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The Chemical Composition of African Lake Waters

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1. Introduction

The chemical composition of African lake waters is extremely varied, and includes features rarely found elsewhere. The published information is very scattered and of varying detail and reliability. Most comparative surveys (e. g., JENKIN 1932, 1936; BEADLE 1932; LOFFREDO and MALDURA 1941; DAMAS 1954) cover only limited areas, and though valuable the more extensive compilation by VAN MEEL (1954) is uncritical and contains some serious errors. The following account is based partly upon earlier data, but mainly upon original analyses of samples collected during 1960—1962. We have attempted to provide a reference-source for the composition of water from most major and many minor lakes; to outline the main trends and sources of variation, although without any detailed treatment of the geochemical processes involved; and to discuss correlations with some aspects of freshwater biology. Patterns of vertical stratification and their effects on dissolved gases will be described in more detail elsewhere. Although the stratification of some constituents is outlined here, the discussion is mainly concerned with the composition of surface waters.

Most of these lake waters show a marked predominance of bicarbonate and carbonate among the anions. This characteristic, together with a considerable development of saline lakes rich in sodium, massive local enrichments of other major cations, and an extremely wide range of lake depth and stratification, leads to an interesting field of comparative chemical limnology.

Much of this work was carried out during a visit in 1960–1961 to the Jinja laboratory of the East African Freshwater Fisheries Research Organisation. We are indebted to the director (the late Dr. V. D. VAN SOMEREN) and staff for their hospitality and much valuable assistance. Samples from many distant lakes were obtained through the kindness of the following individuals: Dr. V. D. VAN SOMEREN (Ethiopian lakes), Mr. H. Y. ELDER (Naivasha), Mr. D. J. GARROD (Mulehe, May 1961), Dr. D. A. LIVINGSTONE and Mr. J. L. RICHARDSON (Tanganyika), Mr. D. H. ECCLES (Nyasa), Mr. T. G. CAREY (Mweru), Mr. L. D. E. F. VESEY-FITZGERALD (Rukwa), Mr. E. HAMBLYN (Rudolf), Mr. M. M. HAMMOND (Kitangiri), Mr. ROBERTS (Baringo), Mr. D. HAMMERTON (White and Blue Niles), and students of Makerere College, Kampala (Manyara). We are also grateful to Dr. G. R. FISH, Mr. D. HARDING and Mr. J. HERON for permission to use unpublished data, and to Mr. F. J. H. MACKERETH for chemical advice. Dr. D. A. LIVINGSTONE, Dr. E. GORHAM, Dr. J. W. G. LUND, F. R. S., Mr. H. C. GILSON, Mr. R. S. A. BEAUCHAMP and Prof. L. C. BEADLE have given helpful comments on the manuscript. Some apparatus used was purchased by means of a grant from the Royal Society, and further financial assistance was received from the Department of Technical Co-operation, London.

2. The geographical groups and types of lakes

The lakes to be discussed in detail are chiefly in east and central Africa (Fig. 1).

Much general information on them can be found in the works of MURRAY (1910), CUNNINGTON (1920), GRAHAM (1929), WORTHINGTON (1932a, 1932b), WORTHINGTON and WORTHINGTON (1933), RICARDO (1939), COPLEY (1948), VAN MEEL (1954), BROOKS (1950), and VERBEKE (1957). Features of the less well known lakes in Ethiopia are described by OMER-COOPER (1930), NILSSON (1940), BINI (1940), BRUNELLI and CANNICCI (1940, 1941), LOFFREDO and MALDURA (1941), MORANDINI (1940, 1942), CANNICCI and ALMAGIÀ (1947), RIEDEL (1962), and by other authors in the reports of the two Italian expeditions to Lake Tana (1940) and the lakes of the Fossa Galla (1941).

As regards their mode of origin, the lakes fall in three main groups.

Graben lakes (Type 9 of HUTCHINSON 1957) are particularly numerous, distributed in the various sections of the Great Rift Valley between latitudes 8°N (Ethiopia) and 15°S (Northern Rhodesia). Most lakes in the East Rift, and one (Rukwa) in the West Rift, lie in basins of closed or internal drainage. Such lakes are usually of high salinity, especially when their depth is small, but a number of low salinity (e. g., lakes Zwi and Baringo) have outflows to adjacent areas. Most of the larger and deeper lakes which are wholly or partly in the Rift areas (e. g., Nyasa, Tanganyika, Edward, Albert) lie in open drainage basins; Lake Rudolf is an exception. Water from saline and often hot springs contributes to the inflows of many Rift lakes.

Volcanic lakes (Types 18 and 19 of HUTCHINSON 1957) are well represented in the region of the Virunga (in part the Mfumbiro) volcanoes, which cross the West Rift. The volcanoes themselves constitute the barrier to drainage by which the large Lake Kivu was formed. Many smaller lakes in the region result from the damming of valleys by lava flows; lakes Bunyoni, Mutanda, Ndalaga and Bulera are examples. The much larger Lake Tana in Ethiopia also belongs here. Small crater lakes, including explosion-craters, are numerous and widely distributed in East Africa. BEADLE (1932) describes characteristics of Naivasha crater lake, L. Kikorongo near L. George, and crater lakes of Central Island in L. Rudolf.

Shallow tectonic basins include the Types 3 and 4 of HUTCHINSON (1957), which are illustrated by lakes Kioga and Victoria respectively and originate by widespread upwarping and other crustal movements. Other lakes in this group are

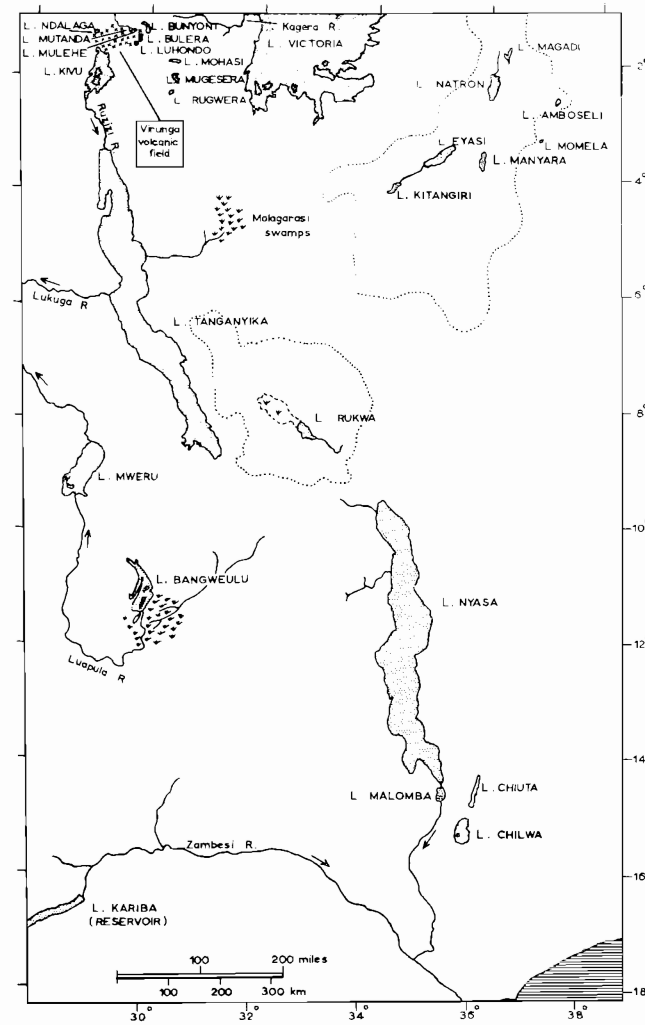
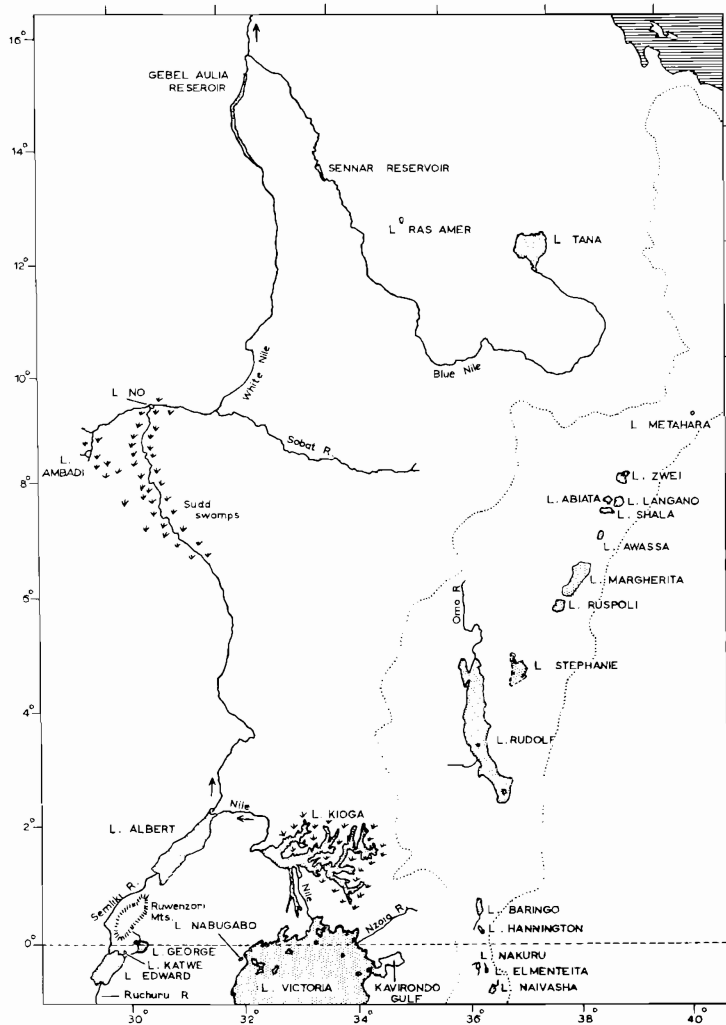


Fig. 1. The principal lakes and rivers of East and Central Africa. Dotted lines indicate the approximate extent of endorheic areas.

Chilwa and Bangweulu. They are characteristically large but relatively shallow: Victoria is much the deepest.

For completeness, four other groups of African lakes can be mentioned briefly. Shallow and often saline lakes, including "Shotts", are common in the north and north-west Sahara. BEADLE (1943) describes the chemistry of a number in Algeria, where the salinity is strongly influenced by sodium, chloride and sulphate ions. The numerous shallow basins or "pans" of South Africa are described by HUTCHINSON, PICKFORD and SCHURMAN (1932) and HUTCHINSON (1957). In these the bicarbonate ion generally forms less than half of the total anions, by equivalents, and chloride is often present in comparable amounts. Nevertheless they show an extensive range of alkalinity; effects on the composition of the plankton were examined by HUTCHINSON *et al.* (1932). A little known class of small lakes is represented at high altitudes on such mountains as Ruwenzori and Mount Kenya. Only recently has their chemistry been investigated in any detail (LÖFFLER 1964), and in some examples shows unusual features such as a marked deficiency of magnesium. Lastly, there is a very heterogeneous but numerous group of "river-lakes", formed by local obstructions in the rivers which naturally determine the major features of their chemistry. This group includes the large reservoirs at Aswan (Egypt), Gebel Aulia (Sudan), Mwadingusha and N'zilo (Katanga), and Kariba (N. Rhodesia); the many smaller "dams" in East, Central and South Africa; and such small, natural river-lakes as lakes No and Ambadi on the White Nile system, Stanley Pool with lakes Upemba and Tumba on the Congo system, and Lake Malomba on the outflow from Lake Nyasa.

3. Methods

Water samples were collected in polyethylene bottles, using a RUTNER or VAN DORN sampler for sampling at depths. The analytical methods listed by TALLING (1963) were generally used. Electrical conductivity was measured in Africa by a hand-operated ("Dionic") meter, and later in England by a mains instrument. pH was determined colorimetrically immediately after collection, or by glass electrode on some stored samples (Fig. 3); sodium and potassium by flame photometer; calcium and magnesium by versenate titration (HERON and MACKERETH 1955); alkalinity due to bicarbonate and carbonate (contributions from hydroxide, phosphate and silicate can be neglected) by titration with HCl to pH 4.5; chloride by titration with silver nitrate using chromate indicator; inorganic phosphate, total phosphorus, silica and nitrate by spectrophotometric estimation according to the methods compiled by MACKERETH (1963). Interference by chloride in the nitrate estimations was avoided. Sulphate was first estimated by precipitation of the barium salt and spectrophotometric estimation of turbidity, but later redetermined on samples stored for 1–2 years by the ion-exchange method of MACKERETH (1955). Concentrations of chloride were also determined by this method, with good general agreement with values obtained by titration. Total iron was determined using α,α -dipyridyl (BARNES 1959), and later, on samples stored for $1\frac{1}{2}$ –2½ years, by the method of MACKERETH (1963) which involves conversion to ferric chloride. Total manganese was determined on fresh samples after conversion to permanganate (MACKERETH 1963); for both metals the colour developed was measured spectrophotometrically. Many samples from distant lakes could not be analysed within 1–3 days after collection, and then measurements of pH and the more labile ions nitrate and phosphate were omitted. The values then obtained for total phosphorus are minimal, and those for silica also possibly modified by storage. To reduce these limitations, phosphate and silica were occasionally determined in the field using a colorimeter and the methods listed by TALLING (1957a).

The methods used by the other authors quoted are varied. These are not always cited in their publications, particularly in many instances where the analyses were made by another worker or are given with little or no discussion in official reports. The latter include a particularly valuable series of analyses in the Annual Reports for 1951 to 1953 of the East African Fisheries Research Organization (E.A.F.R.O.). Most of these were made by Dr. G. R. FISH, and those cited here were generally obtained by methods similar to our own, although visual rather than spectrophotometric estimation was used. Dissolved silica was measured by DENIGÈS' modification of DIÉNERT and WANDENBULCKE's method, and sulphate by precipitation of the barium salt.

A number of published analyses are omitted from this account, or are put in parentheses in Table I, when some analytical error is suspected. The grounds for suspicion include: (i) considerable fluctuation with depth of the concentration of major ions in an apparently mixed water column; (ii) a markedly irregular ratio between the total concentration in meq./L of major ions and electrical conductivity; and (iii) a pronounced divergence between the total concentrations (in meq./L) of the principal cations and anions. Many published measurements of phosphate and nitrate are omitted, as they may have been altered by prolonged storage of samples. Such storage may have also influenced a number of silica determinations. Values for pH are only given here when they were measured shortly after the collection of samples. The published estimations of sulphate are generally based upon precipitation of the barium salt, and may often be underestimates, particularly when the concentration of sulphate is low (p. 440). Conductivity has been variously given for temperatures of 18°, 20°, and 25 °C, but is here recalculated at 20 °C assuming a mean temperature coefficient of 2.3% per °C. This coefficient was obtained by direct measurements on representative samples of African lake waters, and is in reasonable agreement with other recorded values (e. g., MARLIER 1951, SMITH 1962).

4. Tabulated analyses

Table I summarizes the available analyses of African lake waters. So far as possible, these are arranged in a series of increasing salinity and conductivity. A few deep samples are noted, but otherwise surface samples are involved. Dates of collection are given as precisely as possible. Results recorded as absent or in "trace" or "indetectable" amounts are indicated by crosses (x). Some doubtful values (cf. above) are enclosed in brackets. Conductivity values marked by (a) cannot be assigned to a definite temperature. Values for sulphate are listed in two columns, (a) obtained by precipitation of the barium salt or by unstated means, (b) obtained using ion-exchange resins. Where available, the latter are used in calculating the sum of anion concentrations.

5. Total ionic concentration

The lake waters can conveniently be arranged in a series with increasing concentration of total ions. This concentration may be approximated by summing the concentrations expressed in meq./L of either the principal cations ($\text{Na} + \text{K} + \text{Ca} + \text{Mg}$) or the principal anions (HCO_3 and CO_3 "alkalinity" + $\text{Cl} + \text{SO}_4$). These two sums generally agree fairly closely, though less so in waters of high salinity and alkalinity, where values obtained for alkalinity may perhaps be unduly affected by associated carbon dioxide. Electrical conductivity (k_{20}) is, as expected, closely correlated with these estimates of total ionic concentration. The average relation (equivalent conductivity) is $85 \mu\text{mho}$ per meq./L, close to that expected for the principal ions sodium with bicarbonate, and to that found in other lake waters (e. g., HUTCHINSON 1957, Table 69; MORTIMER and MACKERETH 1958, MACKERETH 1963) if the variation of conductivity with temperature is taken into

Table 1. Chemical constitution of African lake waters

Lake	sampling date		reference	k_{20} (μ mho)	total solids (mg./l.)	sum of cations (meq./l.)	sum of anions (meq./l.)	pH
Lungwe	dry season 53		DUBOIS 1955	15.7 _a	—	—	—	6.7
	wet season 53		DUBOIS 1955	17.1 _a	—	—	—	6.5
Nyamagasani (Ruwenzori)	4. July	51	FISH 1952	20	—	—	—	—
Tumba		55-6	DUBOIS 1955, 1959	24-32 _a	72-90	—	—	4.5-4.9
Nabugabo	Sep.	31	WORTHINGTON 1932	—	—	—	—	8.2
Bangweulu	Dec.	36	RICARDO 1939	—	—	0.34	—	7.0
	6. Jan.	56	THOMASSON 1957	35	—	—	—	8.3
		60	HARDING & HERON, unpubl.	—	—	0.285	0.293	—
Mweru		12	STAPPERS 1914	—	76	—	—	—
		58-9	DE KIMPE 1960	70-125 _a	—	—	—	6.6-9.3
	July	61	original	76	—	1.03	1.05	—
Nkugute crater Lake	27. Dec.	60	original	86	—	1.01	1.01	—
Victoria (60 m)	3. Sep.	52	FISH 1953	98	—	—	—	—
	23-25. Ap.	23	TOTTENHAM 1926	—	118	—	—	—
		23	DUKE 1924	—	76	—	—	—
	19. Nov.	27	GRAHAM 1929, WORTHINGTON 1930	—	—	—	1.16	8.5
		51	ANON 1952	—	—	1.21	—	—
		? 51	FISH 1952	91-93	—	—	—	—
	2. Mar.	61	original	97	—	1.04	1.08	8.0
	4. May	61	original	96	—	1.02	1.05	7.1
	19. Nov.	27	GRAHAM 1929, WOR- THINGTON 1930	—	—	—	1.77	9.0
	Dec.	52	FISH, unpubl.	130	—	—	—	8.8
Kariba	5. Dec.	60	original	143	—	—	—	8.2
	17. May	61	original	145	—	—	—	8.75
	Oct.	58	HARDING 1961	121	103	—	1.32	—
	Oct.	59	HARDING 1961	100	74	—	1.19	—
	11. Ap.	60	HARDING & HERON, unpubl.	—	—	1.07	1.01	—
	Oct.	60	HARDING 1961	93	69	—	—	—
	5. Dec.	60	HARDING 1962	98	—	1.02	1.05	—
	11. Oct.	61	HARDING 1964	84	64	—	—	—
Bulera	2. June	52	DAMAS 1954	114	—	—	—	7.9
Rugwero	4. July	52	DAMAS 1954	135	130	—	—	7.9
Upemba		48-9	VAN MEEL 1953	145-255	—	—	—	6.4-8.0
Ndalaga	8. Aug.	35	DAMAS 1937	262	—	—	—	7.1
		? 53	VAN DER BEN 1959	154	—	—	—	7.6
		41-2	ABDIN 1948	—	—	—	—	—
Aswan Reservoir	27. Mar.	58	ELSTER & VOLLEN- WEIDER 1961	162	—	—	—	—
Luhondo	June	52	DAMAS 1954	212	—	—	—	9.1

