1 Eutrophication

1.1 Objectives

The objective of the activities related to eutrophication i.e. the effects of nutrient enrichment of the lake are:

- Through data collected in the Lake Water Quality Monitoring Programme to assess the state of eutrophication in the lake
- To assess the mechanisms by which the lake responds to increased nutrient loadings
- To provide relevant calibration data to the model (nutrient levels, chlorophyll-a, dissolved oxygen etc.)

1.2 Eutrophication Processes

Eutrophication is an alteration of the production cycle of the ecosystem due to enrichment by nutrients (particularly nitrogen and phosphorus). Eutrophication leads to excessive growth of algae or macrophytes affecting seriously the water quality (e.g. low oxygen content, high turbidity, release of toxic gases from the sediments such as hydrogen sulphide). These changes favour the most robust species whilst the more sensitive ones may disappear.

The Lake Victoria ecosystem has reportedly undergone substantial changes over the last decades. Increased algal biomass and changes in the species composition from dominance of diatoms to dominance of cyanobacteria have been reported (Hecky 1993, Mugidde 1993, Lehman and Branstrator 1994) along with increased areas with oxygen depletion (Ochumba 1996, Hecky et al. 1998) and extinction of endemic chiclid species (Goldsmith and Witte 1992). However, the temporal and the spatial scales for the changes are still under debate since no lake-wide studies on nutrients, biomass and oxygen have been done on an annual scale.

There are 3 hypotheses offered for the changes in Lake Victoria (Lehman et al 1998):

- Increased nutrient loading due to population growth and change in agricultural practices.

- Trophic alterations from top-down cascade of predatory interactions by introduction of Nile perch and cichlid species and changes in fishery

- Climate changes towards warmer, more humid and less windy weather reducing mixing depth and frequency of total mixing of the lake

The changes in climate are apparently sufficient to explain the overall change in the lake, but certainly the periodically limitation by nitrogen is influenced by increased nutrient loading from the catchment and most important from wet and dry deposition from the atmosphere. Sediment analyses have verified that increased eutrophication started before the introduction of new fish species (Stager 1998, Lehman et al 1998).

The rehabilitation of the Lake Victoria ecosystem and its catchment must start with a regional environmental effort aiming at a description of the temporal and spatial scales of the problems and aiming at identification of the causes of the problems. A framework for such efforts is the Lake Victoria Water QualityModel with its description of relations between climate, nutrient loading and eutrophication processes. Scenarios run as hindcasts or forecasts will be valuable tools for both the understanding of in-lake processes, for the identification of the important causes to the environmental state and for the analyses of management strategies.

1.3 Methods

The collection of data has been based on monthly and quarterly lake monitoring programmes (see Chapter 6 for details) including standard variables such as nitrogen and phosphorus fractions (inorganic, particulate, organic dissolved, and total), chlorophyll-a, algae species, zooplankton species, light conditions (measured as secchi depths or light), and oxygen conditions (see Chapter 12 on analyses).

After validation, spatial variability has been examined through calculated statistics such as minimum, maximum, average, median, and upper and lower quartiles by station and presented in tables and by using horizontal contour plots and vertical profile plots.

Where the data collection starts to be sufficient, temporal variability has been examined by various time series plots.

The quantitative relation between different parameters have been assessed through regression analysis (light to Chlorophyll-a, particulate N to particulate P, Chlorophyll-a to N and P etc.) and a global ratio of C:N:P:Si has been estimated to preliminarily assess the regime of nutrient limitation of the primary production.

1.4 Data Availability

During the project period the Kisumu laboratory became equipped with adequate instruments and the staff was trained in adequate methods for analysing nutrients. Thus, full campaigns were not executed before August 2001

The Mwanza laboratory suffered, as did the Kisumu laboratory, from lack of adequate equipment and training in low level nutrient analysis for a long time of the project period and therefore substantial gaps are found in the data series for a number of parameters.

Uganda has been able to implement a large part of the planned monitoring programme although some gaps exist due to breakdown of equipment.

Finally, the fact that monitoring and analysis at the limnological level has been new to the laboratories (an on-the-job learning process) it is normal that it has been necessary to discard some of the data during the validation process, thus creating further gaps in the time series. However, the Water Quality Data Base now contains more than 1800 records and around 14000 individual validated values from the lake, and many more in the Profile Data Base. Thus, although conclusions may be considered very preliminary, the monitoring is well over its start-up problems and the amount of data concerning the eutrophication of the lake far exceeds what existed previously.

1.5 Nutrients

Nutrients have been measured according to the sampling scheme described in Chapter 6 i.e. monthly/quarterly and as profiles. The analysis programme has taken into account the different fractions in which the nutrients appear. Thus the following nutrient parameters have been analysed for:

- TN: total nitrogen (only when particulate/dissolved fractions could not be analysed)
- TPN: total particulate nitrogen
- DON: dissolved organic nitrogen
- NO_2: nitrite
- NO_3: nitrate
- NH_4: ammonium
- IN: inorganic nitrogen (calculated as the sum of NO_2+NO_3+NH_4 when all three have been measured)
- TP: total phosphorus (only when particulate/dissolved fractions could not be analysed)
- TPP: total particulate phosphorus
- DOP: dissolved organic phosphorus
- PO_4: orthophosphate
- PBSi: particulate biogenic silicium
- Si: silicium

Various methodological and logistic problems (see sections 1.3 and 1.4) have caused gaps in the data sets. However, the validated database now contains around 8,600 nutrient analyses from the lake distributed among the parameters as follows in Table 1.1.

Table 1.1 Number of samples analysed for nutrients.

Parameter	TN	TPN	DON	NO2	NO3	NH4	IN	TP	TPP	DOP	PO4	PBS	Si
No. Samples	83	296	444	1144	1041	798	681	923	566	297	1321	345	749

The fact that the particulate and dissolved organic fractions (TPN, DON, TPP, DOP, and PBSi) have been measured less frequently than the inorganic fractions reflects late arrival of some equipments as well as late training in these methods which were new to all three laboratories.

The validated database as well as overall statistics of the nutrient data can be found on the CD-ROM.

Examples of nutrient data are given in the following figures. Figure 1.1 to Figure 1.4 show the ranges of concentrations of NH_4, NO_3, PO_4 and Si in the photic zone[1] for the different stations in the lake (minimum, medians, and maximum). Figure 1.5 and Figure 1.6 show time series of nitrate and phosphate in the photic zone.

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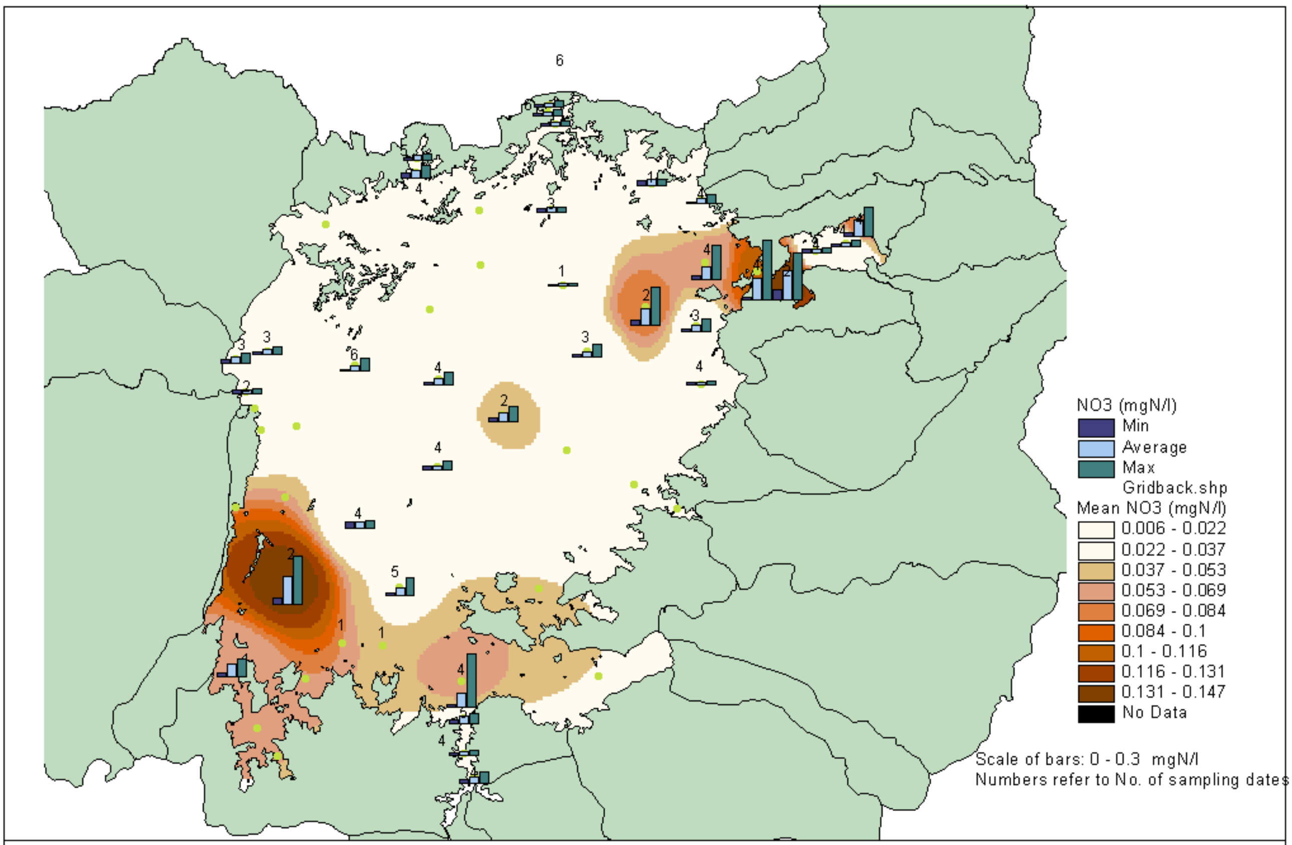
[1] Averages of samples from the photic part of the water column.

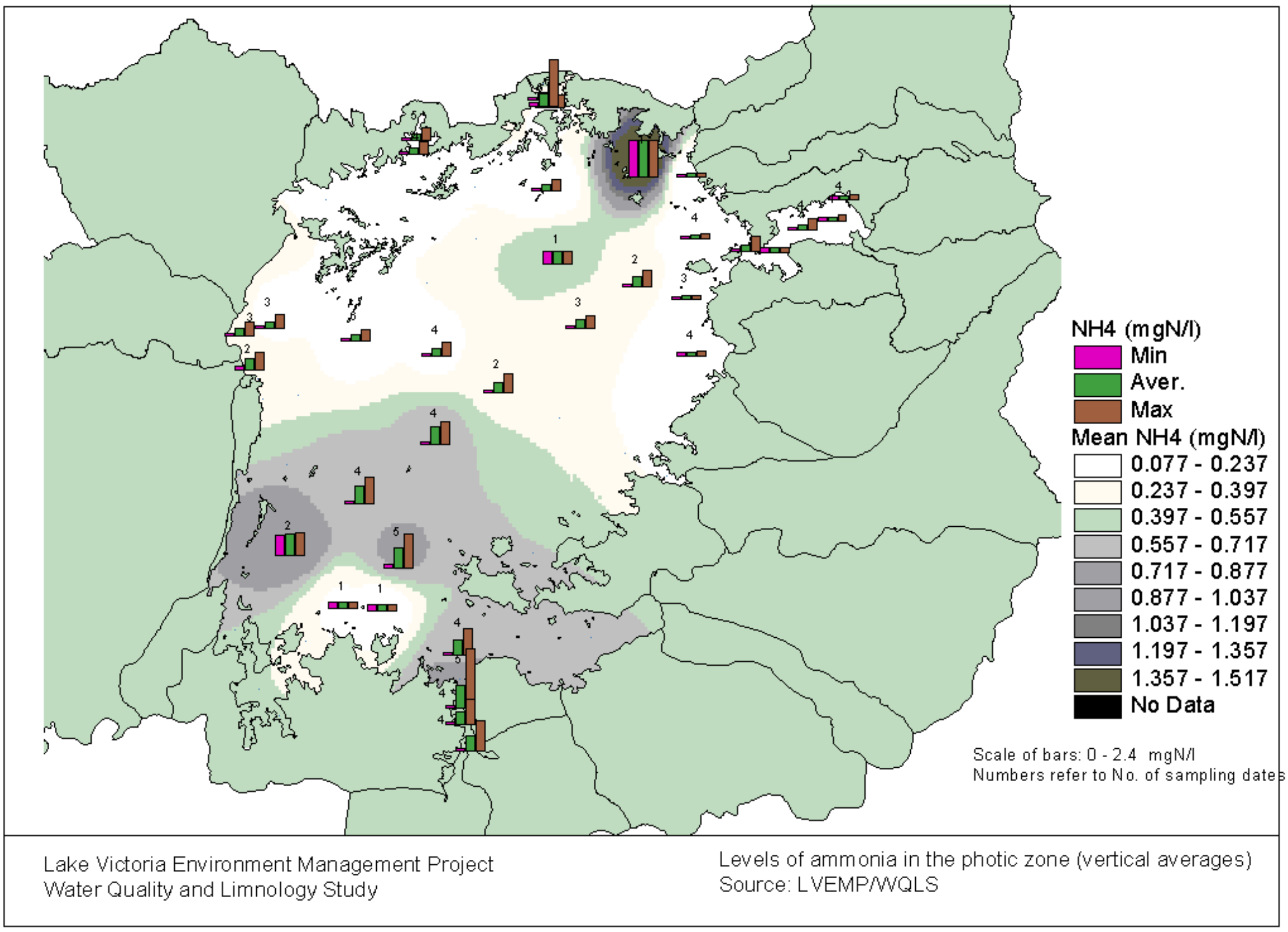


Scale of bars: 0 - 0.3 mgN/l
Numbers refer to No. of sampling dates

Lake Victoria Environment Management Project
Water Quality and Limnology Study

Levels of nitrate in the photic zone (vertical averages)
Source: LVEMP/WQLS

Figure 1.1 Nitrate concentrations in the photic zone, November 2000 - August 2001.



Lake Victoria Environment Management Project
Water Quality and Limnology Study

Levels of ammonia in the photic zone (vertical averages)
Source: LVEMP/WQLS

Figure 1.2 Ammonium concentrations in the photic zone, November 2000 - August 2001.

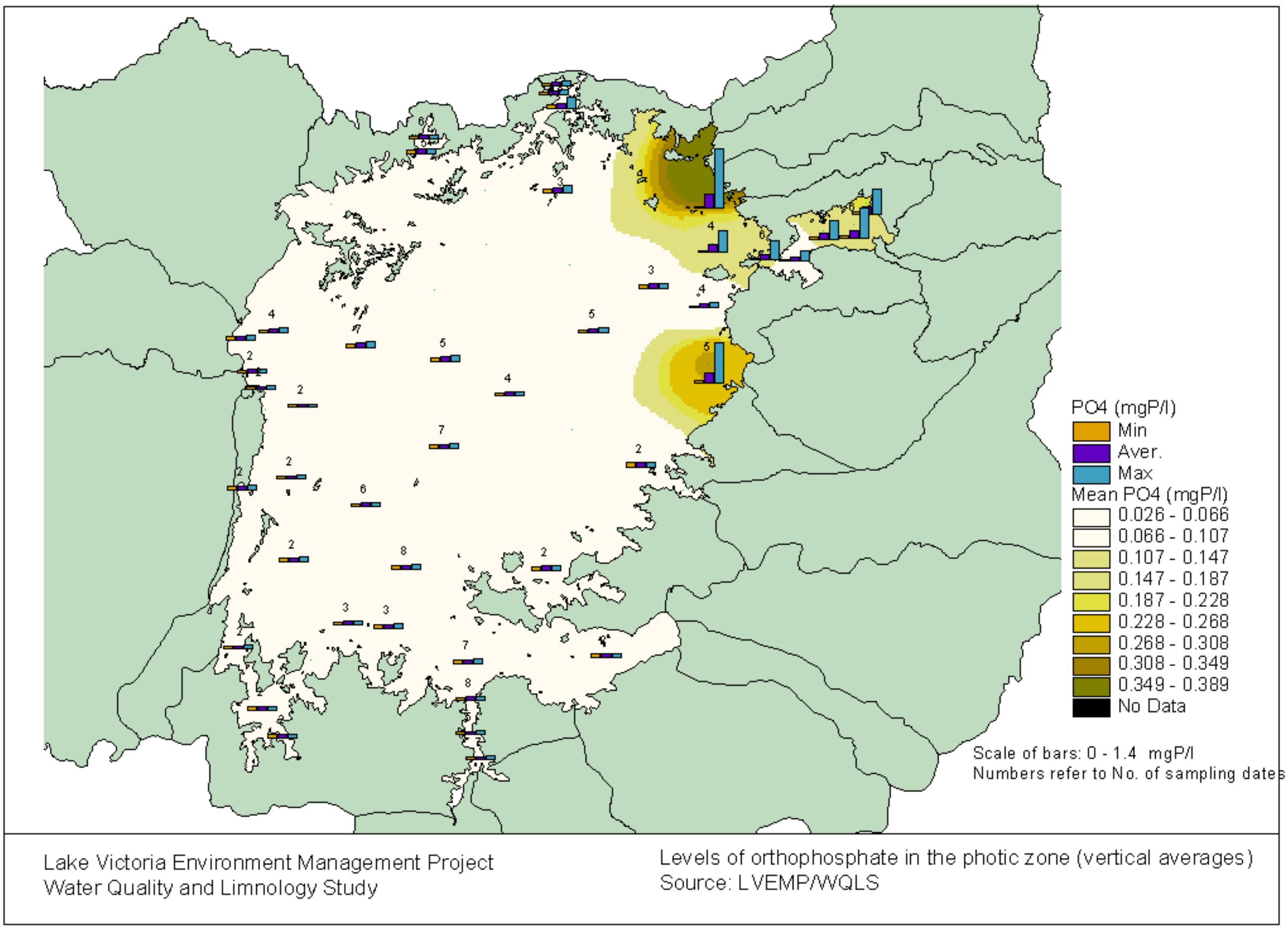


Figure 1.3 Phosphate concentrations in the photic zone, November 2000 - August 2001.

