Hydrobiologia **288**: 1–12, 1994.

The Ethiopian Rift Valley lakes: chemical characteristics of a salinity–alkalinity series

Elizabeth Kebede[1,2], Zinabu G.-Mariam[3] & Ingemar Ahlgren[1]
[1] *Institute of Limnology, Uppsala University, Norbyvägen 20, 752 36, Uppsala, Sweden;* [2] *Biology Department, Addis Ababa University, P.O. Box 3434, Addis Ababa, Ethiopia;* [3] *Awassa College of Agriculture, P.O. Box 5, Awassa, Ethiopia*

Key words: alkalinity, Ethiopian lakes, nutrients, Rift Valley, salinity

Abstract

The study on 10 lakes within the Ethiopian Rift Valley during March-May 1991 covered a range of conductivity (K_{25}) between 286 and 49100 $\mu S\ cm^{-1}$. HCO_3^- – CO_3^{2-} and Na^+ were the dominant ions in all the lakes. Concentrations of K^+, Cl^- and SO_4^{2-} increased with increasing salinity and alkalinity, whereas Ca^{2+} and Mg^{2+} decreased. Comparison of these data with previous records showed that a ten-fold dilution of total ionic concentration occurred over 30 years in Lake Metahara and about three-fold increase occurred over 65 years in Lake Abijata. Concentrations of soluble silica were generally high (12–222 mg $SiO_2\,l^{-1}$) and increased with increasing salinity, except for Lake Chamo which showed SiO_2 depletion (to <1 mg $SiO_2\,l^{-1}$) over the past three decades.

The relationship between ionic concentration and phosphorus was irregular although high phosphorus concentrations generally corresponded with increasing salinity. Fitting data to the Dillon & Rigler (1974) chlorophyll *a* – total phosphorus relationship suggested that lakes Zwai, Awassa and Chamo are phosphorus-limited, whereas others have surplus phosphorus.

Introduction

Development of commercial fishery has been intensified over the last decade in some Rift Valley Lakes in Ethiopia: lakes Zwai, Langeno, Awassa, Abaya and Chamo. However, exploitation of these resources is developing with little knowledge about the fish production potential and basic limnology of the lakes. The two neighbouring lakes Abijata and Shalla are of special importance to wildlife in providing feeding and breeding grounds for a rich bird fauna of over 360 species of resident and migratory birds. The two lakes have been enclosed in a national park since 1970. But it has not been possible to promote conservation due to increasing development activities in the area during the past ten years, which have resulted in progressively lower lake levels and higher salinity in Lake Abijata, the feeding ground for the bird populations. Chemical and biological changes following the increased utilization of these aquatic resources in the country has not been given attention.

The chemical composition of lakes found in Ethiopia is extremely varied. In an attempt to consolidate data collected from the 1960's and 70's, Wood & Talling (1988) surveyed records on 28 Ethiopian lakes and gave an overview of the relationships between ionic composition, nutrients and phytoplankton. Although a substantial amount of data is available on the major ionic composition of these lakes, there is a lack of information concerning nutrients. Continuous environmental changes and recurrent droughts in the country, resulting from both natural causes and human influence, make it necessary to update this data base. Thus, the purpose of this study is to update and compare previous data in order to complement our knowledge on the chemical composition of the major lakes in Ethiopia.

Study area

The lakes in this study all lie within the Ethiopian Rift Valley, running NNE through the middle of the country (Fig. 1). These lakes are similar in altitude and range from 1200 to 1680 m. However, their physical characteristics and catchments are diverse (Table 1). The region experiences moist subhumid to semi-arid climate with evapotranspiration exceeding rainfall, thus incurring rainfall deficit. The mean annual rainfall varies from about 1000 mm around lakes Abaya and Chamo to between 600–1200 mm around lakes Awassa, Shalla and Zwai, and falls below 600 mm as the altitude decreases further north in the rift (Daniel G., 1977). Annual evapotranspiration in the rift area south of, and including Lake Metahara, varies between 1100–1600 mm which contributes to an annual water deficit of up to 1000 mm around Lake Metahara and between 500–750 mm further south in the rift valley (Daniel G., 1977).

The impact of seasonal and interannual variation in rainfall and water input is more pronounced in small, shallow lakes and terminal lakes within closed drainage basins, a common feature within the rift valley. Zwai-Shalla basin includes lakes Zwai, Langeno, Shalla and Abijata with lakes Zwai and Langeno discharging into Lake Abijata. There is presently no surface outlet from lakes Abijata, Shalla and Awassa. Lake Awassa drains a large swampy area and has remained relatively dilute in spite of its closed drainage. It is believed that seepage accounts for solute losses in some of the closed basins. Lakes Abaya and Chamo are connected via a small river and are part of a much larger drainage basin which includes lakes Chew Bahr (Stephanie) and Turkana. The lava-dam lake Metahara, and the crater lake Chitu are closed basins with no obvious surface outflow. A more detailed description of the hydrology of Ethiopian lakes is given in Wood & Talling (1988).

Materials and methods

The study was made during March–May 1991, just after the dry season. Water samples were collected from a single offshore station from different depths and as integrated samples (Table 2) with a weighted, plexiglass tube (2 m height). Samples were then transferred into polyethylene bottles and transported to the laboratory in an ice box. Filtration was done through Whatman GF/C glass fiber filters within 2 to 6 hours after sampling. Electrical conductivity was measured *in situ* with a conductivity meter (YSI Model 33 S-C-T meter) and values were corrected to 25 °C assuming a temperature coefficient of 2.3% per °C (after Talling & Talling, 1965). pH was measured *in situ* with a digital pH meter (Canlab, Model 607). Temperature and dissolved oxygen profiles were measured with a YSI Model 57 oxygen meter and water transparency with a standard Secchi disc.

Carbonate-bicarbonate alkalinity was determined by titration with HCl to a pH of 4.5 (Golterman *et al.*, 1978). Cl^- and SO_4^{2-} were analysed by the ion-exchange method (Mackereth, 1955), and Cl^- was determined separately by the argentometric method (APHA *et al.*, 1980). Na^+, K^+, Ca^{2+} and Mg^{2+} were analysed by ICP (Induced Coupled Plasma) analysis. NO_3^- was determined by the cadmium reduction method (Golterman *et al.*, 1978), NH_4^+ by the indophenol method as modified by Chaney & Marbach (1962), and dissolved SiO_2 (Wetzel & Likens, 1979) and PO_4^{3-} (Murphy & Riley, 1962) by molybdate complex formation. Samples for total phosphorus (TP) analysis were digested with persulphate as described by Valderrama (1981).