No.	Na	K	Ca	Mg	HCO ₃ : CO ₃	Cl	SO ₄ (mg/L)		SiO ₂	NO ₃ · N	PO ₄ · P	total P
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(meq./L)	(mg/L)	(a)	(b)	(mg/L)	(μg/L)	(μg/L)	(μg/L)
1a	—	—	1.45	0.39	—	0.5	x	—	4.0	60	31	—
b	—	—	1.45	0.34	—	0.5	x	—	2.5	20	18	—
2	—	—	2	—	0.165	x	x	—	6	—	—	—
3	—	—	0.7	0.3	0	—	—	—	1—2	x	x	—
4	—	—	—	—	0.28	—	—	—	—	—	—	—
5a	5.1	2.2	1.1	0.1	0	0.8	2.3	—	16.9	—	—	—
b	—	—	3.1	1.65	0.472	—	—	—	—	50	—	—
c	2.6	1.3	1.5	0.8	0.260	0.3	—	1.0	—	—	—	—
6a	—	—	13.7	6.0	0.80	19.8	—	—	1.3	—	—	—
b	—	—	—	—	0.65—1.1	—	—	—	—	—	—	—
c	4.6	1.25	7.5	5.1	0.83	5.0	<5	3.7	10.5	—	—	—
7	3.3	2.9	7.8	4.8	0.92	1.5	<2	2.2	10	—	10	—
8	—	—	11.8	—	0.25	x	x	—	8	—	—	—
9a	—	—	—	—	0.735	6	—	—	—	—	—	—
b	—	—	15	8	0.97	5.0	<0.5	—	—	—	—	—
c	—	—	7.02	2.30	1.003	5.0	0.96	—	—	—	—	—
d	13.2	4.0	6.2	2.7	—	—	—	—	—	—	—	—
e	12.5-13.5	3.7-4.2	5-7	2.3-3.5	1.0-1.1	—	0.8	—	3-9	—	—	—
f	10.4	3.8	5.6	2.6	0.92	3.9	<2	2.3	4.2	11	13	47
g	10.0	3.7	5.6	2.6	0.90	3.9	<2	1.8	8.7	5.5	140	140
10a	—	—	9.25	1.59	1.53	7.0	1.84	—	—	—	—	—
b	—	—	8.6	—	1.44	6.8	—	—	20	—	—	—
c	—	—	8.85	3.06	1.39	—	—	—	4.3	15-28	3	—
d	—	—	—	—	1.38	—	—	—	5.9	29	—	67
11a	8	x	14	3.6	1.18	3	3	—	(10)	—	—	—
b	7	x	14	3.0	1.08	2	2.5	—	(8)	—	—	—
c	4.5	2.5	12.4	2.2	0.88	1.9	—	3.5	—	—	—	—
d	5	x	13	2.0	1.02	1	x	—	(11)	—	—	—
e	4.0	2.1	11	3	0.96	1	3	—	12	—	—	—
f	3	—	11	2.0	0.89	1	x	—	(10)	—	—	—
12	—	—	7.1	3.9	0.86	—	—	—	—	—	<5	—
13	—	—	11.5	9.5	1.47	—	—	—	—	—	—	—
14	—	—	20.6-42.3	2.9-17.3	1.80-3.36	—	—	—	68-144	—	31-65	—
15a	—	—	—	—	1.57	—	—	—	—	80	<3	—
b	—	—	—	—	1.46	—	16	—	17.3	43	—	—
16a	—	—	—	—	1.92	—	—	—	—	—	—	—
b	—	—	—	—	1.95	—	—	—	—	—	—	—
17	—	—	10	8.5	1.52	x	x	—	—	x	x	—

Table 1 cont.

Lake	sampling date		reference	k_{20} (μ mho)	total solids (mg/L)	sum of cations (meq./L)	sum of anions (meq./L)	pH
Tana	25. Feb.	21	GRABHAM & BLACK 1925	—	162	—	—	—
	20. May	21	GRABHAM & BLACK 1925	—	174	—	—	—
	18. Ap.	37	BINI 1940	—	151.5	—	1.93	—
		37	BINI 1940	—	—	—	—	7.5—8.0
Bilila	2. Ap.	52	DAMAS 1954	—	—	—	—	9.0
Mugesera	27. Mar.	52	DAMAS 1954	—	228	—	—	9.1
George	15. Mar.	24	HURST 1925	—	264	—	—	—
	22. July	31	BEADLE 1932	207	—	—	—	9.9
	26. June	51	FISH 1952	185	—	—	—	—
	18. June	52	FISH, unpubl.	170	—	—	1.92	9.4
	25. Nov.	52	FISH 1953	165	—	—	—	—
	24. Mar.	53	FISH 1954	175	—	—	2.38	—
	25. Dec.	60	original	200	—	2.15	2.43	—
	21. June	61	original	201	—	2.37	2.39	9.6
	Mar.-July	39	RICARDO et al. 1942	—	—	—	—	8.5—8.6
	24. Mar.	54	FISH, unpubl.	—	—	—	2.5	—
(300 m)	23. July	55	HARDING 1963	220	—	—	—	8.5
	23. July	55		230	—	—	—	7.7
	21. July	55		235	—	—	—	7.7
(600 m)	26. Sep.	61	original	210	—	2.45	2.59	—
Malombe	16. May	55	HARDING 1963	225	—	—	—	—
Sake	11-20. Mar.	52	DAMAS 1954	232	218	—	—	8.5
Mutanda	12. Oct.	52	FISH 1953	200	—	—	—	—
	28. Dec.	60	original	225	—	2.49	2.65	8.1
	27. June	61	original	230	—	—	2.56	7.8
(24 m)	27. June	61	original	235	—	2.58	2.59	7.2
Bunyoni	Aug.	31	WORTHINGTON & RICARDO 1936	—	—	—	—	7.9—8.1
	13. Oct.	52	FISH 1953	260	—	—	—	—
	26. Nov.	53	FISH 1954	99	—	—	1.4	—
	29. Dec.	60	original	233	—	2.52	2.63	9.3
	25. June	61	original	262	—	2.82	2.83	8.0
	(35 m) 25. June	61	original	286	—	3.01	3.21	7.0
	28. Dec.	60	original	252	—	—	3.00	7.4
	19. May	61	original	255	—	—	2.96	—
	27. June	61	original	260	—	2.94	3.09	8.0
Kioga complex: near Bugondo	Mar.	51	FISH, unpubl.	245	—	—	—	9.0
	26. June	53	FISH 1954	320	—	—	—	7.6
	Aug.	60	EVANS 1962	300	—	—	—	—
L. Salisbury	Mar.	51	FISH, unpubl.	365	—	—	—	7.4
Naivasha	13. June	29	JENKIN 1932	—	—	—	—	—
	23. Nov.	30	BEADLE 1932	—	—	—	—	9.0
	10. Dec.	30	BEADLE 1932	—	—	3.64	3.63	—
	12. Dec.	52	FISH, unpubl.	400	—	—	—	—
	8. Nov.	60	original	318	—	—	—	8.8
	10. Feb.	61	original	335	—	4.00	4.05	—
	5. June	61	original	330	—	3.92	3.97	—

No.	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	HCO ₃ + CO ₃ (meq./L)	Cl (mg/L)	SO ₄ (mg/L)		SiO ₂ (mg/L)	NO ₃ · N (μg/L)	PO ₄ · P (μg/L)	total P (μg/L)
							(a)	(b)				
18a	—	—	27.1	10.0	—	8	x	—	—	—	—	—
b	—	—	22.8	5.1	—	5.5	x	—	—	—	—	—
c	—	—	18.7	9.3	1.70	8	x	—	22	—	—	—
d	—	—	—	—	—	—	—	—	11-14	x	53-70	—
19	—	—	—	—	1.71	—	—	—	—	—	—	—
20	—	—	18.5	11.5	1.89	—	—	—	—	—	—	—
21a	—	—	—	—	—	14.5	—	—	—	—	—	—
b	—	—	—	—	2.1	—	—	—	18.3	—	65	—
c	—	—	24	—	2.09	—	—	—	24	—	—	—
d	—	—	15	—	1.66	9.1	—	—	—	—	—	—
e	—	—	20.8	5.47	1.76	6	—	—	20	—	—	—
f	—	—	17.8	2.5	2.28	3	x	—	32	—	—	—
g	12.9	4.2	20.0	5.8	1.85	8.2	<2	16.7	16	—	—	—
h	13.5	4.2	20.2	8.0	1.91	8.8	<2	11.1	18.2	—	<18	412
22a	—	—	—	—	2.5	—	—	—	—	—	<7-30	—
b	—	—	16.4	7.32	2.41	3.57	x	—	4	—	—	—
c	—	—	18.4	8.8	2.58	—	x	—	1.5	—	x	—
d	—	—	20.7	8.15	2.58	—	x	—	9	—	60	—
e	—	—	18.9	—	2.61	—	—	—	10	—	60	—
f	21.0	6.4	19.8	4.7	2.36	4.3	<5	5.5	1.1	—	—	—
23	—	—	18.4	8.35	2.53	—	—	—	2	—	x	—
24	—	—	18.5	11.7	2.44	x	x	—	—	x	<1	—
25a	—	—	25	—	1.00	2.06	—	—	16	—	—	—
b	15.5	15.3	10.6	10.9	2.01	14.0	6.0	12.2	11	(16.5)	25	—
c	—	—	10.9	11.5	2.03	11.5	10	—	8	27	18	65
d	15.5	15.9	11.2	11.5	2.07	13	10.5	7.4	11	16	93	110
26a	—	—	—	—	2.30	—	—	—	—	—	—	—
b	—	—	25	—	2.06	(150)	—	—	8	—	—	—
c	—	—	11.3	—	1.2	6	x	—	2	—	—	—
d	20.5	6.3	13.0	10.0	1.65	32	2	3.6	2.6	15	10	—
e	20.0	6.6	18.1	10.7	1.95	29	<2	2.8	2.7	17	<10	35
f	20.0	6.5	21.7	10.8	2.22	31	<2	5.8	6.7	(14)	93	—
27a	—	—	20.8	13.0	2.15	14.2	21	—	19.5	22	220	—
b	—	—	21.6	13.6	2.10	12.0	25	—	27	—	228	240
c	10.8	9.6	21.7	13.8	2.18	12.0	31	27	34	22	220	272
28a	—	—	—	—	1.42	—	—	—	24	—	—	—
b	—	—	20.8	1.95	3.21	1.5	x	—	6	—	—	—
c	—	—	—	—	—	—	10	—	25	8	330	—
29	—	—	—	—	2.35	—	—	—	48	—	—	—
30a	—	—	—	2.7	4.0	—	—	—	63	—	2	—
b	—	—	—	—	2.88	—	—	—	25	—	4	—
c	41.0	19.0	16.0	7.0	3.0	10.0	17	—	—	—	—	—
d	—	—	—	—	4.45	—	—	—	—	—	—	—
e	—	—	21.0	6.1	3.30	—	—	—	30	63	—	—
f	41	21.6	21.9	6.9	3.43	16	<2	8.4	31.5	32	—	58
g	45	22.6	15.2	7.7	3.31	14.4	<2	12.1	32.5	(55)	—	122

Table 1 cont.

Lake	sampling date		reference	K_{SO} (μ ml/h)	total solids (mg/L)	sum of cations (meq./L)	sum of anions (meq./L)	pH
Zwei	Apr.-May	38	LOFFREDO & MALDURA 1941	372-427	354.2	—	—	—
	24. May	61	original	370	—	4.46	4.82	—
Baringo	2. May	29	JENKIN 1932	—	—	—	—	9.0
	4. Dec.	30	BEADLE 1932	—	—	—	—	—
	7. Dec.	30	BEADLE 1932	—	—	7.13	7.44	—
	30-31. Jan.	31	BEADLE 1932	—	—	—	—	8.7-8.8
	10. May	62	original	416	—	5.30	5.55	—
Tanganyika		12	STAPPERS 1914	—	460	(5.71)	7.71	—
		? 37	RICARDO 1939,	620	—	7.45	7.25	—
(700 m)		? 37	BEAUCHAMP 1939	—	—	8.01	7.79	—
	8. Mar.	47	KUFFERATH 1952, VAN MEEL 1954	606	—	—	7.63	—
(1300 m)	8-10. Mar.	47	KUFFERATH 1952	—	—	—	7.81	—
	3. May	60	HARDING & HERON, unpubl.	—	—	7.30	7.43	—
	30. Jan.	61	original	610	—	7.46	7.61	—
Mohasi	12. May	52	DAMAS 1954	—	420	7.47	7.19	—
	1. Feb.	52	DAMAS 1954	640	436	—	—	8.35
Albert	7. Jan.	22	WAYLAND 1925	—	540	—	—	—
	27. Mar.	23	TOTTENHAM 1926	—	576	—	—	—
	14. May	28	WORTHINGTON 1929, 1930	—	—	—	—	9.5
	3-4. Aug.	51	FISH 1952	710	—	—	9.2	—
	23. July	53	FISH 1954	700	—	—	8.03	—
	13. Feb.	53	VAN DER BEN 1959	730	580	8.95	9.22	9.1
	27. May	54	TALLING 1957	675	—	—	—	9.0
	2. Feb.	61	original	735	—	8.74	9.02	—
	7-9. Aug.	61	TALLING 1963	730	—	—	—	8.9
Rukwa (south lake)	Oct.	36	RICARDO 1939	—	—	7.99	7.88	8.5
Kitangiri	July	61	original	785	—	8.60	9.15	—
Margherita	Dec. 37		LOFFREDO & MALDURA					
	— Feb.	38	1941	670-766	516.5	—	—	—
	23. May	61	original	900	—	10.5	10.6	—
Edward	23. Mar.	21	PHILLIPS 1930	—	483	—	—	—
	18. Mar.	24	HURST 1925	—	360	—	—	—
	9. July	31	BEADLE 1932	884	—	—	—	8.9
	15. May	35	DAMAS 1937	1130	—	—	—	9.3
	16. Sep.	51	FISH 1952	878	—	—	—	—
(outflow)		51	ANON 1952	—	—	9.2	—	—
	26. Nov.	52	FISH 1953	900	—	—	12.7	—
	27. Nov.	52	FISH 1953	900	—	—	—	—
	26. Mar.	53	FISH 1954	900	—	—	12.5	—
	17. Jan.	54	VERBEKE 1957, V. DER BEN 1959	925	720	11.0	11.6	8.89
	22. June	61	original	925	—	11.6	11.7	9.1

No.	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	HCO ₃ + CO ₃ (meq./L)	Cl (mg/L)	SO ₄ (mg/L)		SiO ₂ (mg/L)	NO ₃ · N (μg/L)	PO ₄ · P (μg/L)	total P (μg/L)
							(a)	(b)				
31a	—	—	—	—	—	—	—	—	—	—	—	—
b	64	14.0	10.2	9.8	3.92	18	<2	29	47	—	—	170
32a	—	—	—	—	10.5	—	—	—	—	—	—	—
b	—	—	—	—	5.5	—	—	—	18.2	—	600	—
c	126.0	15.0	22.0	2.0	5.60	36.0	40.0	—	—	—	—	—
d	—	—	—	—	5.7	—	—	—	15.8	—	545	—
e	95	13	11.6	3.15	4.44	25	19	19.7	23.5	—	—	(66)
33a	(26.6)	18.0	17.6	39.2	6.02	36.6	31.5	—	3.2	—	—	—
b	59.9	33.1	11.9	41.6	6.36	28.3	4.3	—	6.6	—	—	—
c	64.2	33.5	15.2	43.7	6.92	28.0	4.0	—	13.5	—	—	—
d	—	—	13.0	42.6	6.81	27.0	3	—	0.3	x	7	—
e	—	—	17.6	43.2	6.96	27.9	3	—	12	(60)	—	—
f	63.6	35.5	9.2	43.3	6.69	20.9	—	15.3	—	—	—	—
g	57	35	9.8	43.3	6.71	26.5	5	7.2	0.38	—	—	(21)
34a	87.2	9.2	27.8	25	3.104	144	1.07	—	8.8	—	—	—
b	—	—	31.5	29.1	3.07	—	—	—	—	—	—	—
35a	—	—	—	—	7.75	38	—	—	—	—	—	—
b	—	—	—	—	7.9	31	—	—	—	—	—	—
c	—	—	—	—	9.1	—	—	—	—	—	—	—
d	—	—	16	—	8.45	25	<1	—	—	—	—	—
e	—	—	10	—	7.0	21	21.3	—	—	—	—	—
f	97	66	9.3	31.5	7.8	32	25	—	3.4	9	130	—
g	—	—	9.0	—	8.16	18	—	—	1.3	40	180	—
h	91	65	9.8	32.1	7.33	33	32	36.5	0.09–0.9	—	—	200
i	—	—	9.0	31.5	7.25	—	45	—	0.4–0.9	10–33	120–150	133–164
36	149.4	19.4	12.2	4.6	7.09	25.8	2.9	—	76.7	—	—	—
37	155	4.8	24.1	6.7	6.65	64	<5	34	34.5	—	—	1020
38a	(101.5)	14.1	15.9	6.3	—	52	24.6	—	35.5	—	—	—
b	206	16	12.1	5.7	8.50	53	28	28	45	—	—	290
39a	116	—	31	33.5	6.6	10.5	—	—	15	—	—	—
b	—	—	—	—	—	10.3	—	—	—	—	—	—
c	—	—	—	—	9.6	—	—	—	4.0	—	122	—
d	—	—	—	—	9.75	—	—	—	—	—	3	—
e	—	—	16	—	8.7	30	—	—	5	—	—	—
f	88	84	10.5	33	—	—	—	—	—	—	—	—
g	—	—	16.6	—	10.6	48	38	—	5	—	—	—
h	—	—	—	—	9.7	—	(150)	—	8	—	—	—
i	—	—	14	31.8	10.35	23.2	72	—	5	—	—	—
j	112	79	9.7	44.5	10.1	27	35	—	2.0	23	30	—
k	110	90	12.4	47.8	9.85	36	31	43	6.5	24	18	127

Table 1 cont.

