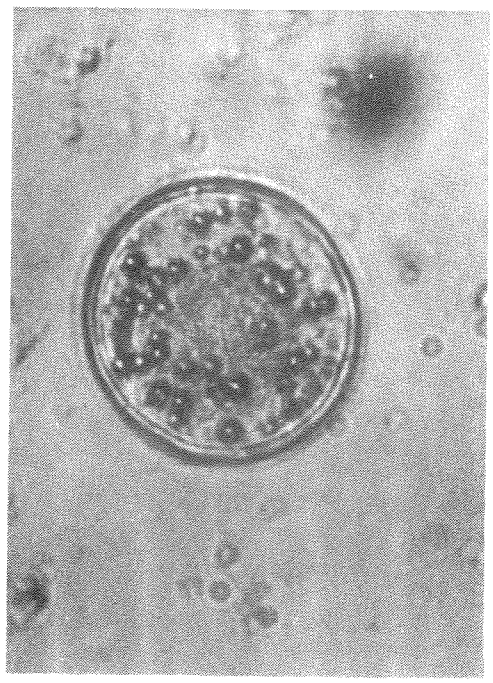


Sphaerocystis schroeteri

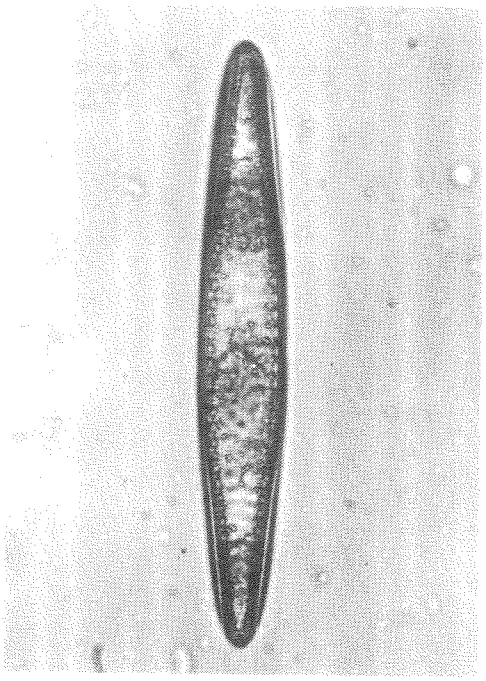
Figure. 4.12-2 The most abundant phytoplankton species in net samples from Lake Turkana



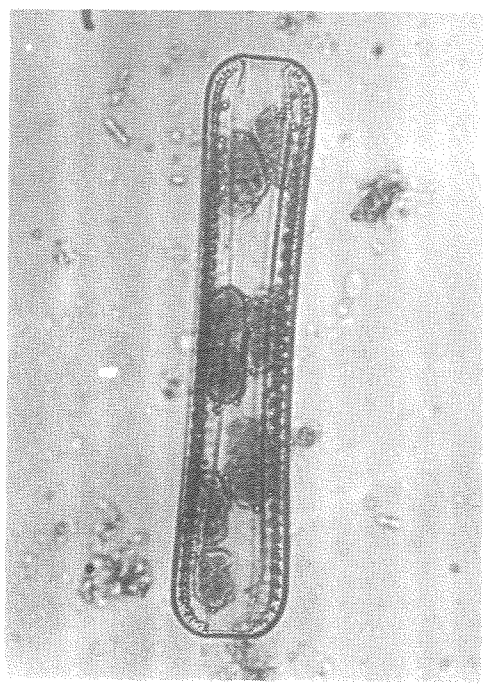
Planctonema lauterbornii



Coscinodiscus sp.

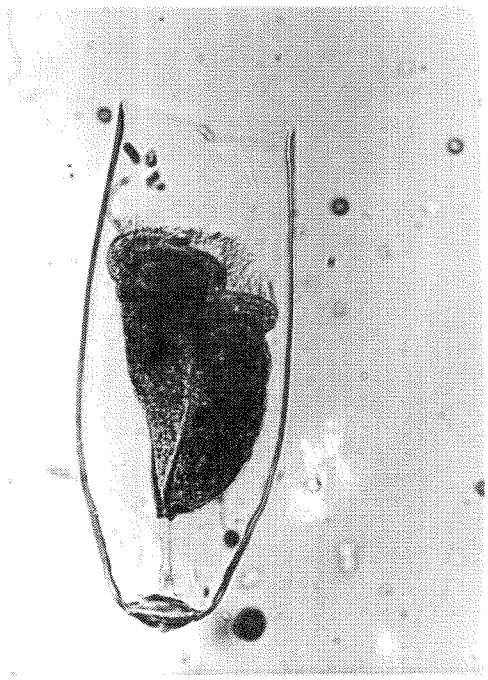


Surirella sp. (top view)

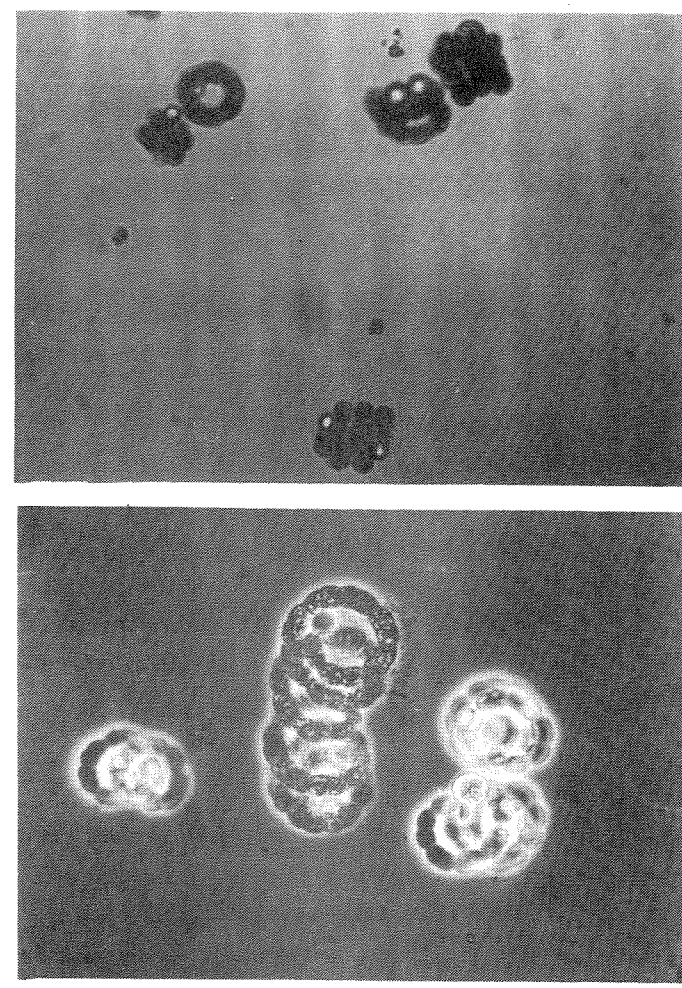


Surirella sp. (side view)

Figure 4.12-3 The most abundant phytoplankton in net samples from Lake Turkana



Vaginocola sp. (ciliate)



Anabaenopsis arnoldii

Figure 4.12-4 Abundant plankton organisms in net samples from Lake Turkana and Ferguson's Gulf (Anabaenopsis arnoldii)

4. 13 Primary production

The photosynthetic production by phytoplankton dominates the primary production in most lakes and thus provides most of the basis for food chains leading to fish. Since primary production is driven by light energy, it is restricted to the upper part of the water column, the euphotic zone. The euphotic zone extends down to the depth where the light intensity is reduced to ca. 1% of the subsurface light intensity. The depth of the euphotic zone depends on the optical properties and the amount of suspended and dissolved material in the water. (See section 4.4).

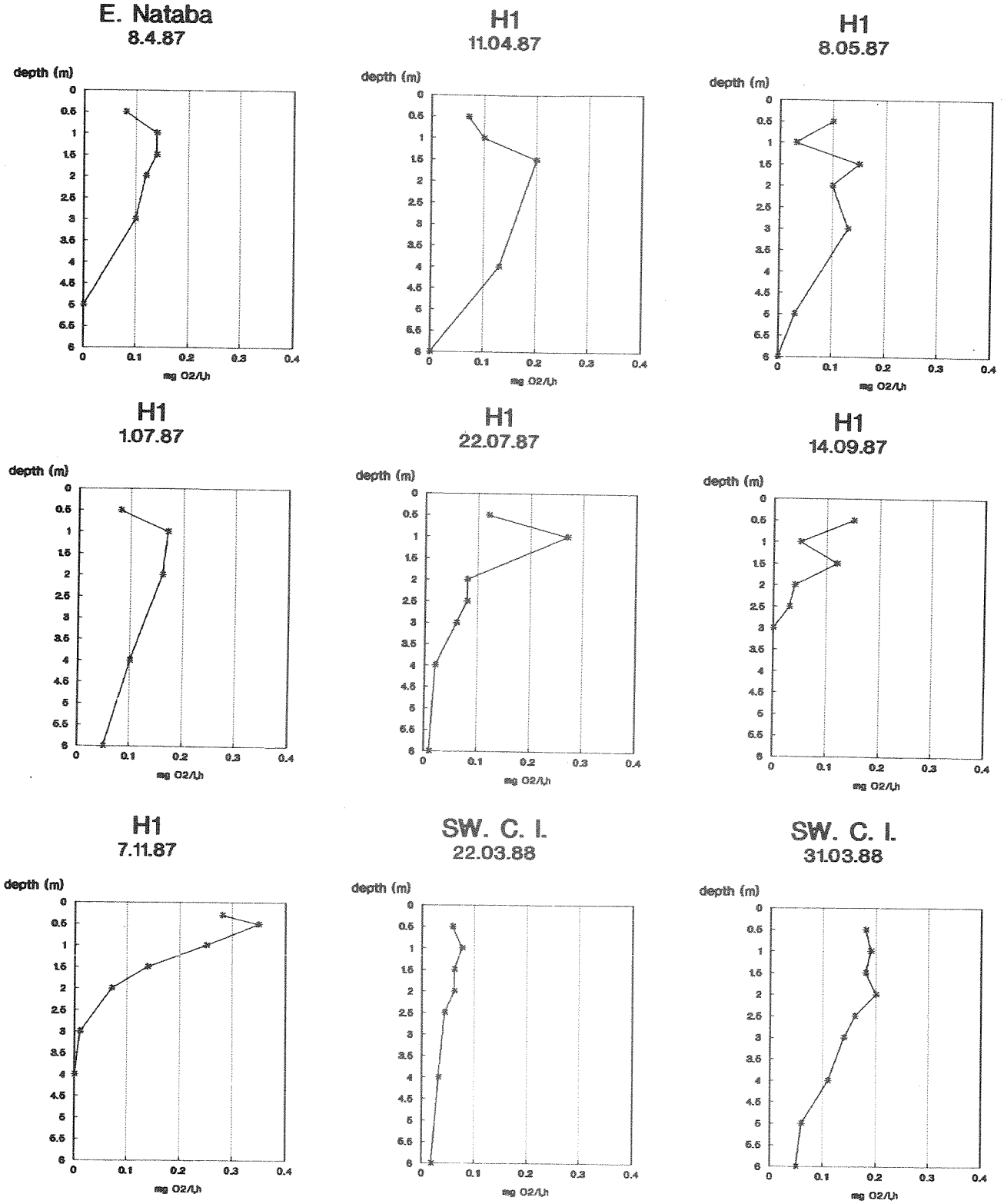


Figure 4.13.1 Profiles of phytoplankton primary production from the central part of Lake Turkana 1987-1988.

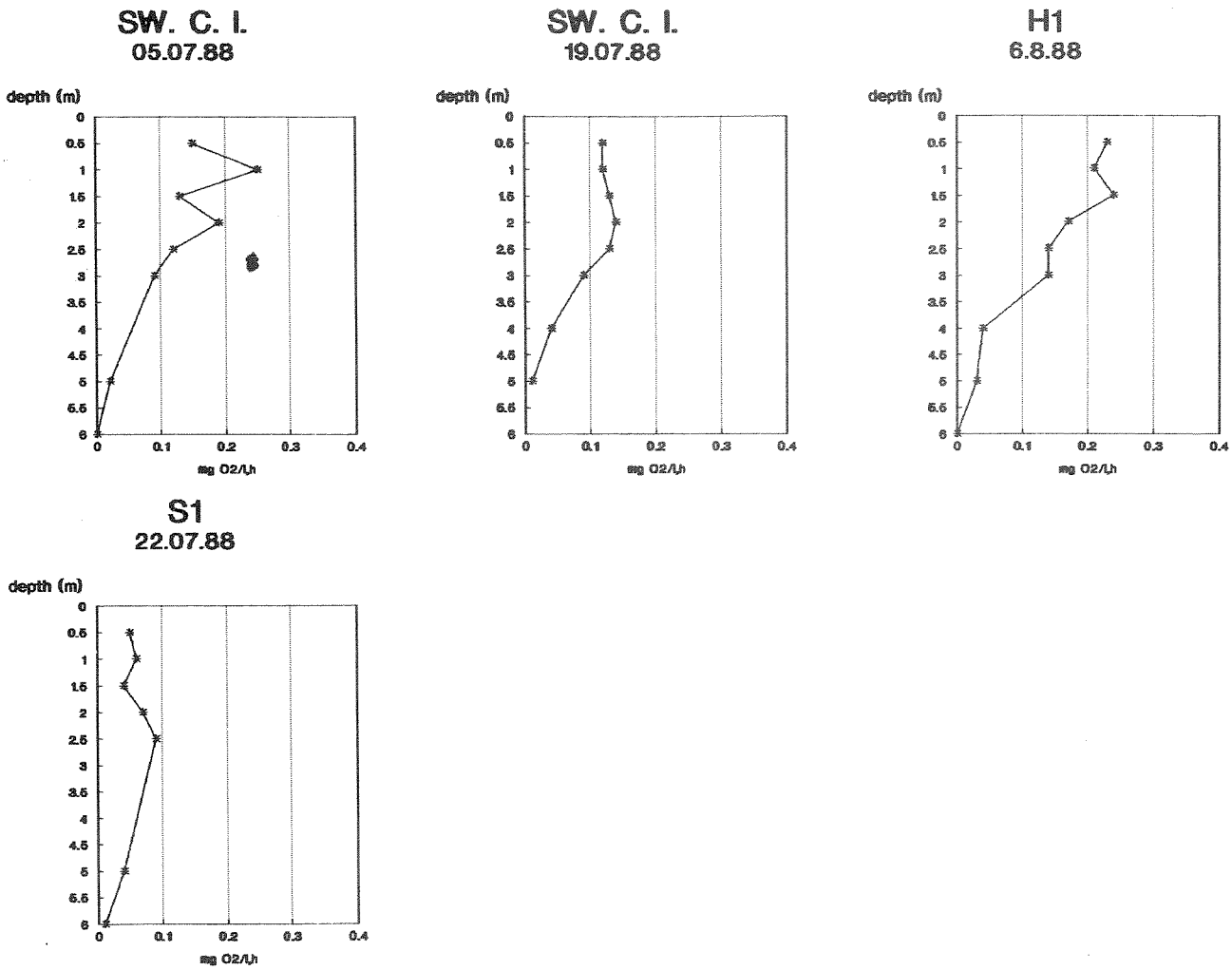


Figure 4.13-2 Profiles of phytoplankton primary production from the central and souther sector of Lake Turkana 1988.

In the photosynthetic reaction, oxygen is produced in proportion to the assimilation of carbon into organic matter. In this study the primary production was measured with the oxygen technique and the results expressed as oxygen produced per hour on volume or areal basis. (For further details on methods, see appendix I.)