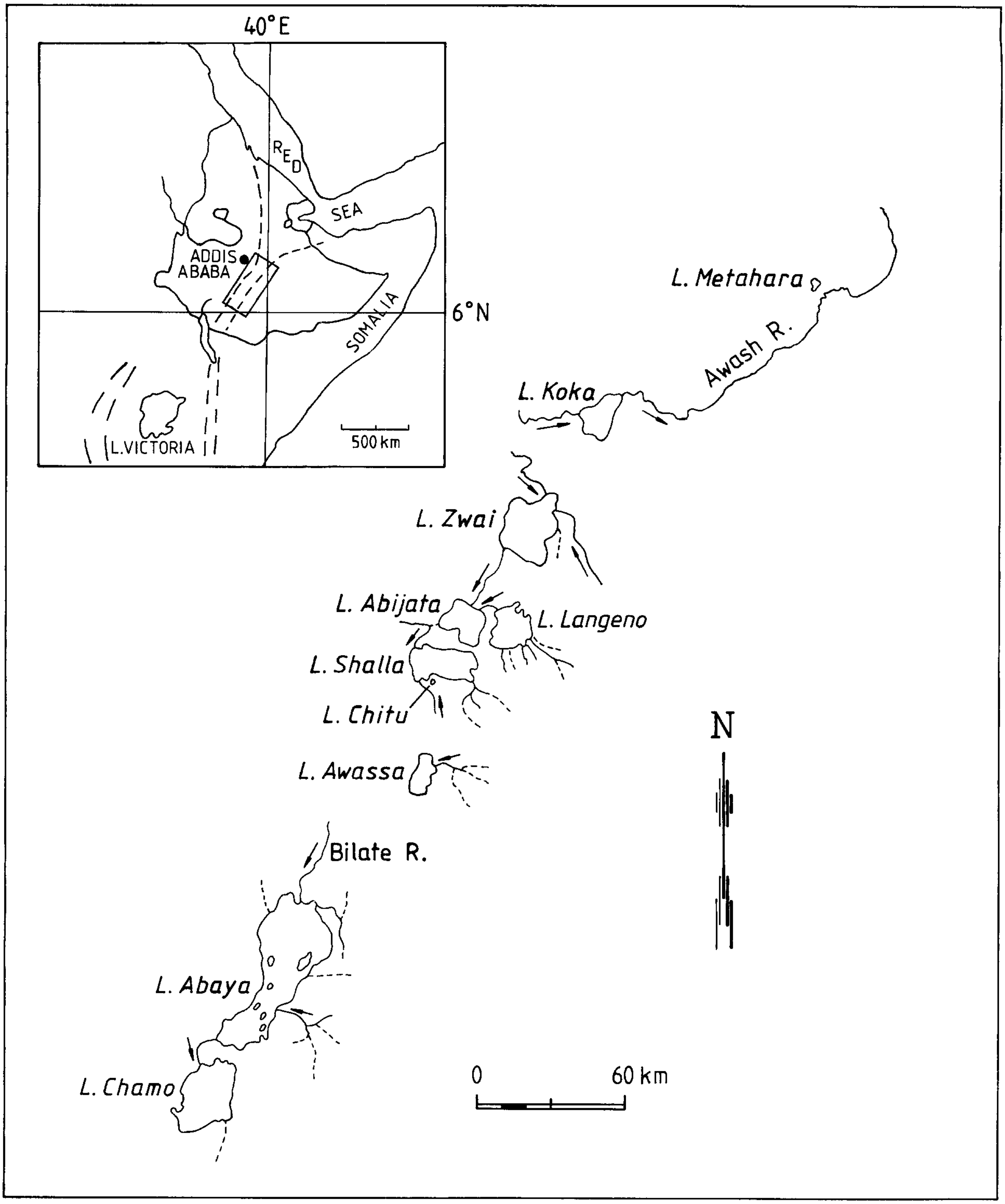

Fig. 1. Location and drainage pattern of lakes in the Ethiopian Rift Valley.

Table 1. Morphometric and physical features of Ethiopian Rift Valley lakes.

Lake	Altitude (m)	Surface area (km^2)	Max. depth (m)	Mean depth (m)	Catchment area (km^2)	Secchi depth (cm)
Metahara* (Besaka)	1200	3.2	–	–	–	41
Koka	1660	200	–	–	–	28
Zwai	1636	442	7	2.5	7025	35
Langeno	1582	241	48	17	1600	25–35[a]
Abijata*	1578	176	14	7.6	1630	65
Shalla*	1558	329	266	87	3920	125
Chitu*	1600	0.8	21	–	–	43
Awassa*	1680	90	23	10.7	1250	70–80[b,c]
Abaya	1285	1162	13	7.1	17300	43
Chamo*	1233	551	13	–	2210	65

* Lack visible outlet. [a] Tudorancea *et al.* (1989); [b] Demeke K. (1985); [c] Elizabeth K. (1987). Where references are not cited, Secchi depth values represent single measurements taken on the sampling dates listed in Table 2.

Chl *a* was determined according to Talling & Driver (1963) on pigments extracted in warm methanol; no correction was made for degradation products.

Results and discussion

Ionic composition

The chemical composition of the lakes is arranged in order of increasing electrical conductivity (Table 2). Electrical conductivity (K_{25}) ranges from 286 to 49100 $\mu S\ cm^{-1}$ and is accompanied by an increase in alkalinity from 2.6 to 573.7 meq l^{-1}. Conductivity and salinity is mainly accounted for by Na^+ and HCO_3^- – CO_3^{2-}, which give rise to high pH in the most saline lakes. Increasing Na^+ concentration and alkalinity is accompanied by an increase in K^+, Cl^- and SO_4^{2-} concentrations (Fig. 2). The divalent cations Ca^{2+} and Mg^{2+} however, show an inverse relationship with salinity and alkalinity, since they are removed from solution when carbonate precipitates under highly alkaline conditions. A detailed discussion of the major ions is given in Wood & Talling (1988).