Lake	sampling date		reference	k_{20} (μ mho)	total solids (mg/L)	sum of cations (meq./L)	sum of anions (meq./L)	pH
Awassa	Mar.-Apr.	38	LOFFREDO & MALDURA 1941	790-860	650.4	—	—	—
Ruspoli	21. May	61	original	1050	—	12.0	12.0	—
	10.-11. Mar.	38	LOFFREDO & MALDURA 1941	927	651.2	—	—	—
Shalafu	24. May	61	original	1170	—	12.7	14.0	—
Kivu (275 m)		07	HUNDESHAGEN 1909	—	1050	20.0	20.0	—
	17. Sep.	35	DAMAS 1937	1390	—	—	—	9.45
	17. Sep.	35	DAMAS 1937	4000	—	—	—	6.85
		? 22	DELIHAYE 1941	—	975	18.2	16.6	—
		52-4	VERBEKE 1957	—	1000	16.9	16.6	9.1-9.3
	1. Feb.	54	VAN DER BEN 1959	1240	1020	15.74	17.6	9.1
Kivu, Kabuno Bay		52-4	VAN DER BEN 1959	—	—	—	—	—
Harsodi	Nov.-Dec.	26	OMER-COOPER 1930	—	1940	—	—	—
	7. May	38	LOFFREDO & MALDURA 1941	2440	1538	11.5	—	—
Langano	23.-24. Apr.	38	LOFFREDO & MALDURA 1941	2220	1644	—	—	—
Rudolf	22. May	61	original	1900	—	22.7	22.5	—
	13. Jan.	31	BEADLE 1932	2860	—	34.3	35.0	—
	2. Apr.	31	BEADLE 1932	—	—	—	—	9.5
	17. Jan.	53	FISH 1954	—	—	—	31.8	9.7
	27. Aug.	54	FISH, unpubl.	2900	—	—	—	—
	17. Jan.	61	original	3300	—	36.2	39.3	—
Small Dariba Lake (Jebel Marra)	19. Dec.	57	ANON 1958	4000	4200	—	73	—
Rukwa N		61	original	5120	—	51.7	67.7	—
Ngorongoro Crater Lake		06-7	JAEGER 1911	—	—	114	—	—
Naivasha W. Crater Lake	16. June	29	JENKIN 1932	—	—	—	—	—
	1. Mar.	31	BEADLE 1932	—	—	—	—	10.3
Momela Lake (Mt. Meru)		32	STURDY <i>et al.</i> 1933	—	—	—	164	—
Large Dariba Lake (Jebel Marra)	20. Dec.	57	ANON 1958	8000	13920	—	242	—
Shala	9.-12. Apr.	38	LOFFREDO & MALDURA 1941	20400	16771	268	—	—
Abiata	21. May	61	original	29500	—	278	306	—
	18. Nov.	26	OMER-COOPER 1930	—	8130	—	—	—
		? 39	DE FILIPPIS 1940	—	8288	151	(122)	—
	20.-21. Apr.	38	LOFFREDO & MALDURA 1941	10700	8358	133	—	—
	22. May	61	original	30000	—	285	316	—

No.	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	HCO ₃ : CO ₃ (meq./L)	Cl (mg/L)	SO ₄ (mg/L)		SiO ₂ (mg/L)	NO ₃ : N (μg/L)	PO ₄ : P (μg/L)	total P (μg/L)
							(a)	(b)				
40a	—	—	—	—	—	—	—	—	—	—	—	—
b	235	45	4.4	4.7	10.5	34	<2	27	72	—	—	98
41	—	—	—	—	—	—	—	—	—	—	—	—
42	270	21	3.6	2.6	10.1	56	68	111	—	—	—	100
43a	202.8	30.7	8.1	122.0	18.17	42.4	32.4	—	—	—	—	—
b	—	—	—	—	16.19	—	—	—	—	10	<1	—
c	—	—	—	—	55.91	—	—	—	—	<2	(3500)	—
d	210	18	37	82	15.5	35	6	—	71	—	—	—
e	130	100	5-15	100	15	35	30	—	2-13	—	—	—
f	129	85	21.2	84	16.4	31	15	—	9.0	41	39	—
44	—	—	599.4	262.5	—	—	—	—	—	—	—	—
45a	370	—	22	180	21.5	220	—	—	—	—	—	—
b	216	26	16	7.7	—	178	—	—	—	—	—	—
46a	—	—	—	—	—	—	—	—	—	—	—	—
b	500	27.5	2.5	2.7	15.0	216	28	68	54	—	—	165
47a	770	23.0	5.0	4.0	21.7	429.0	56	—	4.2	—	—	—
b	—	—	—	—	19.4	—	—	—	5.0	—	715	—
c	—	—	5.8	x	21.6	320	57.6	—	24	—	—	—
d	—	—	—	—	23.0	—	—	—	—	—	—	—
e	810	21	5.7	3.0	24.5	475	64	67	18	—	—	2600
48	—	—	9	10	50.6	780	15	—	100	—	—	—
49	1140	85	<1	<1	53.5	383	130	165	115	—	—	4500
50	2340	420	x	0.6	—	958	380	—	—	—	—	—
51a	—	—	—	—	117	355	—	—	1.2	—	—	—
b	—	—	—	—	84	—	—	—	—	—	353	—
52	—	—	—	—	135.1	369	890	—	—	—	—	—
53	—	—	12	6	169	2580	10	—	100	—	—	—
54a	5894	440	10	8.8	—	3136	128.7	—	(150.5)	—	—	—
b	6250	252	<3	<7.5	200	3300	275	650	130	—	—	900
55a	2870	—	10	10	80	1500	—	—	—	—	—	—
b	3220	402	3.5	0.8	81.5	1415	x	—	55.65	—	—	—
c	3000	75.3	8.5	6.0	—	1500	67.4	—	(130)	—	—	—
d	6375	331	<3	<7.5	210	3240	210	720	—	—	—	890

Table 1 cont.

Lake	sampling date		reference	k_{20} (μ mho)	total solids (mg/L)	sum of cations (meq./L)	sum of anions (meq./L)	pH
Elmenteita	23. May	29	JENKIN 1936	—	—	—	—	10.9
	Dec.	52	FISH, unpubl.	22500	—	—	261.1	—
	24. Feb.	61	original	43750	—	420	481	—
Kikorongo	24. Apr.	30	GROVES 1931	—	—	—	682	—
	28. July	31	BEADLE 1932	34600	—	—	—	—
Hannington	4. Feb.	31	BEADLE 1932	35700	—	634	689	—
Meseche	18. July	31	BEADLE 1932	45100	—	—	—	>10.5
Matahara	27. May	61	original	72500	—	784	831	—
Kasenyi	26. Apr.	30	GROVES 1931	—	59040	895	1033	—
Manyara	10. Mar.	92	LENK 1894	—	—	—	—	—
	26. June	61	original	94000	—	937	1097	—
Eyasi	24. Mar.	92	LENK 1894	—	—	—	—	—
		06-7	JAEGER 1911	—	—	197	—	—
Magadi	23. Feb.	61	original	160000	—	1664	1869	—
Nakuru	22.-27. Apr.	29	JENKIN 1936	—	—	—	—	11.0
	13. May	29	JENKIN 1936	—	—	—	—	—
	9. Dec.	30	BEADLE 1932	—	—	248	249	—
	24. Feb.	61	original	162500	—	1684	1895	—
Natron (average brine)		50	GUEST & STEVENS 1951	—	340000	—	4500	—
Katwe			PAPPE & RICHMOND 1890	—	385000	6300	6300	—
	20. Apr.	30	GROVES 1931	—	452370	8830	6732	—
		31	WAYLAND 1932	—	455500	7537	7447	—

account. Since electrical conductivity is readily and widely measured, this index of total ionic concentration has been used here (Table 1, Figures 2, 4—6) in arranging the lake waters in a series with increasing concentration. For most lake waters under discussion, there is a strong correlation between conductivity and alkalinity, with the former about 100 times the latter expressed in meq./L. Consequently other classifications based upon alkalinity (e. g., JENKIN 1932, 1936; BEADLE 1932) are closely relevant.

From this series three main classes of lakes can be conveniently, though arbitrarily, distinguished. Class I corresponds to waters of lower (and more usual) total ionic concentrations, with conductivity less than 600 μ mho. It includes many lakes supplied directly by surface run-off or rivers of low salt content. The largest are lakes Victoria, Nyasa, and Tana. Several examples lie in the closed drainage basins of the East Rift, but have outflows to neighbouring areas (e. g., ZWEI, OMER-COOPER 1930; Baringo, BEADLE 1932), although this is disputed for Lake Naivasha (cf. JENKIN 1932, BEADLE 1932, SIKES 1935, COLE 1954). Most of the small lakes of volcanic origin (e. g. Bunyoni, Mulehe, Mutanda, Ndalaga, Bulera, Luhondo, Sake) and the "river-lakes" (e. g., at Kariba, Gebel Aulia, Aswan, Mwadingusha) are in this class. Some of the lowest conductivities are found in lakes dependent upon inflow from swampy regions, such as Bangweulu, Nabugabo, Ambadi, and Mweru. Lake and river waters of very low conductivity are particularly widespread in the Congo basin; they often show a dark coloration, and a high content of organic solutes (VAN MEEL 1953, MARLIER et al. 1955, DUBOIS 1955,

No.	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	HCO ₃ +CO ₃ (meq./L)	Cl (mg/L)	SO ₄ (mg/L)		SiO ₂ (mg/L)	NO ₃ · N (μg/L)	PO ₄ · P (μg/L)	total P (μg/L)
							(a)	(b)				
56a	—	—	—	x	227	4370	—	—	0.9	—	—	—
b	—	—	1.1	1.4	146.5	4000	100	—	400	—	—	—
c	9450	381	<10	<30	289	5200	650	2200	295	—	—	2000
57a	11520	2280	—	—	498	5150	1860	—	—	—	—	—
b	—	—	—	—	408	—	—	—	—	—	—	—
58	14360	304.0	26	—	588	3450	204	—	—	—	755	—
59	—	—	—	—	710	—	—	—	—	—	—	—
60	17800	406	<3	<7.5	580	5480	4550	4680	—	—	—	11000
61	19300	2130	x	x	237	22000	8470	—	—	—	—	—
62a	—	137	—	—	—	2920	491	—	—	—	—	—
b	21500	94	<10	<30	806	8670	1056	2280	19	—	—	65000
63a	—	—	—	—	—	11400	1210	—	—	—	—	—
b	4480	55	x	4	—	4366	340	—	—	—	—	—
64	38000	537	<10	<30	1180	22600	900	2400	250	—	—	11000
65a	—	—	—	—	296	—	—	—	21.5	—	40	—
b	—	—	—	—	265	1950	—	—	—	—	—	—
c	5550.0	256.0	10.0	0	205	1375	253	—	—	—	—	—
d	38000	1312	<10	<30	1440	13000	1800	4270	730	—	—	12200
66	—	3800	x	x	2600	65000	3100	—	850	—	290000	—
67a	129000	27000	x	x	1330	141000	47200	—	—	—	—	—
b	180500	38200	—	x	2123	147000	22500	—	—	—	—	—
c	156500	28750	x	x	1917	149000	63800	—	—	—	—	—

1959, CLERFAYT 1956, BERG 1959, 1961). The highest conductivity in this class is from L. Baringo, which has hot saline inflows.

Much of the special interest in African lake waters follows from the existence of a wide range of more saline lakes, caused by accumulation and evaporation in closed basins or by inflows rich in solutes and particularly sodium carbonate and bicarbonate. Drainage from areas of alkaline lavas is especially important. Class II includes lake waters of conductivity between 600 and 6000 μmho ; the corresponding limits of alkalinity are approximately 6 and 60 meq./L. Lake Rudolf is one of the most saline lakes of this group, and occupies a closed basin which formerly contained a larger lake with outflow to the Nile (BEADLE 1932, FUCHS 1939). Lake Rukwa similarly lies in a closed basin. More remarkable are the lower but still considerable salinities of the chain of large lakes (Tanganyika, Kivu, Edward, Albert) in open basins of the West Rift. These contribute considerable quantities of salts annually to the Nile and Congo rivers, which appear to be replaced largely from saline sources in the region of Lake Kivu and the Virunga volcanic field. From here salt-rich river water, often with a very distinctive composition (Table 2), flows south (R. Ruzizi) to Lake Tanganyika and northwards (? R. Ruchuru) to Lake Edward and thence (R. Semliki) to Lake Albert. Finally, this class includes many of the Ethiopian Rift lakes, such as lakes Margherita (Abaya), Awassa, Shalafu, and Langano.

Class III covers very saline lakes in which the accumulation of salts within closed basins has gone further, often forming solid deposits (especially trona,

$\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2 \text{H}_2\text{O}$) around the lakes. In the vast majority of the lakes, where bicarbonate and carbonate predominate among the anions, the conductivity ranges from about 6000 to 160000 μmho , corresponding to alkalinities between approximately 60 and 1500 meq./L. Here the upper limit of salinity is probably determined chiefly by the solubility of trona, but can be exceeded in a few waters rich in sodium chloride, as at L. Katwe (Table 1) and near L. Eyasi (ORR and GRANTHAM 1931). Most of the very saline lakes are found in the closed basins of the East Rift, with lakes Abiata, Shala and Metahara in Ethiopia, Hannington, Ol Bolassat, Elmenteita, Nakuru, and Magadi in Kenya, and Natron, Manyara, and Eyasi in Tanganyika. The majority are very shallow and now probably less than 2 m in maximum depth, though fluctuating from year to year; two adjacent deeper lakes in Ethiopia, Abiata and Shala, are exceptions. Hot springs are often present near the lakes and may contribute largely to the salt content. Lake Magadi, an example, is rising continually over its own salt deposits (cf. WHITE 1953, BAKER 1958, FLINT 1959a). Some volcanic craters elsewhere contain very saline lakes, as Lake Maseche in the West Rift and the crater lake west of L. Naivasha in the East Rift (BEADLE 1932). Other craters near Lake Edward in W. Uganda enclose small saline lakes, such as L. Katwe and L. Kasenyi, which contain much sodium chloride.

The present distribution of saline spring waters suggests that such sources may have influenced the development of saline lakes more than has the direct shrinkage of lakes within closed basins. Examples (particularly L. Magadi) are discussed by BAKER (1958), who believed that the springs may often be supplied from reservoirs of hot saline ground water, with salts previously accumulated in earlier lake deposits. Nevertheless, shrinkage has certainly occurred on a large scale, particularly in the East Rift, and has been discussed by JENKIN (1932) and BEADLE (1932) in relation to the chemistry of certain lakes there (Rudolf, Nakuru, Naivasha). Its influence on L. Rudolf is particularly likely, as strongly saline springs appear to be rare in this closed lake basin (BEADLE 1932, p. 186). Local saline sources may also increase the concentration of lake waters of much lower salinity, such as L. Baringo (BEADLE 1932) and L. Mohasi (DAMAS 1954); the latter contains unusual amounts of chloride, and strictly is probably not a 'bicarbonate water'.

Possibly the most remarkable effect of hot saline inflows is shown by L. Kivu, whose permanently stratified depths contain water both warmer and considerably more saline than the surface water (DAMAS 1937, 1938; see Table 1). A small increase in the salinity and conductivity of the lower layers occurs in some other strongly stratified lakes, including L. Tanganyika (BEAUCHAMP 1939, KUFFERATH 1952), L. Edward (BEADLE 1932; DAMAS 1937, 1938), L. Nyasa (HARDING 1963), and L. Bunyoni (present data). In the last-named lake the effect was chiefly due to an increase in calcium bicarbonate, possibly following precipitation of calcium carbonate from above. Increases of these two ions are also recorded from the meromictic lakes Tanganyika and Nyasa (Table 1). In other lakes (e. g. Victoria, Albert, Mutanda), with a weaker or less persistent stratification, we could not detect any significant difference in the major ionic composition of surface and bottom water.

Horizontal variation of the major ionic composition is probably slight in most lakes. Some semi-enclosed bays may retain a water mass considerably more saline than the main lake, as in the Kavirondo Gulf of L. Victoria and Kabuno Bay of

L. Kivu (Table 1). A recent lava field adjoins the latter, which is presumably fed by strongly saline inflows. In L. Kioga a large area influenced by the inflowing Victoria Nile is of low salinity and conductivity (TALLING 1957a), but merges into other regions of this complex lake which show much higher concentrations (FISH 1954, EVANS 1962: see Table 1).

6. Major anions

The predominance of carbonate and bicarbonate among the anions, characteristic of the lakes under discussion, accounts for the correlation between conductivity and alkalinity (Fig. 2). It also affects the changes of several other constituents with increasing salinity, and distinguishes the more saline lakes from saline waters in north and west Africa (e. g., "Shotts"; BEADLE 1943) and the majority elsewhere in the world. When expressed as milliequivalents the carbonate plus bicarbonate ions are a fairly constant fraction, usually 0.6 to 0.8, of the total ions: the fraction varies little with increasing salinity.

The pH generally rises with increasing carbonate plus bicarbonate alkalinity, though locally depressed by the accumulation of carbon dioxide (e. g., below the deep thermal discontinuity in Lake Victoria) and raised by its active removal in photosynthesis (e. g., in Lake George). In the latter instance strong diurnal changes are likely: examples are described by WORTHINGTON (1930) and TALLING (1957b). In surface waters more closely equilibrated with the atmosphere, the pH is usually between 7.0 and 8.7 in lakes of Class I, 8.8 and 9.5 in those of Class II, and exceeds 9.5 in those of Class III. Values between 4 and 7 are not uncommon in the weakly buffered lake and river waters of conductivity (k_{20}) less than $50 \mu\text{mho/cm}$, where BERG (1961) believed that acidic organic solutes may influence the pH considerably. In such waters (well represented in the Congo Basin) the bicarbonate alkalinity may fall to zero, and hydrogen ions contribute significantly to the total ionic concentration (BERG 1961, 1962).