Phytoplankton primary production was measured on 12 occasions in the central part of the lake between March 1987 and August 1988. The production profiles are shown in figure 4.13.1-2. Most profiles show a production maximum between 1 and 2 m depth. The lower production rate at the surface is caused by too high light intensity (photoinhibition). Below the maximum, the production decreases more or less in proportion to the light extinction. Uneven vertical distribution of the phytoplankton may, however, cause deviations from this pattern.

The limit for photosynthetic production usually appeared to be between 5 and 6 m. The shallowest euphotic zone was observed in September and November 1987. This was a result of the higher turbidity of the water after the flood in River Omo. In November the phytoplankton density was also high, hence contributing to the high light extinction. The Secchi depth was 1.2 m, which indicates that the euphotic zone was ca. 3.2 m.

The maximum production at light saturation varied from 0.08 mg/l/h on 23 March 1988 to 0.35 mg/l/h on 7 November 1987. The corresponding chlorophyll concentrations were 1.7 and 16 µg/l respectively, which shows that the variations in primary production are largely due to the phytoplankton density. The production rates can be compared to the results reported from the central sector of the lake by Hopson (1982), which ranged from 0.37-0.68 mg/l/h. These higher maximum production values may indicate that the phytoplankton density in 1973-1975 was higher than during the present study.

The photosynthetic capacity of the phytoplankton is defined as the gross production at light saturation divided by the chlorophyll-a concentration. The results from this study give very high values for photosynthetic capacity (20-140 mgO_2/mg chl-a/h). These values can be compared to results from other African lakes as e.g. 6.8-14.3 mg O_2/mg chl-a in Lake Naivasha (Källqvist 1987), 8-15 for several Ethiopian lakes (Belay and Wood 1984) and ca. 25 mg O_2/mg chl-a in Lake Victoria (Talling 1987). The exeptionally high photosynthetic capacity found in Lake Turkana can not be fully explained. The high temperatures in the surface water has obviously contributed since the photosynthetic capacity can be expected to increase with temperature (Lemoalle 1981). The high values are indications that the production rate is not severely hampered by nutrient limitation, which means that plant nutrients (mainly nitrogen) are rapidly regenerated.

The areal production, which is obtained by integration of the depth profiles shows less variation than the maximum production. This is a result of the usually deeper euphotic zone when the phytoplankton density is low. The calculated areal production is shown in figure 4.13-3. The values vary from 0.22 g $O_2/m^2/h$ in September 1987 to 0.76 g $O_2/m^2/h$ in March 1988. No distinct pattern of annual variation can be detected. As was observed for the density of algae, large short-term fluctuations in productivity were found, as e.g. in March-88. The reason for these fluctuations is probably primarily the wind induced mixing of the surface water, moving the algae out of the euphotic zone. During calm periods, buoyant algae are able to accumulate near the surface and chlorophyll concentration and primary

production increase. The difference in primary production between the two observations in March 1988 was, however, larger than the difference in chlorophyll, so also other factors, e.g. the nutrient status of the algae and transparency of the water may have influenced the production rate.

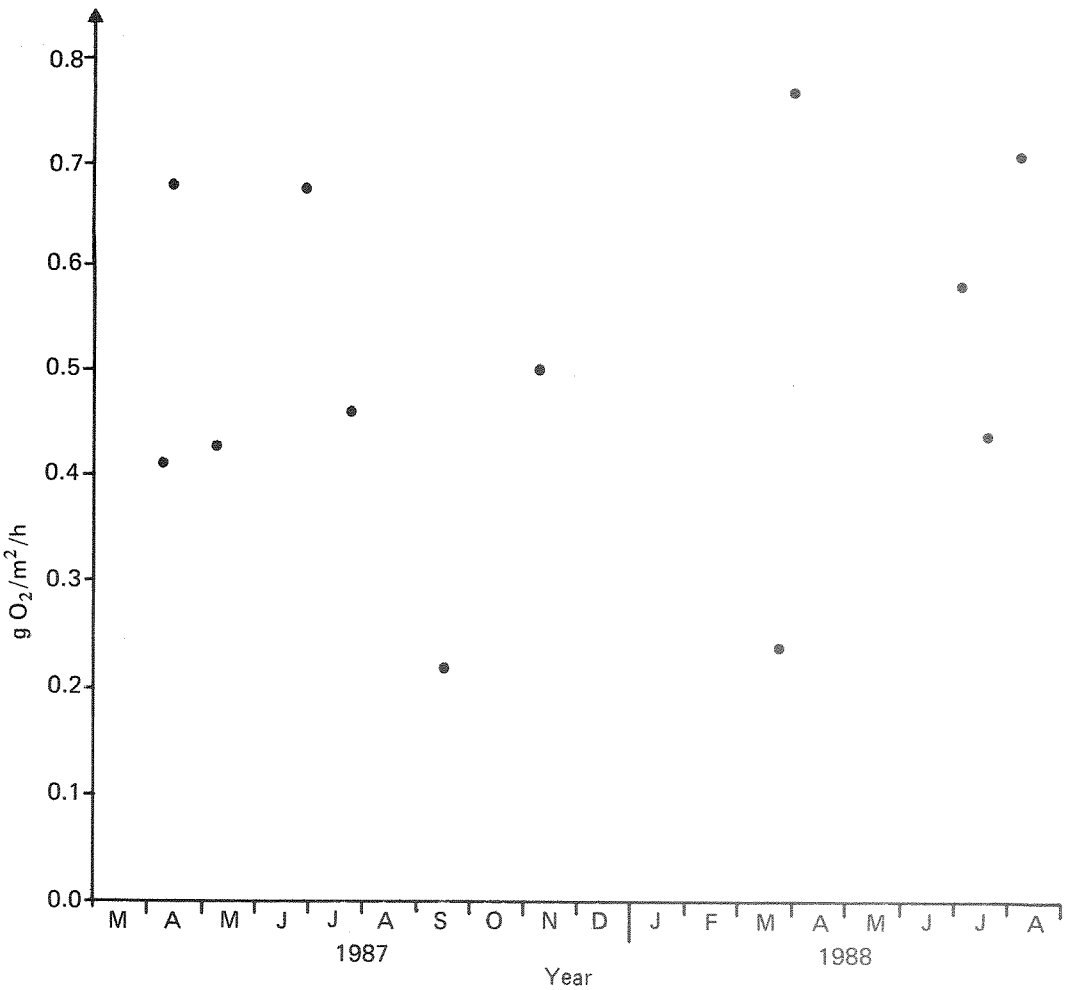


Figure 4.13-3 Areal daily primary production (gross) in the central sector of Lake Turkana 1987-1988.

The areal primary production rates reported by Hopson (1982) from the central sector of the lake were between 0.63-1.14 g $O_2/m^2/h$, i.e. slightly higher than what was found in 1987-1988.

The annual daily primary production can be obtained from the hourly production by applying the formula suggested by Talling (1965). (See appendix I). The daily production (Ad), varied between 2.4 and 8.2 g $O_2/m^2/day$. An estimation of the annual production from the data is difficult because of the non-systematic fluctuations. Since no marked

seasonal variations can be seen, it may be justified to use the mean value for the areal daily production, 5.4 g O_2/m^2/day to obtain a rough estimate of the annual production. The result is approximately 2 kg O_2/m^2/year corresponding to 0.7-0.8 kg C/m^2/year and 1.6-1.8 kg dry weight/m^2/year.

The primary production in Lake Turkana is compared to data from other large African lakes, as refered by Heckey and Kling (1987) and Talling (1965) in table 4.13-1. It can be seen that the annual mean for production in Lake Turkana is lower than in Lake Victoria, but higher than in Lakes Tanganyika and Mali. Compared to other lakes in Kenya, the mean areal production in Lake Turkana is similar to Lake Naivasha in spite of a much lower algal density, and higher than in Lake Baringo (Källqvist 1987).

Table 4.13-1 Primary productivity in large African Lakes. Gross production measured as oxygen evolution (L. Victoria ,L. Turkana , L. Albert and L. Edward), has been converted to carbon, assuming a photosynthetic quotient of 1.2. For the other lakes primary production has been measured as carbon-14 uptake.

Lake	Primary productivity mg C/m^2/ day
Albert[1]	840-3800
Edward[1]	4300
Kivu[2]	660-1000
Tanganyika[3]	400-3100 (800)
Malawi[4]	240-1140 (700)
Victoria[1]	1560-3600 (2300)
Turkana[5]	750-2300 (1700)

[1] Talling (1965),
[2] Jannasch (1965)
[3] Heckey & Fee (1981),
[4] Degnbol & Mapila (1981),
[5] This study.

The production rates in Lake Turkana appear high when the low phytoplankton density and high turbidity are considered. In Lake Victoria, a high rate of primary production is also maintained at a low phytoplankton density, but in much more transparent water which allows photosynthesis to great depth (Talling 1987). Lemoalle (1981) found that the daily gross production (Ad) was 0.14 x ΣB, where ΣB= the chlorophyll-a content in the euphotic zone (mg/m^2) in Lake Chad. This relation was found to be representative for many African lakes. The same relation, calculated from the mean values for chlorophyll, primary production and depth of euphotic zone in Lake Turkana is :

$$Ad=0.19 \times \Sigma B$$

The high relation between production and biomass reflects the high photosynthetic capacity of the phytoplankton in Lake Turkana, which was discussed earlier.

4.14 Phytoplankton and productivity in Ferguson's Gulf and ponds

The wind driven water currents have created several sand spits along the shallow western shore of the lake. The most conspicuous is the Longech spit, which forms a 5 km ridge in the north-south direction. A shallow bay known as the Ferguson`s Gulf is located inside the spit, when the water level is higher than ca. -3m on the scale used in figure 4.1-2. The bay is open to the north and hence is well protected from the prevailing south-easterly winds.

The Ferguson Gulf is a very different environment as compared to the open lake. It was the most important fishing area during the 1970's when as much as 16 000 tons of tilapia was caught annually (1976) (Watson et al. 1985). When this study was started in 1985, Ferguson's Gulf still existed although the water level was low. Some observations were therefore made in 1985 before the gulf dried out completely. These observations, together with observations made in lagoons and experimental ponds may help to explain the very high productivity of the gulf which once formed the basis for the prosperous tilapia fishery.

According to observations by Watson et al. (1985), the gulf was almost dry in April 1985, when only a narrow channel was left. In November the same year, however, the water level was higher, the gulf was several kilometers wide, and the connection to the lake in the north a few hundred meters wide. The depth of the gulf was 0.5-0.7 m over large areas but decreased gradually to the west. The boat wreck "Iji" was surrounded by water ca. 0.45 m deep.

Several samples of phytoplankton and chlorophyll were taken in the gulf on 5. November 1985. Conductivity, temperature, dissolved oxygen and pH were measured in situ (See table 4.14-1). The sampling locations are indicated on the figure 4.13-1. The plankton samples were totally dominated by a filamentous blue-green algae with terminal heterocysts. (see figure 4.11-4). The algae has been designated Anabenopsis arnoldii. During the Hopson study the dominant alga in the gulf was described as Anabaena circinalis. From the description of

this alga by Harbott in Hopson (1982), it appears that this is not the same alga as dominated in 1985 although they are rather similar.

The plankton samples were counted with an electronic particle counter (Coulter Counter) to obtain a measure of the total plankton volume. A peak in the size distribution between 530 and 8500 μm^3 was clearly disinguishable. This was caused by the colonies of Anabaenopsis. The number of colonies could be estimated from the number of particles in this size range. The result of the particle counts are shown in table 4.14-2 together with the chlorophyll-a data.

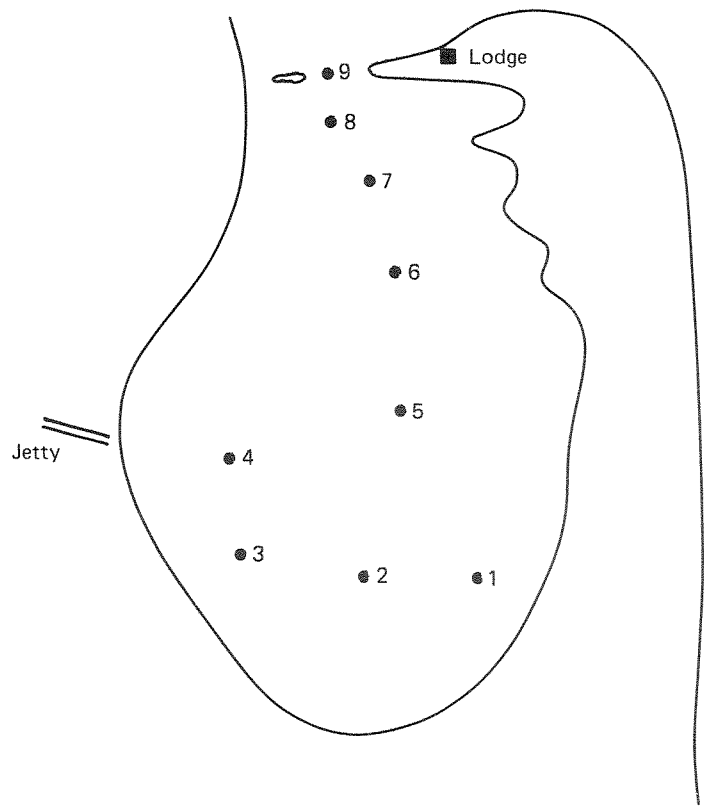


Figure 4.13-1 Sketch of Ferguson's Gulf indicating the sampling stations used in November 1985.

The results show that the water in the gulf had a higher salt content than the open lake. The electrolytical conductivity increased from 362 mS/m in the north to 744 mS/m in the shallow western part of the Gulf..

The phytoplankton density in the Ferguson`s Gulf was very high, as shown by the chlorophyll values and particle counts. The chlorophyll content was three orders of magnitude higher than what is usually found in the open lake. The photosynthetic activity of the dense algal

population caused extremely high oxygen concentrations, which reached almost 500 % saturation in the afternoon.

Table 4.14-1 Results of water analysis in the Ferguson`s Gulf on 5 November 1985. The sampling locations are indicated in figure 4.14-1.

Station	Time	depth cm	temp. °C	O_2 mg/l	conductivity mS/m	pH
1	16.45	60	31.0	30.4	667	10.38
2	17.05	70	32.1	32.5	707	10.44
3	17.12	60	31.9	36.7	723	10.49
4	17.36	45	32.1	36.1	744	10.47
5	17.50	55	31.6	28.2	721	10.46
6	18.06	55	31.3	27.8	640	10.37
7	18.20	-	30.4	16.0	542	10.21
8	18.40	-	30.1	12.1	471	10.03
9	19.00	-	30.0	8.4	362	9.62

Table 4.14-2 Chlorophyll and particle volume (mainly phytoplankton) and estimated number of Anabaenopsis colonies (particles > 530 μm^3) in samples from Ferguson`s Gulf November 1985. Sampling locations are indicated in figure 4.14-1.

Station	Chl-a (µg/l)	Tot. vol. of particles (mm^3/l)	Number of particles > 530 μm^3 (n/l)
1	1450	247	114 x 10^6
2	1330	278	100 x 10^6
3	2280	350	150 x 10^6
4	2650	358	194 x 10^6
5	2700	372	140 x 10^6
6	2760	339	194 x 10^6
7	1660	262	146 x 10^6
8	1104	186	115 x 10^6
9	94	19	9 x 10^6

An experiment to measure the primary production was performed on 8 November 1985, near the British station in the eastern part of the

gulf. A 30 cm long glass cylinder was filled with water, and the dissolved oxygen was measured with an electrode. The cylinder was sealed with a glass lid and incubated suspended from a floater with the top at the surface level (see figure 4.14-2). After 25 minutes incubation around noon, the water in the cylinder was stirred, and dissolved oxygen was measured. The experiment was repeated with the cylinder wrapped in black plastic to exclude light for assessment of respiration.