Temporal changes have occurred in the ionic composition of two lakes. The lava-dam lake Metahara showed a decrease in total ionic concentration by about a factor of 10 over 30 years (Table 3). The decrease in concentration was highest for Na^+, HCO_3^- and Cl^- (10–12 fold) and lowest for K^+ (6 fold). Low concentrations of Ca^{2+} and Mg^{2+} make comparisons difficult, but it appears that decreasing alkalinity accompanied by a slight decrease in pH (by 0.5 unit) could have been accompanied by a rise in the concentration of Ca^{2+}. Lake Metahara has increased in size over the past 20 years, possibly due to a combination of subterranean seepage from the basin and spillage from the nearby river Awash. The change in ionic concentration appears to have been accompanied by a shift in the phytoplankton community. *Arthrospira fusiformis* (Voronich.) Kom. & Lund (= *Spirulina platensis*, the characteristic blue-green algal species in African soda lakes, was reportedly dominant in 1961 in Lake Metahara (Wood & Talling, 1988), but totally absent in 1991 (unpublished data). Instead, the phytoplankton community was composed of a mixture of green and blue-green algae. Although seasonal variation in species composition can not be ruled out, such a succession is unlikely to occur unless there is a major change in the chemical environment.

The terminal lake Abijata showed a considerable increase in ionic concentration with the maximum recorded since 1926 (Table 4). Fluctuations of ionic concentration can be seen from

Table 2. The chemical composition of Ethiopian Rift Valley lakes.

Lake	Sampling date	Depth (m)	K_{25} ($\mu S\ cm^{-1}$)	Sal. ($g\ l^{-1}$)	Σ Cat	Σ An	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3 + CO_3^{2-}	Cl^-	SO_4^{2-}	SiO_2 ($mg\ l^{-1}$)	PO_4-P	TP	NO_3^- NO_2-N	NH_4^+ -N	pH	Chl *a* ($\mu g\ l^{-1}$)
					($meq\ l^{-1}$)										($\mu g\ l^{-1}$)					
1. Koka	10/5/91	0	286			2.97					2.50	0.18	0.29	14.6	9.5		1.4	bd		13.5
		0–0.6	286	0.2	3.08	3.02	1.35	0.14	1.16	0.43	2.60	0.22	0.20	12.5	bd	224.0	bd	bd	8.20	15.6
2. Zwai	27/3/91	0–2	410	0.4	4.38	4.64	2.87	0.31	0.56	0.64	4.00	0.32	0.32	37.0	bd	219.0	3.9	36.3	8.50	154.2
3. Awassa	12/3/91	0												37.9	12.4	30.0	58.3			18.3
		0–3	830	0.8	7.56	9.37	5.96	0.69	0.43	0.48	8.25	0.39	0.73	42.6	12.4	36.2	34.9	5.7	8.75	16.2
4. Abaya	16/3/91	0–2	925	0.9	10.34	11.37	9.13	0.44	0.45	0.32	9.37	1.11	0.89	20.3	147.0	237.0	180.0	13.2	8.65	5.0
		5–6			10.01		8.91	0.41	0.42	0.27				21.4	149.0	216.0	256.0	14.4		3.3
5. Chamo	15/3/91	0–2	1320	1.0	9.06	14.56	7.26	0.78	0.32	0.70	12.00	1.71	0.85	0.4	25.5	135.0	18.6	11.8	8.90	44.2
		4–5	1260		14.14	15.37	12.61	0.49	0.35	0.69	12.25	2.02	1.10	0.6	29.4	165.0	25.7	27.9		34.6
6. Langeno	8/3/91	0			15.28		14.35	0.51	0.23	0.19		3.28	1.16		20.0	99.4		10.0		5.9
		0–2	1770	2.4	16.80	17.32	15.78	0.54	0.25	0.23	12.50	3.66	1.16	27.6	20.0	70.4	44.9	50.0	8.95	2.4
		15			15.65		14.70	0.51	0.24	0.20										
7. Metahara	12/5/91	0	7155	5.3		69.6					44.00	12.8	12.8	106.0	1295		88.7	< 1	9.40	26.7
		0–1.2	7441		80.43	71.2	78.56	1.72	0.11	0.04	46.50	12.6	12.1	105.8	1302	1850	94.6	6.2	9.40	12.9
8. Shalla	20/3/91	0–4	21940	18.1	277	288	272	4.56	0.16	0.07	218	54.4	16.3	56.0	809	860	bd	4.3	9.65	15.8
		16–17			253	268	249	3.51	0.21	0.07	215	40.4	13.1	59.0	818	928	bd	3.8		6.1
9. Abijata	20/3/91	0									349			122.0	115	511			9.85	135.3
		0–2	28130	26.4	426	437	416	9.72	0.12	0.02	325	88.3	24.0	114.0	98	435	bd	88.1	9.85	14.7
		3–4			415	417	397	18.33	0.13	0.02	324	73.2	20.2	111.0	115	413	bd	122.9		10.6
10. Chitu	22/3/91	0									581			189.0	2011	2190	bd	bd	10.20	145.5
		0–1.5	49100	44.9	895	693	864	31.20	0.16	0.05	573	99.0	21.1	222.0	1985	2300	bd	bd	10.15	224.0
		8			709	737	684	23.69	0.12	0.04	576	140.2	20.6	217.5	2347	2492	bd	35.0	10.10	182.0

Salinity values were calculated by summing the concentration of the individual components. bd = below detection.