The trend of rising pH with alkalinity is shown in Fig. 3, based chiefly on measurements with aerated samples. The procedure used may not achieve equilibrium with atmospheric carbon dioxide for the waters of high alkalinity ($>100 \text{ meq./L}$): here some scatter appears in the pH/alkalinity relationship. The figure also illustrates some large deviations in fresh samples of waters of relatively low alkalinity, due to the accumulation or photosynthetic removal of dissolved carbon dioxide. pH values approaching 10 are recorded from L. George in 1930 (BEADLE 1932) and 1961: they are similar to values measured on aerated stored samples from very saline lakes, the alkalinity of which is almost a thousand times higher. During 1929 JENKIN (1936) measured colorimetrically even higher values, between 10.1 and 11.3, on fresh samples from two of these lakes (Elmenteita and Nakuru). The diurnal variation of pH which she described is unexpected in waters so highly buffered. Still more remarkable is the diurnal variation of pH (e. g., 9.3 to 12.5) reported from a small alkaline lake (Zeekoe Vlei) in South Africa (SCHÜTTE and ELSWORTH 1954, HARRISON 1962), with an alkalinity probably less than 6 meq./L .

Of the two other major anions, chloride is generally present in the higher concentration (by equivalents). Its concentration usually increases in a manner parallel with the increase in conductivity and total ions, but shows an even steeper rise in passing between lake classes II to III. Among local variations may be mentioned the unusually low proportion of chloride in Lake Nyasa, and the higher proportion

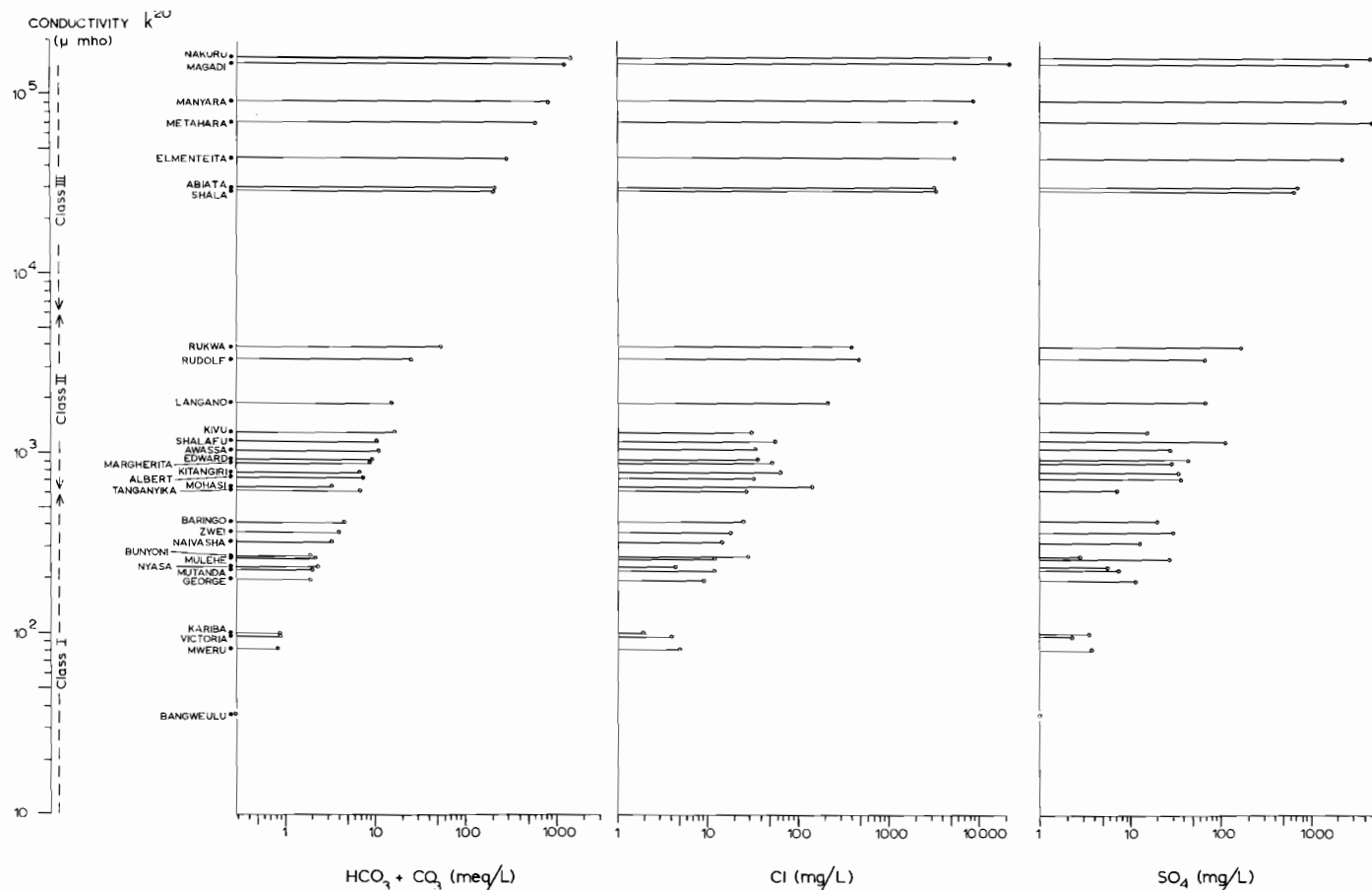


Fig. 2. Variation in concentrations of the major anions (horizontal lines) in surface waters of a series of African lakes arranged in order of increasing electrical conductivity. Both horizontal and vertical scales are logarithmic.

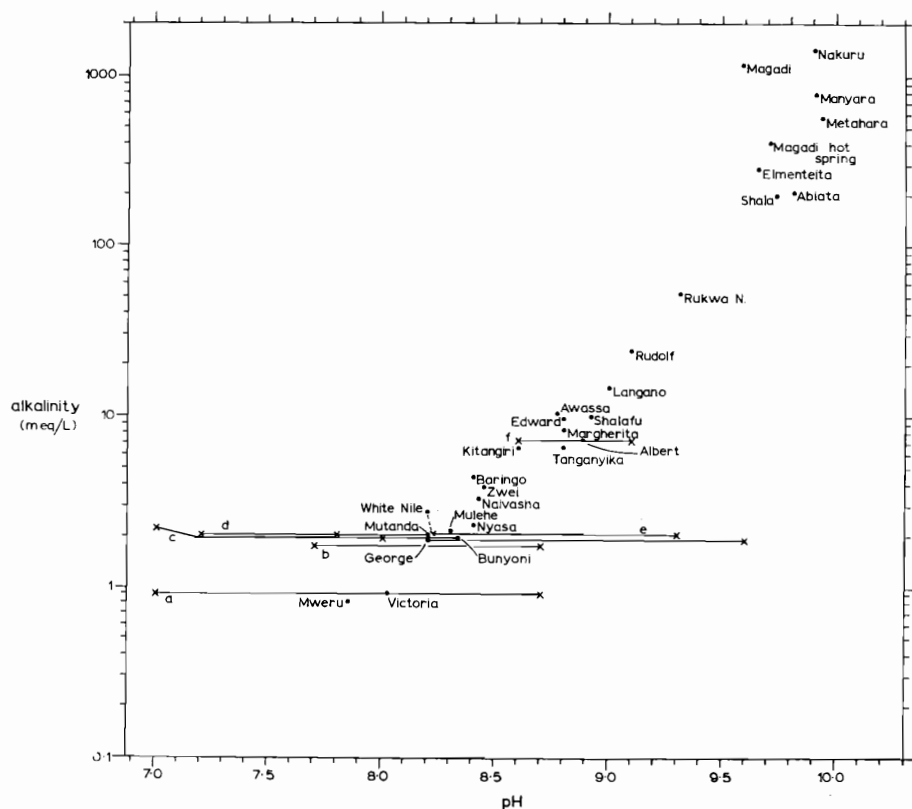


Fig. 3. The variation of pH in lake waters of increasing alkalinity. Most measurements (●) were made by glass electrode on stored samples, previously aerated for half an hour at $18^{\circ} (\pm 2^{\circ})\text{C}$. Crosses and horizontal lines show deviations of pH measured colorimetrically on fresh samples: *a* L. Victoria, all depths at offshore stations during 1960–1 (TALLING, in press); *b* Kavirondo Gulf of L. Victoria, diurnal changes in November 1927 (WORTHINGTON 1930); *c* L. Bunyoni, variation with depth on 25 June 1961; *d* L. Mutanda, variation with depth on 27 June 1961; *e* White Nile below Gebel Aulia reservoir, changes in surface water during phytoplankton growth in 1954–5 (PROUSE and TALLING 1958); *f* L. Albert, all depths during 1960–1 (TALLING 1963).

in lakes Rudolf, Mohasi, and Eyasi; in the last two lakes it may exceed the other anions. Local sources of sodium chloride are well known in the West Rift, including crater lakes near Katwe (GROVES 1931, WAYLAND 1932) and small springs near Lake Albert (cf. WORTHINGTON 1930). Hot spring water in the East Rift, as at Lake Manyara (LENK 1894), Lake Natron (GUEST and STEVENS 1951) and Lake Magadi (Table 2), can include a considerable proportion, similar to that in the very saline lakes of this region. Here probable factors are the high solubility of sodium chloride and the accumulation of leached salts in a low lying sector of an area with closed drainage. Some analyses of saline East Rift lakes listed by BAKER (1958) show remarkably high concentrations of fluoride, with an F/Cl ratio of about 0.2 (by weight) and fluorine concentrations greater than 1 g/L in lakes Nakuru,

Elmenteita and Hannington. Confirmation is required of such high values, which may include interference by phosphate (GUEST and STEVENS 1951). This effect was eliminated in analyses by GUEST and STEVENS (1951) of L. Natron brine, where the concentration of fluorine was approximately 1 g/L and the F/Cl ratio about 0.015.

The small proportion of sulphate is another distinctive feature. The fractional value of the total ionic concentration (by equivalents) varies irregularly without any clear relation to total concentration, and usually lies between 0.04 and 0.12 in all three classes of lakes. A few higher values are found, as in Lake Mulehe. There may be a significant tendency for lower values (<0.04) to exist in the surface waters of lakes with large hypolimnia, which are stratified over long periods, such as Kivu, Tanganyika, and Bunyoni. Here deoxygenation in the hypolimnia is associated with the reduction of sulphate to hydrogen sulphide. Uptake of sulphate by phytoplankton and subsequent sedimentation into the hypolimnion is possibly also of quantitative importance, as BEAUCHAMP (1953) has supposed. Nevertheless, the paucity of sulphate in the primary water supply is of more general significance, and corresponds with the small amounts commonly present in the soils and non-sedimentary rocks of Africa (BEAUCHAMP 1953).

The absolute concentration of sulphate in the lake waters is naturally much more variable than its relative proportion, and exceeds 4 meq./L or approx. 200 mg/L in the saline lakes of Class III. Most lakes of Class II have concentrations far exceeding 0.1 meq./L or approx. 5 mg/L, but in Class I lower values are generally recorded in the literature. However, these records are usually based upon an analytical procedure involving precipitation of the barium salt, which is unreliable for such small concentrations, and can be suspected to underestimate sulphate concentrations for waters rich in organic matter (cf. BERG 1962). Measurements derived from a more reliable method, using ion-exchange columns (MACKE-RETH 1955, 1963), often indicate considerably higher concentrations of sulphate than were found in the same lakes — and often in the same samples — by the older method (Table 1). The difference is particularly large in lakes Zwi and George, which are shallow, very productive, and probably rich in dissolved organic material. The smallest concentration of sulphate obtained by the ion-exchange procedure is 1.0 mg/L from L. Bangweulu. The next lowest concentration (2.3 mg/L) found in surface water by this method, from offshore Lake Victoria, is between two and three times higher than the earlier values of FISH (1952) and HESSE (1957). Other analytical errors may have affected the low estimate of sulphate concentration in Lake Albert which is cited by BEAUCHAMP (1953); later analyses of water from this lake by both types of method have given much higher values. For these analytical reasons, it seems likely (see also LIVINGSTONE 1963) that the survey by BEAUCHAMP (1953) has underestimated the concentration of sulphate in the African lakes. In addition, the accounts of a reduction of sulphate in river water passing through swamps (BEAM 1906, 1908, TALLING 1957a, BISHAI 1962) require confirmation.

7. Major cations

Unlike the major anions, the four major cations (Fig. 4) vary more considerably and consistently in their relative proportions throughout the series of lakes. Sodium is generally predominant, and its concentration increases fairly regularly

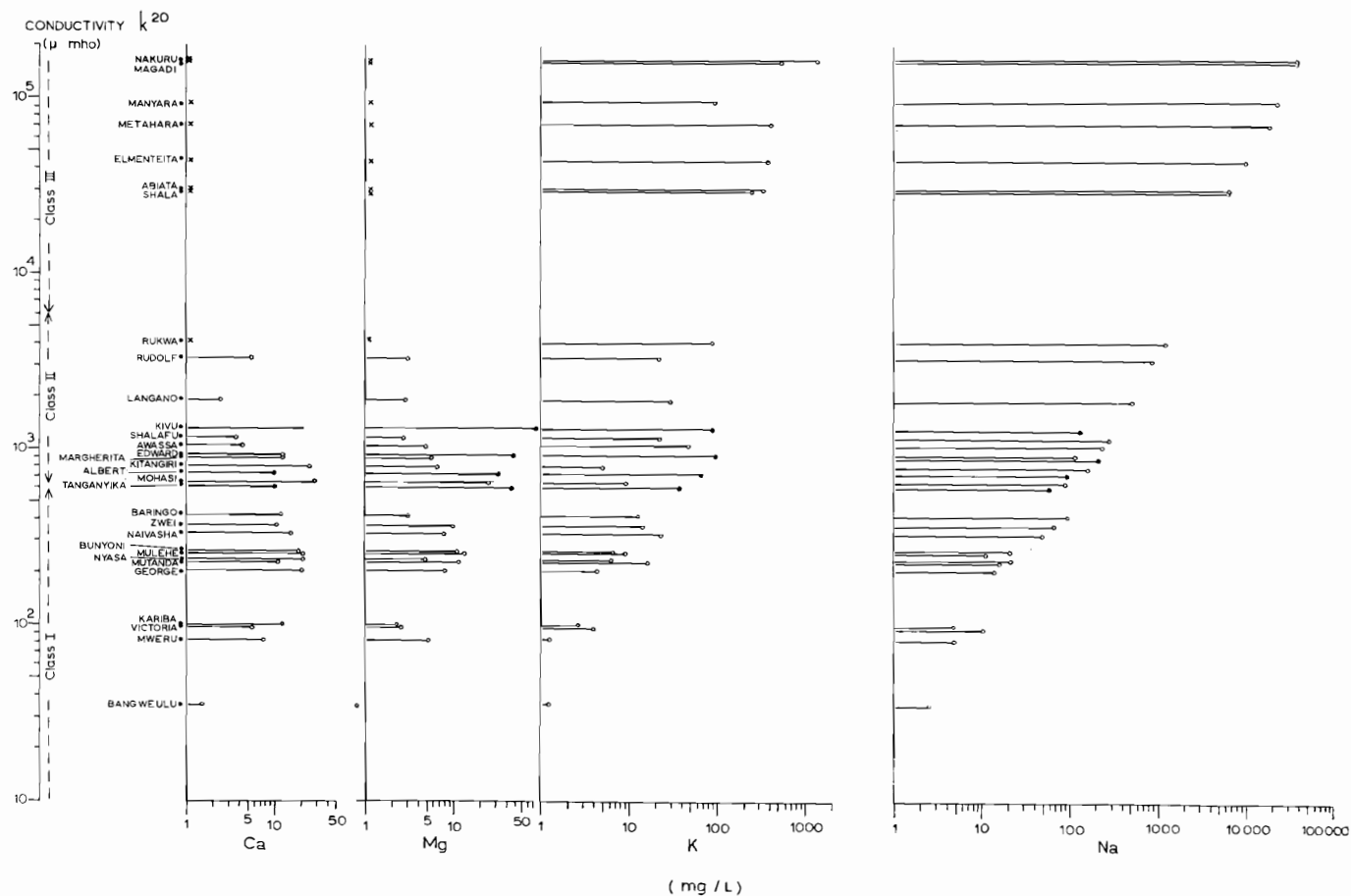


Fig. 4. Variation in concentrations of major cations, arranged as in Fig. 2. Crosses indicate undeterminable, probably very low, concentrations.

with conductivity and total ionic concentration. Its proportion is particularly high, exceeding 0.95 of the total cations (by equivalents), in the very saline lakes of Class III. In at least one such lake, L. Magadi, the high proportion is also found in the main hot spring inflow (Table 2), so that secondary changes within the lake basin (e. g., the loss by selective precipitation of other cations) are probably not influential.

Where saline inflows are of little importance, or where they show an exceptional composition, the dominance by sodium may be lost. This occurs in many of the more dilute lake waters of Class I, where calcium or — less frequently — magnesium is present in a higher proportion by equivalents; L. Victoria is a notable exception. Another example is provided by some lakes of Class II, which are affected by the saline sources in the region of the Virunga volcanic field. Here there are alkaline volcanic rocks of unusual chemical composition, with much magnesium and potassium (COMBE and SIMMONS 1933, HOLMES and HARWOOD 1937, HIGAZY 1954, WATERS 1955). These sources can be particularly rich in magnesium, but may also supply considerable amounts of calcium and potassium, as was shown by the early analyses of HUNDESHAGEN (1909). Magnesium is the principal cation in the two large lakes to the south (Kivu and Tanganyika), and is almost equal to sodium in the two large lakes to the north (Edward and Albert). Extremely high concentrations of calcium and magnesium are recorded from the almost landlocked Kabuno Bay of L. Kivu (Table 1).

Potassium is apparently always present in smaller amounts than sodium, and the difference tends to increase as the salinity rises. The relative proportion of potassium to sodium (Fig. 4), and to total ions, is greatest in the large West Rift lakes affected by inflows from the Virunga volcanic region, as well as in some smaller lakes (Mutanda, Mulehe) in this region.

The variation of calcium and magnesium with total salinity follows a different pattern from any so far considered. The chief controlling process (see BEADLE 1932) is the precipitation of calcium and magnesium carbonates in the waters of higher salinity and alkalinity. The two ions show an initial rise in concentration with salinity within Class I, but decline again in lakes of Class II: we could not estimate either in lakes more saline than L. Rudolf. Even the higher concentrations of calcium, in the range 1.0 to 1.5 meq./L (20 to 30 mg/L) are inconsiderable and can be reached in some lakes of low salinity such as L. George. Magnesium increases to higher concentrations of 2.6 meq./L (L. Albert) to 6.9 meq./L (L. Kivu) in West Rift lakes affected by the saline sources already mentioned. Its carbonate can be expected to precipitate at higher alkalinities than that of calcium. The precipitation of both carbonates is strikingly illustrated around the shores of L. Kivu, where a white tufa composed of them is deposited (MOORE 1903, HUNDESHAGEN 1909, DELHAYE 1941, VERBEKE 1957, p. 72, VAN DER BEN 1959, p. 65). Less extensive deposits of calcium carbonate have formed in some other moderately alkaline lakes, including L. Tanganyika (DUBOIS 1957), L. Edward (FUCHS 1934), and L. Rudolf (BEADLE 1932). In L. Eyasi, and possibly other soda lakes, it occurs in combination with sodium carbonate as crystals of gaylussite (ORR and GRANTHAM 1931).