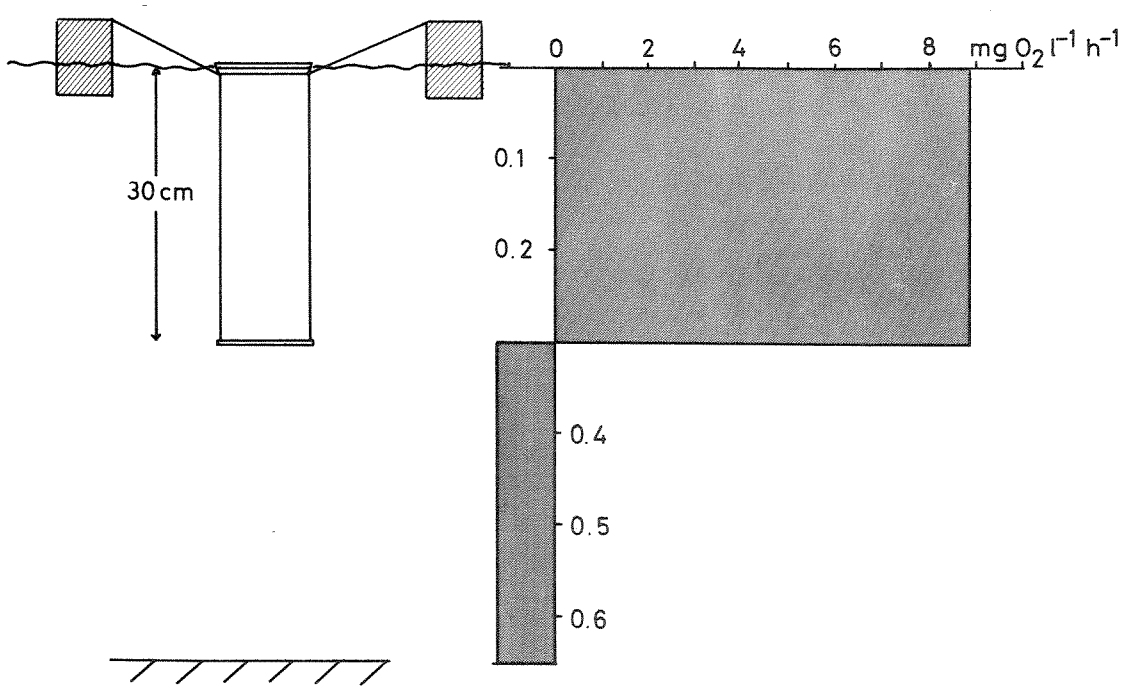


Figure 4.14-2 **Primary production experiment in Ferguson's Gulf 7 November 1985. The experimental design is shown to the left. (See text for explanation).**

In the first incubation , the oxygen concentration incresased at 8.9 mg O_2/l/h, which is the mean net production in the upper 30 cm layer. The respiration rate, measured in the second incubation was 1.3 mg/l/h. The mean gross production in the upper 30 cm is thus 8.9+1.3= 10.2 mg O_2/l/h. Because of the high algal biomass (chlorophyll-a was 1900 µg/l) it is assumed that no photosynthesis occured below 30 cm depth. From 30 cm depth to the bottom at 65 cm, oxygen therefore would be consumed at a rate of 1.3 mg/l/h providing that the plankton distribution was uniform. Integration of the values gives the following areal production and respiration values:

Gross production	3.06 g $O_2/m^2/h$
Respiration	0.84 g $O_2/m^2/h$
Net production	2.22 g $O_2/m^2/h$

The daily gross production, calculated according to Talling (1965) is 33 g $O_2/m^2/d$. The respiration is 20 g $O_2/m^2/day$ if the depth is 65 cm providing that there is no diurnal variation in respiration. This means that the net rate of production is 13 g $O_2/m^2/day$.

The production rate measured in Ferguson`s Gulf is among the highest production rates that have been recorded. Talling et al. (1973) estimated the gross production in the Ethiopian lake Aranguadi to 43 and 57 g O_2/m^2 from diurnal variations of dissolved oxygen measured in situ. The production rate, measured in bottles, was, however lower than the result from Ferguson's Gulf. Chlorophyll concentration in Lake Aranguadi was in the same range as in Ferguson's Gulf in November 1985. Later studies by Melack and Kilham (1974) and Vareschi (1982) have verified that the East African alkaline lakes are particularly productive. The reasons for the high productivity of these lakes are high levels of irradiation, nutrients and alkalinity. The alkalinity is important as a source of carbon for photosynthesis. Harbott estimated the gross production in Ferguson's Gulf to 11.5 g $O_2/m^2/d$ during his study in 1972-1975 (Hopson 1982). This result is only about 1/3 of the result obtained in 1985.

The concentration of phytoplankton in the Ferguson's Gulf in November 1985 was much higher than what was reported from 1972-75 by Hopson (1982). The chlorophyll-a values found in April 1975 were 100-800 µg/l and the volume of phytoplankton recorded during the study ranged from 13-170 mm^3/l. From these data it appears that the density of phytoplankton was 2-3 times higher in 1985 than 10-13 years earlier. The higher algal density was accompanied by higher conductivity and lower water level. The depth of the Gulf was 1-2 m lower in 1985 than in 1973-75. Hopson's observations also show a higher diversity of the phytoplankton as compared to the situation in 1985, when the gulf was virtually a monoculture of Anabaenopsis arnoldii.

In connection with the fish culture project, some experimental ponds were constructed at Nataba. These ponds were fed with lake water by a windmill pump. It was observed, that a bloom of algae developed in the ponds, usually within a week after they were filled with lake water. In April 1987, some observations were made in these ponds, to assess their potential for production of algae as food for tilapia culture.

Microscopic examination, showed that the phytoplankton consisted of

Anabaenopsis arnoldii in addition to some green algae and diatoms. The dominating phytoplankton was thus the same as in Ferguson's Gulf in 1985.

Primary production in one of the ponds were carried out on 12 April 1987, one week after the pond had been filled with lake water. The chlorophyll-a concentration was 320 µg/l. The experiments were carried out with the same technique as was used in Ferguson's Gulf, i.e. the oxygen production was measured in a 30 cm glass cylinder. Several incubations were made for periods of 30-60 min from 8.40 a.m. to 4.10 p.m.

Respiration was measured by incubation of a pond sample in the dark over the night. The results of the experiment is shown in figure 4.13-3. The production in the upper 30 cm layer is expressed on an areal basis. The production curve shows a maximum around noon, and a rapid decrease during the afternoon. If the curve is connected to the measured night-time respiration rate (0.38 g O_2/m^2. h), the daily net production can be found by integration of the curve. The result is 6.8 g O_2/m^2. day (net production) The gross production, obtained by adding the respiration, is 15.8 g O_2/m^2. day.

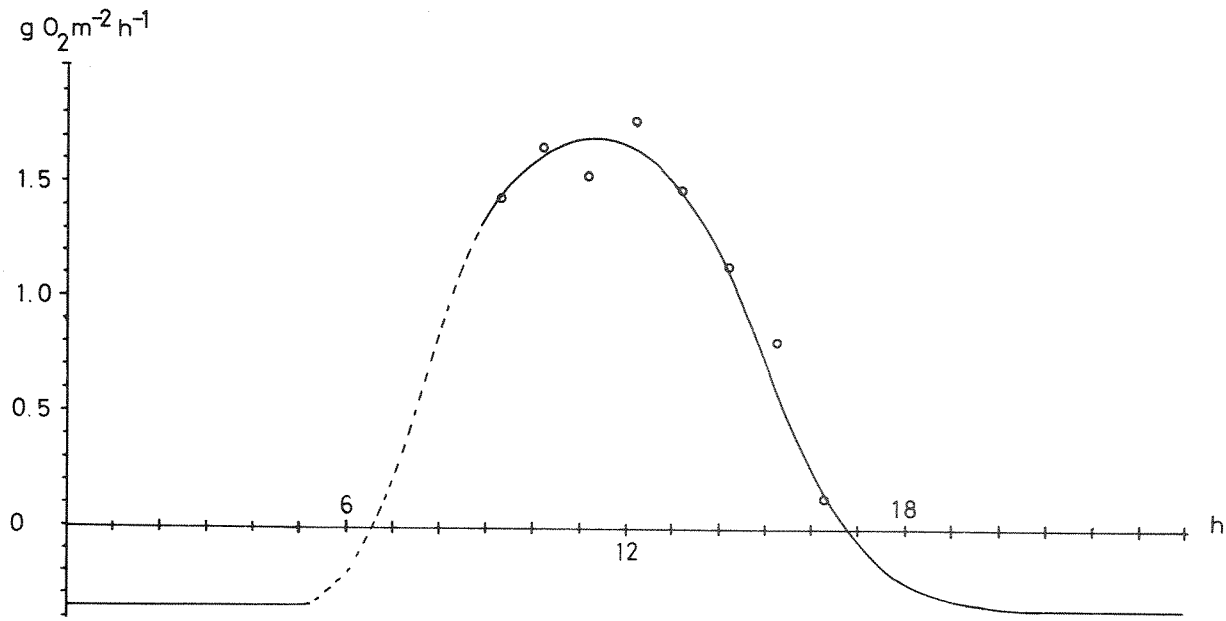


Figure 4.14-3 Photosynthetic oxygen production measured in an algal pond at Nataba 12 April 1987.

The depth of the pond was ca. 0.6 m. From oxygen profiles measured in

situ, it was found that the euphotic zone extended to 0.4-0.5 m, i.e. deeper than the cylinder used for production measurements. The total gross production in the pond was therefore slightly higher than the estimate above.

The observations in the ponds with Lake Turkana water may help to explain the very high production and algal density that occured in the Ferguson's Gulf. Several factors may have contributed to the eutrophic conditions in the gulf. Hopson (1982) pointed at the importance of birds and cattle around the gulf as sources of nutrients, but also mentioned the possible contribution of nitrogen by nitrogen fixation. The experiments with algal ponds showed that high density of algae may develop in the lake water without any addition of nutrients.

As was shown by algal assays, nitrogen is the major limiting nutrient for production of algal biomass in the lake water. When nitrogen is added, a high biomass density may be produced due to the high concentration of other essential nutrients. In the ponds, the algal biomass increased from less than 10 to more than 300 µg chlorophyll-a/l within one week without any external addition of nitrogen. The dominating alga in the pond at that stage was the blue-green alga Anabaenopsis arnoldii which belongs to a group (Nostocales) known to be capable of nitrogen fixation. Most probably the development of algae in the ponds was made possible by nitrogen fixation.

The same blue-green alga, A. arnoldii, was the dominant alga in the Ferguson's Gulf, and was also found in several shallow lagoons on the shore between Elye Springs and Kalokol. It appears, therefore, that nitrogen fixation by blue-green algae contributes significantly to the high productivity of these systems.

Since some algae are able to overcome the shortage of nitrogen by fixing N_2, it remains to explain why these algae do not occur in significant concentrations in the open lake. The answer may be that these algae can not exist under the turbulent conditions with frequent mixing down to great depths that prevail in the lake. These conditions are known to favour diatoms in other African lakes, while blue-green algae generally are favoured by temperature stratification (Heckey and Kling (1987), Talling (1986). The blue-green alga Microcystis aeruginosa may be less susceptible to vertical mixing than the N_2-fixing blue-green algae and therefore able to maintain a substantial population throughout the year in Lake Turkana. Talling (1966) noted that the related species M. wesenbergii had a different response to mixing as compared to other blue-green algae in Lake Victoria.

The pond experiments showed that the conditions at Lake Turkana are ideal for production of algae as food for fish in aquaculture. The alkaline and nutrient rich ground water that can be extracted from the western side of the lake is an ideal growth medium for algae and the stable climatic situation with high irradiation and temperature makes a high production rate possible. Nitrogen fixation makes mass culture of blue-green algae possible also in lake water, but addition of nitrogen would probably be necessary for maximum production in lake water.

4.15 Zooplankton

The description of abundance and biomass of the planktonic crustaceans was based on net hauls mainly from station H1. This station, located north of Central Island, was also used as the main sampling station for zooplankton by A.S.D. Ferguson (Hopson 1982).

Figure 4.15-1 shows the occurrence of the different species of the planktonic crustaceans given as percentage of the number of different species of a subsample each date. Marked fluctuations were seen throughout the year (and between different localities within one period). These phenomena are well documented by Hopson (1982). It is interesting to notice that the most common species in 1973-74 Tropodiatomus banforanus (Hopson 1982) appeared in almost the same frequency in 1987-88 contributing about 60% of the planktonic crustaceans. The other two copepods, Mesocyclops leuckarti and Thermocyclops hyalinus constituted together about 30% both periods, but their mutual relationship had changed. M. leuckarti appeared with 20% in 1973-74, but only with 4% in 1987-88. The cladocerans comprised only 8-10% of the plankton. Diaphanosoma excisum was the most common both periods with 7.6% and 9.5%, respectively. The other cladocerans, Cerodaphnia rigandi and Moina spp. appeared both periods in small numbers, 1% or less. The low frequencies of cladocerans and the small sizes of copepods indicate a high predation pressure upon planktonic crustaceans, probably by fish.

Figure 4.15-2 shows the estimated biomass of zooplankton for the sampling period of 1987-1988 at station H1. The columns indicate a two-peaked fluctuation throughout the year; one peak in March and one in July-August (-September). This is also in accordance with the most numerous species in 1973 (Hopson 1982), and appears to be be a regular annual pattern. Seasonal fluctuations of zooplankton are also documented from other deep tropical lakes, eg. Lake Malawi (Twombly 1983).

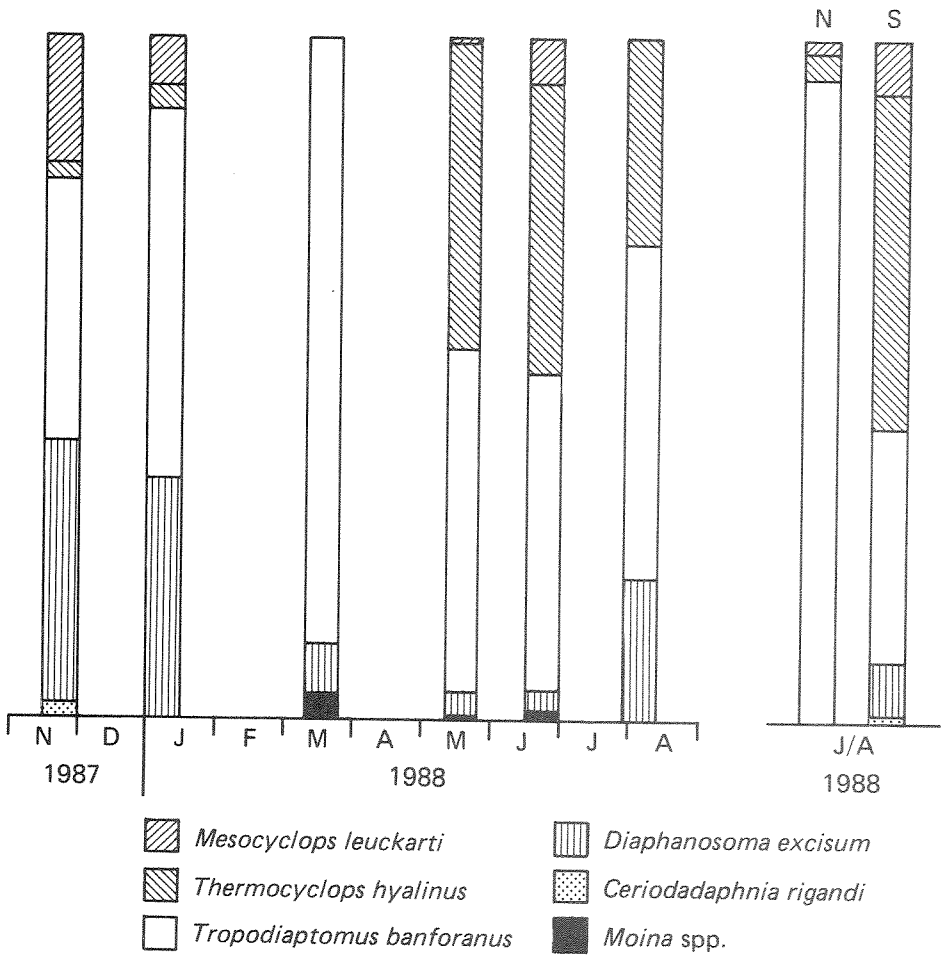


Figure 4.15-1 Composition of zooplankton in the central sector of Lake Turkana 1987-1988.