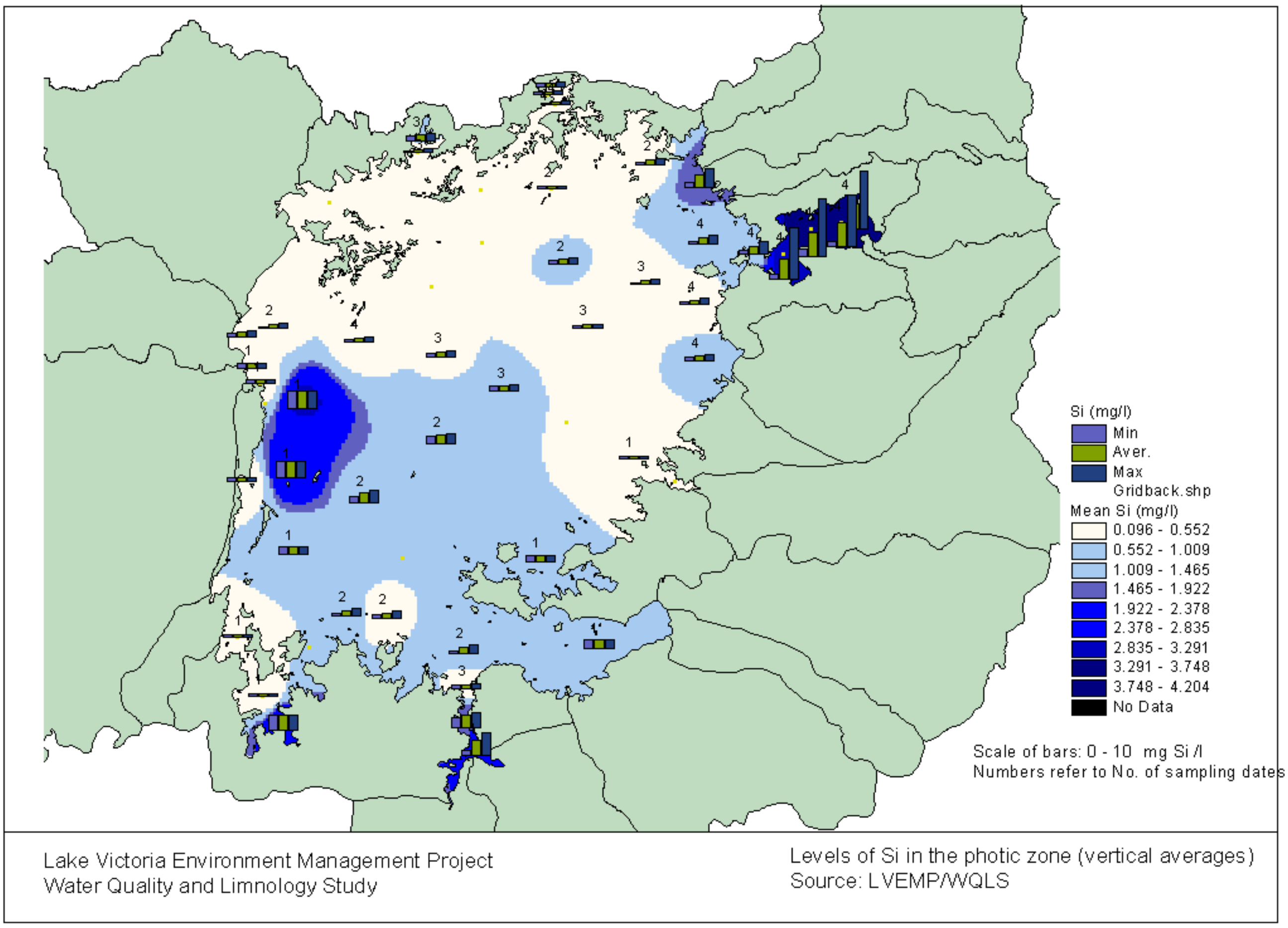


Figure 1.4 Silicate concentrations in the photic zone, November 2000 - August 2001.

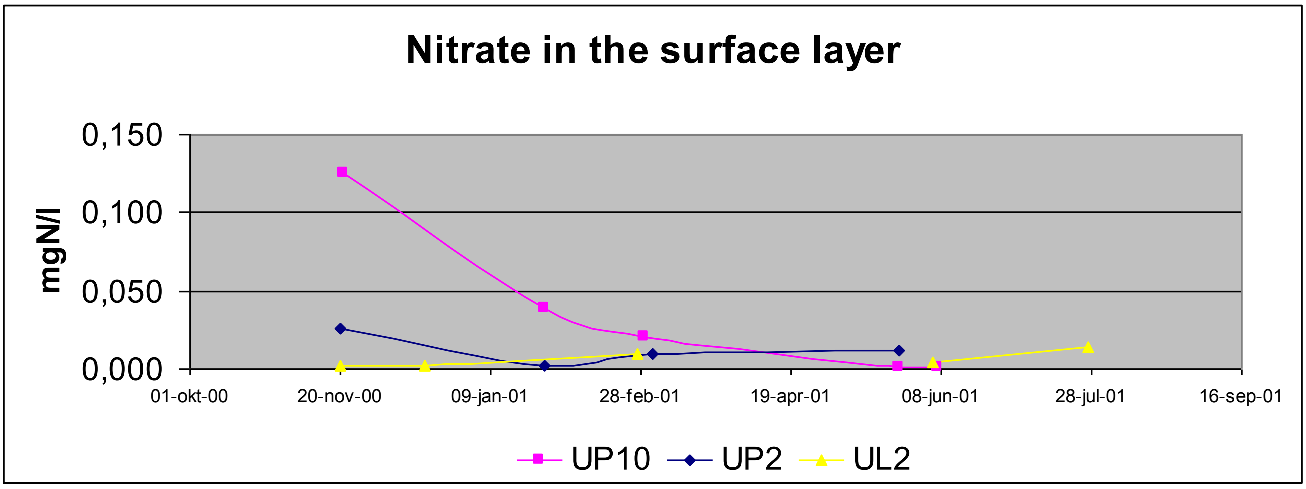


Figure 1.5 Time series of Nitrate in the surface layer at stations UP10, UP, UL2.

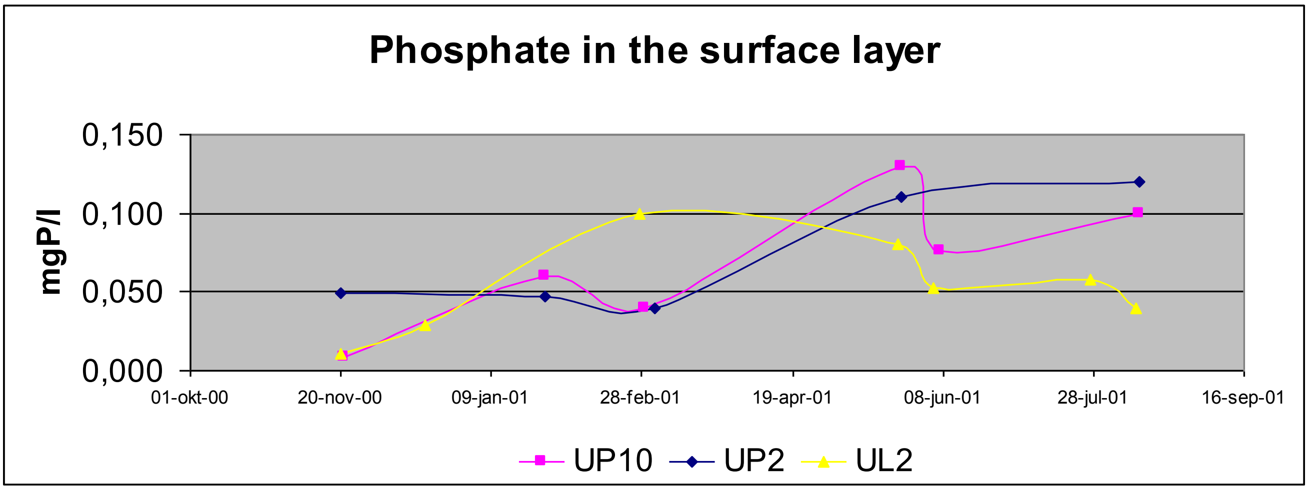


Figure 1.6 Time series of phosphate in the surface layer at stations UP10, UP2, UL2.

The relations between the different nutrient parameters (and also Chlorophyll-a) have been examined by overall regression analyses (the entire data set). The specific relations are given in Table 1.2

Table 1.2 Regressions between nutrient parameters.

TPC/Chl-a: TPC mgC/l = 54.6 x Chl-a mg/l

TPN/TPP: TPN mgN/l = 5.4 x TPP mgP/l

TPP/TPC: TPP mgP/l = 0.04 TPC mgC/l

TBSi/TPP: TBSi mg/l = 7.9 x TPP mgP/l

These relations are all within expected ranges. From the relations above the overall ratio of carbon : nitrogen : phosphorus : silicium can be derived:

$$C_{62.5} : N_{10.9} : P_1 : Si_{7.5}{}^2$$

When comparing to the Redfield Ratio (C_{106}: N_{16}: P_1) it is seen that the overall N/P ratio in the lake is relatively low indicating potential nitrogen limitation, but also that the carbon to nutrients ratio is low which gives an overall indication of light limited algae growth.

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[2] NB! The overall ratio of C:N:P:Si is calculated on stochiometric basis.

Table 1.3 shows the ratios of N/P of particulate matter at stations at different depths in the lake[3]. It indicates that actual nitrogen limitation may occur at the shallower near shore stations (N/P < 8).

Table 1.3 N/P ratios at different depths.

	Depth									
	0m-10m		**10m-20m**		**20m-40m**		**40m-60m**		**60m-80m**	
		No of Counts		**No of Counts**		**No of Counts**		**No of Counts**		**No of Counts**
TPN	**0.378**	**11**	**0.292**	**12**	**0.224**	**8**	**0.228**	**6**	**0.183**	**14**
TPP	**0.056**	**27**	**0.020**	**25**	**0.015**	**9**	**0.024**	**11**	**0.021**	**27**
N/P	**6.74**		**14.89**		**14.96**		**9.33**		**8.55**	

1.6 Chlorophyll-a / Light Relationships

It was concluded by both Talling (1965,1966) and Lehman et al (1998) that the master variable controlling the eutrophication effects in Lake Victoria is the mixing depth. The relation between photic depth and mixing depth varies with the climate. During cooling of the lake in June-July and to some extent in December- January mixing is increased bringing nutrients to the photic zone. Under these circumstances phytoplankton species compete at low average light favouring the growth of diatoms. In periods with less mixing cyanobacteria, some of which may fix nitrogen, are more competitive (Lehman et al 1998).

Figure 1.7 presents in an overview the ranges of measured secchi depths (transparency). The contours interpolate the average of all measurements at each station and the bars show minimum and maximum values. It appears that typical values in the middle of the lake range from 3-6 meters (max. 7.2 m) whereas the values at 1.0 or less are common near the shores and in the bays.

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[3] NB! The N/P ratios in Table 1.3 are calculated on weight basis

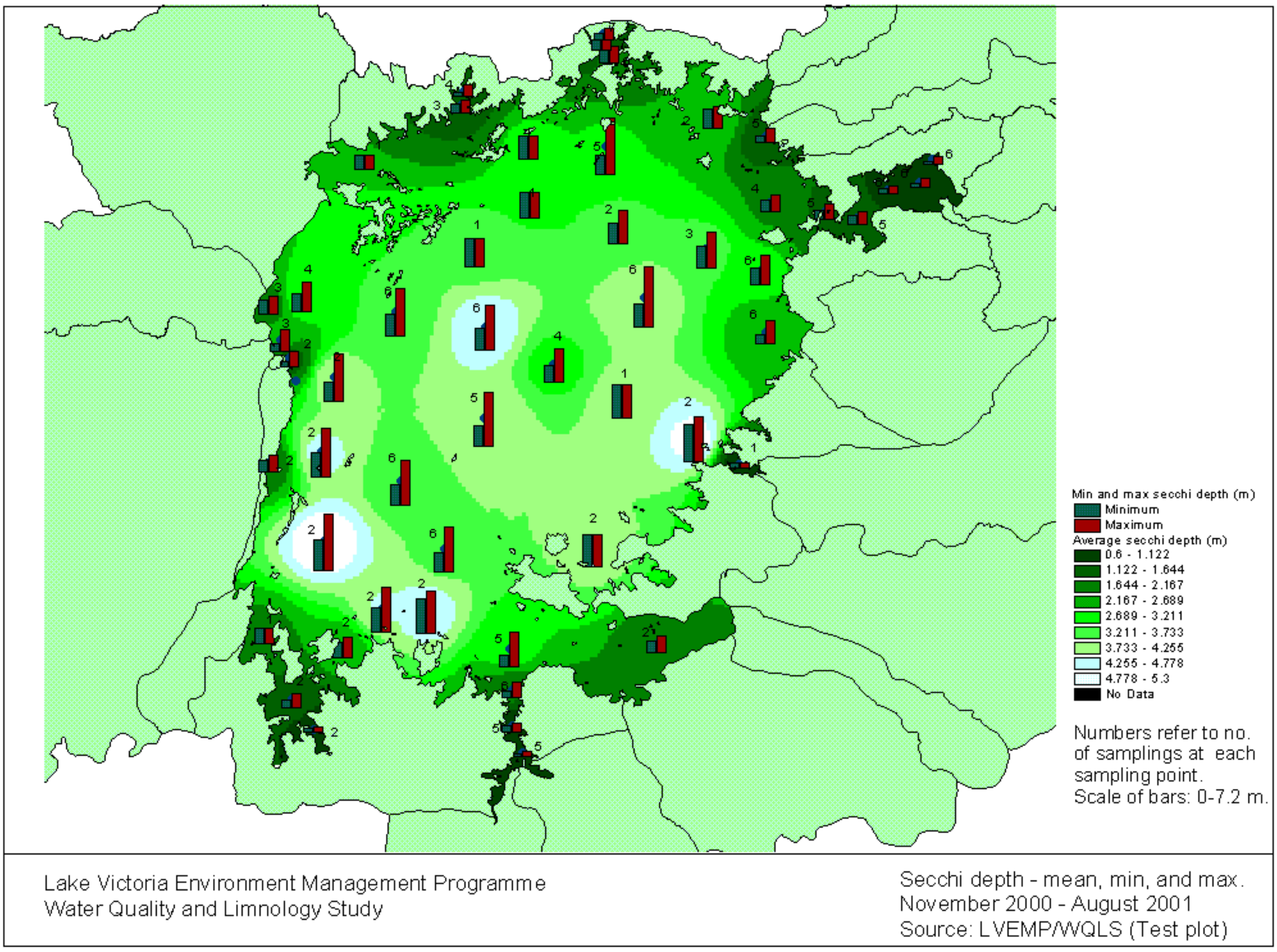

Figure 1.7 Secchi depths November 2000 - August 2001.

The inverse pattern is seen for Chlorphyll-a[4] (see Figure 1.8). Here the open parts of the lake show concentrations of 5-6 ug/l or below and the nearshore areas 10-20 ug/l. Locally in bays Chlorophyll-a can raise to very high levels. Thus in Mwanza Gulf levels up to 172 ug/l were found. Studies of Murchison Bay in 1997 showed Chlorophyll levels of 300 ug/l.

Regressions on spatial scales and temporal/spatial scales were performed in order to investigate the consistency in light climate/phytoplankton biomass relationships as a part of data quality assurance and to compare present monitoring results with historical data.

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[4] Chlorophyll-a is a parameter that was applied relatively late by the Kisumu and Mwanza laboratories and therefore only few measurements contribute to the map.