Some ionic ratios involving cations (Fig. 5) deserve mention, as they have been discussed in some other limnological comparisons (e. g., PEARSALL 1921, 1922) and physiological work on algae (VOLLENWEIDER 1950, PROVASOLI, McLAUGHLIN and PINTNER 1954, MILLER and FOGG 1957, DROOP 1958, FRANK 1962). The ratio of

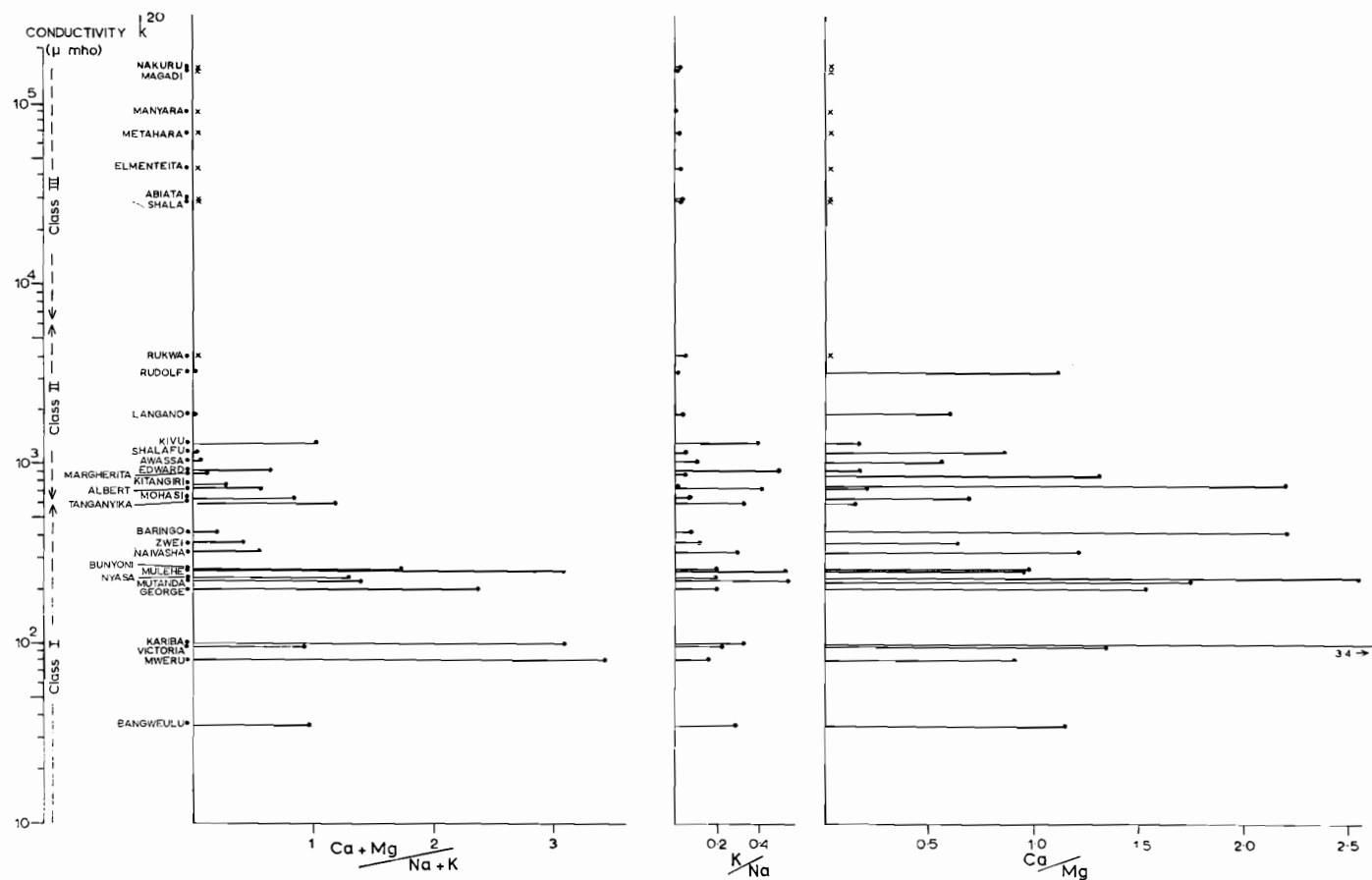


Fig. 5. Variations of three ratios of the concentrations of major cations, by equivalents, arranged as in Fig. 2 and 4.

divalent to monovalent cations, $\text{Ca} + \text{Mg}/\text{Na} + \text{K}$ (by equivalents) clearly declines to near zero in the more saline lakes, but varies rather irregularly in the less saline lakes. High values are most common in the West Rift lakes and the small volcanic lakes near the Virunga volcanos. The ratio of calcium to magnesium (Ca/Mg , also by equivalents) cannot be readily determined in the highly saline lakes, but otherwise is often not far from unity. A high preponderance of magnesium is characteristic of the four large lakes in the West Rift, though not of the small Virunga volcanic lakes. Finally, the ratio of potassium to sodium shows considerable variation (Fig. 5). It is high in lakes affected by drainage from the Virunga volcanic field, and low in the saline lakes of the East Rift.

8. Total and phosphate-phosphorus

The variation of the concentration of total phosphorus is less easily traced, as no earlier analyses appear to exist and some local and seasonal variation within lakes is likely. However two general trends seem to emerge (Fig. 6). High concentrations of $1000 \mu\text{g P/L}$ or more are found in the very saline lakes of Class III, and elsewhere only in two other moderately saline and productive lakes (Rudolf, Margherita). Among the less saline lakes of Classes I and II, the higher concentrations ($>150 \mu\text{g P/L}$) are recorded from the shallower — and often the more productive — lakes, such as George, Mulehe, Zwei, and Kitangiri. Here there is no marked correlation with the total ionic concentration or the conductivity.

Concentrations of inorganic phosphate-phosphorus are even more likely to vary locally and seasonally, but show interesting changes in relation to the total phosphorus. Changes of both with depth and season are best known from an offshore station in L. Victoria (TALLING, in press), where in surface water the phosphate-phosphorus is usually between about 0.2 to 0.6 of the total phosphorus. The proportion and absolute concentration tends to be higher in the deeper layers. Similar proportions and relations with depth were found in a single sampling of L. Mutanda; the depth variation of this proportion in most other deep and stratified lakes (e. g., Nyasa, Tanganyika, Edward) is not known. On present knowledge it is impossible to generalise about the proportions in surface waters of the lakes, but two extreme conditions deserve mention. In one the phosphate-phosphorus is extremely low, often undetectable, although the total phosphorus is high. This condition was found in Lake George, where there was an extremely dense population of the blue-green alga *Microcystis aeruginosa* (= *Diplocystis aeruginosa* (KUTZ.) TREVIS sensu KOMÁREK). In the other, the phosphate-phosphorus constitutes practically all the total phosphorus. This is shown by the many analyses from L. Albert (TALLING 1963) and by the two complete ones from L. Mulehe: both lakes contain large concentrations ($>150 \mu\text{g/L}$) of phosphorus. This unusual situation is particularly interesting in L. Albert, as it differs from the condition shown by the recent analyses from L. Edward which supplies water to L. Albert and determines much of the chemistry of the latter (TALLING 1963). Considerable changes probably occur during the passage of river water between these lakes, possibly by the mineralisation of organic phosphorus compounds. Such interconversion may occur periodically in L. Edward itself, as the inorganic phosphate-phosphorus in its surface waters can apparently vary between $122 \mu\text{g/L}$ (BEADLE 1932) and $2 \mu\text{g/L}$ (DAMAS 1937).

When compared to the concentrations of phosphate and total phosphorus common in lake waters elsewhere (see HUTCHINSON 1957), the concentrations in the

African lake waters are generally high. However, large amounts of total phosphorus as found in the most saline African lakes (Class III) are known from saline lakes elsewhere (HUTCHINSON 1937).

9. Silica

The general variation of dissolved silica with salinity or conductivity is shown in Fig. 6. Considerable concentrations, over 10 mg/L, are common in all three classes of lakes, although there is a general upward trend of concentration with salinity. These features result partly from the usual abundance of dissolved silica in African stream and river drainage, which in turn depends upon its mobility in the surrounding soils. Examples are given in Table 2, and also in analyses of other river waters by FISH (1952, 1953), TALLING (1957a), DUBOIS (1958), BISHAI (1962), and HARDING (1963). Secondly, there is probably a more rapid rate of solution of silicon compounds in saline waters of high pH and alkalinity. The most striking results are seen with several of the more saline and alkaline lakes (Class III), in which measured concentrations of silica exceed 100 mg/L. These high values were not found in earlier analyses by JENKIN (1936) on some of these lakes, probably because of the limitation of the method used on strongly alkaline water. Such high

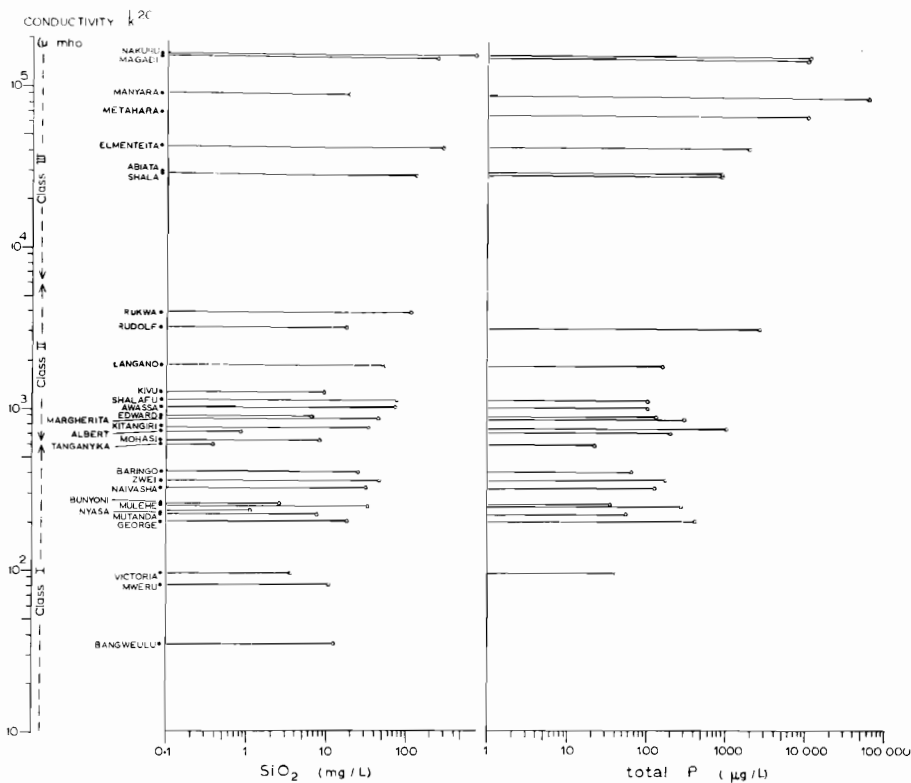


Fig. 6. Variation in the concentrations of dissolved silica and total phosphorus, represented as in Figs. 2 and 4.

values are also apparently not usual, or well known, from highly saline and alkaline lakes elsewhere (HUTCHINSON 1957); a possible example from India is given by CHRISTIE (1912).

A smaller number of lakes in Classes I and II (Nyasa, Tanganyika, Albert, Bunyoni, Mutanda) show comparatively low concentrations of silica, below 4 mg/L. In at least several examples some removal occurs within the lake itself, particularly by the formation and later sedimentation of diatom frustules. These processes could be followed as seasonal changes in L. Victoria (TALLING, in press). For this lake there is additional evidence from the existence of much higher concentrations in the inflows than in the lake water (Table 2), and of extensive diatomaceous deposits on the bed of the lake (cf. GRAHAM 1929, Fig. 20). Such removal is also likely to be of significance in the large, deep and strongly stratified lakes with diatom plankton, such as Nyasa (cf. HARDING 1963) and Tanganyika, as well as in smaller stratified lakes such as Bunyoni and Mutanda. There is strong evidence for a large loss of silica in the less stratified waters of L. Albert, where concentrations below 0.5 mg/L are frequent, but here the importance of uptake by diatoms is not clear. Some deposition of colloidal silica may occur from the waters of the most saline lakes, such as L. Magadi (WHITE 1953, BAKER 1958).

Much increased concentrations of silica are usually present in the deeper layers of lakes under stratification. Examples include lakes Tanganyika (BEAUCHAMP 1939, KUFFERATH 1953, VAN MEEL 1954), Nyasa (BEAUCHAMP 1945, 1953, ILES 1960, ECCLES 1962, HARDING 1963), Edward (BEADLE 1932, FISH 1954), Albert (TALLING 1963), Victoria (FISH 1957, NEWELL 1959, and TALLING, present data), Bunyoni and Mutanda (present data). In L. Victoria the lower layer has been supposed by NEWELL (1960) to originate by an accumulation of cooler inflow water rich in dissolved silica, but we believe that an intra-lacustrine origin is more probable (TALLING, in press).

10. Inorganic nitrogen

Of the three forms of nitrogen involved, nitrate, nitrite, and ammonia, only nitrate-nitrogen has been fairly widely determined in the surface waters of African lakes (Table 1). Seasonal changes are probably often important, but apparently have been followed only in Lake Victoria (TALLING in press) and in the two Nile reservoirs at Aswan (ABDIN 1948) and Gebel Aulia (PROWSE and TALLING 1958). Flood water from Ethiopia brings comparatively high concentrations to certain parts of the Nile (BEAM 1908, TALLING 1955; PROWSE and TALLING 1958; ELSTER and VOLLENWEIDER 1960). In African lakes concentrations are usually very low, below 30 $\mu\text{g NO}_3\text{-N/L}$, and often are not readily estimated. Most temperate lakes probably show larger concentrations, though low values are often associated with higher seasonal temperatures (cf. HUTCHINSON 1957). At present further generalisation on African lakes is dangerous, but it appears from a survey of water chemistry in large West Rift lakes, as yet published only in part (VERBEKE 1957, VAN DER BEN 1959), that concentrations of nitrate may increase along the lake series Albert-Kivu-Edward. Where thermal stratification is pronounced, higher concentrations of nitrate usually exist in deeper layers, provided that deoxygenation is not too extreme (e.g., L. Tanganyika, KUFFERATH 1952, VAN MEEL 1954; L. Albert, TALLING 1963; L. Victoria, FISH 1957, TALLING in press; L. Mutanda, present data). Two analyses of rain water at Jinja gave concentrations of 56 and 83 $\mu\text{g NO}_3\text{-N/L}$, comparable to those measured in the deeper layers of L. Victoria.

Nitrite-nitrogen has apparently not been found in measurable amounts in the lake surface waters. It is recorded from intermediate depths in lakes Edward (DAMAS 1937) and Tanganyika (BEAUCHAMP 1939, KUFFERATH 1952), in relation to the vertical gradient of dissolved oxygen in these strongly stratified lakes.

The distribution of ammonia-nitrogen in the lake surface waters is practically unknown, since analytical methods of sufficient sensitivity have rarely been applied. In general it is probably less than $40 \mu\text{g/L}$. Much larger amounts are usual in the deoxygenated lower layers of stratified lakes, and are readily detected by the insensitive but commonly used method of direct Nesslerisation. Examples include lakes Tanganyika (BEAUCHAMP 1939, KUFFERATH 1952), Kivu (DAMAS 1937, 1938), Edward (BEADLE 1932, DAMAS 1937), Nyasa (HARDING 1963), Luhondo (DAMAS 1954), Bunyoni (present data), Mutanda (present data), and for brief periods in L. Victoria (TALLING, in press).

The total combined nitrogen must be present in large amounts in many of the very saline lakes (Class III), since they bear dense populations of blue-green algae, and receive large quantities of flamingo excreta (cf. JENKIN 1936, p. 151). Unfortunately there appear to be no reliable estimations of the forms of inorganic nitrogen, due to problems of interference from other constituents.

11. Total iron and total manganese

These constituents of African lake waters have rarely been studied systematically, with reliable and stated methods. The following discussion is based almost entirely upon our original analyses, although many important lakes are not represented. Seasonal changes, which may be important, were followed only during part of 1961 in offshore water of L. Victoria; these will be described elsewhere (TALLING, in press).

Total iron was below the limits of detection, which were approximately $5-10 \mu\text{g/L}$, in numerous samples of surface offshore water from L. Victoria, and in a single sample from another large and relatively deep lake, L. Rudolf. It would be of great interest to know if such low concentrations are characteristic of other large and deep African lakes, such as Tanganyika and Nyasa. The highest concentrations, of $500 \mu\text{g/L}$ or more, were generally found in lakes where the mean depth was less than 10 m. Examples include the relatively low-salinity waters of Naivasha (500), Baringo (5330), Margherita or Abaya (13500), Zwei (5000), and the very saline waters of Elmenteita (725), Magadi (1490), Nakuru (2300), and Metahara (500). A sample from L. Shala, the only deep soda lake sampled, contained $13000 \mu\text{g/L}$, whereas one from the shallow neighbouring lake of Abiata showed only $440 \mu\text{g/L}$, although these two lakes were very similar in major ionic composition. High concentrations were also found in two Ethiopian lakes of lower salinity, Langano (9400) and Shalafu (690). Intermediate concentrations were estimated in samples from shallow and productive waters of L. George (250) and north-east L. Edward (232). Moderately low values — between 10 and $100 \mu\text{g/L}$ — were represented in lakes Albert (45–88), Awassa (100), Mutanda (57), Mulche (48), and Bunyoni (60).

Fewer analyses were made of total manganese, but its distribution partly resembles that of total iron. Concentrations in offshore surface water of L. Victoria were very low, at or below the limit of detection of approximately $10 \mu\text{g/L}$. Similarly low concentrations were found in samples from lakes Albert and Edward, although in these the quantities of total iron were more considerable. The highest concentra-

tions of manganese were encountered in the shallow lakes George (260), Naivasha (117), and Mulehe (121); in the first two of these lakes the iron content is also moderately high. The lower concentrations of manganese in the much deeper and stratified lakes Mutanda (21) and Bunyoni (67) are of the same magnitude as the corresponding concentrations of iron.