The biomass of zooplankton in open water of the central part of Lake Turkana ranged from 0.2 to 5.0 g dry weight per m^2 with a mean value of about 1.6 (g dw/m^2). These figures include a calibration factor of 2 to account for filtration losses (see appendix I).

Compared with other deep tropical lakes the biomass figure of 0.2-5 g dw/m^2 is in good agreement with the estimated zooplankton biomass of eg. Lake Tanganyika, which was between 2 and 5 g dw/m^2 in 1974 (Burgis 1984).

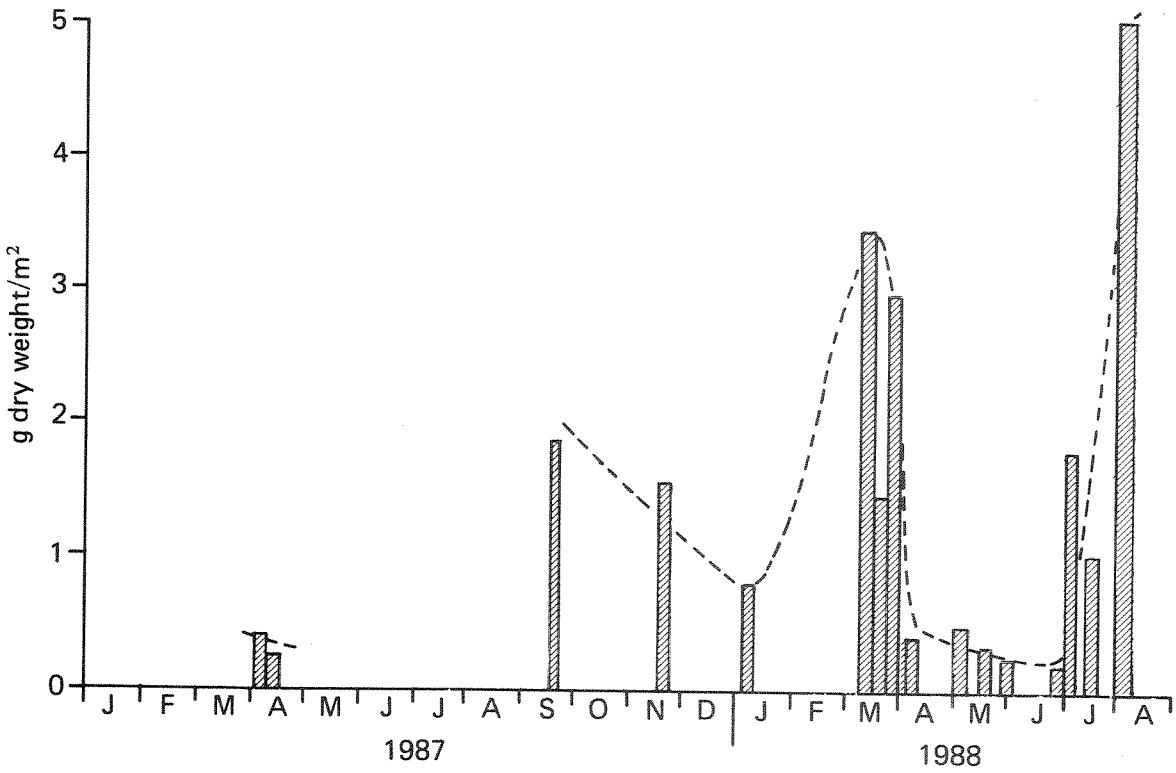


Figure 4.15-2 Biomass of zoplankton in the central sector of Lake Turkana 1987-1988.

Based on the measured zooplankton biomass from Lake Turkana and proportions between production (P) and biomass (B) given in literature, an approximate estimate of zooplankton production can be made. The annual P/B ratio differs between various studies; P/B=20 (Waters 1977), P/B=40-60 (Symoens et al. 1981) and P/B=23 (Burgis 1984). Using the P/B ratios of 20 and 50, the total annual zooplankton production of Lake Turkana is between 216 000 and 540 000 tons dry weight.

Hopson (1982) calculated the annual production of Tropodiaptomus banforanus to about 90 000 -190 000 tons dry weight in Lake Turkana. As T. banforanus made up 60% of the planktonic crustaceans, the total production could roughly be estimated to 150 000-320 000 tons dry weight per year. These values are lower, but still within the same range as the estimate from the present study.

4.16 Energy flow and potential fish yields

An energy flow diagram for the offshore water of Lake Turkana is given in figure 4.16-1. The main purpose to present the energy flow diagram

is to illustrate the size and connections between the different major trophic levels of pelagic Lake Turkana. The diagram illustrates the order of magnitude of the different levels measured, taken from the literature or estimated during this study. The diagram also shows the transformation of energy or biomass between the various trophic levels. Since no observations of production in the littoral zone were made during this study, the contribution of this production has not been assessed. Hopson (1982) has presented some figures that shows the significance of this production.

The diagram includes five trophic levels; the insolation refered by Hopson (1982), the production of phytoplankton and zooplankton estimated from this study, and rough estimates of possible production of fish feeding on zooplankton and predatory fish. An efficiency coefficient of 0.1 is used for energy transfer between the trophical levels of zooplankton and fish feeding on zooplankton, and a coefficient of 0.15 between the zooplankton-feeding fish and the predatory fish. All values are converted to kcal according to Winberg et al. (1971).

The total annual net production of zooplankton in Lake Turkana was estimated to between 216 000 and 540 000 tons dry weight in 1987/88. This forms the basis of a zooplankton-eating fish production of 216 000 - 540 000 tons wet weight (using the conversion factor of 1:10 between dry weight and wet weight of zooplankton and 10:1 as an efficiency coefficient of energy transfer between the two trophical levels).

The fish catch outside the littoral areas of Lake Turkana is composed of many species of different trophical levels. Some feed on zooplankton (Alestes baremose), many are predatory fish like Nile perch (Lates niloticus, L. longispina), tiger fish (Hydrocynus forskalii), bagrus (Bagrus bayad, B. docmac) and some species are feeding on both zooplankton, fish and other items like cat fish (Synodontis schall). Using the efficiency coefficient of production between zooplankton-eating fish and predatory fish (10:1.5), the annual production of predatory fish and prawn-eating fish is between 32 000 and 81 000 tons. A sustainable annual yield of 30% of the production then becomes between 10 000 and 24 000 tons. As a certain amount of the fish traditional catch consists of partly zooplankton-eating fish, the sustainable yield should be higher, roughly 15 000 to 30 000 tons fish per year in the offshore waters. The sustainable yield will, however, depend on several biological conditions, e.g. successful spawning of all major species, suitable food and growth

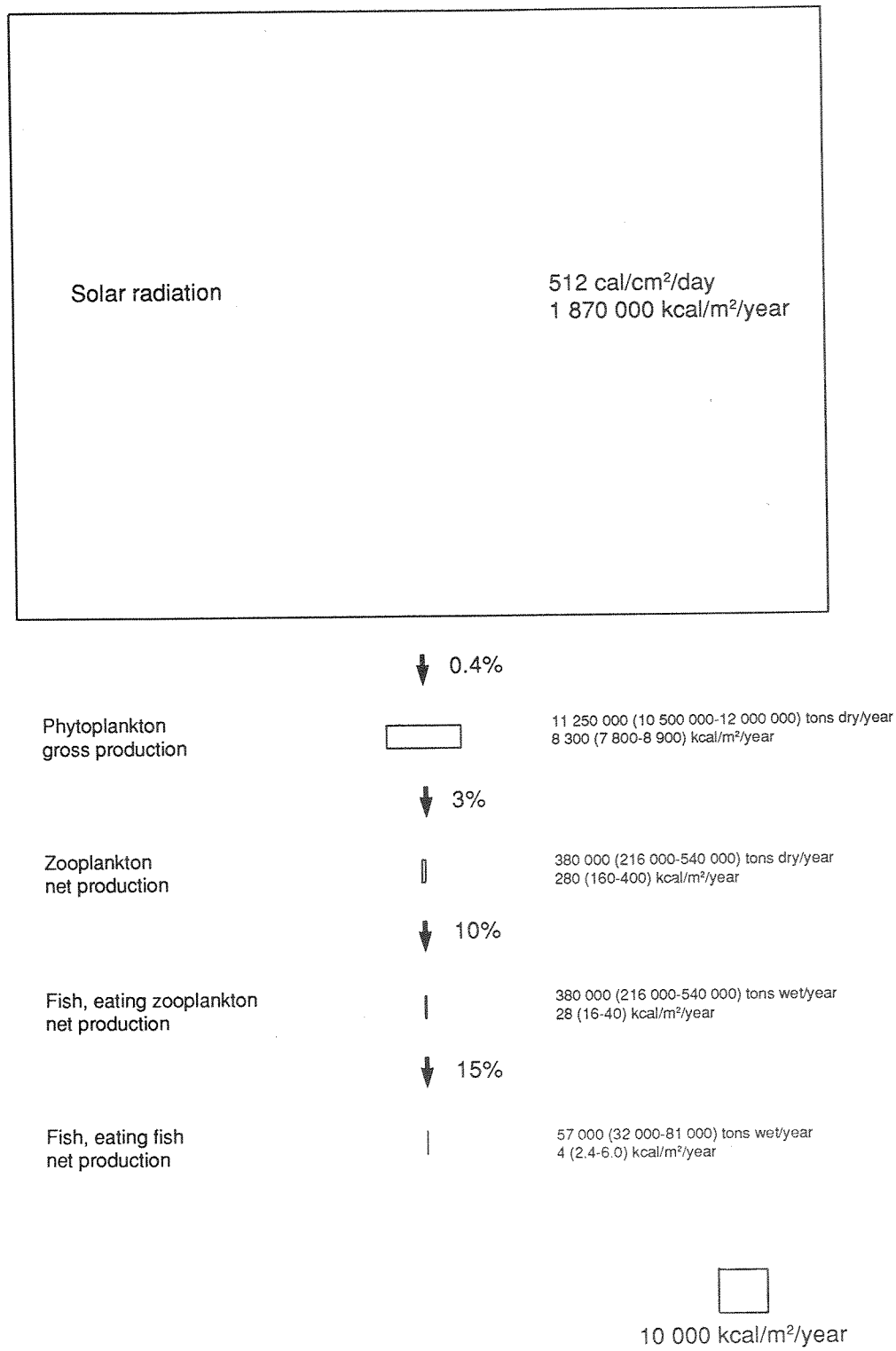


Figure 4.16-1 Energy flow diagram for the offshore water of Lake Turkana.

conditions for fry and young fish, no overfishing of the various species (especially not in the spawning area), suitable water quality etc.

An estimate of potential fish yield can also be obtained from the phytoplankton primary production by applying the empirical relationship described by Melack (1976). During this study, primary production was only measured in the central sector of the lake and previous studies have shown that there is a gradient in productivity from north to south (Hopson 1982). If the results from the central sector is taken as representative for the whole lake, the fish yield would be 33 kg/ha/year according to Melack's (1976) equation. This corresponds to 22 000 tons/year.

Both estimates of fish yield above are speculative and must be used with caution. However, the fact that the predictions obtained are rather similar, indicates that they may be realistic.

Hopson (1982) also made estimates of fish yields in Lake Turkana, based on biomass, growth and mortality of each fish species. The sustainable yield for the same species that are included in this study was estimated to 37 000 tons, which is higher than our estimate. However, the yield calculated by Hopson is given as a maximum yield and is also based on a lake level 5 m higher than in 1988. (An estimate based on a 5 m higher water level gave in our study a maximum sustainable yield of 34 000 tons). The faster decline of the water level during 1985-1988 compared to 1972-1975 (See figure 4.1-2) implies less influx of plant nutrients with the rivers in the 80's and possibly a lower production potential. This will also affect the annual sustainable yield of fish.

Two small zooplankton-eating fish species, Alestes minutus and A. ferox account for the major part of the pelagic fish production in the lake (Hopson 1982). These species are also the main link between zooplankton and fish-eating fish. Hopson (1982) made an estimate of sustainable yield of these two species. His maximum yield figure of 560 000 tons/year is almost identical with our estimate of total fish production, and appeares to be an overestimation. Hopson's estimate of yield of Alestes spp. also seems too high when compared to his own estimate of zooplankton production. In order to maintain the offshore traditional catch of predatory fish, the small Alestes species should not be exploited.

The morphoedaphic index (dissolved solids/mean depth, Ryder 1965) has

been shown to be useful for estimatating fish yields within groups of lakes. The concept has been used in African lakes by Henderson and Welcomme (1974). This approach can not be expected to be applicable for estimation of fish yield in Lake Turkana from empirical relations obtained in other African lakes because of the particular chemical conditions in Lake Turkana. Melack (1976) found that the morphoedaphic index did not predict the fish yield satisfactory in 9 African lakes.

4.17 Productivity limits

The production base is made up by phytoplankton production, benthic algae production, aquatic macrophyte production and input of organic material from rivers and flooded land when the lake level rises. Among these phytoplankton production dominates because it takes place over the whole lake area, but the other factors may be locally important. The factors that determine the phytoplankton productivity are therefore important to understand for a proper utilization of the resources and for assessment of concequences of environmental changes e.g. large variations in lake level.

The possible limitation of phytoplankton production by availability of plant nutrient were discussed in sections 4.8 and 4.9. It was concluded that there is a high surplus of phosphate in the lake at all times, which rules out the possibility of phosphorus limitation. The concentrations of nitrogen compounds available for algal production are usually low in the euphotic zone and may be limiting for the production of algae.

A second factor which limits the algal production is the availability of light for photosynthesis. The euphotic zone is restricted to 6 m as an average in the central sector of the lake. This means that only ca. 17% of the lake volume contributes to the primary production. If the water circulates continuously, the algae thus spend only 17% of the time in the euphotic zone. The rest of the time organic material produced by photosynthesis will be lost by algal respiration. Because of the high temperature, respiration loss in the deep water will be substantial.

Two factors counteract the respiratory losses of phytoplankton; temperature stratification, which restricts the vertical mixing, and buoyancy of algae, which make some algae able to accumulate near the surface.