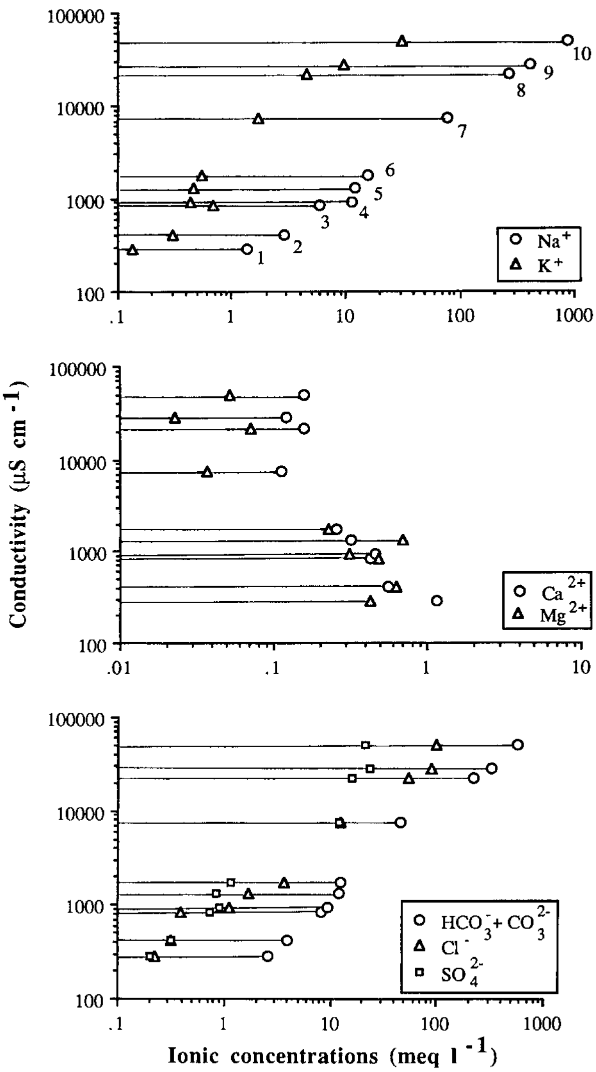

Fig. 2. Concentration of the major ions in the Ethiopian Rift Valley lakes in relation to total ionic concentration (expressed as conductivity). Numbers by the horizontal lines represent the lakes arranged in order of increasing conductivity as in Table 2.

the records over the past few decades. Between 1926 and 1991 the salinity has increased by more than 2.6 times and the alkalinity by about 4 times. Cl^- showed a two-fold increase over the 42 meq l^{-1} recorded both in 1926 (Omer-Cooper, 1930) and 1938 (Loffredo & Maldura, 1941). The dominant cation Na^+ appears to have been concentrated more than three-fold. The increase in salinity and alkalinity was accompanied by a decrease in Ca^{2+} and Mg^{2+} concentrations (Fig. 3), as is often the case with saline lakes.

A one-year study in 1981 by Kassahun W. (1982) showed seasonal variation in the ionic concentration of Lake Abijata. Na^+ concentration and alkalinity increased by about 1.6 times by the end of the dry season, but current values still exceed the maximum concentration recorded in 1981. Past fluctuations of lake level were mainly attributed to seasonal and interannual variations in rainfall within the drainage basin. Additionally, the loss of water from Lake Abijata has been enhanced by recent development schemes in the area such as pumping of water from the lake for soda ash extraction, diversion of the feeder rivers to Lake Zwai and direct use of Lake Zwai water for irrigation. Relatively shallow depth and terminal position in the drainage area make Lake Abijata more susceptible than the other three lakes in the basin (lakes Zwai, Langeno, Shalla) to the effects of changes in water input. Wood & Talling (1988) previously pointed out the salinity increase in the closed basins of lakes Abijata, Awassa, Abaya and Chamo.

Nutrients

Si concentration was variable among the lakes with a general tendency to increase with increasing salinity (Table 2). Values exceeding 100 mg dissolved SiO_2 l^{-1} were found in the saline lakes. Concentrations over 10 mg SiO_2 l^{-1} are common in African lakes due to high mobility of Si in most tropical soils and porous volcanic lavas, relatively high importance of ground water inputs, and enhanced dissolution of Si compounds in saline waters of high alkalinity and pH (Talling & Talling, 1965).

With the exception of Lake Chamo, concentration of Si in the surface waters ranged from 14.6 mg l^{-1} in the most dilute Lake Koka to 189 mg l^{-1} SiO_2 in Lake Chitu. The concentration in Lake Chamo was the lowest reported in 25 years. It has decreased consistently over the years from 28 mg l^{-1} in 1964 (Wood & Talling, 1988) to less than 1 mg l^{-1} SiO_2 in 1991 (Fig. 4). Al-

Table 3. Change in the ionic composition of Lake Metahara.

Year	K_{25} ($\mu S\ cm^{-1}$)	Σ Cat	Σ An	Na^+	K^+	Ca^{2+}	Mg^{2+}	$HCO_3^- + CO_3^{2-}$	Cl^-	SO_4^{2-}	TP ($\mu g\ l^{-1}$)	pH
		(meq l^{-1})										
1961*	74170	784	831	774	10.4	<0.15	<0.6	580	154.6	97.5	11000	9.9
1991	7440	80	71	79	1.7	0.11	0.04	46	12.6	12.1	1850	9.4

* Data from Talling & Talling (1965).

Table 4. Fluctuations with time in ionic composition of the surface water of Lake Abijata.

Reference	Date	Salinity ($g\ l^{-1}$)	Σ Cat	Na^+	K^+	Ca^{2+}	Mg^{2+}	Alkal.	Cl^-	SO_4^{2-}
			(meq l^{-1})							
Omer-Cooper (1930)	Nov. '26	8.13		125		0.500	0.833	80	42	
Loffredo & Maldura (1941)	Apr. '38	8.36	133	130	1.9	0.425	0.50		42	1.4
De Filippis (1940)	Apr. '39		150	140	10.3	0.175	0.067	81	40	
Talling & Talling (1965)	May '61	19.38	285	277	8.5	<0.15	<0.6	210	91	15.0
Wood & Talling (1988)	Mar. '64	16.20	228	222	6.5	<0.1	<0.1	166	51	22.5
Von Damm & Edmond (1984)	Jan./Feb. '76	12.96	199	194	4.9	0.084	0.046	138	54	0.3
Kassahun W. (1982)	Nov. '80–Oct. '81	21	238–388	231–378	6.9–9.9	<0.01	<0.01–0.01	180–297	82–121	4.0–5.7
	Mar. '91	26	425	416	9.7	0.120	0.023	326	88	24.0

though not as pronounced, a decline was also found in some of the other lakes.