The tendency for shallower lakes to show higher surface concentrations of total iron and manganese is also known from other regions (GORHAM 1955). Possible explanations include the upward transport of particulate iron and manganese by turbulence; a similar transport after the liberation of ferrous and manganous ions under reducing conditions at the mud surface; and a stabilising influence of dissolved and particulate organic material, which is probably often abundant in the usually very productive shallow lakes. Thus lakes George, Baringo and Margherita often bear dense blooms of the blue-green alga *Microcystis aeruginosa*. In L. George a temporary, probably diurnal, stratification was observed to allow an oxygen depletion (49% of saturation) to develop at a depth of only 1.8 m, although the surface water was strongly supersaturated (216%).

In the African lakes, as elsewhere, relatively large concentrations of iron and manganese are found in the poorly oxygenated depths of the deeper lakes under stratification. Examples include lakes Victoria (TALLING, in press), Albert (TALLING 1963), Mutanda, and Bunyoni, although none showed concentrations greater than 1000 $\mu\text{g/L}$. Such high concentrations of iron may occur in surface waters of the White Nile under the influence of the extensive "Sudd" swamps (TALLING 1957a), and in some lake and river waters of very low conductivity and alkalinity where the iron is probably associated with organic "humic" material (DUBOIS 1959; BERG 1961, 1962).

12. Relation between the composition of lake and inflow waters

Some comparisons between the chemical constitution of lake waters and their inflows have been made in previous sections. One of the simplest — though exceptional — situations is probably found in L. Magadi, and is described in detail by BAKER (1958). Here the composition of the hot saline inflows (BAKER 1958, and Table 2) agrees with the proportions of major ions in the small areas of lake water, though concentrations have risen in the latter from evaporation in this climatically arid and closed lake basin. Deep salt deposits have also developed here, as in the nearby L. Natron (GUEST and STEVENS 1951). The salts are probably not of deep-seated and "juvenile" origin, but leached from a large volcanic area, repeatedly concentrated by evaporation in Pleistocene lakes, and finally accumulated in alkaline ground water beneath the low-lying Magadi and Natron basins. In each case numerous hot springs of very similar composition supply this water to the lake, which constitutes a large evaporating pan; a recycling of the salts probably occurs. Conditions in the larger lakes of open drainage basins are very different and have been discussed by BEAUCHAMP (1939, 1940, 1946, 1953, and 1964). He has reasoned that the lake and inflow waters often differ so markedly in the proportions and concentrations of major ions that processes (largely biological) of selective elimination must have occurred extensively in the large African lakes. We believe that the facts can often be interpreted otherwise.

Lake Tanganyika provides the most remarkable and best-discussed example. Only one large inflow, the Ruzizi River from L. Kivu, contains ionic proportions broadly similar to those of the lake water (Table 2) and is appreciably more saline.

Table 2. Chemical constitution of lake inflows

Lake River	sampling date	reference	k ₂₀ (μmho)	sum of cations (meq./L)	sum of anions (meq./L)	Na (mg/l)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	No.	HCO ₃ ⁻ CO ₃ (meq./L)	Cl (mg/L)	SO ₄ (mg/L)	SiO ₂ (mg/L)
Victoria														
Kagera R.	20. Mar. 53	FISH, unpubl.	86	—	—	—	—	5.4	3.45	1a	1.16	1	—	18
	May. 54	FISH, unpubl.	93	—	—	—	—	7.0	—	b	0.86	0.36	—	16
	9. Oct. 60	original	99	—	—	—	—	5.4	4.1	c	0.86	—	—	17
Nzoia R.	50	FISH 1952	85— 125	1.17	—	11.5	4.0	6.4	3.1	2	1.05	—	0.8	40
George														
Mpanga R.	25. Nov. 52	FISH 1953	135	—	—	—	—	17.8	3.22	3a	1.34	4	—	24
	24. Mar. 53	FISH 1954	180	—	1.9	—	—	14.6	3.6	b	1.7	3.3	2.8	24
Nyasa														
S. Rukuru R.	Oct. 54	HARDING 1963	55	—	—	—	—	—	—	4a	0.485	—	—	16
	July. 55	HARDING 1963	53	—	—	—	—	5.1	1.9	b	0.58	—	—	14
	11. Aug. 55	HARDING 1963	75	—	—	—	—	6.8	2.1	c	—	—	—	8
Songwe R.	Feb. 55	HARDING 1963	62	—	—	—	—	4.7	—	5a	0.65	—	—	—
	17. Aug. 55	HARDING 1963	100	—	—	—	—	7.9	3.3	b	—	—	—	14.5
Luweya R.	1. June. 54	HARDING 1963	—	—	—	—	—	5.2	—	6a	0.78	—	—	14
	18. Oct. 54	HARDING 1963	—	—	—	—	—	5.8	3.1	b	0.73	—	—	24
	18. July. 55	HARDING 1963	63	—	—	—	—	4.8	4.6	c	0.74	—	—	25
Ruhuhu R.	Feb. 55	HARDING 1963	69	—	—	—	—	6.7	—	7	0.72	—	—	—
Bua R.	Aug. 54	HARDING 1963	—	—	—	—	—	17.4	7.8	8	1.86	—	—	—
Naivasha														
Malewa R.	4. July. 29	JENKIN 1932	—	—	—	—	—	—	—	9a	0.67	—	—	—
	25. Nov. 30	BEADLE 1932	—	—	—	—	—	—	—	b	0.64	—	—	15.4
Baringo														
hot spring	2. Feb. 31	BEADLE 1932	—	—	—	—	—	—	—	10	32	—	—	—
Tiggeri R.	7. Dec. 30	BEADLE 1932	—	—	—	—	—	—	—	11	0.89	—	—	—
Tanganyika														
Malagarasi R.	? 37	BEAUCHAMP 1939	195	2.16	2.03	16.4	2.4	12.9	9.1	12	1.55	15.5	2.1	22.4— 28
Ruzizi R.	? 38	BEAUCHAMP 1939	910	—	—	94.8	63.0	8.4	67.0	13a	10.46	23.8	17.8	9.0— 9.8
	May-June 53	DUBOIS 1958	801	—	—	98.0	74.0	8.5	101.6	b	9.60	16.6	9.0	8.0

Table 2. cont.

Lake River	sampling date	reference	k ₂₀ (μmho)	sum of cations (meq./L)	sum of anions (meq./L)	Na (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	No.	HCO ₃ + CO ₃ (meq./L)	Cl (mg/L)	SO ₄ (mg/L)	SiO ₂ (mg/L)
Mohasi 7 inflows	6-8. May. 52	DAMAS 1954	294— 7400	—	—	—	—	26— 432	4.1— 404	14	2.59— 18.09	—	—	—
Albert Semliki R.	16. June. 52	FISH 1953	800	—	—	—	—	15	—	15a	7.16	x	x	24
	? 53	VAN DER BEN 1959	766	—	—	—	—	—	—	b	7.3	30.7	36.4	3.8
Muzizi R.	17. June. 52	FISH 1953	93	—	—	—	—	10	—	16	0.938	x	x	40
Edward Ruchuru R.	26	HURST 1927	—	—	—	—	—	—	—	17a	17.2	12	—	—
	2. Feb. 50	MARLIER 1951	427	—	—	—	—	—	—	b	—	—	—	—
Hannington North inflow	4. Feb. 31	BEADLE 1932	—	—	—	—	—	—	—	18	6.4	—	—	—
Elmenteita Kariandusi R.	30. June. 29	JENKIN 1932	—	—	—	—	—	—	—	19	2.5	—	—	—
Nakuru hot spring	9. Dec. 30	BEADLE 1932	—	—	—	—	—	—	—	20	19	—	—	—
Magadi hot spring (a)	4. May. 19	GREGORY 1921	—	—	370	—	—	—	—	21	253	4100	88	—
hot spring (b)	23. Feb. 61	original	55500	557	602	12750	188	<10	<30	22	411	6200	790	72

It has been estimated very roughly by GILLMAN (1933) to supply 13.5% of the total inflow stream water, and its salinity has been given either as 10 times (BEAUCHAMP 1939) or 4 times (BEAUCHAMP 1946, 1953) that of the "average" of other inflows. These factors may be underestimates (BEAUCHAMP 1939), as the inflows were sampled during the dry season. If the higher factor of 10 is applicable (cf. BEAUCHAMP 1939, Table III), the Ruzizi will probably supply more than 50% of the total salts entering the lake (BEAUCHAMP 1939). Then a divergence between constitutions of lake and "average inflow" need not require any assumption of biological precipitation in the lake, since the ionic proportions visualised for the "average inflow" appear insufficiently weighted for the contributions of the more saline inflows. Unusually saline inflows are not uncommon in other lakes such as Albert (Semliki River) and Edward (Ruchuru River), where also their influence on lake chemistry is disproportionate to their discharge. Further, the "average inflow" concentration (or salinity) cannot be viewed in isolation from the water flow represented by the difference between rainfall and evaporation on the lake surface. For example, the effects of an inflow of very low salinity may be equivalent to that of a slight excess of direct rainfall, though the salinity of the latter is not involved in estimates of the "average inflow" concentration.

A number of the unusual chemical features of the lake water cited by BEAUCHAMP are paralleled in the Ruzizi inflow water (Tables 1, 2). They include high ratios of magnesium to calcium, of chloride to sulphate, and considerable concentrations of potassium. If, as seems possible, the Ruzizi supplies most of the salts entering the lake, these similarities are to be expected, and make it unnecessary to postulate a large-scale biological removal of such ions as calcium and sulphate in the lake.

Large differences exist between the chemical composition of L. Nyasa water and many of the inflows, in which the concentrations of major ions are relatively low (HARDING 1963; and Tables 1, 2). It seems likely that much of the salts entering the lake is contributed by the rivers of seasonal flow and higher salinity in the south-west, whose drainage area includes some limestone (HARDING 1963).

For L. Tanganyika and several other large lakes (e. g. Albert, Victoria, Nyasa), some chemical implications of the unusual water budget may be mentioned. In these lakes the gain of water by the direct rainfall on the lake is either roughly equal (L. Albert) or greatly exceeds (L. Tanganyika, L. Nyasa, L. Victoria) that from inflow streams, and the chief loss is by evaporation from the lake. Consequently, if the "average inflow" and the lake water are of similar salinity, there is unlikely to be any large difference between precipitation and evaporation. In the hydrological budgets for the large lakes of Victoria, Albert, Nyasa and Edward (GILLMAN 1933, KANTHACK 1941, HURST and PHILLIPS 1938, HURST 1952), these two items are roughly estimated to be similar in magnitude and between 1000 and 1440 mm per year. The comparison with inflow salinity would assume that the salinity of the rain water is much lower than that of the lake water. Although VISSER (1961) has recorded a few remarkably saline rain waters at Kampala (Uganda), the analyses involved show some internal inconsistencies (e. g., between conductivity and total ionic concentration) and require confirmation, as do various unusual features, such as the implied preponderance of magnesium, in his analyses (VISSER 1961, 1962) of waters from L. Victoria and lakes Bunyoni, Mutanda and Mulehe. Even with the lower concentrations of major ions common in rain water

elsewhere (cf. GORHAM 1961), this source could form an appreciable part of the total supply of L. Victoria, where the salinity is comparatively low and direct rainfall supplies roughly six times more water than do the inflow streams (HURST 1952). The supply of sulphate to the lake from rain water was considered insignificant by HESSE (1957), as he estimated only 0.03 mg/L of sulphate in rainfall collected at Jinja. Confirmation is required, in view of the much higher concentrations usually recorded elsewhere (cf. VISSER 1961). Nevertheless, the concentrations of major ions in L. Victoria water seem to be quite similar to those in the two principal inflows (Table 2). The concentrations in L. Albert can be related to the average constitution of its main inflow, the Semliki River (TALLING 1963), and the total salinity of the lake water is consistent with the salinities and discharges of the principal inflows and outflows (HURST and PHILLIPS 1938). The small and probably periodic outflow of L. Tanganyika could involve some degree of progressive concentration of salts in the lake (BEAUCHAMP 1939), although such changes must be very slow in view of the immense replacement time, estimated by BEAUCHAMP (1939) as 1800 years.

13. Discussion

Much of the distinctive character of the African lake waters follows from the frequently high content of sodium bicarbonate and carbonate, coupled with the wide range of salinity. From this basis a considerable variation of cationic proportions is inevitable, by the elimination of calcium and magnesium in the more alkaline waters. Such variation is further compounded by the relative abundance of these divalent cations in sources of low salinity, and by the widespread effects in many West Rift lakes of the volcanic sources unusually rich in magnesium and potassium. The anions sulphate and chloride show no remarkable variation in their relative proportions, although these proportions are unusually low, particularly for sulphate. It is clear the major ionic composition of most African lake waters is very different from that of most temperate lakes, where calcium and bicarbonate often tend to predominate, and cannot be interpreted in terms of any idealised "standard composition" (cf. RODHE 1949, HUTCHINSON 1957); the limitations of this concept are discussed by GORHAM (1955, 1961). The high proportions of sodium and bicarbonate/carbonate also distinguish the very saline African lakes from the majority of saline lakes elsewhere, and eliminate most of the trends of anionic proportions discussed by HUTCHINSON (1957). Among minor constituents, the generally high concentrations of silica and low concentrations of nitrate are features probably widespread in tropical lakes: the former is also noted by HUTCHINSON (1957, p. 791).

The relatively small outflows and large volumes of the bigger lakes imply very long periods of retention within the lakes, which would oppose any short-period changes in major ionic composition due to varying inflows. Over a year (1960–61) no such changes could be detected in L. Victoria, and in fewer samples from L. Albert (TALLING 1963) they were very small. There is some evidence (Table 1) for rather larger changes in several small lakes, including George and Naivasha. The biggest recorded changes with time are from the shallow, closed and saline lakes of Nakuru and Elmenteita, which were much larger, deeper, and less saline when sampled during 1928–1930 by JENKIN (1932, 1936) and BEADLE (1932). Both have been known to dry up completely in recent years. Considerable changes in the area and depth of L. Naivasha (see SIKES 1935, COPLEY 1948) are not simply

correlated with records of total dissolved solids (Kenya Hydrological Department, unpublished data). Possibilities of analytical error may affect many differences between older and recent results, such as the 1927–28 and 1960–61 values for the alkalinity of lakes Victoria and Albert, and the 1951–2 and later analyses of sulphate in L. Albert.

Long-term changes of water chemistry must have been considerable in many lakes, in view of the occurrence of volcanic activity with pluvial and interpluvial periods during their Pleistocene history (see FUCHS 1934, 1936, 1939, WILLIS 1936, SOLOMON 1939, WHITE 1953, COLE 1954, FLINT 1959a, b, BEADLE 1962). Though evidence from the chemical analyses of lake sediments is required, the present results have some implications for the chemical history of the large West Rift lakes. Here many distinctive chemical features of these lakes have been related to saline sources, rich in magnesium and potassium, situated in the region of volcanic activity near the Virunga volcanoes. If these sources developed in the same period as the volcanoes, the earlier lakes of the West Rift probably did not have their present high proportions of magnesium and potassium, and low ratios of calcium to magnesium. This situation would eliminate certain chemical bases, some also criticised by HUTCHINSON (1933) and BROOKS (1950), which have been proposed to account for some apparently marine ("halolimnic") elements in the fauna of L. Tanganyika. The marine appearance of some molluscs has been particularly discussed. BEAUCHAMP (1939, 1940) emphasised the high ratios of magnesium to calcium and of chloride to sulphate. It is doubtful whether any of these characteristics prevailed during the longer and more influential early history of the lake, when the conditions now responsible for the peculiar Ruzizi inflow did not exist. Then in a closed basin, the lake may have become considerably more saline than it is today (CUNNINGTON 1920, FUCHS 1936), even if (cf. GILLMAN 1933, BEAUCHAMP 1939) most of its water income was by direct rainfall on the lake.

The variable proportions and concentrations of the major cations may have other biological consequences. The absence or extreme scarcity of Cladocera from L. Tanganyika was once suggested (CUNNINGTON 1920) to be possibly due to the salinity, or, more specifically, the high concentration of magnesium. This appears very unlikely in view of later evidence from experiment and observation (HUTCHINSON 1930, 1933). The exclusion of many molluscs from waters low in calcium is likely from the distributional evidence elsewhere (e. g., BOYCOTT 1936, MACAN 1950), but a detailed survey of the problem in African lakes appears to be lacking. L. Victoria shows a varied molluscan fauna, in water containing only 5–6 mg Ca/L (cf. GRAHAM 1929, p. 161), a concentration which is probably limiting to many gastropods in some temperate lake waters in which calcium is the principal cation (e. g., MACAN 1950).

The most striking biological consequences of lake chemistry are undoubtedly connected with the enormous range of alkalinity, with which total ionic concentration and conductivity are closely correlated. Changes of the plankton in passing to the most saline and alkaline lakes, here grouped as Class III, are described by BEADLE (1932) and JENKIN (1932, 1936). These include the disappearance, above an alkalinity of approx. 80 meq./L. of most Entomostraca and the often dense occurrence in such alkaline lakes of a few species of Rotifera (e. g., *Brachionus pala*) and blue-green algae (e. g., *Spirulina* (*Arthrospira*) *platensis*, *Anabaenopsis arnoldii*). L. Rudolf, with an alkalinity of 20–25 meq./L., contains both planktonic organisms abundant in lakes of Class III (e. g., *Spirulina platensis*, *Anabaenopsis*

arnoldii: FISH 1955, ROSS 1955) — and others which are apparently excluded from such lakes. In this connexion a comparative survey of the plankton in waters within the alkalinity range 25–100 meq./L would be of interest; such waters are chiefly found in small and little known crater lakes (see Table 1).

The consequences of the transition between lakes in Classes I and II have been less discussed, although undoubted trends occur in the composition of the phytoplankton. In general, Class I includes lakes in which species of the diatom *Melosira* and of desmids are numerous. In Class II lakes neither are common, but species of the diatom *Nitzschia* are often abundant. These differences in the diatom plankton have previously been noted by HUSTEDT (1949) from a more restricted sampling of African lakes; he believed that alkalinity was the most significant factor. Other records suggest that *Melosira* is, at least seasonally, one of the more important algae in the phytoplankton of the major lakes of Class I. Examples are lakes Victoria (FISH 1957, EVANS 1962, TALLING, in press), Nyasa (SCHMIDLE 1902, WEST 1907, ILES 1960), Naivasha (RICH 1932, 1933; WORTHINGTON and RICARDO 1936, ROSS 1955, and personal observations), and Tana (BRUNELLI and CANNICCI 1940). Similarly HUTCHINSON *et al.* (1932) found that in South African pans *Melosira* spp. were only abundant in the waters of lower salinity and alkalinity, while localities rich in desmids showed alkalinities less than 2.6 meq./L and had relatively low concentrations of the two other major anions.