Temperature stratification has been shown to occur in Lake Turkana in

spite of the low annual temperature variation. (See section 4.2). The vertical mixing is therefore usually restricted to some extent, but the lack of a well defined thermocline and oxygen content of the deep water shows that considerable vertical transport takes place most of the year. The distribution of chlorophyll measured during this study, and of phytoplankton reported by Hopson (1982) shows that most of the phytoplankton biomass may be below the euphotic zone under these conditions.

In March-May, stratification may be stronger, and the vertical mixing more efficiently restricted. The phytoplankton is then distributed mainly above the thermocline and will spend a proportionally longer time in the euphotic zone. This will tend to increase the production and reduce the respiratory losses.

In spite of the more favourable light conditions for the phytoplankton during temperature stratification, no biomass increase was observed during the periods of stratification in 1987 and 1988. This implies that light is not the only limiting factor or that the algal biomass is efficiently controlled by grazing by zooplankton. The distribution of nitrate during stratification periods shows depletion above the thermocline which can be explained by the algal assimilation. The thermocline restricts the transport of nitrate from the deep water, where the concentrations are higher. Under these conditions the availability of nitrogen may limit algal production. The annual variations in crustacean zooplankton do not indicate that the grazing pressure on the algae is particularly high during stratification periods, since the highest biomass was found in August when the water was well mixed.

It follows from the discussion above that the two most important factors limiting the production of phytoplankton are nitrogen and light. Probably the relative importance of these factors varies depending on the conditions. When vertical mixing is strong, the availability of light becomes limiting, and during stratification nitrogen limitation occurs. The most important external supply of nitrogen to Lake Turkana is the Omo River. The influence on the nutrient input can be seen in the productivity gradient from north to south documented by Hopson (1982) and is also reflected by the chlorophyll distribution recorded in July-August 1988 (figure 4.10-2). The potential production increase caused by the nutrient influx during River Omo floods is, however, counteracted by the high silt content, which reduces the light availability. This condition probably reduces the annual variation in productivity that would be expected from the seasonal nature of the floods.

The species composition of the phytoplankton appears to be influenced by the physical conditions in the lake. The dominant species, Microcystis aeruginosa and Botryococcus braunii both form large colonies. The aggregates of algae have a positive buoyancy created by gas vaccuoles (Microcystis) and storage of lipids in the cells (Botryococcus). The large size of the colonies increases the vertical speed of rising algae. The effect of the buoyancy can be observed during periods of low wind mixing of the surface water, when blooms of both species on the surface may develop. The ability to, at least to some degree, counteract the vertical mixing must be an important property of algae in lakes where the euphotic zone is much shallower than the mixing zone. The importance of the buoyancy mechanism for maintaining a dense population of Microcystis near the surface in a lake with a diurnal mixed layer caused by solar heating has recently been shown by Zoharty and Robarts (1989).

While the composition of the phytoplankton reflects adaption to a light-limited environment, effects of the limited availability of nitrogen on the selection are less obvious. Since some blue-green algae can utilize nitrogen as N_2, these algae would have a competitive advantage in the chemical environment in Lake Turkana, where other nutrients are in surplus (See section 4.9). The experiments carried out in ponds with water from the lake, and the observations in Ferguson's Gulf show that nitrogen-fixing blue-green algae (Anabaenopsis arnoldii) have the potential of developing dense populations in Lake Turkana water. (See section 4.14). Still these algae are of no significance in the pelagic plankton community. A potentially nitrogen-fixing blue-green alga (Anabaena constricta) was found only in one sample from the open lake.

The reason for the lack of nitrogen-fixing algae in Lake Turkana is not known, but the physical conditions, with frequent, efficient vertical mixing may be unfavourable for this group of algae. Talling (1987) noted that Anabaena flos-aquae in Lake Victoria declined strongly during periods of increased vertical mixing.

The limiting effect of nitrogen on the productivity of Lake Turkana, and the dominant influence of Omo River on the influx of this nutrient imply that the variations in discharge of Omo River have important consequences not only for the lake level, but also for the productivity of the whole system. In addition to bringing nutrients and allochtonous organic matter to the lake, nutrients are released from flooded land. Additional positive effects of a rising lake level are food and shelter for fish provided by the submerged terrestial

vegetation. Variations in discharge of River Omo, caused by climatic variations will therefore most probably have a substantial effect on the potential fish production. Periods with successive reduction of the lake level as during this study will probably be less productive than periods with increasing lake level.

The data on primary production from Lake Turkana are too limited to show possible connections between river discharge and productivity. During both periods when primary production was measured (1973-1975 and 1987-1988) the lake level was receding, and the rate of pelagic production was within the same range.

Because of the importance of the fluctuations of river discharge and lake level on the ecology of the lake, continuous monitoring of the lake level and, if possible, the discharge of River Omo should be undertaken. Developments in the catchment area, which may affect the discharge of water to the lake may have serious effects on the lake ecosystem.

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APPENDIX I

METHODS

Sampling

A Ruttner sampler of 2 l capacity was used to collect water from various depths. Water for chemical analysis in the laboratory was transfered to plastic bottles that were stored in an insulated box and analysed within 6 hours after collection.

Water was analysed for nutrients ($N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4$) and other chemical constituents. Total nitrogen, phosphorus major ions, heavy metals and other analyses which needed more sophisticated methods were analysed at NIVA's laboratory. The rest of the analyses were carried out at a field station (Nataba) located on the western shore of the central part of the lake.

Transparency

Underwater light penetration was determined by using both a 25 cm circular plastic Secchi disc and a submersible celanium cell photometer, model 268 WA 300 (Gm mfg New York, USA). The white Secchi disc was also used for water colour determination. Secchi disc depth was taken as the depth when the disc could no longer be seen, and half of this depth was used for colour determination.

Temperature

Temperature was measured in situ by using a mercury glass thermometer mounted on the inside of the sampler and readable to 0.1 ^0C.

Dissolved oxygen

Dissolved oxygen levels were measured both by use of oxygen meter, (WTW OXI 91) and Winkler's method. BOD bottles of volumes ca. 120 ml and fitted with ground stoppers were filled with samples from the sampler displacing three times of each bottles' volume. The samples were immediately fixed with 1 ml of each Winkler reagents. When not immediately analysed the bottles with fixed samples were stored under water. Titration was usually done within a period of not more than six hours by filtration with 0.01 M $Na_2S_2O_3$ after acidification with conc. sulphuric acid.

In analysis of dissolved oxygen data, priority was given to the Winkler titration data.

Conductivity/pH

Most conductivity and pH measurements were made in the field. A conductivity meter, Model LF91 of WIW was used to follow conductivity. The meter had a compensatory temperature range of 0-50 ^{0}C. Samples brought to NIVA were analysed with a Philips PW 9527 conductivity meter.

pH was measured by a pH meter model PH91 of WTW with a pH range of 0-14. An electrode type E50 was used in conjunction with the metre.

Alkalinity

Alkalinity was estimated by titration using mixed indicator (Bromocresol green and methyl red) for total alkalinity and phenophthalein-indicator for phenophthalein alkalinity. Stepwise pofentiometric Gran titration was also used and both these methods gave similar results.

Major ions and metals

Atomic adsorption spectrometry according to Norwegian Standards(NS) were used for the determination of Ca and Mg (NS 4776), Na and K (NS 4775), Al (NS 4772), Cr (NS 4777), Fe, Mn, Cu, Zn, Co, Ni, Cd and Pb (NS 4773). (Pb was preconcentrated by freon extraction). Hg was determined by a cold vapour technique according to NS 4768. Cl and SO_4 was analysed by ionic chromatography usoing model ILC-2 from Waters, without suppressor column. F^- was determined by a potentiometric method according to NS 4740 using a ion selective electrode (LaF_3), and SiO_2 was analysed according to Standard Methods (1985) using an automated method for molybdate-reactive silicate.

Nutrients

$N\text{-}NH_4$/$P\text{-}PO_4$

Spectrophotometric methods for a determination of $N\text{-}NH_4$ and $P\text{-}PO_4$ were used as described in Golterman 1978 and FBA Water Analysis (1978). Samples brought to Norway for analysis were preserved by adding 1 ml 25 % H_2SO_4 pr 100 ml water. The analysis were carried out on auto-analysers according to NS 4746 (ammonia) and NS 4724 (phosphate).

$N\text{-}NO_3$

Two methods were used for determination of this ion.

(i) The samples were evaporated to dryness. Sodium salicylate solution was added and evaporated again to dryness. The residue was dissolved in 1ml conc. suplphuric acid. The colour developed after adding destilled water and subsquent treatment with strong alkaline solution of sodium hydroxide and EDTA was measured at 415 nm. The method is described in detail in (ISO/DIS/7890-3).

(ii) Nitrate was reduced to nitrite using amalgamated cadmium. The colour of the azo compound formed by reaction of the nitrite with sulphanilamide and coupling with N-(1-naphtyl) ethylenediamine tetraacetate was measured at 545 nm. The method is described in Golterman (1978). This method was also used for analysis at NIVA, although a Cu/Cd-column was used for reduction of nitrate (NS 4745). Samples brought to Norway was preserved using 1 ml 25% H_2SO_4 pr 100 ml.

Total P and total N

The analysis were carried out at NIVA on preserved samples (1 ml H_2SO_4 pr 100 ml). The samples were digested using peroxidisulphate before analysis as phosphate and nitrate (Tot. P: NS 4725, tot. N: NS 4743).

Suspended solids

Suspended solids ware analysed after collection of the particulate material on pre-weighed glass fibre filters (Whatman GF/C). The filters were dried at 104 ^{0}C for 1 hour. The weight after drying was used for determination of total suspended solids. Thereafter the filters were treated at 550 ^{0}C for 1 hour and weighed again. The decrease in weight during this treatment was used to calculate the amount of organic suspended solids.

Chlorophyll-a

Chlorophyll-a pigments were determined by filtering the samples through Whatman GF/C glass fibre filters. The filters were put in glass vials containing 10 ml of 90% methanol. Extraction was done in darkness and cold between 10-12 hours. Absorbance was measured on a spectrophotometer with 5 cm cells at 665 and 750 nm (for turbidity correction).

Calculations were done according to the relation described by Talling and Driver (1963), Vollenweider (1969):

$$\text{chl·a} = \frac{(A_{665}-A_{750})\text{x}13.9\text{x}v}{L \times V} \quad \mu g/l$$

where A_{665} = Absorbance at 665 nm

A_{750} = Absorbance at 750 nm

v = Volume of methanol extract (ml)

V = Volume of sample filtered (l)

L = Length of the cell used (cm)

Concentrations of chlorophyll-a per m^2 over the euphotic zone were estimated by integrating the curve.

Primary production

Primary production was estimated by using light and dark bottles. Samples were taken from various depth and incubated at the same depth from which they were taken for periods varying between 1-3 hours around noon, but incubations were usually between 2-3 hrs. After incubation the samples were fixed with Winkler reagents and dissolved oxygen determined by titration (see above).

Gross primary production per hour was calculated from the difference in dissolved oxygen between the dark and clear bottle and a plot of these over the euphotic zone was used to calculate areal, primary production per hour (Ah). Daily rate of primary production per m^2 (Ad) was obtained by using the formula used by Talling (1965): $Ad=Ah\text{x}0.9\text{x}\Delta t$ (where Δt = number of hours from sunrise to sunset).

Phytoplankton

Most phytoplankton samples from the open lake was taken by net hauls near the surface. The mesh size was 25 um. In the Ferguson`s Gulf, unconcentrated samples of plankton was taken for quantitative analysis. All samples were preserved with Lugol`s solution.

The net samples were analysed using a light microscope at 125-400 x magnification. The relative abundance of the different species was assessed. The quantitative samples from Ferguson's Gulf were analysed with an electronic particle counter (Coulter Counter ZB) with a 100 um orfice tube. A few quantitative samples taken from the open lake was concentrated by sedimentation and investigated using an inverted microscope (Utermöhl 1958). This technique proved not applicable on samples from the open lake because of low phytoplankton density and high concentration of particulate material.

Zooplankton

The samples were taken with nets hauled from 40 m to the surface. (Two samples from April 1987 were taken from 30 m.) The net had a mesh size of 75 µm and a mouth of 0.044 m^2. The mesh size of 75 µm was chosen in order to make comparisons with former studies (Hopson 1982). The losses due to clogging of the net were assumed to be about 50% (Koksvik & Arnekleiv 1988). The samples were usually divided into four equal portions; one for identification, and one for determination of dry weight. The weight portion was filtered on a pre-veighted glassfibre filter and dried at about 100 ^0C prior to reweighting. The rest of the samples were stored at NIVA.

Algal growth potential, AGP

Preliminary tests with the commonly used species Selenastrum capricornutum (Skulberg 1964, EPA 1971) showed that this alga did not grow well in Lake Turkana water. For this reason a related green alga, Monoraphidium minutum, which was isolated from a fish pond in Kalokol was used in the AGP-tests. A stock culture of the alga is kept in the growth medium 10% Z8 (Staub 1961).

Water samples were filtered through 0.45 µm membrane filters and poured into 100 ml flat bottom flasks, 50 ml in each. 10^4 cells/ml of the test alga were added to each flask. The flasks were incubated on a shaking table at 20 ^0C, illuminated by cool-white fluorescent tubes (ca. 60 µE m^{-2} s^{-1}). The growth of the algae was followed by daily counting, using a Coulter Counter ZB electronic particle counter equipped with a Coulter Channelyzer and a computer for calculation of total particle volume. The maximum yield of algae in each flask was recorded. Calculation of biomass from algal volume was made using an empirical conversion factor (dry weight (mg/l)= 0.38 * algal volume (mm^3/l). All tests were made with three replicates.

Tests for potentially limiting nutrients were performed with parallell

series of flasks spiked with 50 μg P/l as K_2HPO_4 , 500 μg N/l as $NaNO_3$ and the two nutrients combined (50 μg P/l + 500 μg N/l).

APPENDIX II

PHYSICAL/CHEMICAL DATA

Sampling stations are shown on figure 3.4-2.

O2-titr. = dissolved oxygen measured with D.O.-meter

O2-met. = dissolved oxygen determined by Winkler titration.

Cond. = electrolytical conductivity (10^{-2} mS/m)

PO4-P = orthophosphate-P (Soluble reactive phosphorus)

Tot. P = total phosphorus

NO3-N = nitrate-N (* denotes samples analysed by Cu/Cd reduction technique at NIVA. Other data refer to the salycilate technique. Parallel analysis using Hg/Cd reduction is shown in appendix III.