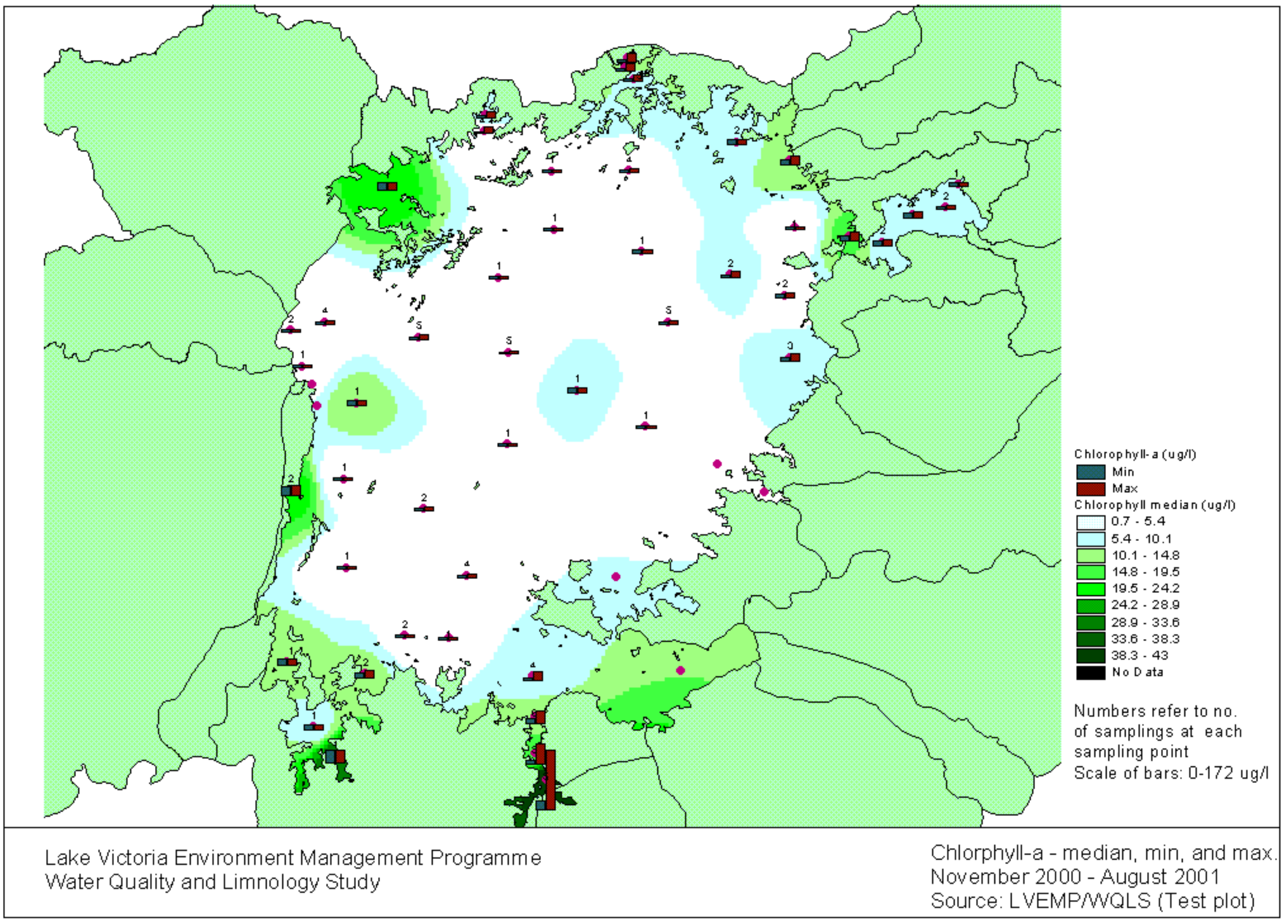


Figure 1.8 Chlorophyll-a concentrations November 2000 - August 2001.

Figure 1.9 and Figure 1.10 show regressions from the cruise 20. - 22. Nov. 2000 to UL 1, UL 2, UL 3, UP 2 (Bugaia), UP 6, UP 7 and UP 10. The regression between extinction coefficient and chlorophyll can be compared to that performed on Tallings 1965 data augmented with modern data by Lehman et al (1998):

Light extinction coefficient (m^{-1}) = 0.036 (chl ug/l) + 0.15

The slope value indicates a high efficiency in chlorophyll and thus light stressed phytoplankton communities. This is also reflected in the high carbon/chlorophyll ratio = 54. The higher value for background extinction in the present study reflects the contribution from the shallow stations.

Lake wide regressions on an annual scale are shown in Figure 1.11.

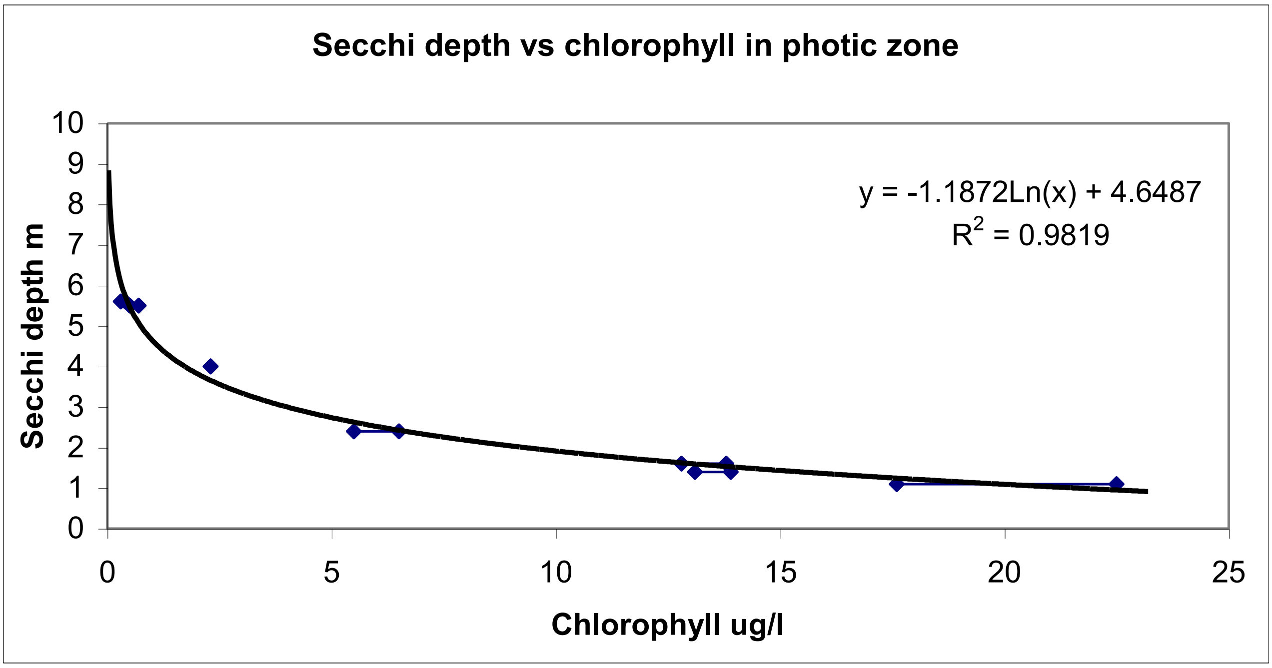


Figure 1.9 *Regression: Secchi depth vs chlorophyll-a in photic zone in Ugandan waters, November 2000.*

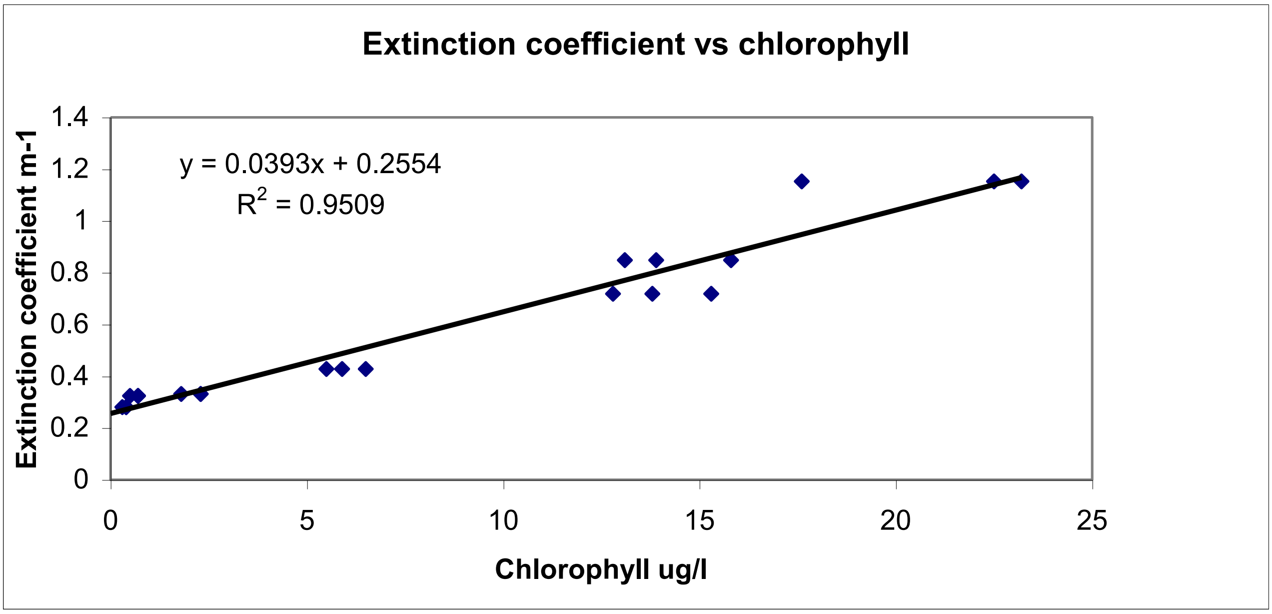


Figure 1.10 *Regression: Light extinction coefficient vs chlorophyll-a in Ugandan waters, November 2000.*

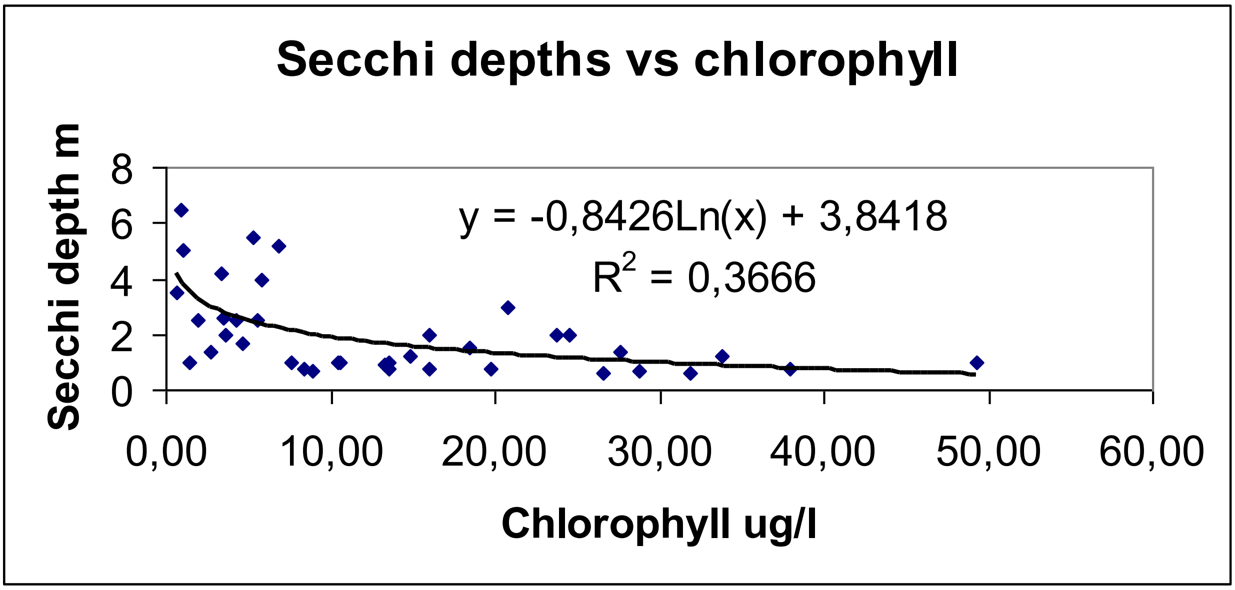


Figure 1.11 Regression: Secchi depth vs chlorophyll-a for all measurements in lake.

1.7 Oxygen

All three countries have possessed (or been able to borrow) oxygen profiling equipment during most of the study period. This implies that a relatively good coverage of oxygen measurements has been obtained from the lake and that some tendencies regarding the general oxygen conditions start to appear.

The following figures (Figure 1.12 to Figure 1.14) present statistically the magnitude of oxygen deficits at the bottom in the different parts of the lake based on the entire dataset collected.

Oxygen deficits are normally categorised according to effects as follows:

- Dissolved oxygen concentration between 2-4 mg/l: fish and mobile animals flee to better conditions

- Dissolved oxygen concentration between 1-2 mg/l: remaining animals suffers significantly

- Dissolved oxygen concentration below 1 mg/l: remaining animals die

The first figure (Figure 1.12) shows the estimated (interpolated) area of the lake where at least once during the sampling programme oxygen at the bottom was measured to be below 2 and 1 mg/l respectively (minimum values). The second (Figure 1.13) shows the areas where 25 % of the measurements have been below 2 and 1 mg/l (lower quartile), and the third (Figure 1.14) the areas where half of the measurements were below 2 and 1 mg/l respectively.

It should be noted that the amount of data available is still limited, that some stations have only very few measurements and that the assessment value of such maps will improve substantially when one or two full years of measurements exist.

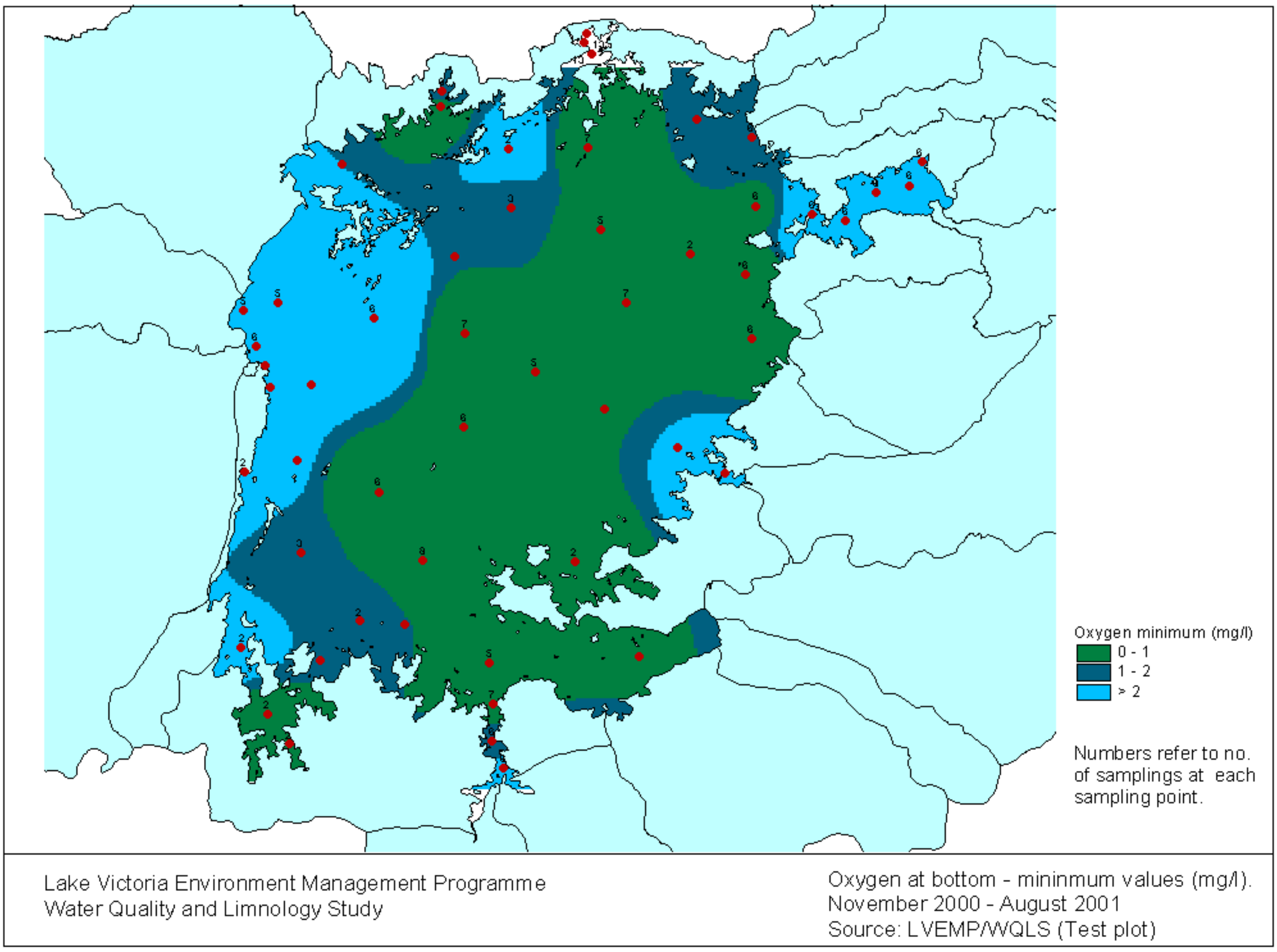


Figure 1.12 Oxygen concentration at the bed of lake - minimum values.