The reduced representation of desmids in the plankton of more saline and alkaline lakes is well known in other continents; its illustration among the African lakes is particularly striking. Accounts of the profusion of desmids in the least saline and alkaline lakes include those of WEST (1907) and THOMASSON (1957) for L. Victoria, EVANS (1949) for L. Mweru, GRÖNBLAD (1962) and GRÖNBLAD, PROWSE, and SCOTT (1958) for L. Ambadi, and THOMASSON (1956, 1961) for L. Bangweulu. The upper limit of alkalinity, at which an appreciable desmid plankton exists, appears to be reached at L. Nyasa with 2.5 meq./L; this is close to the limit given by HUTCHINSON *et al.* (1932) for the South African pans. This upper limit is probably higher than that suggested by most records from the north temperate lakes, where calcium is usually the predominant cation. In the African waters the distributional limit may be extended by the usually high ratio of monovalent to divalent cations. This possible factor is discussed by PEARSALL (1922), partly with reference to L. Victoria, and by HUTCHINSON *et al.* (1932).

The correlation of species occurrence with alkalinity may conceivably arise indirectly, through a secondary correlation of alkalinity with another and more relevant feature of water chemistry. In this category one may consider calcium concentration, total salinity, and pH. The first is very unlikely to be an important primary factor in this context. In the African lakes its correlation with alkalinity is small because of loss by precipitation in the more alkaline waters. This situation contrasts with that in many temperate lake waters where the correlation is high. Although total salinity is strongly correlated with alkalinity in these African lakes, it is probably not more important in restricting the distribution of *Melosira*. Species of this diatom are well represented in the plankton of Lake Mohasi (LEMMERMANN 1914, DAMAS 1955), where an unusual enrichment in chloride leads to the combination of a comparatively high salinity and conductivity with a comparatively low alkalinity and pH (DAMAS 1954). There is other evidence that in some of the less saline lakes, chloride content can vary widely with little effect upon the composition of the phytoplankton. Thus the community described by

DAMAS (1955) from L. Mohasi, with 144 mg Cl/L, appears qualitatively similar to those which we have observed in L. Bunyoni (TALLING, in press) and in inshore Bay areas of L. Victoria, where the recorded chloride concentrations are respectively 29–32 and 3.9–7 mg Cl/L. A general comparison can be made with more saline lakes in central Canada described by RAWSON and MOORE (1944), in which magnesium and sulphate were the predominant ions. Here very high salinities were reached at a relatively low level of alkalinity and pH, and species of the phytoplankton occurred over a wider range of salinities than in the African lakes.

Separation of the influences of alkalinity and pH is more difficult, and probably even impossible on the present distributional evidence for the more strongly buffered lake waters of high alkalinity. For waters of lower alkalinity some separation can be attempted. For example, there are indications that the occurrence of *Melosira* plankton may be limited more specifically by high pH than by high alkalinity. In Lake Baringo a considerable population of *M. granulata* var. *angustissima* was found during 1929 and 1931 in water of unusually high alkalinity (5.5–10.5 meq./L), but measurements of pH did not exceed 9.0 in 1929 or 8.8 in 1931 (BEADLE 1932, RICH 1933, JENKIN 1936; cf. also HUSTEDT 1949, p. 179). In other African lakes an appreciable *Melosira* plankton does not appear to be recorded from lake waters with pH higher than 9.0, a value which is correlated — in the absence of intense photosynthesis — with an alkalinity of approximately 6–8 meq./L. If photosynthesis is intense, a higher pH can develop in waters of comparatively low alkalinity (Fig. 3.). This occurs seasonally in the White Nile near Khartoum (PROWSE & TALLING 1958; also Fig. 3) where the final decline of populations of *M. granulata* and its var. *angustissima* coincided with the development at midday of pH values exceeding 9.0–9.2. Equally high or higher values are common in some other shallow and very productive waters of low alkalinity (e. g., L. George) but are not accompanied by an appreciable *Melosira* plankton. Although these features can be interpreted in terms of competitive exclusion, they are consistent with the limitation of *Melosira* abundance by pH values which are usual in most lakes of Class II and frequent in the most densely populated lakes of Class I.

The present observations do not permit a separation of pH and alkalinity as factors restricting the occurrence of a desmid plankton. However, HUTCHINSON *et al.* (1932) recorded a profusion of desmids in a South African pan where a low alkalinity was accompanied by a pH of 9.0. They concluded that here alkalinity was more significant than pH as a controlling factor.

The limnological significance of minor chemical constituents, as plant nutrients, is not readily illustrated by an extensive survey of many lakes. Because of the usual finding in surface waters of very low concentrations of nitrate-nitrogen, it has been suggested that this constituent may limit phytoplankton growth in certain African lakes (BINI 1940; DAMAS 1954; VERBEKE 1957). More direct evidence for such limitation is provided by seasonal studies of the occurrence of *Melosira granulata* in the White and Blue Niles near Khartoum (PROWSE & TALLING 1958; TALLING, unpublished). BEAUCHAMP (1953) believed that low concentrations of sulphate may often limit the growth of phytoplankton in African lakes, and specifically in Lake Victoria. However, the estimates of sulphate concentration which he quoted are probably often too low (p. 440), and the direct experimental evidence available (FISH 1956) depends upon measurements of growth over several months, in very dense enriched cultures inoculated with species not characteristic of African

phytoplankton. Even the densest populations in nature, such as occur in Lake George, are unlikely to incorporate much more sulphur than phosphorus; the latter is apparently always present in much lower concentration in the lake waters. Dissolved silica is generally present far in excess of the concentrations (0–1 mg/L) likely to limit diatom growth. Such low concentrations have been recorded periodically in the three large Rift lakes of Tanganyika (BEAUCHAMP 1939, VAN MEEL 1954), Nyasa (BEAUCHAMP 1940, 1953b; ILES 1960, ECCLES 1962), and Albert (TALLING 1963), where they may possibly have a significance as limiting factors. Equally speculative (TALLING, in press) is a possible limiting effect of the very low concentrations of manganese, and particularly of iron, in the offshore waters of Lake Victoria.

14. Summary

A survey is given, largely from original analyses, of the chemical composition of lakes in east and central Africa. These include the majority of large African lakes. Bicarbonate is almost always the principal anion. The total ionic concentration and alkalinity vary very widely, due largely to saline inflows from volcanic areas and evaporation within basins of closed drainage. Variation in the proportions of the major anions is limited, although enrichment in chloride occurs locally. The proportion of sulphate is particularly low in some lakes with deoxygenated hypolimnia, but concentrations of less than 2 mg/L appear to be very rare in lake surface waters. The proportions of cations show greater variations. These are influenced by a frequently reduced proportion of sodium in the less saline waters, by drainage into West Rift lakes from deposits rich in potassium and magnesium in the Virunga volcanic field, and by the precipitation of calcium and magnesium carbonates from waters of high alkalinity. In many lakes sodium is the principal cation, and the monovalent cations often preponderate over the divalent.

The concentration of nitrate-nitrogen is usually very low in lake surface waters, whereas amounts of dissolved silica and total phosphorus are generally high — exceptionally so in some very saline and alkaline lakes. The fraction of the inorganic phosphate-phosphorus in the total phosphorus content varies widely. Examples are given of the accumulation of these and other minor constituents in the lower layers of stratified lakes; similar increases in some major constituents occur in a few strongly stratified, often meromictic, lakes. In the better known examples, the major ionic composition of even the larger lakes appears to be similar to that expected from the combined contributions of the inflows, although there is evidence for the removal of dissolved silica.

Some biological consequences are discussed. They include the apparent restriction of certain planktonic organisms to waters of low and of high alkalinity, and possible effects of the variation in concentrations and proportions of the major cations and in concentrations of some other plant nutrients.

15. References

- ABDIK, G., 1948: The conditions of growth and periodicity of the algal flora of the Aswan reservoir (Upper Egypt). *Bull. Fac. Sci. Egypt. Univ.* No. 27: 157–175.
- Anon., 1952: Spectrographic analyses. Appendix A, Annual Report for 1951, East African Fisheries Research Organization, Jinja, Uganda. East Africa High Commission. 49 pp.
- Anon., 1958: Jebel Marra investigations. Report to Ministry of Irrigation and Hydro-electric Power, Ministry of Agriculture, Government of the Republic of the Sudan. Hunting Technical Services Ltd., London. 112 pp.
- BAKER, B. H., 1958: Geology of the Magadi area. *Rep. geol. Surv. Kenya*, No. 42. Nairobi. 81 pp.
- BARNES, H., 1959: Apparatus and methods of oceanography. Part 1. Chemical. Allen and Unwin, London. 341 pp.

- BEADLE, L. C., 1932: Scientific results of the Cambridge Expedition to the East African Lakes, 1930—31. 4. The waters of some East African Lakes in relation to their fauna and flora. *J. Linn. Soc. (Zool.)* **38**: 157—211.
- 1943: An ecological survey of some inland saline waters of Algeria. *Ibid.* **41**: 218—242.
- 1962: The evolution of species in the lakes of East Africa. *Uganda J.* **26**: 44—54.
- BEAM, W., 1906: Chemical composition of the Nile waters. Second Report Wellcome Res. Lab., Khartoum, pp. 206—214.
- 1908: Nile waters. Third Report Wellcome Res. Lab., Khartoum, pp. 386—395.
- BEAUCHAMP, R. S. A., 1939: Hydrology of Lake Tanganyika. *Int. Rev. Hydrobiol.* **39**: 316—353.
- 1940: Chemistry and hydrography of lakes Tanganyika and Nyasa. *Nature, Lond.* **146**: 253—256.
- 1946: Lake Tanganyika. *Ibid.* **157**: 183—184.
- 1953a: Sulphates in African inland waters. *Ibid.* **171**: 769—771.
- 1953b: Hydrological data from Lake Nyasa. *J. Ecol.* **41**: 226—239.
- 1956: The electrical conductivity of the head waters of the White Nile. *Nature, Lond.* **178**: 616—619.
- 1964: The Rift Valley lakes of Africa. *Verh. Int. Ver. Limnol.* **15**: 91—99.
- BEN, D. VAN DER, 1959: La végétation des rives des lacs Kivu, Édouard et Albert. *Explor. Hydrobiol. Lacs Kivu, Édouard et Albert (1952—1954), Rés. Sci., Vol. IV, Fasc. I*, 191 pp. Inst. Roy. Sci. Nat. Belg. Bruxelles.
- BERG, A., 1959: Analyse des conditions impropres au développement de la jacinthe d'eau *Eichhornia crassipes* (MART.) SOLMS dans certaines rivières de la cuvette congolaise. *Bull. agric. Congo belge* **50**: 365—394.
- 1961: Rôle écologique des eaux de la cuvette congolaise sur la croissance de la jacinthe d'eau (*Eichhornia crassipes* (MART.) SOLMS). *Mém. Acad. Sci. belge Outre-Mer, Sci. nat.* 8 n.s. **12** 3: 120 pp.
- 1962: Exposé des méthodes d'analyse chimique et physico-chimique des eaux humiques. *Mem. Ist. Ital. Idrobiol.* **15**: 183—206.
- BINI, G., 1940: Ricerche chimiche nella acque del lago Tana. *Miss. di studio al lago Tana, III, 2, Reale Accademia d'Italia, A*: 9—52.
- BISHAI, H. M., 1962: The water characteristics of the Nile in the Sudan with a note on the effect of *Eichhornia crassipes* on the hydrobiology of the Nile. *Hydrobiologia* **19**: 357—382.
- BOYCOTT, A. E., 1936: The habitats of freshwater Mollusca in Britain. *J. Anim. Ecol.* **5**: 116—186.
- BROOKS, J. L., 1950: Speciation in ancient lakes. *Quart. Rev. Biol.* **25**: 131—176.
- BRUNELLI, G. and G. CANNICCI, 1940: Le caratteristiche biologiche del lago Tana. *Missione di Studio al lago Tana. Ricerche limnologiche, B., Chimica e biologia III (2)*: 71—116.
- 1941: Ricerche sul plancton e sulle caratteristiche biolimnologiche del lago Margherita. *Esplorazione dei Laghi della Fossa Galla, vol. I*, 26 pp. Ministero dell' Africa Italiana.
- CANNICCI, G. and F. ALMAGIÀ, 1947: Notizie sulla "facies" planctonica di alcuni laghi della Fossa Galla. *Boll. Pesca Piscic. Idrobiol.*, year 23, 2 n.s.: 54—77.
- CHRISTIE, W. A. K., 1912: Notes on the Lonar soda deposit. *Rec. geol. Surv. India* **41**: 276—285.
- CLERFAYT, A., 1956: Composition des eaux de rivières au Congo. Influence des facteurs géologiques et climatiques. *Bull. Cent. belge d'Étude Docum. Eaux* **31**: 26—31.
- COLE, S., 1954: The prehistory of East Africa. Penguin Books, London. 301 pp.
- COMBE, A. D. and W. C. SIMMONS, 1933: The volcanic area of Bufumbiro. *Mem. geol. Surv. Uganda III, pt. 1, Entebbe*. 150 pp.
- COPLEY, H., 1948: Lakes and rivers of Kenya. Longmans, Green & Co., Nairobi, 80 pp.
- CUNNINGTON, W. A., 1920: The fauna of the African lakes: a study in comparative limnology with special reference to Tanganyika. *Proc. zool. Soc. Lond. (1920)*, 507—622.

- DAMAS, H., 1937: Recherches hydrobiologiques dans les lacs Kivu, Édouard, et Ndalaga. Explor. Parc Albert, Mission H. DAMAS (1935—1936), fasc. I, 128 pp. Inst. Parcs nat. Congo belge, Bruxelles.
- 1938: La stratification thermique et chimique des lacs Kivu, Édouard et Ndalaga (Congo Belge). Verh. Int. Ver. Limnol. **8**: 51—68.
- 1954: Étude limnologique de quelques lacs ruandais. II. Étude thermique et chimique. Mém. Inst. colon. belge, Cl. Sci. nat. **24** 4: 1—116.
- 1955: Étude limnologique de quelques lacs ruandais. III. Le plancton. Mém. Acad. Sci. colon. belge, Classe Sci. nat. n.s. **1** 3: 1—66.
- DE FILIPPIS, N., 1940: Condizioni chimiche del lago Hora Abiata. Boll. Idrobiol. A.O.I. **1**: 77—79.
- DE KIMPE, P., 1960: Observations hydrobiologiques au Luapula-Moero. Hydrobiologie et pêche en eaux douces. Colloque sur les problèmes des Grands Lacs. (Lusaka, 18—21 août 1960). London: CCTA/CSA LACS (60) 39, 17 pp.
- DELHAYE, F., 1941: Les volcans au nord du lac Kivu. Bull. Inst. colon. belge **12**: 409—459.
- DROOP, M. R., 1958: Optimal relative and actual ionic concentrations for growth of some euryhaline algae. Verh. Int. Ver. Limnol. **13**: 722—730.
- DUBOIS, J. T., 1955: Étude hydrobiologique d'un lac africain d'altitude: Le Lungwe. Étude physique et chimique. Bull. Cent. belge d'Étude Docum. Eaux **53**: 79—82.
- 1957: Note sur la composition chimique des dépôts calcaires des rives rocheuses du lac Tanganika. Folia Sci. Afr. Centr. **3**: 45—46.
- 1958: Composition chimique des affluents du nord du lac Tanganika. Bull. Acad. Sci. Colon. belge, n.s. **4**: 1226—1237.
- 1959: Note sur la chimie des eaux du lac Tumba. Bull. Acad. Sci. outremer belge **5**: 1321—1334.
- DUKE, H. L., 1924: Water Analyses. Ann. Rep., Bacteriol. Dept., Uganda Protectorate, for year ended 31st Dec. 1923. Entebbe, Uganda.
- ECCLES, D. H., 1962: Activities of the Organisation in Nyasaland. I. Hydrology. Section 3 B, pp. 41—47, in Annual Report No. 10 for 1960, Joint Fisheries Research Organisation, Northern Rhodesia. Government Printer, Lusaka. 71 pp.
- ELSTER, H. J. und R. A. VOLLENWEIDER, 1961: Beiträge zur Limnologie Ägyptens. Arch. Hydrobiol. **57**: 241—343.
- EVANS, J. H., 1962: The distribution of phytoplankton in some Central East African waters. Hydrobiologia **19**: 299—315.
- EVENS, F., 1949: Le plancton du lac Moero et de la région d'Elisabethville. Rev. Bot. Zool. Afr. **41**: 233—277; **42**: 1—64.
- FISH, G. R., 1952: Appendix A. Annual Report for 1951, East African Fisheries Research Organization, Jinja, Uganda. East Africa High Commission. 49 pp.
- 1953: Appendix A, Chemical analyses. Ibid., Annual Report for 1952, 42 pp.
- 1954: Appendices A1—A6. Ibid., Annual Report for 1953, 44 pp.
- 1955: The food of *Tilapia* in East Africa. Uganda J. **19**: 85—89.
- 1956: Chemical factors limiting growth of phytoplankton in Lake Victoria. E. Afr. agric. J. **21**: 152—158.
- 1957: A seiche movement and its effect on the hydrology of Lake Victoria. Colon. Off., Fish. Publ., Lond. **10**, 68 pp.
- FLINT, R. F., 1959a: Pleistocene climates in eastern and southern Africa. Bull. geol. Soc. Amer. **70**: 343—374.
- 1959b: On the basis of Pleistocene correlation in East Africa. Geol. Mag. **96**: 265—284.
- FRANK, E., 1962: Vergleichende Untersuchungen zum Calcium-, Kalium- und Phosphat-haushalt von Grünalgen. II. Calciummangel bei *Hydrodictyon*, *Sphaeroclea* und *Chlorella*. Flora, Jena **152**: 157—167.
- FUCHS, V. E., 1934: The geological work of the Cambridge Expedition to the East African lakes, 1930—31. Geol. Mag. **71**: 97—112 and 145—166.