The reason for this decline is not clear. Removal of silicate from solution can be significant in lakes dominated by diatoms (e.g. lake Shalla) or in others with large diatom populations (e.g. lakes Zwai, Awassa, Chamo, Abaya). In Lake Chamo, Belay & Wood (1982) found a relation between decreasing SiO_2 concentrations and larger diatom growth, which simultaneously removed much of the nitrogen (N) and phosphorus (P) from the water. Algal blooms and fish kills have been more common in this lake since 1978, when they were first reported (Belay & Wood, 1982), and the severe depletion of Si is commonly associated with increased diatom growth and lower dissolution rates of silicic acid from diatom frustules. A 10 fold decline in SiO_2 concentration accompanied by increased algal production has been recently reported from Lake Victoria (R.E. Hecky-SIL Congress, 1992). A gradual decrease of Si concentration with increasing diatom production (due to increased N and P concentrations) has been documented from lakes Michigan (Schelske, 1988) and Ontario (Stoermer *et al.*, 1985), and the Baltic Sea (Wulff & Rahm, 1988). Active dissolution of diatom frustules is inhibited by organic matter accumulation in the sediments as was shown by Hecky & Kilham (1973) for some alkaline lakes in East Africa. This suggests that diatoms are acting as a permanent sink in the lakes with appreciable diatom populations (Lake Shalla) and progressive phytoplankton production (lakes Chamo, Zwai). All comparisons were made on surface values (Table 2) and samples from Lake Shalla (max. depth, 266 m) would have probably shown higher SiO_2 concentrations at greater depths.

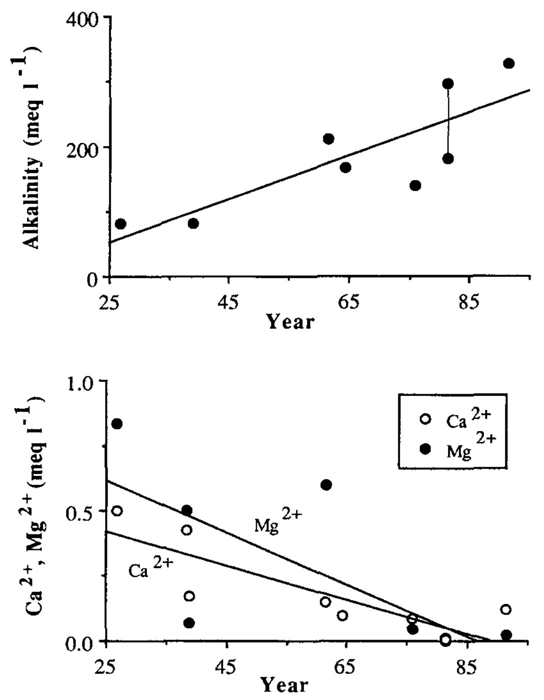

Fig. 3. Fluctuations with time in a) alkalinity level and b) concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the surface waters of Lake Abijata. Vertical line between two values represents the range of measured concentrations. Regression between time (years) and the ions gives the equations: alkalinity = 58.000 + 3.3128 years ($r^2 = 0.668$); $Ca^{2+} = 0.404 - 0.00655$ years ($r^2 = 0.722$); $Mg^{2+} = 0.598 - 0.01008$ years ($r^2 = 0.530$).

Reverse weathering (neoformation of aluminosilicate minerals) has been proposed as a major process in closed basins of Ethiopian rift lakes, removing Si, base cations and HCO_3^- from solution (Von Damm & Edmond, 1984). An example of this reaction is

$$\underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + 5Mg^{2+} + Si(OH)_4 + 10CO_3^{2-} + 5H_2O \rightarrow$$

$$\rightarrow \underset{\text{chlorite}}{Mg_5Al_2Si_3O_{10}(OH)_8} + 10HCO_3^- .$$

The decline of Si concentration in the Ethiopian rift lakes is not accompanied by decreasing levels of alkalinity and Mg^{2+}, but Ca^{2+} showed a decrease in the dilute lakes Chamo and Abaya. Other biogenic processes influencing alkalinity and Ca^{2+} levels might also mask the possible effect of reverse weathering in the removal of those solutes. Wood & Talling (1988) have cast doubt on the proposal by Von Damm & Edmond for Ethiopian lakes, the reason being that the mass balance calculations were based on rough hydrological information. However, the phenomenon has been identified as one of the gradual, biogeochemical pathways in saline lake evolution of Basuto Lake District, Tanzania (Kilham & Cloke, 1990).

No apparent relationship was found between ionic concentration and N (Table 2). NO_3^--N was depleted in all the saline lakes except in the surface waters of Lake Metahara (88.7 μg l^{-1}). In Lake Abijata, NH_4^+-N increased with depth from 88 μg l^{-1} in the 0–2 m column of water to 123 μg l^{-1} in 3–4 m. The increase was more pronounced in Lake Chitu where NH_4^+-N was below detection level in the surface waters and 35 μg l^{-1} at 8 m. Dissolved O_2 showed sharp discontinuities between 0.5–1.5 m and between 3–4.5 m, with complete deoxygenation below 5 m. The smell of hydrogen sulphide was detected at depths below 8 m. Stratification was sharp in Lake Abijata between 0.50–1.25 m with the temperature dropping from 25 °C to 21.2 °C, and dissolved O_2 from supersaturation to 4.2 mg l^{-1}, which further decreased to 1.4 mg l^{-1} at 4 m. With a maximum depth of less than 14 m, stratification is largely diurnal in Lake Abijata (Baxter *et al.*, 1965), but can be seasonal in the deeper and protected crater Lake Chitu. Thus the reduced forms of N and S (sulphur) can be transported up from the anoxic layer during destratification. Sampling was done immediately after the dry season, when the cooling effect of the short rains and inflows can disrupt the stability of the water column, an important factor governing stratification patterns in most African lakes (Talling, 1986). It is also worthy to note that NH_4^+ input from excreta of the large population of waterfowl (mainly flamingoes) feeding on and around lakes Abijata and Chitu can be large.