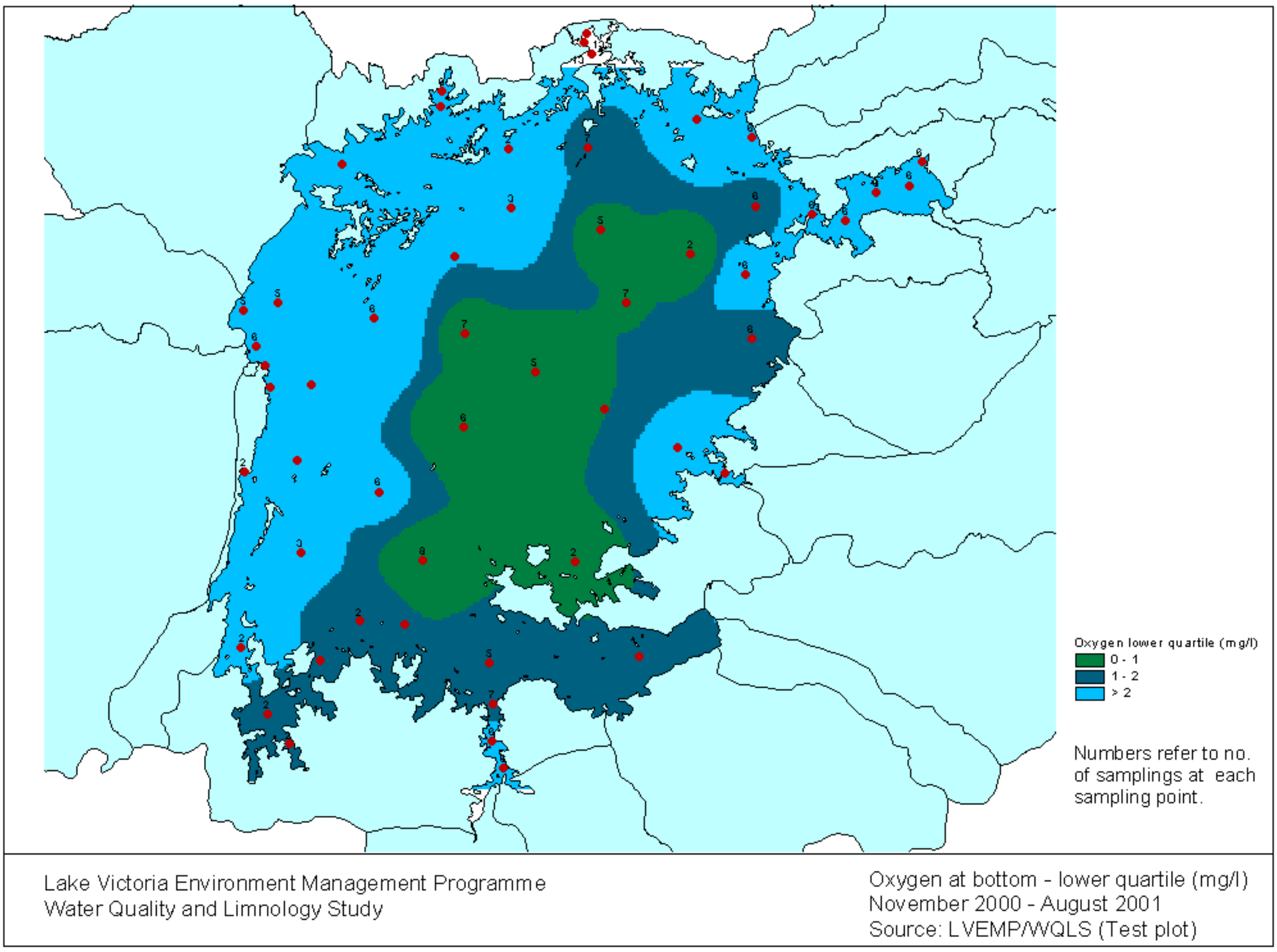


Figure 1.13 Oxygen concentration at bed of lake - lower quartile.

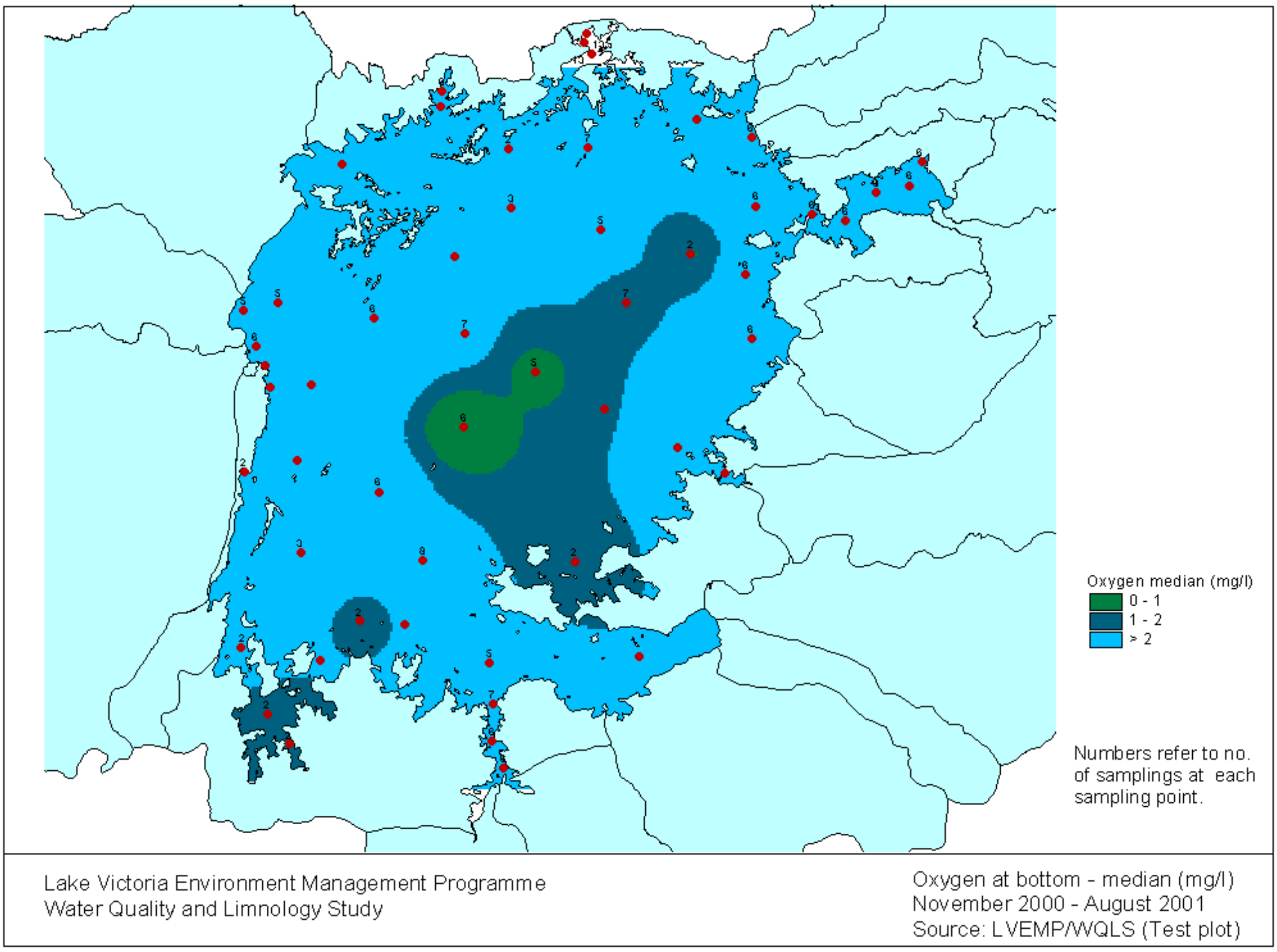


Figure 1.14 Oxygen concentration at bed of lake - median.

For some of the Ugandan and Tanzanian stations the frequency of measurements is sufficient to allow the drawing of time series of the oxygen condition in the water column. See Figure 1.15 to Figure 1.21.

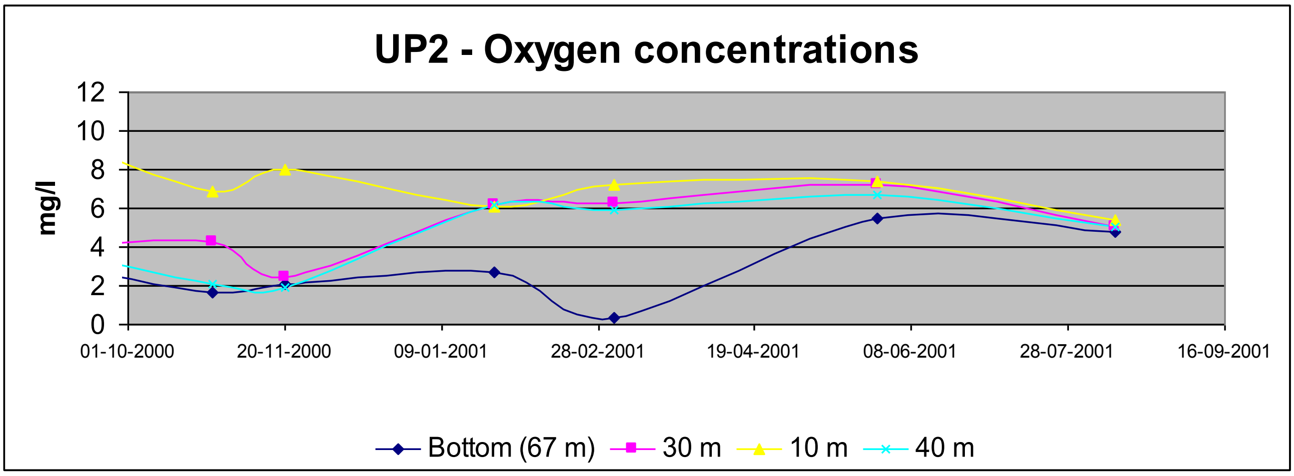


Figure 1.15 Station UP2 - time series of oxygen concentrations.

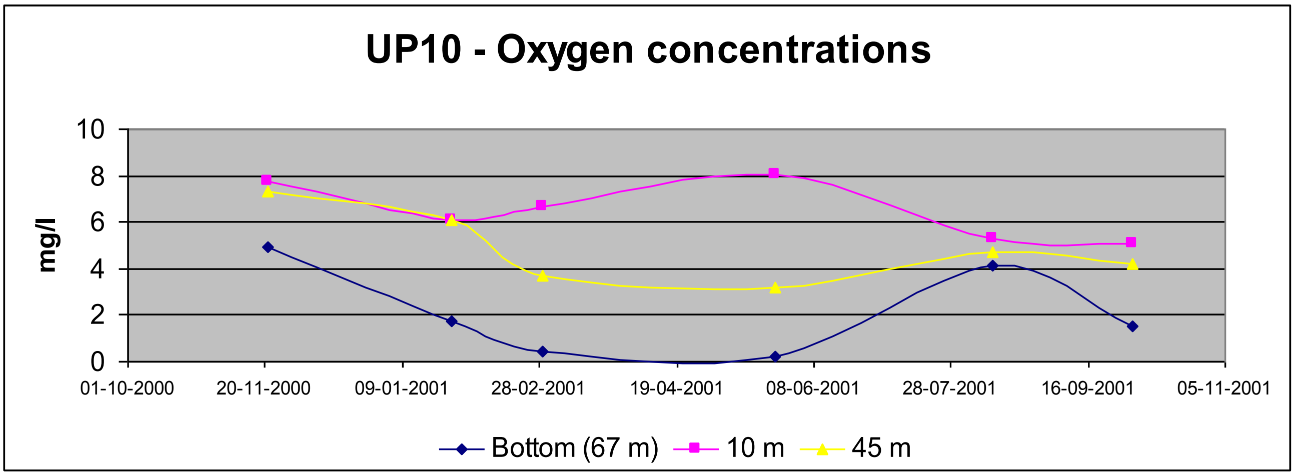


Figure 1.16 Station UP10 - time series of oxygen concentrations.

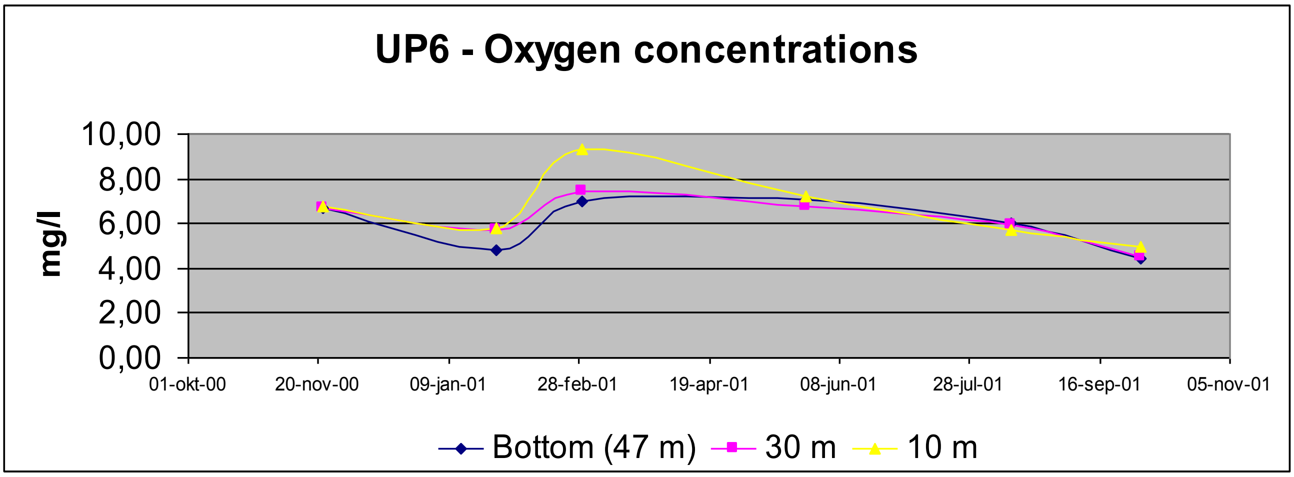


Figure 1.17 Station UP6 - time series of oxygen concentrations.

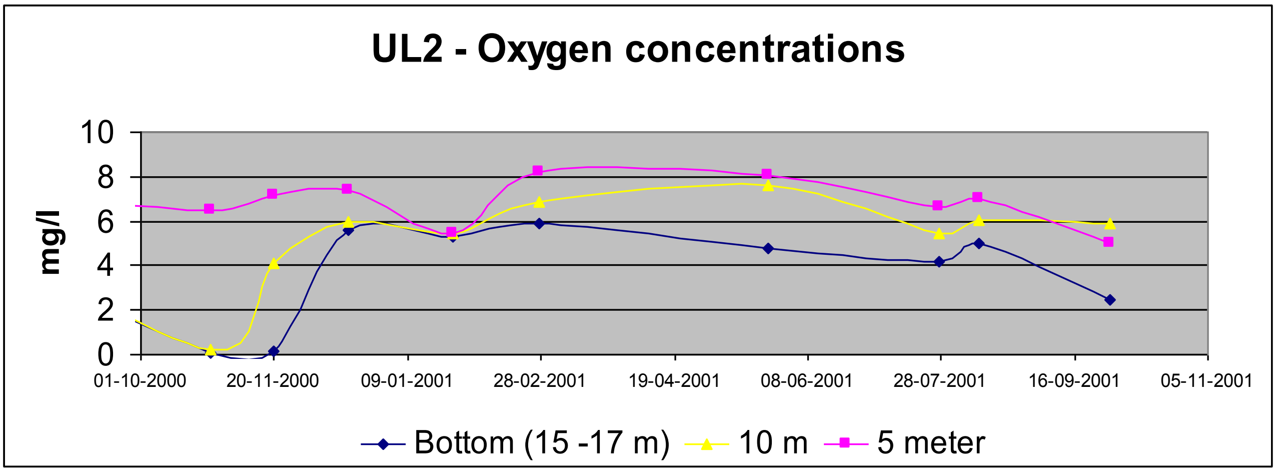


Figure 1.18 Station UL2 - time series of oxygen concentrations.

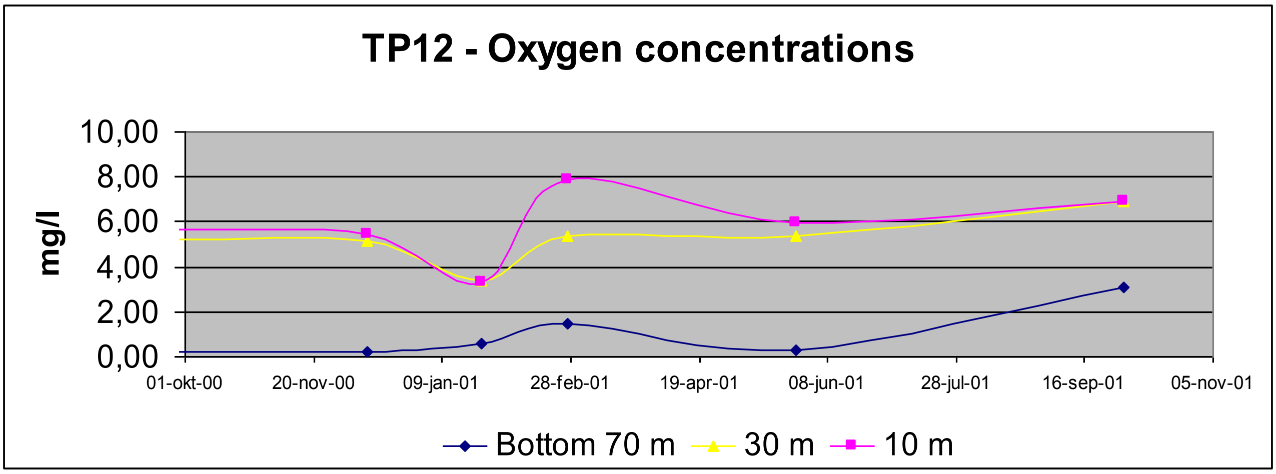


Figure 1.19 Station TP12 - time series of oxygen concentrations.