- 1936: Extinct Pleistocene mollusca from Lake Edward, Uganda, and their bearing on the Tanganyika problem. *J. Linn. Soc. (Zool.)* **40**: 93—106.
- 1939: The geological history of the Lake Rudolf basin, Kenya Colony. *Phil. Trans., Ser. B* **229**: 219—274.
- GILLMAN, C., 1933: The hydrology of Lake Tanganyika. *Bull. geol. Surv. Tanganyika*, No. 5, 25 pp.
- GORHAM, E., 1955: On some factors affecting the chemical composition of Swedish fresh waters. *Geochim. et cosmoch. Acta* **7**: 129—150.
- 1961: Factors influencing supply of major ions to inland waters, with special reference to the atmosphere. *Bull. geol. Soc. Amer.* **72**: 795—840.
- GRABHAM, G. W., and R. P. BLACK, 1925: Report of the Mission to Lake Tana, 1920—21. *Min. of Public Works, Egypt*. Government Press, Cairo. 207 pp.
- GRAHAM, M., 1929: The Victoria Nyanza and its fisheries. *Crown Agents for the Colonies*, London. 255 pp.
- GREGORY, J. W., 1921: The Rift valleys and geology of East Africa. Seeley, Service and Co., London. 479 pp.
- GROVES, A. W., 1931: Lakes Katwe, Kikorongo and Kasenyi. *Annual Report, Geol. Surv. Dept., Uganda Protectorate, for the year ended 31st December 1930*. 44 pp.
- GRÖNBLAD, R., 1962: Sudanese Desmids. *Acta bot. Fenn.* **63**: 3—19.
- G. A. PROWSE, and A. M. SCOTT, 1958: Sudanese Desmids. *Ibid.* **58**: 82 pp.
- GUEST, N. J., and J. A. STEVENS, 1951: Lake Natron, its springs, rivers, brines and visible saline reserves. *Geol. Surv. Tanganyika, Mineral Resources Pamphlet no. 58*. 21 pp.
- HARDING, D., 1961: Limnological trends in Lake Kariba. *Nature, Lond.* **191**: 119—121.
- 1962: Research on Kariba. Section D, pp. 32—40, in *Annual Report No. 10 for 1960*, Joint Fisheries Research Organisation, Northern Rhodesia. Government Printer, Lusaka. 71 pp.
- 1963: Studies on the hydrology of Lake Nyasa and associated rivers. In JACKSON et al., 1963.
- 1964: Hydrology and fisheries in Lake Kariba. *Verh. Int. Ver. Limnol.* **15**: 139—149.
- HARRISON, A. D., 1962: Hydrobiological studies on alkaline and acid still waters in the western Cape Province. *Trans. roy. Soc. S. Afr.* **36**: 213—244.
- HERON, J., and F. J. MACKERETH, 1955: The estimation of calcium and magnesium in natural waters, with particular reference to those of low alkalinity. *Mitt. Int. Ver. Limnol.* No. 5, 7 pp.
- HESSE, P. R., 1957: The distribution of sulphur in the muds, water and vegetation of Lake Victoria. *Hydrobiologia* **11**: 29—39.
- HIGAZY, R. A., 1954: Trace elements of volcanic ultrabasic potassic rocks of southwestern Uganda and adjoining part of the Belgian Congo. *Bull. geol. Soc. Amer.* **66**: 39—70.
- HOLMES, A., and H. F. HARWOOD, 1937: The volcanic area of Bufumbira. *Mem. geol. Surv. Uganda* **3**, 2: xiv + 1—300.
- HUNDESHAGEN, F., 1909: Analyse einiger ostafrikanischer Wässer. *Z. öff. Chem.* (1909): 202—205, 311—312.
- HURST, H. E., 1925: The Lake Plateau Basin of the Nile. Ministry of Public Works, Egypt. Physical Dept., Paper no. 21, Govt. Press, Cairo. (Section 13: Salt content of the water of the Lake Plateau, pp. 67—73).
- 1927: The Lake Plateau Basin of the Nile, Part II. Ministry of Public Works, Egypt. Physical Dept., Paper no. 23, Govt. Press, Cairo. 66 pp.
- 1952: The Nile. Constable, London. xv + 326 pp.
- and P. PHILLIPS, 1938: The Nile Basin. V. The hydrology of the Lake Plateau and Bahr el Jebel. Ministry of Public Works, Egypt. Physical Dept., Paper no. 35, Govt. Press, Cairo. 251 pp.
- HUSTEDT, F., 1949: Süßwasser-Diatomeen aus dem Albert National Park in Belgisch Congo. *Explor. Parc Albert, Mission H. DAMAS (1935—1936), Fasc. 8*, 199 pp. *Inst. Pares nat. Congo Belge, Bruxelles*.

- HUTCHINSON, G. E., 1930: On the chemical ecology of Lake Tanganyika. *Science* **121**: 616.
- 1933: Experimental studies in ecology. I. The magnesium tolerance of Daphniidae and its ecological significance. *Int. Revue ges. Hydrobiol. u. Hydrogr.* **28**: 90—108.
- 1937: A contribution to the limnology of arid regions. *Trans. Conn. Acad. Arts Sci.* **33**: 47—132.
- 1957: A treatise on limnology. I. Geography, physics, and chemistry. John Wiley and Sons, xiv + 1015 pp.
- G. E. PICKFORD, and J. F. M. SCHUURMAN, 1932: A contribution to the hydrobiology of pans and other inland waters of South Africa. *Arch. Hydrobiol.* **24**: 1—136.
- ILES, T. D., 1960: Activities of the Organisation in Nyasaland. Section 3, pp. 7—41, in Annual Report No. 9 for 1959, Joint Fisheries Research Organisation, Northern Rhodesia. Government Printer, Lusaka. 58 pp.
- JACKSON, P. B. N., T. D. ILES, D. HARDING, and G. FRYER, 1963: Report on the survey of northern Lake Nyasa by the Joint Fisheries Research Organization, 1954—55. Government Printer, Zomba, Nyasaland. XII + 171 pp.
- JAEGER, F., 1911: Das Hochland der Riesenkrater und die umliegenden Hochländer Deutsch-Ostafrikas. Teil I. Mitt. a. d. deutsch. Schutzgebieten, Ergänzungsheft No. 4, Berlin. 133 pp.
- JENKIN, P. M., 1932: Report on the PERCY SLADEN Expedition to some Rift Valley lakes in Kenya in 1929. I. Introductory account of the biological survey of five freshwater and alkaline lakes. *Ann. Mag. nat. Hist. Ser. 10*, **9**: 533—553.
- 1936: Reports on the Percy Sladen Expedition to some Rift Valley Lakes in Kenya in 1929. VII. Summary of the ecological results, with special reference to the alkaline lakes. *Ibid. Ser. 10*, **18**: 133—181.
- KANTHACK, F. E., 1942: Hydrology of Lake Nyasa. *S. Afr. geogr. J.* **24**: 3—34.
- KUEFFERATH, J., 1952: Le milieu biochimique. Exploration hydrobiologique du lac Tanganyika (1946—1947). Résultats scientifiques I, 31—47. *Inst. Roy. Sci. Nat. Belg. Bruxelles*.
- LEMMERMANN, E., 1914: Schizophyceae-Rhodophyceae. *Wiss. Ergebn. Deutsch. Zentral-Afrika Exp., 1907—1908. Bd. II. Botanik*, pp. 89—94. Leipzig.
- LENK, H., 1894: Über Gesteine aus Deutsch-Ostafrika. In O. BAUMANN, *Durch Massailand zur Nilquelle*. Berlin, pp. 263—294.
- LÖFFLER, H., 1964: The limnology of tropical high-mountain lakes. *Verh. Int. Ver. Limnol.* **15**: 176—193.
- LOFFREDO, S., and C. M. MALDURA, 1941: Risultati generali delle ricerche di chimica limnologica sulle acque dei laghi dell'Africa orientale italiana esplorati dalla Missione ittiologica. In PICCOLI, A., 1941. *Esplorazione dei laghi della Fossa Galla. Collezione scientifica e documentaria dell'Africa Italiana III, vol. I*: 181—200.
- MACAN, T. T., 1950: Ecology of fresh-water mollusca in the English Lake District. *J. Anim. Ecol.* **19**: 124—146.
- MACKERETH, F. J. H., 1955: Rapid micro-estimation of the major anions of freshwater. *Proc. Soc. Water Treatment Exam.* **4**: 27—42.
- 1963: Some methods of water analysis for limnologists. *Sci. Publ. Freshwat. biol. Ass. (England)*, No. 21, 71pp.
- MAGIS, N., 1961: Nouvelle contribution a l'étude hydrobiologique des lacs de Mwadingusha, Koni et N'Zilo. Fondation de l'Université de Liège pour les recherches scientifiques au Congo et au Ruanda-Urundi. 71 pp.
- MARLIER, G., 1951: Recherches hydrobiologiques dans les rivières du Congo Oriental. Composition des eaux. La conductibilité électrique. *Hydrobiologia* **3**: 217—227.
- J. BOUILLON, J. T. DUBOIS, et N. LELEUP, 1955: Le lac Lungwe. *Bull. Acad. Sci. colon. belge, n.s.* **1**: 665—676.
- MEEL, L. VAN, 1953: Contribution à l'étude du lac Upemba. A. Le milieu physico-chimique. Exploration du Parc National de l'Upemba, Fasc. 9. 190 pp. *Inst. Parcs nat. Congo Belge, Bruxelles*.

- 1954: Le phytoplancton. Explor. Hydrobiol. lac Tanganika (1946—1947) 4 1: 681 pp. Inst. Roy. Sci. Nat. Belg. Bruxelles.
- MILLER, J. D. H., and G. E. FOGG, 1957: Studies on the growth of Xanthophyceae in pure culture. I. The mineral nutrition of *Monodus subterraneus* PETERSEN. Arch. Mikrobiol. 28: 1—17.
- MOORE, J. E. S., 1903: The Tanganyika problem. London, 371 pp.
- MORANDINI, G., 1940: Missione di studio al lago Tana: 3. Ricerche limnologiche, parte prima, Geografia — Fisica. Roy. Acad. d'Italia, Rome. 315 pp.
- 1942: Recenti studi limnologici nell'Africa orientale Italiana. Mem. Ist. Ital. Idrobiol. 1: 255—266.
- MURRAY, J., 1910: The characteristics of lakes in general, and their distribution over the surface of the globe. In: MURRAY, J., and L. PULLAR, ed., Bathymetrical survey of the fresh water lochs of Scotland, Vol. I, 514—658. Edinburgh.
- NEWELL, B. S., 1960: The hydrology of Lake Victoria. Hydrobiologia 15: 363—383.
- NILSSON, E., 1940: Ancient changes of climate in British East Africa and Abyssinia. A study of ancient lakes and glaciers. Geogr. Ann. 22: 1—79.
- 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.
- ORR, D., and D. R. GRANTHAM, 1931: Some salt lakes of the northern Rift zone. Tanganyika Territory, Geological Survey Dept., Short Paper No. 8. 23 pp.
- PAPPE, A., and H. D. RICHMOND, 1890: A Central African salt lake. J. Soc. chem. Ind., Lond. 9: 734.
- PEARSALL, W. H., 1921: The development of vegetation in the English Lakes, considered in relation to the general evolution of glacial lakes and rock basins. Proc. roy. Soc. B 92: 259—284.
- 1922: A suggestion as to factors influencing the distribution of aquatic vegetation. J. Ecol. 9: 241—253.
- PHILLIPS, T., 1930: Crocodiles in Africa. "Times", London, April 11, 1930, p. 12. (data also given in WORTHINGTON 1932b, p. 18; VAN MEEL 1954, p. 148).
- PROVASOLI, L., J. J. A. McLAUGHLIN, and J. J. PINTNER, 1954: Relative and limiting concentrations of major mineral constituents for the growth of algal flagellates. Trans. N.Y. Acad. Sci. 16: 412—417.
- PROWSE, G. A., and J. F. TALLING, 1958: The seasonal growth and succession of plankton algae in the White Nile. Limnol. Oceanog. 3: 222—238.
- RAWSON, D. S., and J. E. MOORE, 1944: The saline lakes of Saskatchewan. Canad. J. Res., D 22: 141—201.
- RICARDO, C. K., 1939: Report on the fish and fisheries of Lake Rukwa in Tanganyika Territory and the Bangweulu region in Northern Rhodesia. Crown Agents for the Colonies, London. 78 pp.
- RICARDO-BERTRAM, C. K., H. J. BORLEY, and E. TREWAVAS, 1942: Report on the fish and fisheries of Lake Nyasa. Crown Agents for the Colonies, London. 181 pp.
- RICH, F., 1932: Phytoplankton from the Rift Valley lakes in Kenya. Reports on the Percy Sladen expedition to some Rift Valley lakes in Kenya in 1929. Ann. Mag. nat. Hist. Ser. 10, 10: 233—262.
- 1933: Scientific results of the Cambridge Expedition to the East African lakes, 1930 — I. 7. The Algae. J. Linn. Soc. (Zool.) 38: 249—275.
- RIEDEL, D., 1962: Der Margheritensee (Südabessinien) — Zugleich ein Beitrag zur Kenntnis der abessinischen Grabenseen. Arch. Hydrobiol. 58: 435—466.
- RODHE, W., 1949: The ionic composition of lake waters. Verh. Int. Ver. Limnol. 10: 377—386.
- ROSS, R., 1955: The algae of the East African Great Lakes. Verh. Int. Ver. Limnol. 12: 320—326.
- SCHMIDLE, W., 1902: Das Chloro- und Cyanophyceenplankton des Nyassa und einiger anderer innerafrikanischer Seen. Bot. Jb. 33: 1—33.

- SCHÜTTE, K. H., and J. F. ELSWORTH, 1954: The significance of large pH fluctuations observed in some South African vleis. *J. Ecol.* **42**: 148—150.
- SIKES, H. L., 1935: Notes on the hydrology of Lake Naivasha. *J. E. Afr. Ug. nat. Hist. Soc.* **13**: 73—84.
- SMITH, S. H., 1962: Temperature correction in conductivity measurements. *Limnol. Oceanogr.* **7**: 330—334.
- SOLOMON, J. D., 1939: The Pleistocene succession in Uganda. In O'BRIEN, T. P., 1939. *The prehistoric Uganda Protectorate*. Cambridge Univ. Press, Cambridge, 318 pp.
- STAPPERS, L., 1914: Composition chimique de l'eau de surface des lacs Moëro et Tanganika. *Reenseignements de l'office colonial, Ministère des Colonies, Bruxelles*, 1914, 189 pp.
- STURDY, D., W. E. CALTON, and G. MILNE, 1933: A chemical survey of the waters of Mount Meru, Tanganyika Territory. *J. E. Afr. Ug. nat. Hist. Soc.* **11**: 1—38.
- TALLING, J. F., 1955: Chemical and physical characteristics of Nile waters in relation to phytoplankton production. *First Ann. Rep., Hydrobiol. Res. Unit, Univ. Coll. Khartoum*, pp. 10—12.
- 1957a: The longitudinal succession of water characteristics in the White Nile. *Hydrobiologia* **11**: 73—89.
- 1957b: Diurnal changes of stratification and photosynthesis in some tropical African waters. *Proc. roy. Soc. B* **147**: 57—83.
- 1963: Origin of stratification in an African Rift lake. *Limnol. Oceanogr.* **8**: 68—78.
- 1965: The photosynthetic activity of phytoplankton in East African lakes. *Int. Rev. Hydrobiol.* **50**: 1—32.
- (in press): The annual cycle of stratification and phytoplankton growth in Lake Victoria (East Africa). *Int. Rev. ges. Hydrobiol.*
- THOMASSON, K., 1955: A plankton sample from Lake Victoria. *Svensk. bot. Tidskr.* **49**: 259—274.
- 1957: Notes on the plankton of Lake Bangweulu. *Nova Acta Soc. Sci. upsal. Ser. 4*, **17** 3: 1—18.
- 1960: Notes on the plankton of Lake Bangweulu. Part 2. *Nova Acta Soc. Sci. upsal. Se. 4*, **17** 12: 1—43.
- TOTTENHAM, P. M., 1926: *The Upper White Nile Mission, 1923. Interim Report*. Government Press, Cairo.
- VERBEKE, J., 1957: Recherches écologiques sur la faune des grands lacs de l'Est du Congo Belge. *Explor. Hydrobiol. Laes Kivu, Édouard et Albert (1952—1954)*, **3**, 1: 177 pp. *Inst. Roy. Sci. Nat. Belg. Bruxelles*.
- VISSER, S., 1961: Chemical composition of rain water in Kampala, Uganda, and its relation to meteorological and topographical conditions. *J. geophys. Res.* **66**: 3759—3765.
- 1962: Chemical investigations into a system of lakes, rivers and swamps in S. W. Kigezi, Uganda. *E. Afr. agric. For. J.* **28**: 81—86.
- VOLLENWEIDER, R. A., 1950: Ökologische Untersuchungen von planktischen Algen auf experimenteller Grundlage. *Schweiz. Z. Hydrol.* **12**: 193—262.
- WATERS, A. C., 1955: Volcanic rocks and the tectonic cycle. In A. POLDENVAART, ed., *Crust of the Earth*. *Geol. Soc. Amer., Special Paper* 62: 703—722.
- WAYLAND, E. J., 1926: *Petroleum in Uganda*. *Mem. geol. Surv. Uganda*, **1**. Government Printer, Uganda. Entebbe. 61 pp.
- 1932: Analyses of waters from Katwe Salt Lake. *Annual Report Geol. Surv. Dept., Uganda Protectorate for year ended 31st December 1931*. Government Printer, Entebbe. 20 pp.
- WEST, G. S., 1907: Report on the freshwater algae, including phytoplankton, of the third Tanganyika Expedition conducted by Dr. W. A. CUNNINGTON, 1904—1905. *J. Linn. Soc. (Bot.)* **38**: 81—197.
- WHITE, T. H., 1953: Some speculations on the sudden occurrence of floods in the history of Lake Magadi. *J. E. Afr. nat. Hist. Soc.* **22**: 69—71.

- WILLIS, B., 1936: East African plateaus and Rift Valleys. Publ. Carneg. Instn. Wash. **470**: 358 pp.
- WORTHINGTON, E. B., 1930: Observations on the temperature, hydrogen-ion concentration and other physical conditions of the Victoria and Albert Nyanzas. *Int. Revue ges. Hydrobiol. u. Hydrogr.* **24**: 328--357.
- 1932a: The lakes of Kenya and Uganda. *Geogr. J.* **79**: 275--297.
- 1932b: A report on the fisheries of Uganda investigated by the Cambridge expedition to the East African lakes 1930--1931. Crown Agents for the Colonies, London. 88 pp.
- and C. K. RICARDO, 1936: Scientific results of the Cambridge expedition to the East African lakes, 1930--1. — No. 17. The vertical distribution and movements of the plankton in Lakes Rudolf, Naivasha, Edward and Bunyoni. *J. Linn. Soc. (Zool.)* **40**: 33--69.
- WORTHINGTON, S., and E. B. WORTHINGTON, 1933: Inland waters of Africa. Macmillan, London. xix + 259 pp.

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