Very low NO_3^- concentration was found in the dilute, shallow lakes Koka and Zwai. However, NH_4^+-N concentration was still considerable in Lake Zwai (36.3 μg l^{-1}), which had a comparable phytoplankton density with the most saline

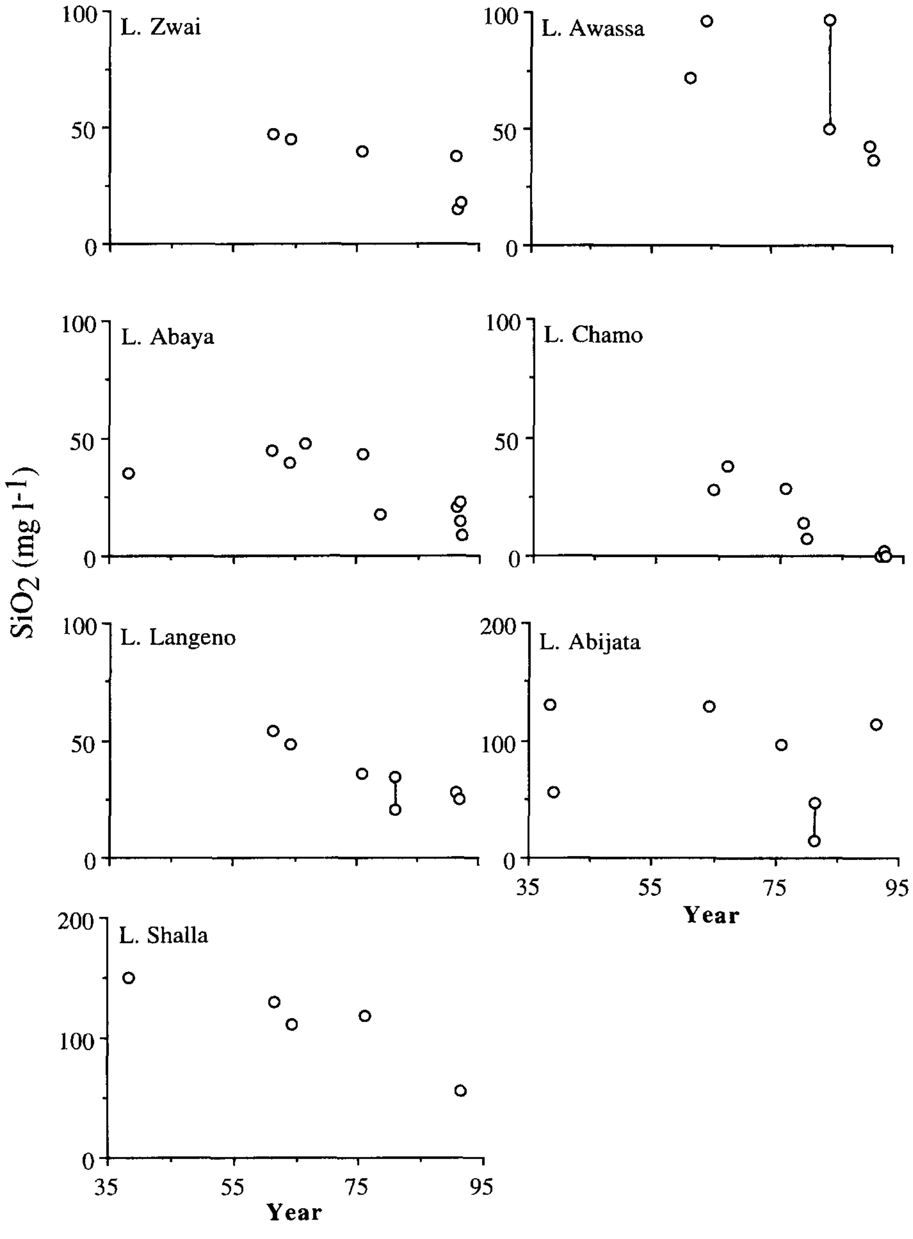

Fig. 4. Concentration of dissolved silica (mg SiO_2 l^{-1}) recorded during 1938–1991 in some lakes of the Ethiopian Rift Valley. Vertical line between two values represents the range of measured concentrations.

Lake Chitu. The highest concentration of NO_3^-, as well as dissolved inorganic nitrogen (DIN), was found in Lake Abaya where a low phytoplankton density was estimated (chl *a*, 5 μg l^{-1}).

High ionic concentration corresponded with high PO_4-P (SRP-soluble reactive phosphorus) and TP (Fig. 5), with levels of up to and exceeding 2 mg l^{-1} PO_4-P in Lake Chitu. The freshwater lakes (salinity $<$ 3.0 g l^{-1}) had relatively much lower P with PO_4-P concentrations below detection limit in the productive Lake Zwai (chl *a*, 154 μg l^{-1}). The PO_4-P to TP proportion by weight was less than 0.4 in the dilute lakes except

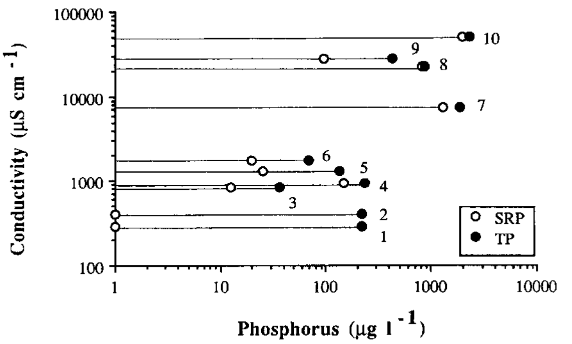

Fig. 5. Concentrations of soluble reactive phosphorus (SRP) and total phosphorus (TP) in the Ethiopian Rift Valley lakes in relation to ionic concentration. Numbers by the horizontal lines represent the lakes as in Table 2.

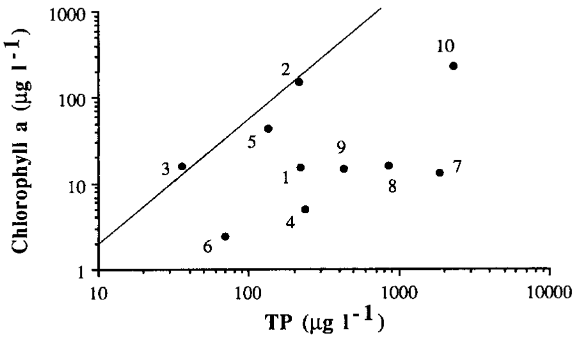

Fig. 6. The relationship of chlorophyll *a* to total phosphorus (TP) in the Ethiopian Rift Valley lakes; the line passing through the points is the regression line from Dillon & Rigler (1974). Numbers represent the lakes as in Table 2.

in Lake Abaya (0.6) where production is limited due to high inorganic turbidity. The proportion was lowest in the most dilute lakes Koka and Zwai and highest (*ca* 0.9) in the saline lakes Shalla and Chitu. In spite of the high algal standing crop in Lake Chitu (chl *a*, 224 μg 1^{-1}), there was still a large supply of available P.