NH4-N = ammonium-N

tot. N = total nitrogen

STATION	DATE mm/dd/yy	DEPTH m	TEMP. °C	O2-titr. mg/l	O2-met. mg/l	Cond. mS/m x 10^{-2}	PO4-P µg/l	Tot. P µg/l	NO3-N µg/l	NH4-N µg/l	Tot. N µg/l
H1	05/04/84	0				3.33	2300	2300	4.0*	10.0	600
H1	12/17/84	0				3.47	2200	2400	59.0*		2100
H1	11/07/85	0	26.8		7.60	3.31					
H1	11/07/85	5	26.8		7.50	3.33	2200	2200	108.0*	10.0	1100
H1	11/07/85	10	26.8		7.40	3.36					
H1	11/07/85	20	26.5		7.40	3.37					
H1	11/07/85	40	26.2		7.30	3.54					
H1	11/07/85	60	25.7		6.90	3.54					
H1	11/07/85	80	25.6		6.80	3.60					
H1	11/07/85	90	25.3								
H1	11/21/85	0	27.9		8.10	3.35					
H1	11/21/85	5	27.1		7.90	3.40					
H1	11/21/85	10	27.0		7.60	3.50					
H1	11/21/85	20	26.2	7.30		3.60					
H1	11/21/85	40	26.0		7.20	3.60					
H1	11/21/85	60	25.2		7.10	3.60					
H1	11/21/85	80	25.2		6.20	3.60					
H1	01/23/86	0	28.0		8.10	3.50					
H1	01/23/86	10	27.6		8.00	3.50					
H1	01/23/86	20			8.10	3.50					
H1	01/23/86	30	26.5		8.00	3.60					
H1	01/23/86	40	26.5		7.80	3.60					
H1	02/03/87	0	28.5	7.90		3.50					
H1	02/03/87	10	28.0	7.50		3.50					
H1	02/03/87	20	27.5	7.00		3.57					
H1	02/03/87	30	27.0	6.60		3.58					
H1	02/03/87	40	26.7	6.30		3.64					
H1	02/03/87	50	26.7	5.70		3.69					
H1	02/03/87	60		5.50		3.64					
H1	02/03/87	70	26.4	4.00		3.66					
SW.C.I	04/08/87	0	31.0	7.40	7.10	3.65					
SW.C.I	04/08/87	5	29.0	7.10	7.10	3.64					
SW.C.I	04/08/87	10	29.0	7.10	7.00	3.67					
SW.C.I	04/08/87	20	29.0	7.00	7.30	3.65					
SW.C.I.	04/08/87	15	29.1	7.00	7.20	3.64					
SW.C.I.	04/08/87	30	27.5	5.80	5.90	3.66					
SW.C.I.	04/08/87	40	26.5	4.70	4.70	3.71					
H1	04/11/87	0	29.9	7.40	7.30	3.57					
H1	04/11/87	5	28.7	7.30	7.10	3.56			25.0*		800
H1	04/11/87	10	28.7	7.00	7.10	3.54			35.0*		800
H1	04/11/87	20	28.7	6.90	7.00	3.55			29.0*		800
H1	04/11/87	30	28.5	6.90	6.80	3.56			37.0*		900
H1	04/11/87	35	26.5	4.30	4.40						
H1	04/11/87	40	26.5	4.10	4.40	3.59			104.0*		900
H1	04/11/87	50	26.2	3.90	4.60	3.59			111.0*		900
H1	04/11/87	60	26.1	3.50	4.20	3.63			113.0*		1000
H1	04/11/87	70	26.2	3.60	4.00	3.65			111.0*		1000
E. Nataba	04/14/87	3					2190		19.0*		
SW. C.I.	04/14/87	5	28.7	7.60	7.50						
SW. C.I.	04/14/87	1	28.9	7.40	7.60						

STATION	DATE mm/dd/yy	DEPTH m	TEMP. °C	O2-titr. mg/l	O2-met. mg/l	Cond. mS/m x 10^{-2}	PO4-P µg/l	Tot. P µg/l	NO3-N µg/l	NH4-N µg/l	Tot. N µg/l
H1	07/04/87	70	26.8	2.90		3.72	1744			19.9	
H1	07/15/87	0	27.9	7.70	7.50	3.60	1925		8.0	19.1	
H1	07/15/87	10	27.0	7.20	6.90	3.64	1820		13.0	25.6	
H1	07/15/87	20	27.0	7.10	6.90	3.65	1742		25.0	17.8	
H1	07/15/87	30	26.9	7.10	6.60	3.64	1742		45.0	15.2	
H1	07/15/87	40	26.8	6.90	6.20	3.67	2082		21.0	19.1	
H1	07/15/87	50	26.7	6.70	6.00	3.65	1977		23.0	20.4	
H1	07/15/87	60	26.7	7.40	6.20	3.68	1977		2.0	23.0	
H1	07/15/87	70	26.7	6.70	6.30	3.68	1925		1.0	38.5	
H1	07/27/87	0	27.5	7.90	7.70	3.60					
H1	07/27/87	10	26.5	7.50	7.30	3.62					
H1	07/27/87	20	26.3	7.50	7.10	3.63					
H1	07/27/87	30	26.3	7.50	7.00	3.63					
H1	07/27/87	40	26.2	7.50	6.90	3.64					
H1	07/27/87	50	26.2	7.50	6.80	3.67					
H1	07/27/87	60	26.1	7.10	6.60	3.68					
H1	07/27/87	70	26.1	6.90	6.40	3.69					
H1	07/30/87	0	27.0								
H1	07/30/87	10	26.7								
H1	07/30/87	20	26.7								
H1	07/30/87	30	26.7								
H1	07/30/87	40	26.5								
H1	07/30/87	50	26.3								
H1	07/30/87	60	26.2								
H1	07/30/87	70	26.2								
H1	08/19/87	0	27.8	8.00	8.10	3.64					
H1	08/19/87	10	27.7	7.70	7.80	3.66					
H1	08/19/87	20	26.5	7.60	7.70	3.69					
H1	08/19/87	30	26.4	7.60	7.60	3.66					
H1	08/19/87	40	26.1	7.60	7.50	3.65					
H1	08/19/87	50	26.1	7.30	7.60	3.68					
H1	08/19/87	60	26.0	7.00	7.50						
H1	08/19/87	70	26.0		7.40	3.70					
H1	08/22/87	0	28.1	8.00			1844		26.0	30.2	
H1	08/22/87	10	26.4	7.70			1998		0.6	22.5	
H1	08/22/87	20	26.3	7.60			1790		15.0	20.0	
H1	08/22/87	30	26.3	7.60			1766		0.2	21.9	
H1	08/22/87	40	26.1	7.60			1770		23.0	27.6	
H1	08/22/87	50	25.9	7.30			1840			39.0	
H1	08/22/87	60	25.9	7.20			1820		7.0	35.2	
H1	09/08/87	0	27.6		8.50	3.64	1902			7.9	
H1	09/08/87	10	26.4		7.60	3.67	1956		40.0		
H1	09/08/87	30	26.2		7.40	3.67	1956		14.9		
H1	09/08/87	40	25.9		7.90	3.67	1956		12.1		
H1	09/08/87	50	25.8		7.10	3.68	1929		13.3		
H1	09/08/87	60	25.7		7.10	3.68	1875		10.7		
H1	09/08/87	70	25.7		6.90	3.67	1929		12.8		
H1	09/08/87	20	26.3		7.50	3.67	1902		12.6		
SW. C.I	09/15/87	0	27.2		7.50	3.60					
SW. C.I.	09/15/87	10	26.2		7.40	3.65					
SW. C.I.	09/15/87	20	26.2		7.30	3.66					
SW. C.I.	09/15/87	30	26.1		7.20	3.66					
SW. C.I.	09/15/87	40	26.0		7.20	3.67					
SW. C.I.	09/15/87	50	26.0		6.90	3.66					
H1	09/25/87	0	28.5	9.00	8.10	3.62	1990		37.7	8.1	
H1	09/25/87	10	27.0	8.20	7.40	3.63	1930		76.7	5.3	
H1	09/25/87	30	25.8	7.70	7.00	3.68	2040		39.3	4.7	
H1	09/25/87	40	25.7	7.40	6.70	3.66	2010		33.5	5.4	
H1	09/25/87	50	25.5	7.00	6.50	3.73	2010		33.5	4.7	
H1	09/25/87	60	25.5	7.30	6.50	3.69	2060		33.5	4.7	
H1	09/25/87	70	25.5	7.00	6.40	3.74	2060		37.7	3.3	
H1	09/25/87	20	26.5	7.80	7.10	3.66	2670		37.7	7.4	
H1	10/06/87	0	28.3	8.60	7.60	3.59	2422		15.8	10.7	
H1	10/06/87	10	26.7	7.60	7.20	3.59	2455		30.0	5.5	
H1	10/06/87	20	26.7	7.90	7.10	3.62	2455	2200	21.9	5.5	1200
H1	10/06/87	30	26.3	7.40	6.80	3.61	2555		25.8	9.9	
H1	10/06/87	40	26.0	7.20	6.90	3.62	2389		27.9	11.6	
H1	10/06/87	50	26.0	7.40	6.60	3.63	2555		18.3	2.0	
H1	10/06/87	60	25.8	7.50	6.40	3.64	2355		18.5	3.8	
H1	10/06/87	66	25.5	7.00	6.60	3.66	2455		20.2	7.2	
H1	10/15/87	0	29.8		8.40	3.54	2012	2200	14.1	6.8	1200
H1	10/15/87	10	27.5		6.90	3.56	1956		44.4	8.0	
H1	10/15/87	20	26.5		6.70	3.65	1984		18.3	0.0	
H1	10/15/87	30	26.1		6.90	3.67	2012	2300	17.0	60.8	1000
H1	10/15/87	40	26.0		6.40	3.69	2038		25.4	1.8	

STATION	DATE mm/dd/yy	DEPTH m	TEMP. °C	O2-titr. mg/l	O2-met. mg/l	Cond. mS/m x 10^{-2}	PO4-P µg/l	Tot. P µg/l	NO3-N µg/l	NH4-N µg/l	Tot. N µg/l
H1	10/15/87	50	26.0		6.20	3.70	2039		15.2	15.1	
H1	10/15/87	60	25.9		5.40	3.72	2012		20.9	3.5	
H1	10/15/87	70	25.9		5.20	3.72	2039	2300	29.1	3.5	1000
H1	11/02/87	0	28.7		7.90	3.56	1994		33.1	9.7	
H1	11/02/87	10	27.5		7.50	3.56	2023		46.4	11.4	
H1	11/02/87	20	27.4		7.40	3.58	1994		37.5	9.7	
H1	11/02/87	30	26.8		7.00	3.66	2081		41.7	8.1	
H1	11/02/87	40	26.4		7.00	3.67	2081		33.4	3.9	
H1	11/02/87	50	26.0		6.70	3.67	2110		40.5	5.6	
H1	11/02/87	60	26.0		6.70	3.68	2081		42.3	3.9	
H1	11/02/87	70	25.9		6.40	3.68	2081		37.8	3.9	
H1	11/21/87	0	28.4	8.10	8.30	3.66	2016		36.5	5.4	
H1	11/21/87	10	27.5	7.30	7.30	3.64	2044		48.2	11.4	
H1	11/21/87	20	27.4	7.10	7.10	3.65	2044		44.1	4.5	
H1	11/21/87	30	27.0	6.50	6.30	3.62	1989		59.1	4.5	
H1	11/21/87	40	26.8	6.40	6.20	3.65	2072		50.0	6.2	
H1	11/21/87	50	26.6	6.70	6.60	3.69	2017		55.5	6.2	
H1	11/21/87	60	26.2	6.70	6.50	3.69	2044		43.8	8.0	
H1	11/21/87	70	26.1	6.20	6.40	3.71	2072		57.0	6.2	
H1	11/27/87	0	28.1		7.10		2280		33.7	10.8	
H1	11/27/87	10	28.0		6.90		2344		34.8	28.9	
H1	11/27/87	20	27.2		6.70		2344		34.5	6.3	
H1	11/27/87	30	27.0		6.60		2344		36.8	6.3	
H1	11/27/87	40	26.4		6.60		2344		36.8	25.9	
H1	11/27/87	50	26.4		5.90		2407		36.5	10.8	
H1	11/27/87	60	26.1		5.80		2375		38.6	7.8	
H1	11/27/87	70	26.0		5.20		2344		41.7	10.8	
H1	01/07/88	0	28.5		8.30		2411		29.4		
H1	01/07/88	10	28.2		7.80		2379		58.0		
H1	01/07/88	20	28.1		7.70		2475		42.1		
H1	01/07/88	30	27.5		7.60		2411		38.5		
H1	01/07/88	40	27.5		7.50		2443		30.0		
H1	01/07/88	50	26.9		6.40		2379		46.0		
H1	01/07/88	60	26.7		5.50		2507		49.7		
H1	01/07/88	70	26.2		4.20		2507		52.8		
SW. C.I	03/17/88	0	30.0			3.67					
SW. C.I.	03/17/88	6	29.3								
SW. C.I.	03/17/88	10	29.3			3.67					
SW. C.I.	03/17/88	20	28.8			3.67					
SW. C.I.	03/17/88	30	28.0			3.73					
SW. C.I.	03/17/88	40	27.5			3.69					
H1	03/18/88	0	30.5	7.40	8.20	3.68	2303		41.1	9.7	
H1	03/18/88	5	29.3	6.90	7.20		2200	2200	27.0	1.0	
H1	03/18/88	10	28.8	6.60	6.70	3.69	2276	2200	48.8	14.2	
H1	03/18/88	20	28.6	6.60	6.70	3.69	2395		46.5	9.7	
H1	03/18/88	30	28.0	5.80	6.00	3.69	2276		55.0	12.0	
H1	03/18/88	40	27.8	5.60	5.80	3.69	2223		57.3	14.2	
H1	03/18/88	50	27.5	5.20	5.30	3.70	2276		60.0	25.6	
H1	03/18/88	60	27.4	4.40	4.40	3.69	2329	2200	60.4	25.6	
H1	03/18/88	70	26.1	2.50	2.80	3.69	2276		71.7	23.0	
SW. C.I.	03/22/88	0	30.5		7.20						
SW. C.I.	03/22/88	5	29.9		7.10						
SW. C.I.	03/22/88	10	29.5		6.70						
SW. C.I.	03/22/88	20	28.5		5.80						
SW. C.I.	03/22/88	30	28.0		5.50						
SW. C.I.	03/22/88	40	27.5		4.20						
SW. C.I.	03/22/88	46	27.4		3.60						
S. N.I.	03/24/88	0	29.6		7.20	3.65					
S. N.I.	03/24/88	4	29.5		7.10	3.68					
S. N.I.	03/24/88	10	29.4		6.70	3.67					
S. N.I.	03/24/88	20	28.6		6.50	3.68					
S. N.I.	03/24/88	30	28.5		6.10	3.67					
S. N.I.	03/24/88	40	27.8		4.90	3.68					
S. N.I.	03/24/88	50	27.7		4.80	3.69					
S. N.I.	03/24/88	60	27.2								
H1	03/26/88	0	0.0	7.10	7.30	3.70	2490		41.0	12.9	
H1	03/26/88	5	0.0	6.80	7.10	3.69	2200		27.0	0.0	572
H1	03/26/88	10	0.0	6.70	7.10	3.69	2200		41.0	9.3	
H1	03/26/88	20	0.0	6.50	6.80	3.68	2460		47.0	9.3	
H1	03/26/88	30	0.0	5.90	6.20	3.68	2370		52.0	14.6	
H1	03/26/88	40	0.0	5.20	5.40	3.69	2520		60.0	9.3	
H1	03/26/88	50	0.0	4.10	4.40	3.70	2520		75.0	16.4	
H1	03/26/88	60	0.0	2.80	2.70	3.70	2370	2200	70.0	7.5	
H1	03/26/88	70	0.0	1.50	1.70	3.71	2200	2200	129.0	11.1	