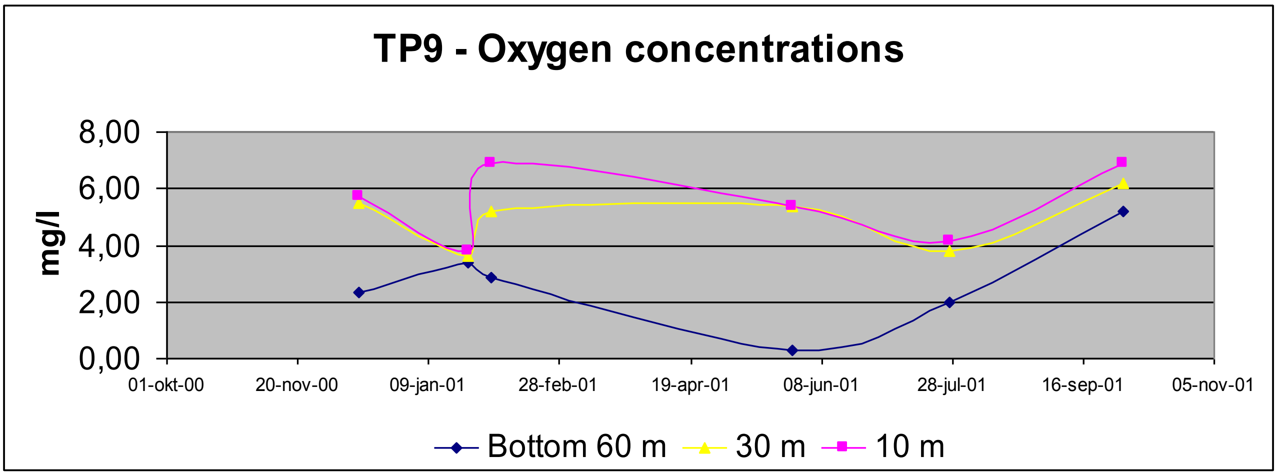


Figure 1.20 Station TP9 - time series of oxygen concentrations.

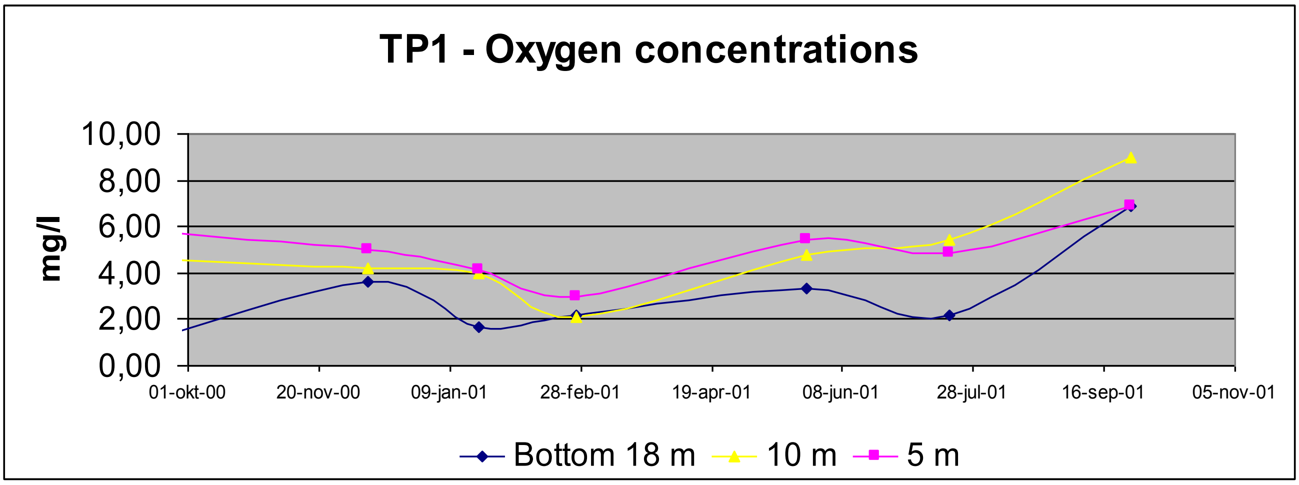
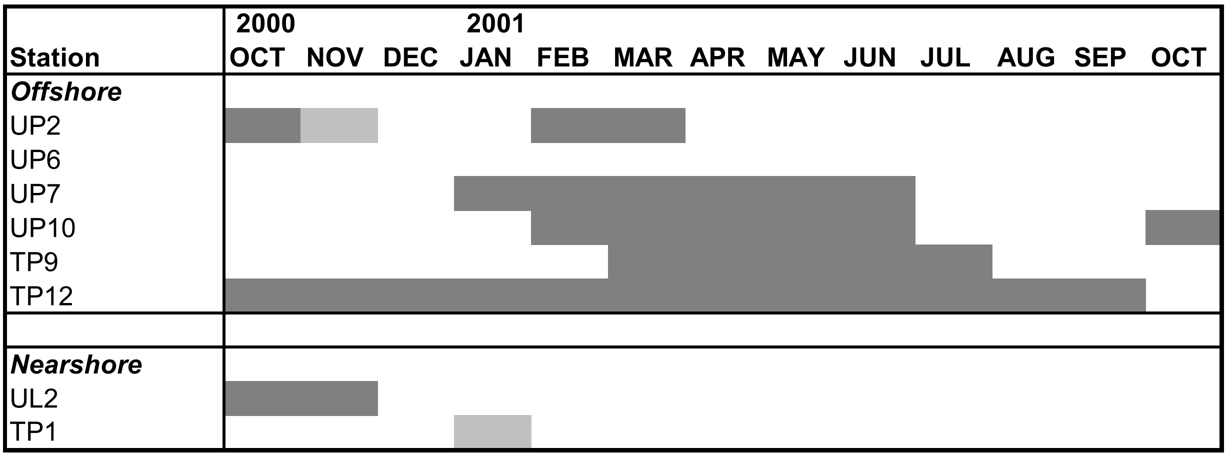


Figure 1.21 Station TP1 - time series of oxygen concentrations.

Figure 1.22 shows the temporal extent of oxygen deficits defined as oxygen concentration below 2 mg/l at the bottom for a number of stations in the lake (dark grey indicates full month oxygen deficit, light grey partial deficit).



	2000			2001									
Station	**OCT**	**NOV**	**DEC**	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**
Offshore													
UP2	▓	░			▓	▓							
UP6													
UP7				▓	▓	▓	▓	▓	▓				
UP10					▓	▓	▓	▓	▓				▓
TP9						▓	▓	▓	▓	▓			
TP12	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	▓	
Nearshore													
UL2	▓	▓											
TP1				░									

Figure 1.22 Temporal extent of oxygen deficits.

The figure indicates the following (preliminary) conclusions:

- The main period of oxygen deficit at offshore stations was Jan/Feb to Jun/Jul.
- The length and timing of the oxygen deficit are not the same at all offshore stations (UP6,7 and TP9 appr. 6 months, TP12 almost permanent)
- UP2 (Bugaia) is not representative for the oxygen conditions offshore.

Finally, the data shows that at offshore stations oxygen deficits are rare above 40 meters, but in near shore areas even total oxygen depletion occurs from time to time

1.8 Phytoplankton

Approximately 1500 samples of phytoplankton have been collected during the monitoring cruises in the period November 2000 - September 2001. Most of the samples consist of 100 ml of lake water preserved with Lugol solution as prescribed, but due to misunderstandings some of the Kenyan samples were taken by net in a non-quantitative method. Enumeration of cells in the preserved samples has started, but compiled data from only few sampling stations/dates are yet available. The phytoplankton is being counted by use of inverted microscopy of settling chambers or by direct counting in haemacytometers. Using standard cell sizes from the literature the counts are converted into carbon content and the phytoplankton are, to be in conformity with the Lake Victoria Water Quality Model, being divided in the following groups:

- Diatoms
- Flagellates
- Green algae
- Aphanizomenon
- Microcystis
- Oscillatoria

These groups being divided again into 3 types:

- N-types
- P-types
- E-types

I.e. algae dominating under nitrogen, phosphorus and light limiting conditions respectively.

An example from Mwanza of enumeration of phytoplankton taxa and the calculated values of their C, N, and P content based on standard stochiometric composition from Reynolds (1984) is shown in Table 1.4:

Table 1.4 Phytoplankton biomass from Tanzanian stations May 2001

							C	P	N
Date	**Station**	**Depth**	**Class**	**TYPE**	**Taxa**	**um3/m3**	**mg/L**	**mg/L**	**mg/L**
May, 2001	TP02	1,5 m	Diatom	N	Nitzchia	2,47E+09	0,5569	0,0124	0,0990
May, 2001	TP02	1,5 m	Diatom	N	Synedra	1,58E+08	0,0355	0,0008	0,0063
May, 2001	TP02	1,5 m	Cyanobacteria	P	Gomphoshaeria	1,72E+08	0,0387	0,0009	0,0069
May, 2001	TP02	1,5 m	Cyanobacteria	P	Microcystis	2,25E+06	0,0005	0,0000	0,0001
May, 2001	TP02	1,5 m	Cyanobacteria	E	Anabaena	2,36E+07	0,0053	0,0001	0,0009
May, 2001	TP02	1,5 m	Cyanobacteria	P	Anabaenopsis	4,06E+08	0,0912	0,0020	0,0162
May, 2001	TP02	1,5 m	Cyanobacteria	P	Lyngbya	1,95E+08	0,0438	0,0010	0,0078
May, 2001	TP02	1,5 m	Green	N	Pediastrum	1,20E+08	0,0270	0,0006	0,0048
May, 2001	TP02	1,5 m	Cyanobacteria	P	Chroococcus	6,50E+06	0,0015	0,0000	0,0003
May, 2001	TP02	1,5 m	Cyanobacteria	P	Merismopedia	5,39E+06	0,0012	0,0000	0,0002
May, 2001	TP02	1,5 m	Diatom	N	Aulosera/melosira	2,36E+07	0,0053	0,0001	0,0009
May, 2001	TP02	1,5 m	Green	N	Botryococcus	8,65E+06	0,0019	0,0000	0,0003
May, 2001	TP02	1,5 m	Cyanobacteria	P	Coelosphaerium	3,98E+06	0,0009	0,0000	0,0002
May, 2001	TP02	1,5 m	Diatom	N	Navicula	1,45E+07	0,0033	0,0001	0,0006
May, 2001	TP02	1,5 m	Cyanobacteria	P	Merismopedia	2,69E+06	0,0006	0,0000	0,0001
May, 2001	TP02	1,5 m	Cyanobacteria	P	Microcystis	2,29E+07	0,0052	0,0001	0,0009

1.8.1 Spatio-temporal patterns of algal biomass

Phytoplankton wet biomass was in the range of 0.3 to 2830 ug L^{-1}, average 187.4 ug L^{-1}, in the Tanzanian waters of Lake Victoria (Table 1.5). Average total wet biomass was typically 3 times higher the inshore waters than offshore. Similarly, biomass of particulate nutrient concentrations were higher inshore than offshore.

Table 1.5 Phytoplankton wet-biomass from the Tanzanian waters of Lake Victoria during May 2001 .

	Wet biomass (ug L^{-1})		
	All stations	Inshore	Offshore
Average	187.3	411.2	146.0
Minimum	0.3	5.5	0.3
Maximum	2829.9	2830.9	2616.2
Std	505.6	758.2	431.2

The higher phytoplankton biomass inshore than offshore is because mean light conditions were better inshore. Inshore, reduced mixing depth allows relatively high mean water column irradiance unlike offshore where the deeper mixed layer leads to low light availability. The mixing depths are often ≥ 20 m in offshore areas and compatible with only low algal biomass as light limits photosynthesis over most of mixing layer.

1.8.2 Species composition and particulate nutrients

The phytoplankton community of inshore was as diverse as offshore Lake Victoria. Cyanobacteria were the most common phytoplankton as they appeared nearly continuously in all the samples in both inshore and offshore waters.

Consequently cyanobacteria contributed to > 50% to the particulate nutrient concentrations in May 2001 (Table 1.6). Overall, cyanobacteria contributes a larger fraction while blue-greens contributed the least particulate biomass.

Table 1.6 *Particulate nutrient (P, N and C) calculated from wet- biomass of phytoplankon from the Tanzanian waters of Lake Victoria during May 2001 .*

	Wet biomass (ug L^{-1})		
	Carbon	Phosphorus	Nitrogen
Blue-greens	1.677	0.037	0.298
Diatoms	0.985	0.022	0.175
Green	0.087	0.002	0.016

Based on qualitative consinderations of available data from the Ugandan and Tanzanian waters, eight cyanobacterial species and one diatom were frequently encountered during this study. This applied to both Ugandan and Tanzanian waters (Figure 1.23).

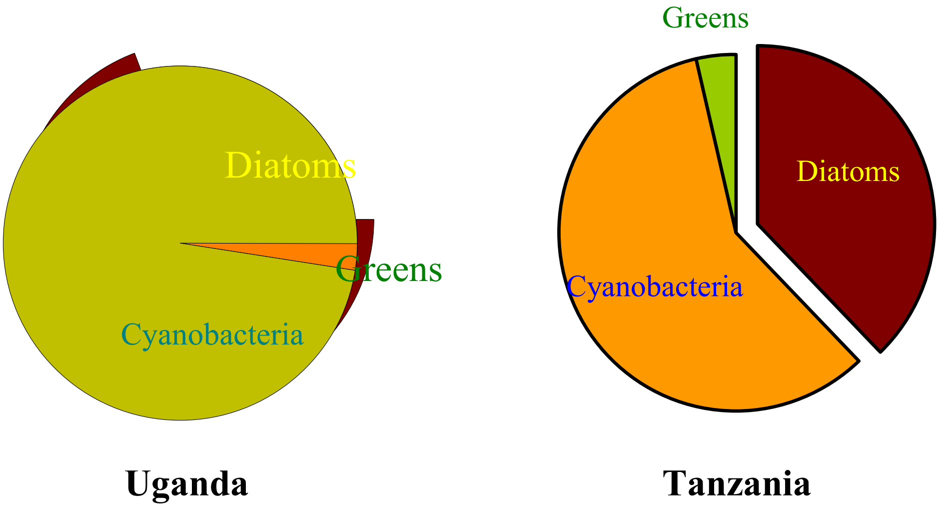


Figure 1.23 *Distribution of phytoplankton biomass in Ugandan and Tanzanian waters, 2000-01.*

The large filamentous cyanobacteria (*Anabaena,* and *Planktolyngbya*) and the colonial mucilaginous forms (*Aphanocapsa, Aphenotheca, Microcystis*, *Chroococcus*, *Coeleospharium* and *Merismopedia* were the most common cyanobacteria during 2000-2001. The biomass distribution over the year showed that nitrogen fixers dominated over non-fixers ().

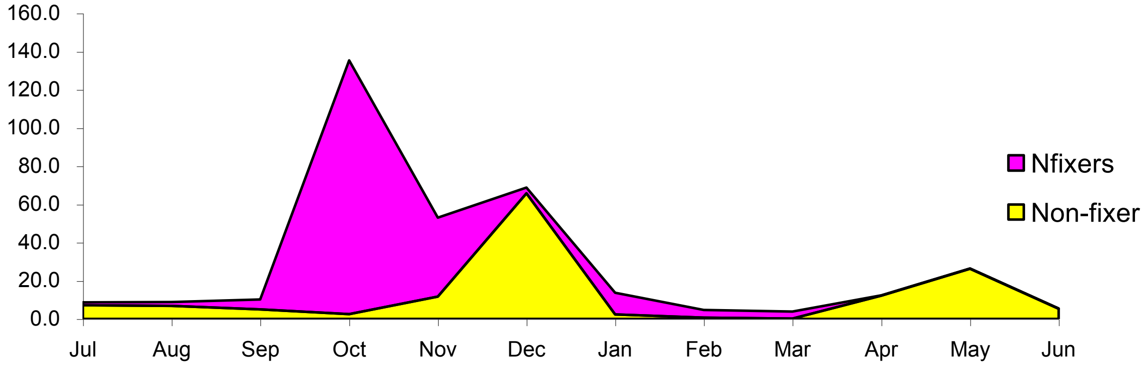


Figure 1.24 Seasonal variation of nitrogen fixing and non-fixing cyanobacteria in Tanzanian waters, 2000-01, in µg/l wet weight.

As mentioned above, the major part of the phytoplankton samples awaits counting and final compilation, thus, apart from the dominance of cyanobacteria, no other preliminary conclusions can be drawn yet.

1.9 Zooplankton

Samples for quantification of zooplankton biomass were taken at the same stations and depths as water samples - all together approximately 1500 samples. A known water volume - 2-3 liters - was filtered through a 50 um net and preserved with 50 ml 4% formalin. After identification and counting biomass was converted to carbon using standard weights and standard stochiometry.