Lake Abijata had a relatively low TP concentration compared to the other saline lakes. However the actual TP is believed to be higher than the measured concentration, because at the time of sampling there was high spatial heterogeneity of phytoplankton and suspended matter. For example, the northern shoreline of the lake was covered by a thick algal mat extending about 20–30 m offshore. Surface accumulation of plankton can be noted from chl *a* values which show a nine-fold difference between the surface and 0–2 m water column (Table 2). The proportion of PO_4-P to TP is only 0.2, and is much lower than in the saline lakes and most of the dilute lakes. Thus, most of the P is bound in either organic or unavailable forms, but there is still surplus SRP.

Very low inorganic N concentration, in contrast to their high P content, was suggested by Talling & Talling (1965) to be limiting algal production in some African lakes. Melack *et al.* (1982) showed that P was more limiting than NH_4^+-N in two Kenyan soda lakes, Elementeita and Sonachi. They based their conclusion on analyses of N, P and C (carbon) content of the lake water, and P enrichment experiments in Lake Sonachi. Inorganic N and P were nearly undetectable in both lakes, and enrichment with P in Lake Sonachi enhanced algal abundance. The salinity and TP concentrations reported from Lake Elementeita are comparable to values found in Lake Abijata. Available P, however, is much higher in Lake Abijata which suggests that P is not limiting. The net phytoplankton of Lake Abijata was dominated by *Arthrospira fusiformis* and a filamentous blue-green algal species with a high density of heterocysts, indicating that they are N limited (although N fixation was not measured).

It appears that there was no simple relationship between chl *a* and TP (Fig. 6), and DIN (Table 2) among the series of lakes. Interpretation would be difficult without information on total nitrogen (TN) concentration as employed by Kalff (1983). The ratio of dissolved inorganic N and P (DIN:PO_4) is lowest (<0.1) in the saline lakes Chitu, Shalla and Metahara, and highest (>3) in the dilute lakes Zwai, Langeno and Awassa (Table 5). The ratio DIN:TP gives the same trend as DIN:PO_4, with the exception of Lake Zwai with undetectable PO_4-P concentration and high DIN:PO_4. From these ratios, N limitation seems more likely to occur in the saline lakes with decreasing importance in the freshwater lakes.

The freshwater lakes Zwai, Awassa and Chamo fit the plot of the relationship between chl *a* and TP derived by Dillon & Rigler (1974)

Table 5. The ratios by weight of dissolved inorganic nitrogen, to dissolved inorganic and total phosphorus ($DIN:PO_4$, DIN:TP) in Ethiopian Rift Valley lakes.

Lake	$DIN:PO_4$	DIN:TP
Koka	bd:bd	bd:224
Zwai	40.2:bd	0.2
Awassa	3.3	1.1
Abaya	1.3	0.8
Chamo	1.2	0.2
Langeno	4.7	1.3
Metahara	0.1	0.05
Shalla	0.005	0.005
Abijata	1.0	0.2
Chitu	bd:1985	bd:2300

bd = concentration below detection.

for temperate lakes and used as an index of P limitation. Another indication of P limitation is generally supported in lakes with high chl *a* content relative to TP (Fig. 7). The chl *a*:TP ratio suggests surplus P in all the lakes where algal production is possibly limited by low light conditions (Secchi depths, Table 1); this was also noted by Kalff (1983) for some Kenyan lakes. High chl *a* content relative to TP and a good fit to the Dillon & Rigler relationship were found in the two Kenyan freshwater lakes Naivasha and Oloiden (Kalff, 1983), and suggest that they are P limited.

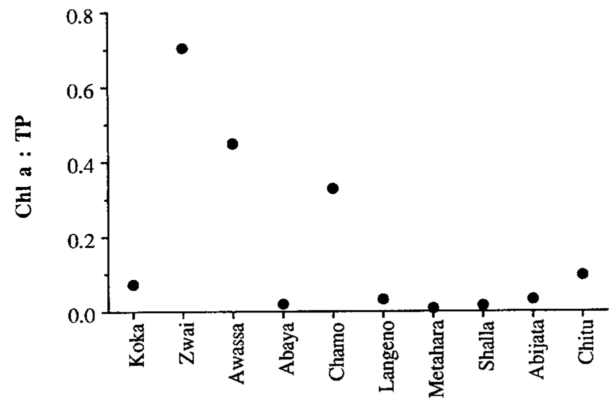

Fig. 7. Chlorophyll *a* content per unit phosphorus in the Ethiopian Rift Valley lakes. The lakes are arranged in order of increasing conductivity.

A stable colloidal suspension of silt imparts high turbidity in lakes Langeno and Abaya reducing the production zone (Zeu). Wood *et al.* (1978) have shown that light attenuation due to non-algal turbidity was high in the four lakes they investigated: lakes Langeno, Shalla, Zwai and Abijata. In the last two lakes, windy conditions and mixing commonly result in resuspension of sediments from their shallow depths. High algal biomass is maintained within the narrow euphotic zone of lakes Zwai (<1 m) and Chitu (<1.5 m) and contributes to light attenuation. A deep mixing zone in contrast to a relatively shallow euphotic zone makes Lake Shalla an optically deep and light-limited lake. Light can also be a limiting factor in the reservoir-lake Koka (Zeu ~ 0.6 m) with high silt load transported by the river Awash, and Lake Metahara (Zeu $\sim$ 1 m) with an opaque, brown coloured water probably from inorganic sources. Low light climate in seven out of the ten lakes studied is highly likely to impart light limitation and mask nutrient limitation. Experimental testing of natural populations of phytoplankton with lake water under different nutrient and light conditions would help to distinguish between the limiting factors.

Acknowledgements

We are very grateful to Demeke Admassu for his invaluable help in the field and suggestions, and C. Hillman for providing us with an outboard engine and a boat. We express our thanks to all colleagues and friends in Ethiopia who made it possible for us to travel in the country at a time with the most severe shortage of petrol. We thank R. Figueroa and J. Petterson for analyses of the cations, and Å. Olin for ideas and discussions on ion analyses. We are very grateful to J. F. Talling, G. Ahlgren and E. Willén for their valuable comments and improvements on the manuscript. The study was conducted within the Ethiopian Flora Project, a SAREC-sponsored project between Addis Ababa University and Uppsala University.