STATION	DATE mm/dd/yy	DEPTH m	TEMP. °C	O2-titr. mg/l	O2-met. mg/l	Cond. mS/m x 10^{-2}	PO4-P µg/l	Tot. P µg/l	NO3-N µg/l	NH4-N µg/l	Tot. N µg/l
H1	03/29/88	0	30.5	7.70	7.20	3.70					
H1	03/29/88	10	29.3	7.10	6.60	3.67					
H1	03/29/88	20	28.7	6.20	5.80	3.60					
H1	03/29/88	30	28.3	5.80	5.30	3.69					
H1	03/29/88	40	27.9	5.30	4.90	3.70					
H1	03/29/88	50	27.0	2.80	2.60	3.67					
H1	03/29/88	60	26.9	2.20	2.10	3.68					
H1	03/29/88	70	26.7	1.50	1.50	3.68					
SW. C.I.	03/31/88	0	30.0		8.30	3.71					
SW. C.I.	03/31/88	10	29.4		7.50	3.71					
SW. C.I.	03/31/88	20	28.7		6.30	3.69					
SW. C.I.	03/31/88	30	28.0		5.80	3.70					
SW. C.I.	03/31/88	40	27.3		4.40	3.74					
SW. C.I.	03/31/88	50	26.7		5.30	3.83					
H1	04/08/88	0	30.1	7.90	7.50	3.72	2500		38.5	8.6	
H1	04/08/88	10	29.1	7.00	6.00	3.71	2470		53.5	14.5	
H1	04/08/88	20	29.1	6.90	6.40	3.70	2470		52.5	10.6	
H1	04/08/88	30	27.9	4.90	4.60	3.70	2500		63.8	4.7	
H1	04/08/88	40	27.4	4.70	3.10	3.70	2440		77.9	6.7	
H1	04/08/88	50	26.8	1.70	1.70	3.69	2470		88.1	8.6	
H1	04/08/88	60	26.7	0.80	0.90	3.68	2470		83.8	10.6	
H1	04/08/88	70	26.6	0.80	0.80	3.68	2500		88.1	20.4	
H1	04/22/88	0	29.2	7.70	7.30	3.72	2480		33.0	1.3	
H1	04/22/88	10	28.7	7.20	6.90	3.71	2510		33.4	0.0	
H1	04/22/88	20	28.7	7.10	6.70	3.70	2530		36.9	4.7	
H1	04/22/88	30	28.5	6.70	6.50	3.71	2430		36.1	0.0	
H1	04/22/88	40	27.8	4.60	4.40	3.71	2480		52.4	0.0	
H1	04/22/88	50	27.4	2.80	2.80	3.68	2480		61.0	4.7	
H1	04/22/88	60	27.1	1.30	1.40	3.68	2450		63.7	3.0	
H1	04/22/88	70	27.1	0.50	0.80	3.68	2620		64.8	13.1	
SW. C.I.	04/26/88	0	28.7		7.40	3.74			0.0		
SW. C.I.	04/26/88	5	28.4	7.20	6.60	3.72			0.0		
SW. C.I.	04/26/88	10	28.4	7.10	6.10	3.74			0.0		
SW. C.I.	04/26/88	20	28.3	7.10	6.00	3.74			0.0		
SW. C.I.	04/26/88	30	28.3	7.10	6.00	3.74			0.0		
SW. C.I.	04/26/88	40	27.6	4.70	4.40	3.76			0.0		
SW. C.I.	04/26/88	45	27.4	3.10	4.00	3.75			0.0		
H1	05/03/88	0	30.1	8.00	8.30	3.74	2490		23.0		
H1	05/03/88	10	28.5	6.90	7.20	3.71	2260		41.9		
H1	05/03/88	20	28.4	6.70	6.90	3.71	2350				
H1	05/03/88	30	28.3	6.40	6.60	3.71	2290		42.4		
H1	05/03/88	40	27.6	3.00	3.20	3.69	2320		76.5		
H1	05/03/88	50	27.0	2.00	2.20	3.71	2320		76.5		
H1	05/03/88	60	26.9	1.30	1.50	3.70	2320		56.1		
H1	05/03/88	70	26.7	0.40	0.40	3.69	2320		47.8		
H1	05/19/88	0	29.3	8.60	7.00	3.74	2340		24.4		
H1	05/19/88	5	28.4		6.30						
H1	05/19/88	10	28.2	7.70	6.20	3.72	2340		31.6		
H1	05/19/88	20	28.2	7.50	6.10	3.72	2290		29.5		
H1	05/19/88	30	28.2	7.30	5.90	3.72	2400		32.4		
H1	05/19/88	40	27.5	3.10	2.40	3.72	2430		50.1		
H1	05/19/88	50	27.3	2.50	2.10	3.72	2450		52.2		
H1	05/19/88	60	27.0	0.50	0.50	3.71	2370		61.9		
H1	05/19/88	70	26.9	0.30	0.40	3.71	2430		49.3		
SW. C.I.	05/25/88	0	29.0	8.40	7.80	3.73					
SW. C.I.	05/25/88	5	28.0		6.90	3.73					
SW. C.I.	05/25/88	10	28.0	7.70	6.90	3.73					
SW. C.I.	05/25/88	20	28.0	7.70	6.80	3.73					
SW. C.I.	05/25/88	30	28.0	7.60	6.60	3.72					
SW. C.I.	05/25/88	40	27.7	6.40	5.70	3.73					
SW. C.I.	05/25/88	50	27.4	2.00	2.00	3.70					
H1	05/30/88	0	28.5	7.40	7.20	3.74	2450		30.9	4.9	
H1	05/30/88	10	28.0	7.00	6.70	3.73	2680		31.7	6.8	
H1	05/30/88	20	27.9	7.00	6.90	3.74	2770		32.9	6.8	
H1	05/30/88	30	27.9	6.90	6.90	3.72	2740		32.2	0.0	
H1	05/30/88	40	27.8	6.90	6.80	3.73	2710		23.3	8.7	
H1	05/30/88	50	27.5	3.30	3.40	3.73	2680		45.1	0.0	
H1	05/30/88	60	27.2	0.60	0.80	3.70	2830		54.5	16.2	
H1	05/30/88	70	27.0	0.20	0.40	3.71	2450		42.3	21.7	
Todenyang	06/27/88	0	26.7		8.50	3.79					
Todenyang	06/27/88	1	26.5		8.40	3.79	2673				
Todenyang	06/27/88	2	26.3		8.20	3.79					
Todenyang	06/27/88	3	26.0		7.80	3.79					
Lowarengak	05/28/88	0	27.8		9.80	3.73					

STATION	DATE mm/dd/yy	DEPTH m	TEMP. °C	O2-titr. mg/l	O2-met. mg/l	Cond. mS/m x 10^{-2}	PO4-P µg/l	Tot. P µg/l	NO3-N µg/l	NH4-N µg/l	Tot. N µg/l
Lowarengak	05/28/88	5	26.7		9.10	3.71					
Lowarengak	05/28/88	10	26.6		8.80	3.71					
Lowarengak	05/28/88	15	26.5		8.20	3.79	2390				
N. N.I.	05/28/88	0	28.2		9.80	3.76					
N. N.I.	05/28/88	5	26.6		8.80	3.78					
N. N.I.	05/28/88	10	26.6		8.50	3.78					
N. N.I.	05/28/88	20	26.5		8.40	3.78					
N. N.I.	05/28/88	25	26.5		8.40	3.77	2910				
S. N.I.	05/28/88	0	29.3		8.80	3.74					
S. N.I.	05/28/88	5	26.8		8.30	3.73					
S. N.I.	05/28/88	10	26.7		8.40	3.75					
S. N.I.	05/28/88	20	26.7		8.10	3.75					
S. N.I.	05/28/88	30	26.7		8.00	3.75					
S. N.I.	05/28/88	40	26.6		8.10	3.73					
S. N.I.	05/28/88	50	26.6		8.10	3.74					
H1	06/30/88	0	28.7		7.50	3.75	2394		44.4	20.0	
H1	06/30/88	10	27.0		7.20	3.74	2340		48.7	1.5	
H1	06/30/88	20	26.9		7.10	3.75	2370		43.1	0.0	
H1	06/30/88	30	26.9		7.00	3.75	2420		48.0	12.6	
H1	06/30/88	40	26.9		6.90	3.75	2390		51.5	10.7	
H1	06/30/88	50	26.0		7.00	3.75	2394		50.5	21.8	
H1	06/30/88	60	26.7		7.00	3.75	2390		44.2		
SW. C.I.	07/05/88	0	28.5	7.20	8.20	3.77	2470				
SW. C.I.	07/05/88	5	26.7								
SW. C.I.	07/05/88	10	26.7	7.20	7.60	3.77	2263				
SW. C.I.	07/05/88	20	26.6	7.10	7.40	3.78	2340				
SW. C.I.	07/05/88	30	26.5	7.20	7.10	3.78	2340				
SW. C.I.	07/05/88	40	26.4	7.20	7.10	3.78	2260				
SW. C.I.	07/05/88	50	26.3	7.30	7.10	3.80	2290				
H1	07/07/88	0	28.1		7.30	3.80					
H1	07/07/88	10	26.7		7.00	3.77					
H1	07/07/88	20	26.7		6.70	3.77					
H1	07/07/88	30	26.7		6.70	3.76					
H1	07/07/88	40	26.7		6.60	3.75					
H1	07/07/88	50	26.7		6.60	3.76					
H1	07/07/88	60	26.6		6.60	3.76					
H1	07/07/88	70	26.4		6.70	3.77					
H1	07/17/88	0	26.8	7.70		3.76	2390		38.7	8.8	
H1	07/17/88	10	26.6	7.40		3.77	2310		39.4	34.2	
H1	07/17/88	20	26.6	7.30		3.77	2205		47.7	12.7	
H1	07/17/88	30	26.5	7.20		3.79	2340		39.7	24.5	
H1	07/17/88	40	26.5	7.20		3.79	2390		39.9	14.7	
H1	07/17/88	50	26.5	7.30		3.79	2360		43.6	10.8	
H1	07/17/88	60	26.3	6.90		3.80	2390		43.6	38.2	
H1	07/17/88	70	26.2	6.60		3.80	2310		45.3	6.9	
S1	07/21/88	0	28.7	8.20	7.90	3.85	2400		21.7		
S1	07/21/88	10	26.5	8.40	8.00	3.86	2400		23.3		
S1	07/21/88	20	26.3	7.80	7.60	3.86	2430		27.8		
S1	07/21/88	30	26.1	7.90	7.40	3.86	2400		27.8		
S1	07/21/88	35	25.8								
S1	07/21/88	40	25.4	7.50	7.40	3.89	2510		35.8		
S1	07/21/88	50	25.3	7.40	7.30	3.89	2450		38.9		
S1	07/21/88	60	25.3	7.40	7.20	3.90	2479		39.2		
S1	07/21/88	70		7.20	7.80	3.86	2450		27.3		
S1	07/21/88	85	25.3	7.40	7.70	3.89	2453		38.9		
H1	08/02/88	0	28.4	7.70						18.4	
H1	08/02/88	10	26.5	7.20						13.0	
H1	08/02/88	20	26.5							29.2	
H1	08/02/88	30	26.5	7.20						42.7	
H1	08/02/88	40	26.5	7.20						21.2	
H1	08/02/88	50	26.5	7.20						18.4	
H1	08/02/88	60	26.5	7.20						18.4	
H1	08/02/88	70	26.4	7.20							
E. H1	08/04/88	0	28.3	8.00		3.78	2430		31.1	14.3	
E. H1	08/04/88	5	26.4								
E. H1	08/04/88	10	26.3	7.40		3.78	2480		36.3	17.1	
E. H1	08/04/88	20	26.3	7.30		3.80	2480		36.5	28.6	
E. H1	08/04/88	30	26.2	7.40		3.80	2450		33.4	22.8	
E. H1	08/04/88	40	26.2	7.40		3.80	2507		33.0	20.0	
E. H1	08/04/88	50	26.1	7.30		3.81	2530		41.1	11.4	
W. H1	08/04/88	0	29.2	8.90		3.77	2510		23.6	14.3	
W. H1	08/04/88	5	26.8								
W. H1	08/04/88	10	26.6	7.70		3.77	2480		35.1	0.0	
W. H1	08/04/88	20	26.5	7.30		3.77	2430		36.9	5.7	
S. N.I.	08/08/88	0	27.4	8.00		3.67	2497		59.5	29.1	
S. N.I.	08/08/88	10	26.5	7.40		3.68	2810		55.6	25.8	
S. N.I.	08/08/88	20	26.4	7.10		3.75	2611		47.7	29.1	
S. N.I.	08/08/88	30	26.2	7.10		3.78	2950		42.1	59.7	
S. N.I.	08/08/88	40	26.2	7.10		3.77	2580		48.8	8.8	

APPENDIX III

NITRATE CONCENTRATIONS

In this appendix results of parallel nitrate analysis using the Hg/Cd-reduction method at the field laboratory are listed.

STATION	DATE mm/dd/yy	DEPTH m	NO_3-N µg/l
H1	04/22/88	0	2
H1	04/22/88	10	17
H1	04/22/88	20	37
H1	04/22/88	30	44
H1	04/22/88	40	113
H1	04/22/88	50	145
H1	04/22/88	60	171
H1	04/22/88	70	152
H1	05/30/88	0	17
H1	05/30/88	10	31
H1	05/30/88	20	11
H1	05/30/88	30	24
H1	05/30/88	40	26
H1	05/30/88	50	42
H1	05/30/88	60	80
H1	05/30/88	70	65
H1	06/30/88	20	55
H1	06/30/88	30	60
H1	06/30/88	40	57
H1	06/30/88	50	51
H1	06/30/88	60	49
H1	07/17/88	0	52
H1	07/17/88	10	51
H1	07/17/88	20	56
H1	07/17/88	30	61
H1	07/17/88	40	60
H1	07/17/88	50	37
H1	07/17/88	60	65
H1	07/17/88	70	49
S1	07/21/88	0	2
S1	07/21/88	10	2
S1	07/21/88	20	9
S1	07/21/88	30	13
S1	07/21/88	40	2
S1	07/21/88	50	51
S1	07/21/88	60	55
S1	07/21/88	85	53
H1	08/02/88	0	55
H1	08/02/88	10	66
H1	08/02/88	20	70
H1	08/02/88	30	57
H1	08/02/88	40	66
H1	08/02/88	60	63
H1	08/02/88	70	63
E. H1	08/04/88	0	11
E. H1	08/04/88	10	2
E. H1	08/04/88	20	31
E. H1	08/04/88	30	2
E. H1	08/04/88	40	36
E. H1	08/04/88	50	16
W. H1	08/04/88	0	5
W. H1	08/04/88	10	15
W. H1	08/04/88	20	49
S. N.I.	08/08/88	0	62
S. N.I.	08/08/88	10	63
S. N.I.	08/08/88	20	65
S. N.I.	08/08/88	30	58
S. N.I.	08/08/88	40	53

APPENDIX IV

MAJOR IONS

LAKE TURKANA MAIN IONS

Station	Date	Depth m	Cond. mS/m,s	Na mg/l	Ca mg/l	K mg/l	Mg mg/l	Fe µg/l	Mn mg/l	Cl mg/l	SO_4 mg/l	Alkalinity meq/l	F mg/l	SiO_2 mg/l
H1	11/07/85	0-10	331	931		21	2.22	1590	19	-	-	21.4		
H1	04/11/87	-	350	800		18	1.78	36	1.7	440	38	23.2		
H1	10/15/87	10	348	920	4.31	14.6	2.28	1560		420	36	23.2	10	
H1	03/26/87	10	358	700	4.26	18	2.31	62	2.3	440	37	23.9	11.9	25
H1	08/11/88	1	376	790	4.03	18.2	2.14			440	38			24
H1	08/11/87	10	377	770	4.09	18.3	2.4			440	37			24
H1	08/11/88	68	378	780	3.7	18.3	2.4			440	39			39
S. N.I.	08/08/88	1	361	760	4.61	17.6	2.21			420	35			24
S. N.I.	08/08/88	10	367	750	4.02	17.8	2.05			430	35			24
S1	07/21/88	1	387	800	3.7	18.7	2.3			460	40			21
S1	07/21/88	10	387	810	3.71	19.1	2.4			460	38			26
S1	07/21/88	85	390	820	3.7	19	2.4			460	39			26

APPENDIX V

MINOR IONS

Concentrantions of metal ions in µg per liter from Lake Turkana. (Cu - copper, Zn - zink, Co - cobalt, Pb - lead, Hg - mercury, Mn - manganese, Ni - nickel, Al - aluminium, Fe - iron, Cd - cadmium and Cr - chrome). Secchi depth in meters is also listed.