The investigation recorded some 30 Rotifer species (taxon) from the Tanzanian and Ugandan part of Lake Victoria. Those that occurred numerously in the quantitative samples were: *Asplanchna spp, Branchionus angularis, Branchionus caudatus, Branchionus falcatus, Branchionus forticula, Euclanis spp, Filinia longiseta, Filinia opoliensis, Hexarthra spp, Keratella cochlearis, Keratella tropica, Lecane bulla, Polyarthra spp, Synchaeta spp* and *Trichocerca spp*. The major zooplankton groups including Rotifers were more associated with the lake nearshore stations than offshore stations. See Figure 1.25. This follows trends in the phytoplankton biomass and production which are usually high in nearshore stations (See also Mugidde, 1993).

The macrozooplankton of the lake was completely dominated by copepods (cyclopoids and calanoids) during the whole period of investigation. Those species that occurred numerously in the quantitative samples were *Thermocyclops emini, Thermocyclops neglectus, Thermocyclops oblongatus, Tropocyclops confinnis, Tropocyclops tenellus, Mesocyclops spp.* and *Thermodiaptomus galeboides*. The following Cladocera species that occurred in low numbers during the study period were also found to be quantitatively important: *Allona spp, Bosmina longiristris, Ceriodaphnia cornuta, Chydorus spp, diaphanasoma ex-*

cisum, Daphnia longispina, Daphnia lumholtzi, Moina micrura and *Macrothrix spp.*

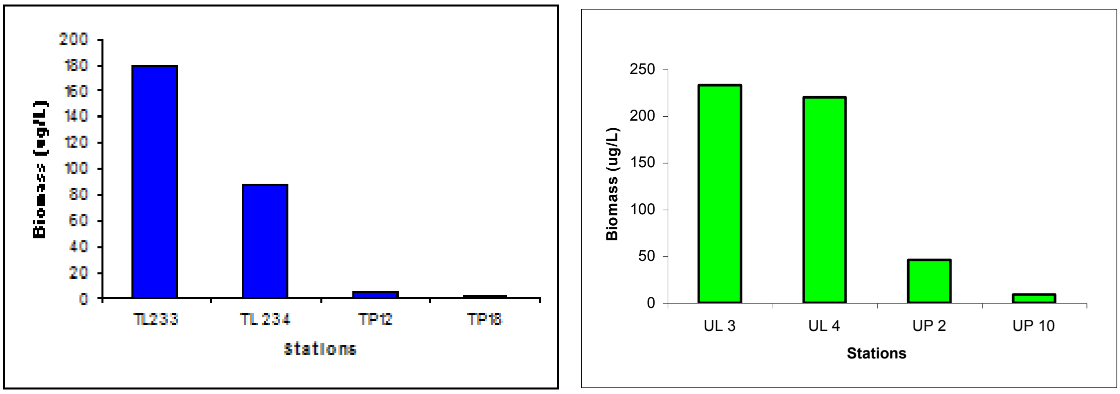


Figure 1.25 Zooplankton biomass at nearshore and offshore stations, May 2001.

There was a tendency for the Cladocera to increase in numbers and biomass during the rainy season. Similar observations have been made in Mwanza Gulf (Akiyama 1977).

Table 1.7 shows the percent biomass contributions of the major zooplankton groups. The copepods already noted earlier contributed greatest towards the total zooplankton biomass. The calanoid contributions became increasingly important in the lake pelagic than in the nearshore stations.

The Cladocera and Rotifer contributions towards the total biomass appeared negligible when compared to that of Copepods.

Table 1.7 Relative contribution of zooplankton groups bioimass (%).

	SAMPLING STATIONS			
	UL 1 (20.11.00)	**UP 2 (20.11.00)**	**TL 230 (15.12.00)**	**TP 8 (Jan, 2001)**
Cyclopoids adults + copepodites	62.69	56.69	57.11	37.32
Calanoids adults + copepodites	11.61	35.81	35.07	55.75
Cladocera	2.10	1.08	1.23	0.00
Naupliar larvae	28.92	6.19	2.91	3.93
Rotifers	1.66	0.21	3.66	2.98

The species composition was the same in Ugandan and Tanzanian waters (Figure 1.26).

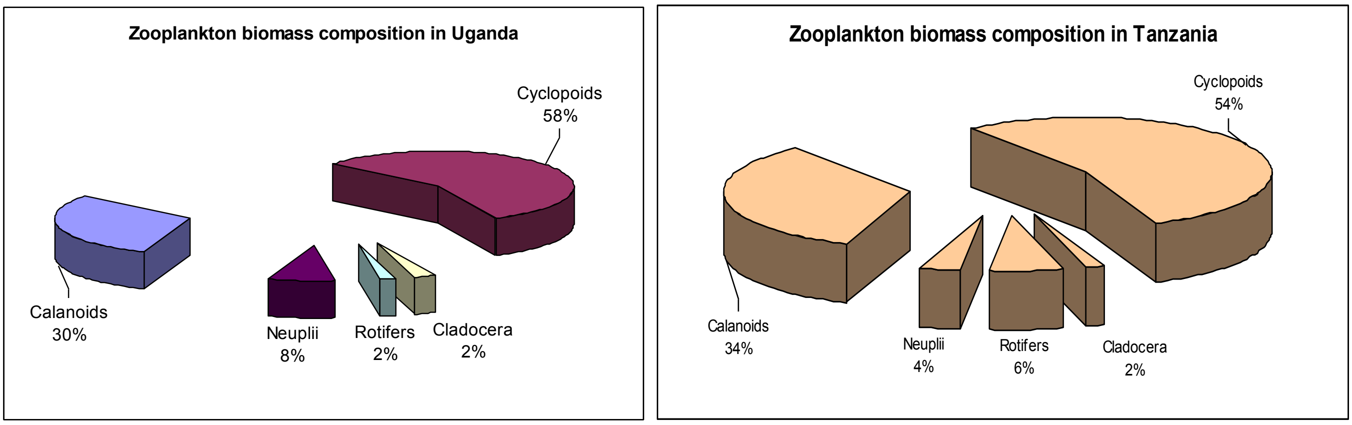


Figure 1.26 Zooplankton biomass composition in Ugandan and Tanzanian waters.

The percent composition (numerical) and relative importance of the main zooplankton groups in the northern Lake Victoria have been reported in Worthington (1931), Rzoska (1956) and Mwebaza-Ndawula (1994). The data of Worthington indicates a predominance of Calanoid (50.1%) at an offshore station. Rzoska's data collected 25 years later at an open water station showed a predominance of Cyclopoids (45.0%). Mwebaza-Ndawula's (1994) study at Bugaia sampling station showed a predominance of cyclopoids. There has never before been a lake-wide sampling of Lake Victoria as has been the case for the present investigation. The present study reveals both temporal and spatial variations in the zooplankton biomass distributions (Figure 1.27) which makes it difficult to make direct comparison with historical findings. Nevertheless, the present investigation almost comes to a similar conclusion that Copepods contribute the greatest towards the zooplankton total biomass. The present study converts the zooplankton counts per litre to biomass (carbon/litre) and computes the percent compositions using biomass instead of counts per litre. This in a way gives a more realistic picture of the zooplankton group percent compositions than is the case when computation is done using numerical counts. Mwebaza-Ndawula (1994) emphasises the central role zooplankton plays as major primary consumers and converters of algal production into animal materials. In this regard, therefore, they indirectly exert influence on the lake's nutrient dynamics and trophic status.

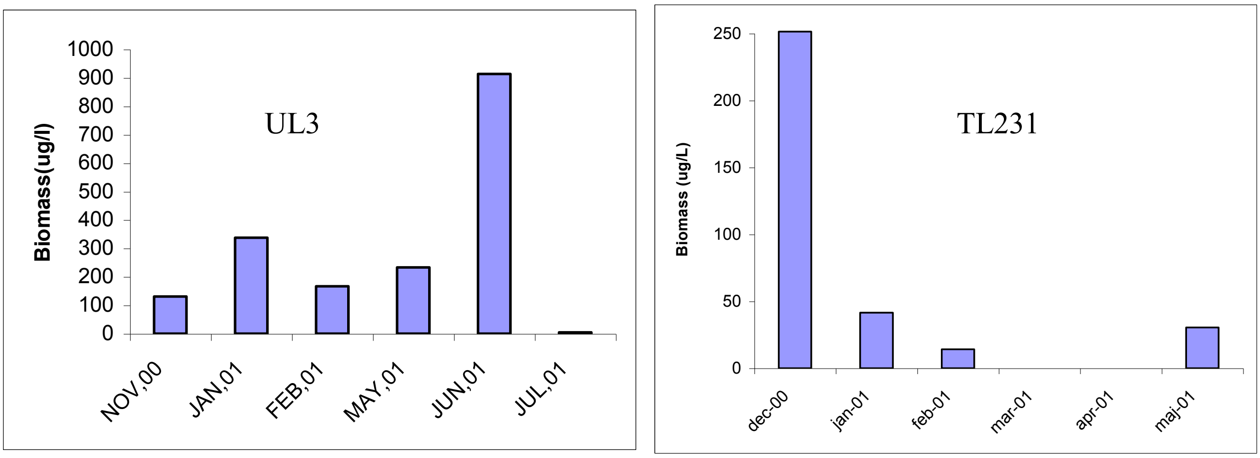


Figure 1.27 *Temporal distribution of zooplankton biomass at two nearshore stations, UL3 and TL231*

The vertical distribution of the biomass (Figure 1.28) clearly indicates diel vertical migration with maximum biomass in the deeper parts during daytime - provided that there is no oxygen depletion. In the dark hours the zooplankton migrates to the surface waters for foraging among other reasons.

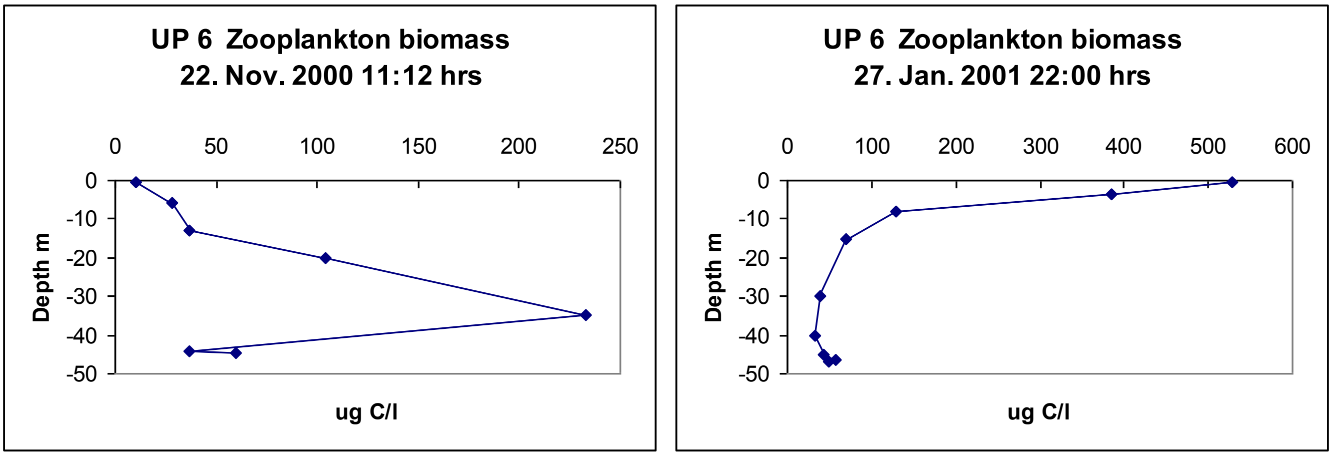


Figure 1.28 *Diurnal variation of zooplankton biomass at station UP6.*

1.10 Nutrient Mass Balance

1.10.1 Lake Victoria

Figure 1.29 and Figure 1.30 indicate the overall balances of phosphorus and nitrogen for the lake as they can be derived from the results of the present study.

The atmospheric inputs as well as the inputs from the catchments of N and P have been estimated by the non-point pollution task (see Chapter 4). It should be noted that the overall estimates of loads from catchments includes point sources up-stream in the catchment as they are based on calculated transports of N and P in the rivers[5]. Consequently the contribution of municipal and industrial loads to the mass balance only includes the towns and industrial centres located at the lake shores and discharging directly to the lake. However, these include the main centres such as Kampala, Jinja, Kisumu, and Mwanza.

A standing stock (pool) of N and P in the lake water has been estimated from measurements in the lake and a yearly increment of that pool has been estimated by comparing historical measurements back to the studies of Talling in 1960-61 with the general levels in 2001. The estimated output to the Nile is based on concentrations of N and P at the monitoring station UL2 located in Napoleon Gulf and the discharge of water at Owen Falls. For demonstration the export of N and P by fish catches is included. This estimate is based on the fishery when it was at its highest level.

Adding the estimated inputs and outputs for phosphorus:

> *Atmospheric deposition + non-point source loads + municipal/ind. loads – increment of pool – export to the Nile – export through fishery*

gives an amount of 20,100 t P/y which is considered buried in the sediments. As the actual sedimentation rate has been estimated based on measurements at 523,000 t P/y a yearly release of 502,900 t P[6] is expected to keep the water/sediment flux balanced.

The same calculation based on the present study's load estimates for Nitrogen gives a net deposition of 73,400 t of N in the sediments. However, knowing from several former studies that the general N/P ratio in the sediments is around 10:1, this amount is much too small to balance the calculated phosphorus deposition (20,100 t P/y). Thus, just to keep the normal N/P ratio in the sediments an additional input of 127,000 t N/y is required. In fact, more than that is necessary to also account for some denitrification which certainly occurs in the lake.

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[5] The contribution of "upstream" municipal and industrial load to the total load of the catchment can be considered small (< 5-10%)

[6] Measurement of the release of nutrients from the sediments was planned to be a part of the present study, but was not possible due to slow procurement of necessary equipment.

An input source, which has not been covered by measurements in the present study is the fixation of nitrogen by blue-green algae. It has been shown in section 10.8 that this group of algae is dominant in the lake. Some researchers (Lehman et al 1998) have suggested that this source of nitrogen could be considerable.

On the other hand the present study has also shown that inorganic nitrogen is generally available all over the lake. Since it is "costly" with respect to energy for the algae to fix nitrogen such fixation would normally only occur under real nitrogen limiting conditions and consequently it is a question if this source should account for an input of several hundred thousands tonnes of nitrogen per year. It should be mentioned that the nitrogen fixation, when it occurs, does not only "import" nitrogen from the air, but also may use N_2 in the water, which have been released from denitrification. This part of nitrogen fixation will thus not add to the overall input of nitrogen to the lake.

Another possibility is that the atmospheric deposition is overestimated as regard phosphorus in the present study. As mentioned in Chapter 4, the rainwater concentrations of phosphorus found in Uganda were much higher than found in the other two countries. Thus, a scenario applying the same levels as found in Tanzania and Kenya (0,04 mgP/l) to the Ugandan near shore rain-boxes has been made for the mass balance (values in brackets in Figure 1.29 and Figure 1.30). Using this scenario, the net deposition of phosphorus is estimated at 11,100 t P/y and the required extra input of nitrogen to balance phosphorus in the sediments will fall to 37,000 t N/y, a value which could be explained more reasonably by the net balance of nitrogen fixation and denitrification.

It can be concluded that the nutrient mass balance still needs to be refined. Thus, estimates of atmospheric deposition need to be improved and the two, maybe very important open ends, nitrogen fixation and denitrification, should be quantified. Moreover, sediment flux experiments would strongly support the understanding of exchange of nutrients between the sediments and the water column. However, it is believed that the preliminary mass balance is a realistic estimate of the overall relative importance of atmospheric deposition, catchment contribution, contribution from municipal/industrial loads as well as the export of nutrients to the outflow and the sedimentation rates.

It should also be noted that these overall relations are not necessarily representative for each and every local area in the lake. It has been shown that the lake conditions are not homogeneous, that eutrophication is a real problem near shore, and that these areas are relatively more affected by land based nutrient load sources than the open parts of the lake. This can be illustrated by taking a closer look at two near shore areas: the Inner Murchison Bay and Winam Gulf (Figure 1.31).

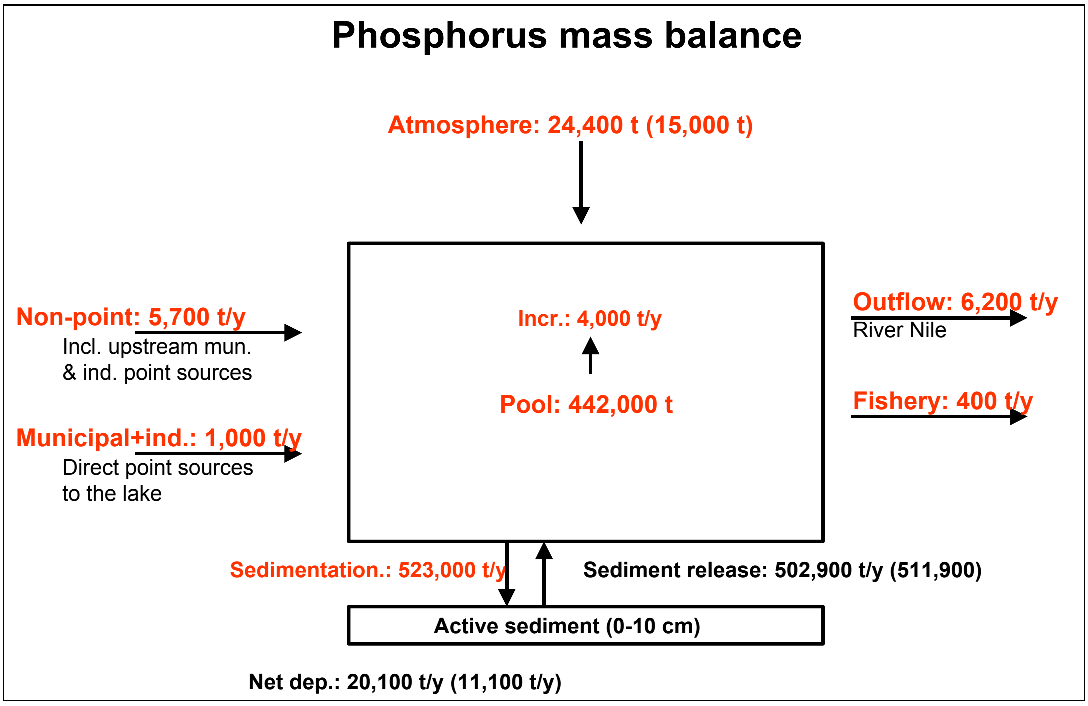

Figure 1.29 Phosphorus mass balance for Lake Victoria.