References

APHA, AWWA & APCF, 1980. Standard methods for the examination of water and waste water. Fifteenth edn. American Public Health Association, New York, 1134 pp.

Baxter, R. M., M. V. Prosser, J. F. Talling & R. B. Wood, 1965. Stratification in tropical African lakes at moderate altitudes (1500 to 2000 m). Limnol. Oceanogr. 10: 611–520.

Belay, A. & R. B. Wood, 1982. Limnological aspects of an algal bloom on Lake Chamo in Gamo Gofa administrative region of Ethiopia in 1978. Sinet: Ethiopian J. Sci. 5: 1–19.

Chaney, A. L. & E. P. Marbach, 1962. Modified reagent for the determination of urea and ammonia. Clin. Chem. 8: 130–132.

Daniel Gamachu, 1977. Aspects of climate and water budget in Ethiopia. Addis Ababa University Press, Addis Ababa, 71 pp.

De Filippis, N., 1940. Condizioni chimiche del lago Hora Abiata. Boll. Idrobiol. Africa Orientale Italiana 1: 77–79.

Demeke Kifle, 1985. Variation in phytoplankton primary production in relation to light and nutrients in Lake Awassa. M.S. Thesis, Addis Ababa University, Addis Ababa, 116 pp.

Dillon, P. J. & F. H. Rigler, 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr. 19: 767–773.

Elizabeth Kebede, 1987. A seasonal study of the species composition and phytoplankton biomass in Lake Awassa, Ethiopia. M.S. Thesis, Addis Ababa University, Addis Ababa, 70 pp.

Golterman, H. L., R. S. Clymo & M. A. M. Ohnstad, 1978. Methods for physical and chemical analysis of freshwaters. IBP Handbook No. 8, Blackwell Scientific Publications, 213 pp.

Hecky, R. E. & P. Kilham, 1973. Diatoms in alkaline, saline lakes: ecology and geochemical implications. Limnol. Oceanogr. 18: 53–71.

Kalff, J. 1983. Phosphorus limitation in some tropical African lakes. Hydrobiologia 100: 101–112.

Kassahun Wodajo, 1982. Comparative limnology of Lake Abijata and Lake Langeno in relation to primary and secondary production. M.S. Thesis, Addis Ababa University, Addis Ababa, 112 pp.

Kilham, P. & P. L. Cloke, 1990. The evolution of saline lake waters: gradual and rapid biogeochemical pathways in the Basuto Lake District, Tanzania. Hydrobiologia 197: 35–50.

Komarek, J. & J. W. G. Lund, 1990. What is '*Spirulina platensis*' in fact? Arch. Hydrobiol./Suppl. 85, Algolog. Studies 58: 1–13.

Loffredo, S. & C. M. Maldura, 1941. Resultati generali delle ricerche di chimica limnologica sulle acque dei laghi dell'Africa orientale italiana esplorati della Missione ittiologica. In Piccioli, A. (ed.), Esplorazione dei laghi della Fossa Galla. Collezione scientifica e documentari dell'Africa Italiana III, Vol. I, 181–200.

Mackereth, F. J. H., 1955. Ion-exchange procedures for the estimation of total ionic concentration, chlorides and sulphates in natural waters. Mitt. int. Ver. Limnol. 4: 1–17.

Melack, J. M., M. P. Kilham & T. R. Fisher, 1982. Responses of phytoplankton to experimental fertilization with ammonium and phosphate in an African soda lake. Oecologia 55: 1–6.

Murphy, J. & J. P. Riley, 1962. A modified single-solution method for the determination of phosphate in natural waters. Analyt. chim. Acta 27: 31–36.

Omer-Cooper, J., 1930. Dr. Hugh Scott's expedition to Abyssinia. A preliminary investigation of the freshwater fauna of Abyssinia. Proc. Zool. Soc. Lond. (1930): 195–207.

Schelske, C., 1988. Historic trends in Lake Michigan silica concentrations. Int. Revue ges. Hydrobiol. 73: 559–591.

Stoermer, E., J. Wolin, C. Schelske & D. Conley, 1985. An assessment of ecological changes during the recent history of Lake Ontario based on siliceous algal microfossils preserved in the sediments. J. Phycol. 21: 257–276.

Talling, J. F., 1986. The seasonality of phytoplankton in African lakes. Hydrobiologia 138: 139–160.

Talling, J. F. & D. Driver, 1963. Some problems in the estimation of chlorophyll *a* in phytoplankton. Proceedings of a conference on primary productivity measurements, marine and freshwater. U.S. Atomic Energy Comm. TID-7633: 142–146.

Talling, J. F. & I. Talling, 1965. The chemical composition of African lake waters. Int. Revue ges. Hydrobiol. 50: 421–463.

Tudorancea, C., R. M. Baxter & C. H. Fernando, 1989. A comparative limnological study of zoobenthic associations in lakes of the Ethiopian Rift Valley. Arch. Hydrobiol./Suppl. 83: 121–174.

Valderrama, J. C., 1981. The simultaneous analysis of total nitrogen and total phosphorus in natural waters. Mar. Chem. 10: 109–122.

Von Damm, K. L. & J. M. Edmond, 1984. Reverse weathering in the closed-basin lakes of the Ethiopian Rift. Amer. J. Sci. 284: 835–862.

Wetzel, R. G. & G. E. Likens, 1979. Limnological analyses. W. B. Saunders Co., Philadelphia, 357 pp.

Wood, R. B., M. V. Prosser & R. M. Baxter, 1978. Optical characteristics of the Rift Valley Lakes, Ethiopia. Sinet: Ethiop. J. Sci. 1: 73–85.

Wood, R. B. & J. F. Talling, 1988. Chemical and algal relationships in a salinity series of Ethiopian inland waters. Hydrobiologia 158: 29–67.

Wulff, F. & L. Rahm, 1988. Long-term, seasonal and spatial variations of nitrogen, phosphorus and silicate in the Baltic: an overview. Mar. Envir. Res. 26: 19–37.