Date	Locality	Depth	Cu	Zn	Co	Pb	Hg	Mn	Ni	Al	Fe	Cd	Cr		Secchi depth
15-16/10-87	H-1	0m	2.7	<10	<5		<0.50	14.5	<5	3110	1320	<0.1	1.5		0.95
"	H-1	10m	4.8	30	<5			14.5	<5	2490	1560	0.12	1.4		"
"	H-1	70m		50	<5		<0.50	6.0	<5	710	550	<0.1	1.2		"
23/6-88	H-1	5m	3.07	10	<5		<0.5	6.8	<5	365	88	0.16	<0.5		3.1
17/7-88	H-1	0m	3.1					6.3		500	310				1.4
"	H-1	10m	5.0			0.81		7.3		511	260				"
"	H-1	70m	2.3			0.98		6.9		546	290				"
21/7-88	South South Island	0m	4.4					4.0		253	86				3.0
8/8-88	South North Island	0m	3.1					30.8		3750	2150				0.4

APPENDIX VI

PRIMARY PRODUCTION AND CHLOROPHYLL

O2L = Dissolved oxygen in light bottles

O2D = Dissolved oxygen in dark bottles

DELTA O2 = Gross oxygen production (O2L-O2D)/incubation time.

CHL = Chlorophyll-a

LAKE TURKANA - PRIMARY PRODUCTION AND CHLOROPHYLL-a

STATION	DATE mm/dd/yy	DEPTH m	TEMP C	O2(l) mg/l	O2(d) mg/l	deltaO2 mg/l/h	CHL-a ug/l
H1	11/07/85	0.2		6.79	6.40	0.25	5.60
H1	11/07/85	0.5		6.88	6.45	0.27	4.10
H1	11/07/85	1.0		7.24	6.64	0.38	5.60
H1	11/07/85	2.0					3.50
H1	11/07/85	4.0		6.65	6.64	0.01	6.20
H1	11/07/85	6.0					4.10
E. Nataba	04/08/87	0.5		7.40	7.20	0.08	1.44
E. Nataba	04/08/87	1.0		7.45	7.10	0.14	1.27
E. Nataba	04/08/87	1.5		7.45	7.10	0.14	1.48
E. Nataba	04/08/87	2.0		7.40	7.10	0.12	1.50
E. Nataba	04/08/87	3.0		7.35	7.10	0.10	2.72
E. Nataba	04/08/87	5.0		7.10	7.10	0.00	2.02
H1	04/11/87	0.5		7.30	7.10	0.07	1.40
H1	04/11/87	1.0		7.50	7.20	0.10	1.40
H1	04/11/87	1.5		7.50	6.90	0.20	1.40
H1	04/11/87	2.5					1.40
H1	04/11/87	4.0		6.50	6.10	0.13	1.40
H1	04/11/87	6.0	7.0				1.40
Moite	04/16/87	0.5	28.9				3.64
S. C.I.	04/16/87	0.5	29.1				2.14
SE. Nataba	04/16/87	0.5	29.0				2.66
Alli Bay	04/17/87	0.5	28.5				2.27
H1	04/17/87	0.5	28.9				2.78
Longech	04/17/87	0.5	29.0				1.66
H1	05/08/87	0.5	30.0	7.90	7.70	0.10	
H1	05/08/87	1.0	30.0	7.85	7.80	0.03	
H1	05/08/87	1.5	29.5	8.00	7.70	0.15	
H1	05/08/87	2.0	29.5	7.90	7.70	0.10	
H1	05/08/87	3.0	29.4	7.85	7.60	0.13	
H1	05/08/87	5.0	29.3	7.65	7.60	0.03	
H1	05/08/87	6.0	29.2	7.60	7.60	0.00	
H1	07/01/87	0.5		8.13	7.97	0.08	
H1	07/01/87	1.0		8.27	7.93	0.17	
H1	07/01/87	2.0		8.23	7.90	0.16	
H1	07/01/87	4.0		8.00	7.81	0.10	
H1	07/01/87	6.0		7.80	7.70	0.05	
H1	07/22/87	0.5	29.9	7.93	7.70	0.12	
H1	07/22/87	1.0	27.2	8.20	7.66	0.27	
H1	07/22/87	2.0	27.1	7.83	7.66	0.08	
H1	07/22/87	2.5	27.0	7.73	7.57	0.08	
H1	07/22/87	3.0	27.0	7.73	7.60	0.06	
H1	07/22/87	4.0	26.9	7.60	7.56	0.02	
H1	07/22/87	6.0	26.9	7.42	7.40	0.01	
H1	08/25/87	0.5					5.56
H1	08/25/87	1.0					6.95
H1	08/25/87	2.0					5.56
H1	08/25/87	2.5					2.22
H1	08/25/87	3.0					1.67
H1	08/25/87	4.0					4.17

LAKE TURKANA - PRIMARY PRODUCTION AND CHLOROPHYLL-a

STATION	DATE mm/dd/yy	DEPTH m	TEMP C	O2(l) mg/l	O2(d) mg/l	deltaO2 mg/l/h	CHL-a ug/l
H1	08/25/87	6.0					4.72
H1	09/14/87	0.5	27.7	7.73	7.43	0.15	
H1	09/14/87	1.0	27.0	7.70	7.60	0.05	
H1	09/14/87	1.5	26.7	7.70	7.47	0.12	
H1	09/14/87	2.0	26.7	7.70	7.63	0.04	
H1	09/14/87	2.5	26.5	7.66	7.60	0.03	
H1	09/14/87	3.0	26.4	7.60	7.63	0.00	
H1	11/07/87	0.3	29.5	9.49	8.93	0.28	20.00
H1	11/07/87	0.5	29.4	9.79	9.09	0.35	16.20
H1	11/07/87	1.0	28.9	9.53	9.02	0.25	17.60
H1	11/07/87	1.5	28.5	8.59	8.30	0.14	10.70
H1	11/07/87	2.0	28.5	8.41	8.27	0.07	9.30
H1	11/07/87	3.0	28.4	7.98	7.97	0.01	12.80
H1	11/07/87	4.0	28.3	7.76	7.06	0.30	6.40
SW. C.I.	03/17/88	0.5	30.5				2.70
SW. C.I.	03/17/88	1.0					3.19
SW. C.I.	03/17/88	1.5	29.6				2.92
SW. C.I.	03/17/88	2.0	29.6				3.07
SW. C.I.	03/17/88	2.5					3.79
SW. C.I.	03/17/88	3.0	29.4				3.29
SW. C.I.	03/17/88	4.0	29.4				3.07
SW. C.I.	03/17/88	6.0	29.3				2.79
H1	03/18/88	1.0					1.82
H1	03/18/88	2.0					2.00
H1	03/18/88	5.0					2.38
SW. C.I.	03/22/88	0.5	30.3	7.53	7.28	0.06	1.62
SW. C.I.	03/22/88	1.0	30.3	7.62	7.29	0.08	1.71
SW. C.I.	03/22/88	1.5	30.2	7.56	7.23	0.06	1.62
SW. C.I.	03/22/88	2.0	30.1	7.50	7.23	0.06	1.54
SW. C.I.	03/22/88	2.5	30.1	7.47	7.28	0.04	1.67
SW. C.I.	03/22/88	3.0	30.2	7.42	7.36	0.00	1.59
SW. C.I.	03/22/88	4.0	30.1	7.35	7.21	0.03	1.67
SW. C.I.	03/22/88	6.0	30.1	7.22	7.14	0.02	1.30
S. N.I.	03/24/88	0.2	29.6				2.01
S. N.I.	03/24/88	4.0	29.5				2.10
S. N.I.	03/24/88	6.0	0.0				2.30
SW. C.I	03/31/88	2.5	29.7	7.80	7.39	0.16	3.60
SW. C.I.	03/31/88	0.5	30.0	7.79	7.31	0.18	3.30
SW. C.I.	03/31/88	1.0	30.0	7.89	7.31	0.19	3.50
SW. C.I.	03/31/88	1.5	29.9	7.86	7.40	0.18	3.80
SW. C.I.	03/31/88	2.0	29.8	7.84	7.32	0.20	3.80
SW. C.I.	03/31/88	3.0	29.7	7.82	7.34	0.14	3.80
SW. C.I.	03/31/88	4.0	29.6	7.46	7.18	0.11	4.10
SW. C.I.	03/31/88	5.0	29.6	7.22	7.07	0.06	4.10
SW. C.I.	03/31/88	6.0	29.5	7.16	7.03	0.05	3.40
H1	04/08/88	0.1	30.1				4.17
H1	04/08/88	10.0	29.1				3.60
H1	04/08/88	20.0	29.1				3.30
H1	04/08/88	30.0	27.9				0.20
H1	04/08/88	40.0	27.4				0.60

LAKE TURKANA - PRIMARY PRODUCTION AND CHLOROPHYLL-a

STATION	DATE mm/dd/yy	DEPTH m	TEMP C	O2(l) mg/l	O2(d) mg/l	deltaO2 mg/l/h	CHL-a ug/l
H1	04/08/88	50.0	26.8				0.20
H1	04/08/88	60.0	26.7				0.20
H1	04/08/88	70.0					0.00
H1	06/30/88	0.1	28.7				2.20
H1	06/30/88	10.0	27.0				1.10
H1	06/30/88	20.0	26.9				1.40
H1	06/30/88	30.0	26.9				1.40
H1	06/30/88	40.0	26.9				1.70
H1	06/30/88	50.0	26.9				1.40
H1	06/30/88	60.0	26.7				1.40
SW. C.I.	07/05/88	0.1	28.5				3.50
SW. C.I.	07/05/88	0.5	27.5	8.42	8.01	0.15	5.10
SW. C.I.	07/05/88	1.0	27.5	8.52	7.85	0.25	5.60
SW. C.I.	07/05/88	1.5	27.3	8.33	7.98	0.13	4.30
SW. C.I.	07/05/88	2.0	27.3	8.44	7.93	0.19	6.30
SW. C.I.	07/05/88	2.5	27.1	8.26	7.98	0.12	6.30
SW. C.I.	07/05/88	3.0	27.1	8.10	7.87	0.09	6.40
SW. C.I.	07/05/88	4.0	27.1	7.92			5.00
SW. C.I.	07/05/88	5.0	27.0	7.80	7.74	0.02	5.80
SW. C.I.	07/05/88	6.0	27.0	7.73	7.75	0.00	5.70
SW. C.I.	07/05/88	10.0	26.7				1.70
SW. C.I.	07/05/88	20.0	26.6				1.90
SW. C.I.	07/05/88	30.0	26.5				2.20
SW. C.I.	07/05/88	40.0	26.4				2.00
SW. C.I.	07/05/88	50.0	26.3				2.80
H1	07/17/88	0.1	26.8				2.50
H1	07/17/88	1.0					2.80
H1	07/17/88	2.0					3.30
H1	07/17/88	3.0					2.50
H1	07/17/88	4.0					2.50
H1	07/17/88	5.0					2.20
H1	07/17/88	6.0					2.50
SW. C.I.	07/19/88	0.5	27.1	7.90	7.57	0.12	2.90
SW. C.I.	07/19/88	1.0	27.0	7.94	7.61	0.12	3.10
SW. C.I.	07/19/88	1.5	26.9	7.94	7.58	0.13	2.90
SW. C.I.	07/19/88	2.0	26.7	7.88	7.50	0.14	3.20
SW. C.I.	07/19/88	2.5	26.7	7.74	7.39	0.13	3.20
SW. C.I.	07/19/88	3.0	26.6	7.56	7.33	0.09	2.80
SW. C.I.	07/19/88	4.0	26.5	7.37	7.27	0.04	3.00
SW. C.I.	07/19/88	5.0	26.5	7.29	7.26	0.01	3.10
S1	07/22/88	0.5	27.2	8.25	8.14	0.05	1.70
S1	07/22/88	1.0	27.2	8.31	8.19	0.06	1.80
S1	07/22/88	1.5	27.2	8.29	8.20	0.04	2.10
S1	07/22/88	2.0	27.2	8.29	8.15	0.07	2.10
S1	07/22/88	2.5	27.1	8.32	8.14	0.09	1.90
S1	07/22/88	3.0	26.7				1.90
S1	07/22/88	4.0	26.4				2.10
S1	07/22/88	5.0	26.3	7.86	7.78	0.04	2.10
S1	07/22/88	6.0	26.2	7.82	7.80	0.01	1.90
H1	08/02/88	0.1	28.4				1.90

LAKE TURKANA - PRIMARY PRODUCTION AND CHLOROPHYLL-a

STATION	DATE mm/dd/yy	DEPTH m	TEMP C	O2(1) mg/l	O2(d) mg/l	deltaO2 mg/l/h	CHL-a ug/l
H1	08/02/88	1.0					2.20
H1	08/02/88	2.0					2.40
H1	08/02/88	3.0					2.60
H1	08/02/88	4.0					2.20
H1	08/02/88	5.0					2.10
H1	08/02/88	6.0					1.80
H1	08/02/88	10.0	26.5				1.80
H1	08/02/88	20.0	26.5				1.70
H1	08/02/88	30.0	26.5				1.70
H1	08/02/88	40.0	26.5				1.50
H1	08/02/88	50.0	26.5				1.50
H1	08/02/88	60.0	26.5				1.40
H1	08/02/88	70.0	26.4				1.70
E. H1	08/04/88	0.1	28.3				3.70
E. H1	08/04/88	1.0					4.00
E. H1	08/04/88	2.0					3.60
E. H1	08/04/88	3.0					4.00
E. H1	08/04/88	4.0					2.80
E. H1	08/04/88	5.0	28.4				3.50
E. H1	08/04/88	6.0	0.0				2.80
W. H1	08/04/88	0.1	29.2				6.50
W. H1	08/04/88	1.0					6.70
W. H1	08/04/88	2.0					6.90
W. H1	08/04/88	3.0					6.80
W. H1	08/04/88	4.0					6.90
W. H1	08/04/88	5.0					5.80
W. H1	08/04/88	6.0					5.40
H1	08/06/88	0.5	26.9	8.60	7.94	0.23	8.10
H1	08/06/88	1.0	26.9	8.57	7.96	0.21	7.60
H1	08/06/88	1.5	26.8	8.56	7.88	0.24	8.50
H1	08/06/88	2.0	26.7	8.32	7.83	0.17	8.30
H1	08/06/88	2.5	26.7	8.14	7.74	0.14	7.20
H1	08/06/88	3.0	26.7	8.15	7.74	0.14	7.40
H1	08/06/88	4.0	26.7	7.87	0.69	0.04	7.10
H1	08/06/88	5.0	26.7	7.69	7.61	0.03	6.90
H1	08/06/88	6.0	26.7				6.40
S. N.I.	08/08/88	0.2					23.80
S. N.I.	08/08/88	1.0					12.20
S. N.I.	08/08/88	2.0					7.50
S. N.I.	08/08/88	3.0					5.00
S. N.I.	08/08/88	4.0					3.30
S. N.I.	08/08/88	5.0					4.30
S. N.I.	08/08/88	6.0					3.60