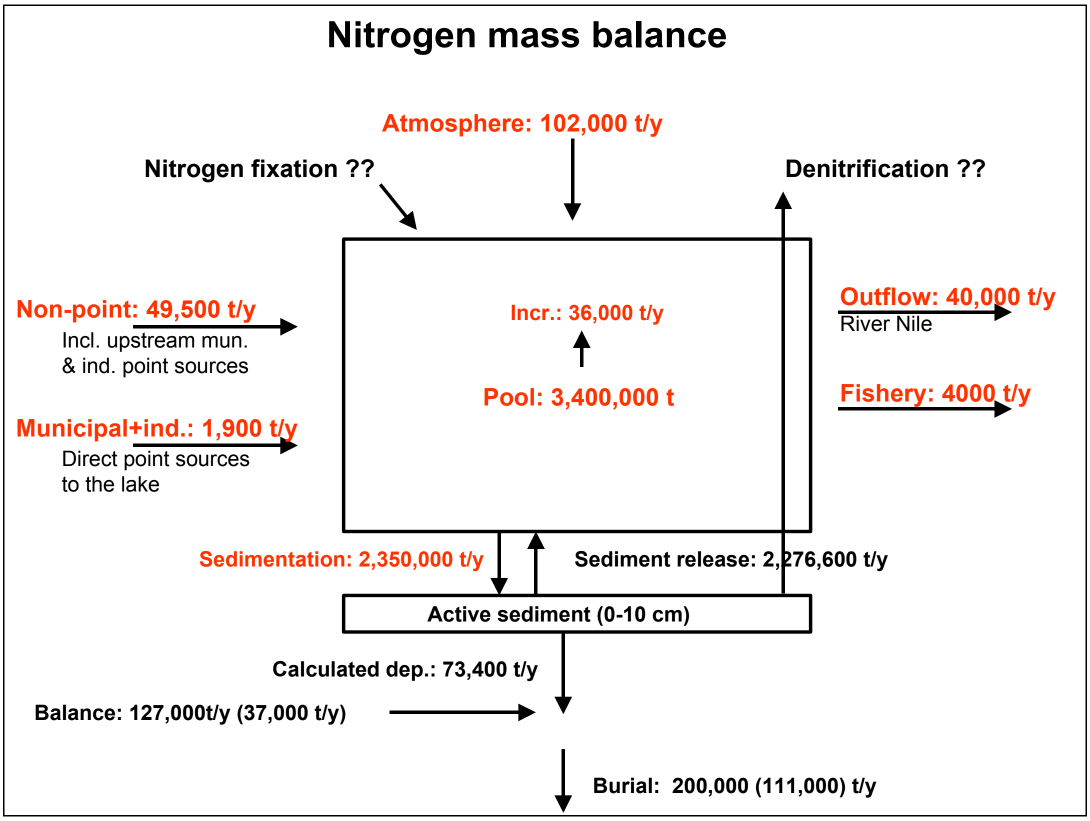

Figure 1.30 Nitrogen mass balance for Lake Victoria.

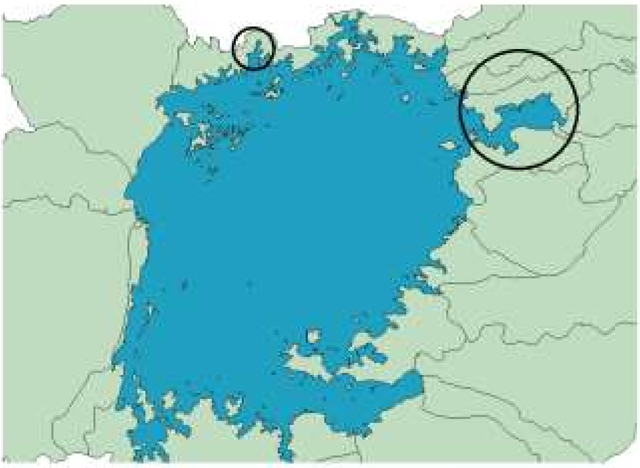

Figure 1.31 Location of Inner Murchison Bay and Winam Gulf.

1.10.2 Inner Murchison Bay

It has been shown by detailed studies in 1997 by the Ugandan National Water and Sewerage Corporation that the Inner Murchison Bay is highly eutrophicated (transparency < 1m, chlorophyll-a up to 300 ug/l, heavy oxygen deficits etc.). The bay has surface area of approximately 20 km^2, small catchments and one of the largest point sources (Kampala city) is discharging into it. Moreover, the water exchange with the rest of the lake is relatively limited. Figure 1.32 shows the Inner Murchison Bay and its catchments.

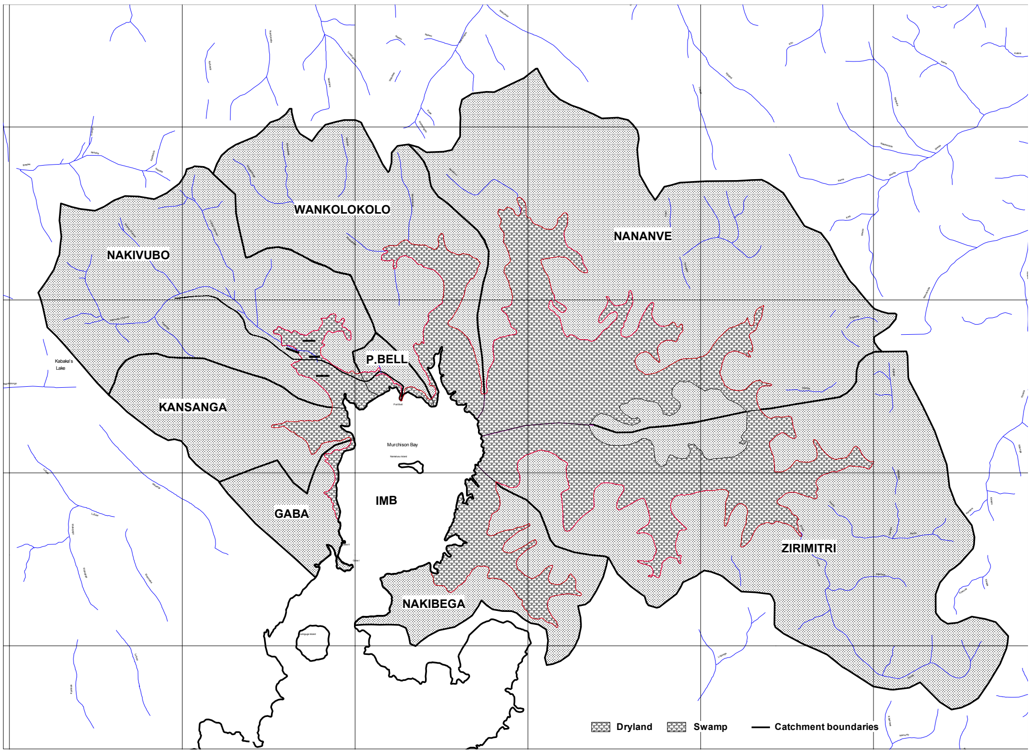

Figure 1.32 Inner Murchison Bay and its catchments

The estimated yearly loads of N and P from the city, the catchments, and the atmosphere respectively are given in Table 1.8.

Table 1.8 Loadings of nitrogen and phosphorus to the Inner Murchison Bay

Loads t/y	N	P	N	P
Mun/ind	454	317	76%	85%
Non-point	100	33	17%	9%
Atmosphere	42	22	7%	6%

It appears clearly from the table that the relative importance of the nutrient load sources in the Inner Murchison Bay is completely opposite to the indications of the overall mass balance for the lake. Here, the city of Kampala is the overwhelming dominating factor for both N and P, and any remedial measures to improve the conditions of the bay would naturally address this source.

1.10.3 Winam Gulf

Winam Gulf shows again a different picture. The bay shows also clear signs of eutrophication, but it is much larger that Murchison Bay (approx. 1,400 km^2) and four relatively large catchments drain into it (North and South Awach, Nyando and Sondu). Moreover, it receives waste water directly from Kisumu as well as from some smaller towns. Figure 1.33 shows the Winam Gulf.

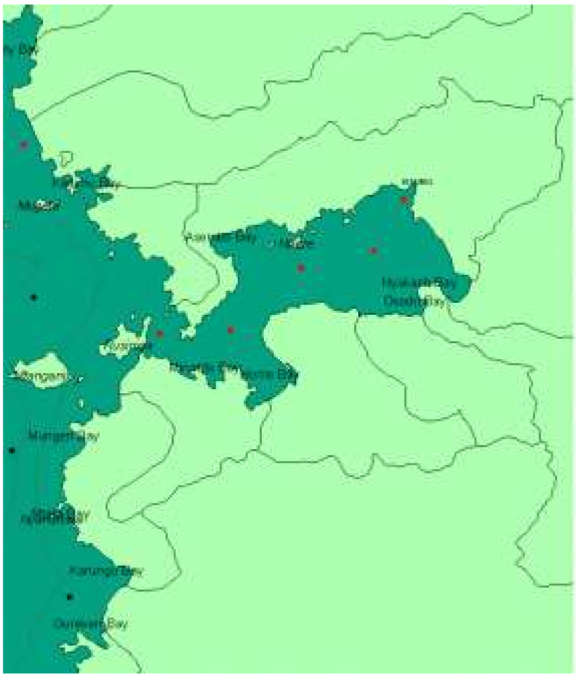

Figure 1.33 Winam Gulf

In Table 1.9 the estimated individual loads from municipalities/industries, catchments, and the atmosphere are given. Here, the catchments account for the largest contribution of both N and P (> 50 %), but both the town discharges and the atmosphere contribute significantly. Since atmospheric deposition is difficult to reduce a mixed management approach addressing both municipal/industry as well as catchment runoff would be appropriate in this case.

Table 1.9 Loads of nitrogen and phosphorus to Winam Gulf.

Loads t/y	N	P	N	P
Mun/ind	410	198	10%	20%
Non-point	2300	547	57%	56%
Atmosphere	1300	240	32%	24%

1.11 Historical changes in Lake Victoria 1960 – 2001

Historical data and LVEMP data demonstrate a high variability in physical and biogeochemical parameters. These variations occur at both temporal and spatial scales. The temporal scales are at diurnal, seasonal and annual levels and spatial scales are at vertical and lake wide levels. Thus, robust trend analysis requires long time series with high frequency performed lake wide. Such data do not exist for Lake Victoria. The only regular time series are from the traditional offshore station UP 2 (Bugaia) in the period 1990-2001. These data have been analysed for changes in the photic depth – upper 10 meters - of chlorophyll, nitrate, phosphate, silicate and for the dissolved oxygen in the 40-60 m layer.

1.11.1 Methods

Five samplings were carried out by the LVEMP study: Nov. 2000, Jan.2001, March 2001, May 2001 and Aug. 2001.

For these data average values were calculated for chlorophyll, nitrate, phosphate and silicate in the photic zone upper (upper 8 –10 m) and for the lower 40 – 60 m the average dissolved oxygen was calculated.

From our historical database, where tables and figures have been digitised to values for every 5 m depth in the photic zone and every 10 m in the remaining water column, similar average values calculated on the dates, which where within +/- 5-10 days of the LVEMP sampling dates.

The historical data are from the following sources:

1960 – 61:	Talling (1966)
1991 – 92	Lehman and Branstrator (1998)
1994	Bugenyi and Magumba (1996)

1994 – 95	Lehman et al. (1998)
1998	Mugidde (2001)

1.11.2 Results

The results of the analyses are shown in the Figure 1.34 to Figure 1.38.

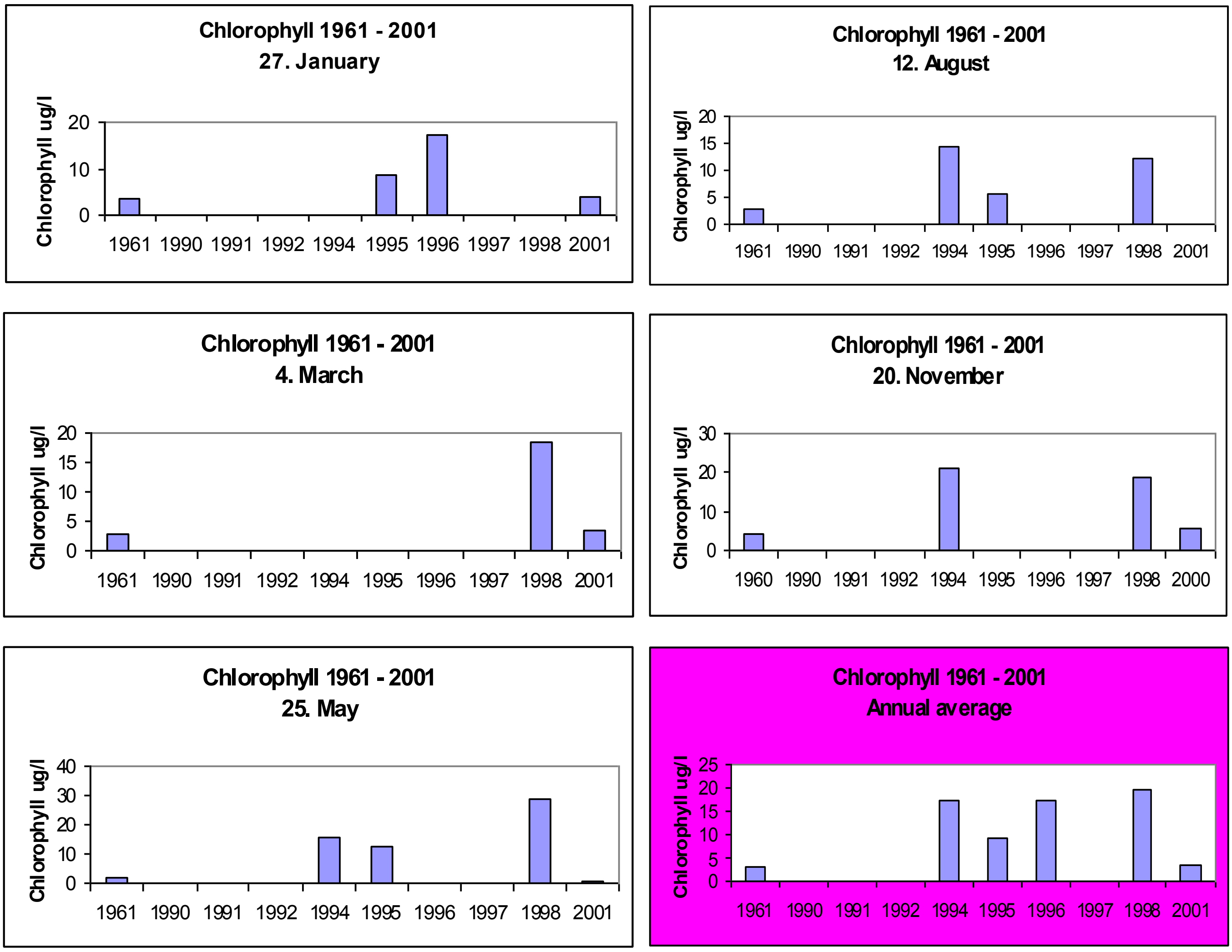

Figure 1.34 Historical changes in chlorophyll.

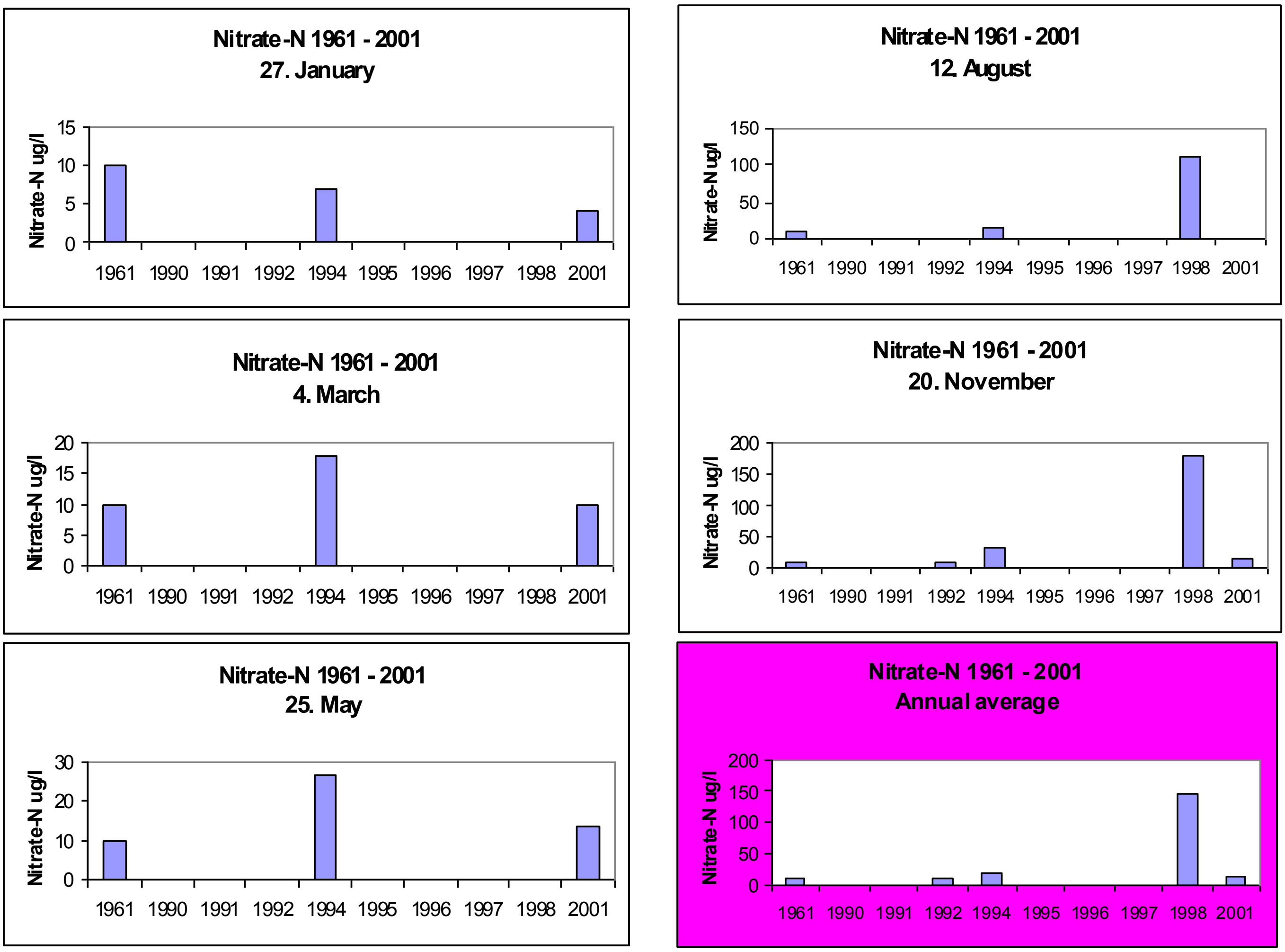

Figure 1.35 Historical changes in nitrate.

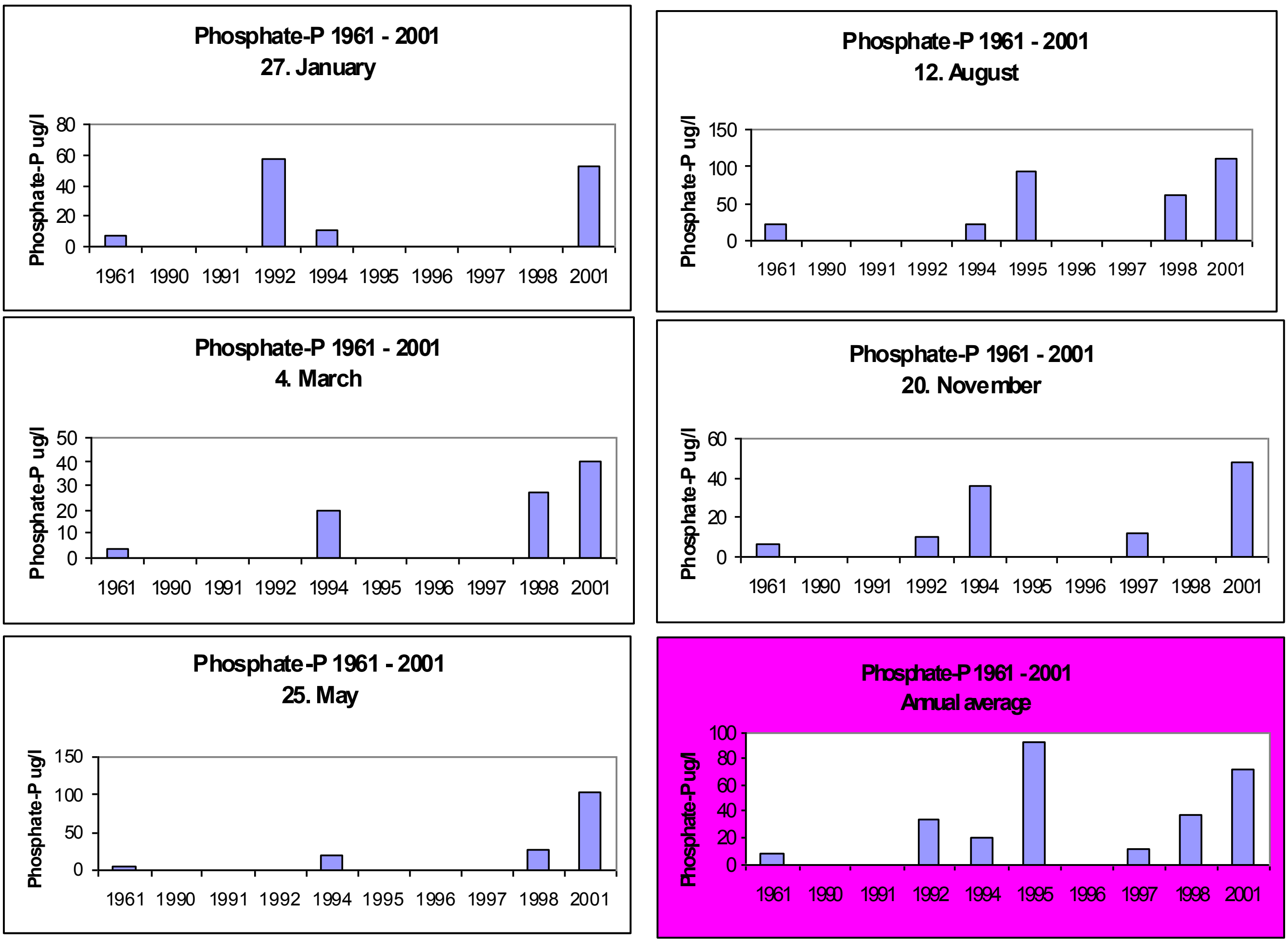

Figure 1.36 Historical changes in phosphate.

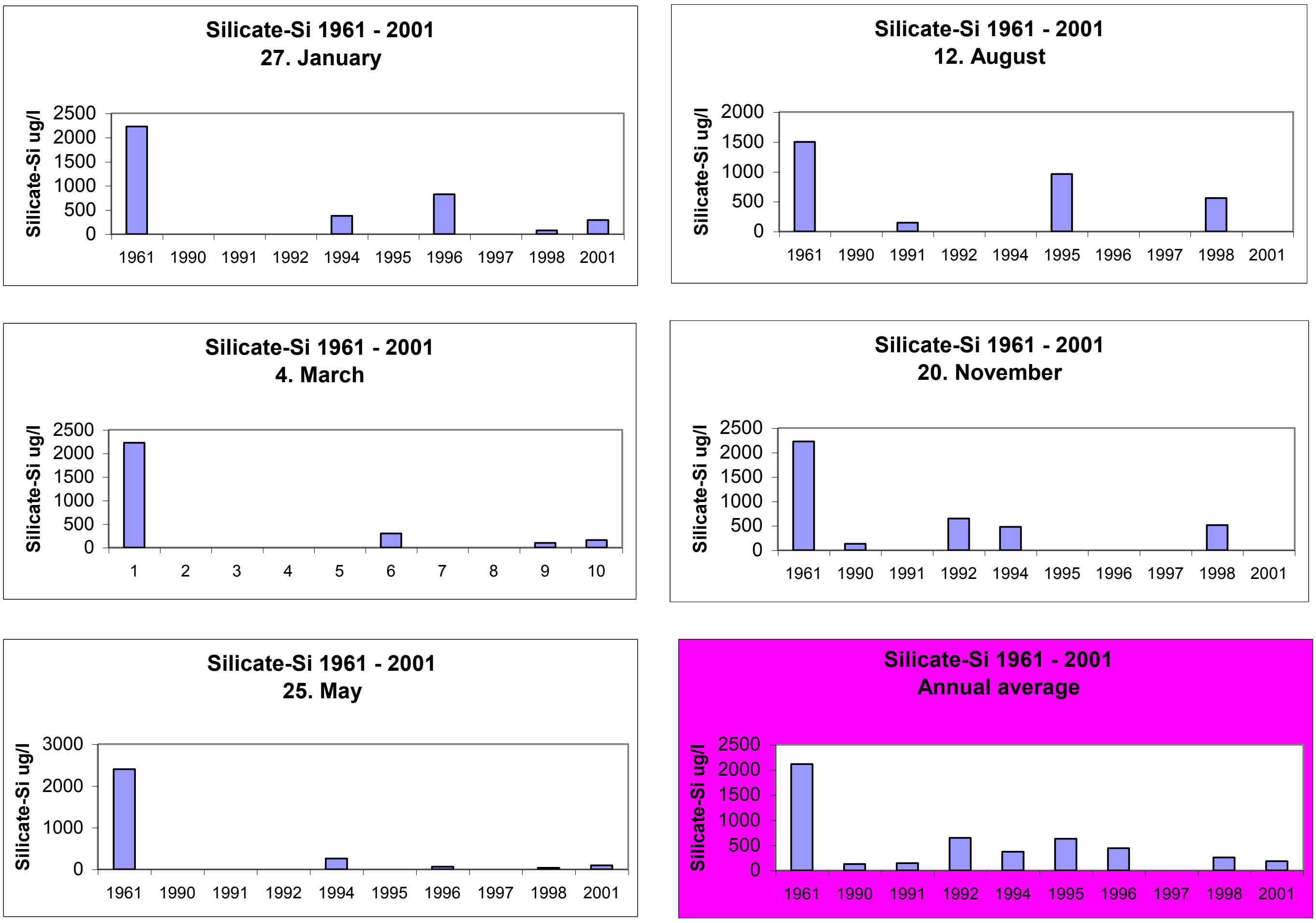

Figure 1.37 Historical changes in silicate.

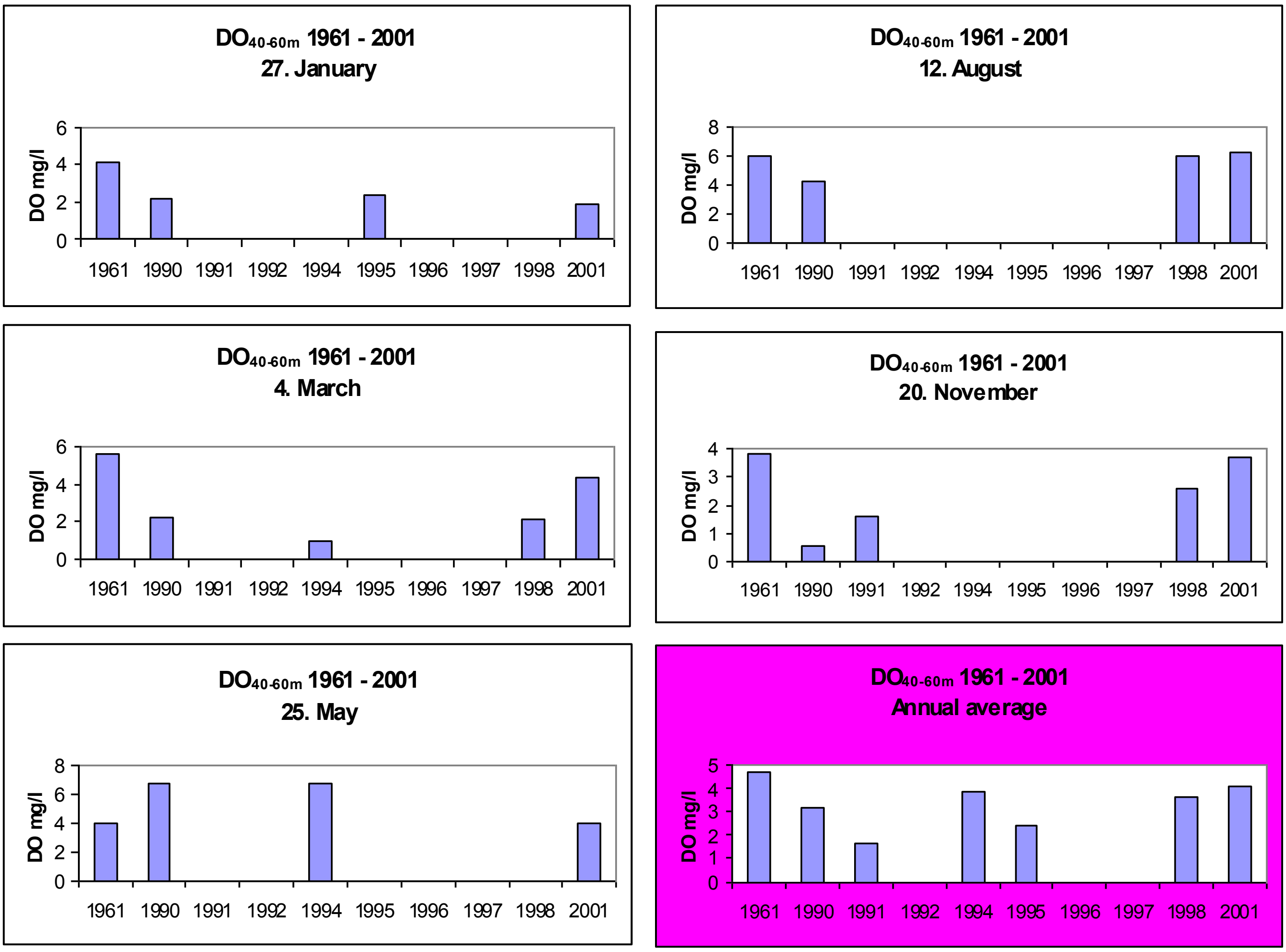

Figure 1.38 Historical changes in oxygen at 40-60 m.

- The overall pattern is a high inter-annual variability.
- Chlorophyll has been high during the 1990`s but in 2001 is the 1960 level.
- Nitrate varies from year to year, but in 2001 is at the 1960 level.
- Phosphate has increased since 1960 maintaining low nitrogen levels.
- Silicate has decreased and has been steadily low during the 1990`s.
- Dissolved oxygen was low during the 1990`s with variations from year to year, but in 2001 is at the 1960 level.

1.12 Summary of Findings

The in-lake monitoring of water quality is now operational, but a proper assessment of the state of eutrophication of the lake requires at least one full year of measurements, which has not been obtained during the project period for various reasons. However, the data set available at the end of the project is much more comprehensive regarding combined spatial and temporal extent than what has been the basis of former "conclusions" on the lake and gives some indications regarding future conclusions.

Overall, the data indicates that due to combination of a large surface area and relatively shallow depth, the lake does not react homogenously. Thus, mixing occurs at different times and to different degrees in different parts of the lake (see Chapter 8) and e.g. oxygen deficits do the same. Generally, the offshore part of the lake (60 – 70% of the lake area) has relatively low chlorophyll-a concentrations and often measurable nutrient concentrations indicating that the primary production offshore may not be limited by nutrients but rather by light due to the mixing regime. Moreover, the general carbon/nutrient ration is low which also supports this hypothesis. This implies that the ecological turn-over in the offshore parts of the lake may not be significantly affected by inputs of nutrients to the lake.

Oxygen deficits occur in the offshore parts of the lake, but the data from the study indicates that lesser parts of the lake are affected, and for a shorter time than was expected based on former studies.

On the other hand, the data shows clearly that near shore areas may be highly affected by eutrophication, especially the hot-spot areas such as Winam Gulf, Murchison Bay, Napoleon Gulf, and Mwanza Gulf. In these areas chlorophyll-a concentrations today rise far beyond what has been measured previously. Thus, the present study has measured 170 ug/l of chlorophyll-a in Mwanza Gulf and a study on Murchison Bay in 1997 measured up to 300 ug/l. For comparison, Talling (1965, 1966) reported maximum values of chlorophyll-a of 70 ug/l in near shore areas of the lake. A low N/P ratio in the near shore waters of the lake indicates that nitrogen may occasionally be limiting here.

It is likewise evident, that strong oxygen deficits occur in the hot-spot areas independently of the general oxygen regime of the lake. Thus, several meters of oxygen free water column has been registered both in Mwanza Gulf and Napoleon Gulf, and in Murchison Bay the whole water column was deoxygenated in November 1997. Such events are related to local conditions such as high nutrient input, high algae production and, at the same time low wind mixing.

1.13 Recommendations

The basic recommendation is to finalise outstanding data compilation (especially phytoplankton and zooplankton) and to continue with the data collection to obtain at least one full year's data. At the inception workshop, the proposed monitoring program was meant to evaluate the variability of the various eutrophication indicators within the lake with the intension to propose a reduced future monitoring program. The collected data has shown that the ongoing monitoring program must be considered a minimum for the next years to reveal the spatial and temporal variability of the eutrophication indicators within the lake.