Major ion chemistry in a tropical African lake basin

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SUMMARY. The amount of water lost by seepage from Lake Naivasha, calculated as the residual in the water budget, was 5 (1973), 11 (1974) and 20% (1975) of the total water loss. Direct measurements of seepage in near-shore shallows indicated that water entered the lake via ground-water seepage in the northern portion and left the lake in the southern portion. Naivasha lies in a topographic closed basin but is hydrologically a seepage lake; it is distinctive among the lakes lying in the endorheic rift valleys of Ethiopia, Kenya and Tanzania because the water is fresh.

The mean chemical composition (mg l^{-1}) of bulk precipitation collected on two transects across the rift valley near L. Naivasha and at three stations near Nairobi was: Na, 0.54, K, 0.31; Ca, 0.19; Mg, 0.23; SO$_4$, 0.72 and Cl, 0.41. The major inflow, the Malewa River, was largely a solution of bicar-bonate (1.15 m-equiv. l^{-1}), sodium (9 mg l^{-1}) and calcium (8 mg l^{-1}) and carried a total dissolved solid load (kg ha^{-1}) of 62 (1973) and 120 (1974). Total dissolved solids, sodium, calcium and bicarbonate concentrations were inversely related to discharge.

Among the standing waters in the Naivasha basin, sodium and bicar-bonate are predominant and the mean total dissolved solute content (mg l^{-1}) increased from a low under the northern papyrus swamp (217) to intermediate values in L. Naivasha (329), the nearshore lagoons (367) and Crescent Island basin (394) to a high in Oloidien Lake (831). Ion ratios and stability field diagrams indicated that calcite is formed in the Crescent Island basin and Oloidien Lake. Calcite was detected in the sediments of the two basins. Ion ratios also indicated that sulphate was retained in the sediments of the northern papyrus swamp.

Several factors combine to keep L. Naivasha's water fresh. A large fraction of the water supplied to the lake comes from dilute rivers and rain. The lake does not lie in a closed basin, but loses water and solutes via seepage. Exchanges with sediments both in the pelagic and littoral regions of the lake are the major routes for solute movement and biochemical sedi-mentation is a major factor in removal of silica. Both geochemical and biochemical sedimentation account for much of the potassium, calcium, magnesium and bicarbonate removal. Only low levels of the conservative ions, sodium and chloride, are taken up by the sediments, while very low levels of sulphate and fluoride are actually released.

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Introduction

Lake Naivasha is distinctive among the lakes lying in the rift valley of central Ethiopia, Kenya and Tanzania because its water is fresh, an anomaly for an endorheic basin. The fresh water provides a habitat suitable for extensive swamps of *Cyperus papyrus* L., a varied association of littoral aquatic macrophytes (Gaudet, 1977), a diverse avifauna and a commercial and sport fishery. The chemical composition of the waters in the Naivasha basin has been determined by Beadle (1932), Talling & Talling (1965) and Kilham (1971), but no repetitive, systematic analyses spanning a full year have been done. In fact, very few complete year studies of tropical drainage basins inclusive of rivers and lakes have been made. Kilham & Hecky (1973) classified L. Naivasha as a low chloride, high fluoride, sodium bicarbonate water and suggested that such waters develop in warm humid regions where the acquisition of solutes by weathering of the feldspathoid volcanic rocks masks the chemical composition of the rain. No determinations of rainwater chemistry or of rates of weathering in the Naivasha basin or in any other similar basin were available to substantiate the suggestion of Kilham & Hecky.

The objectives of this paper are to quantify the chemical differences among waters of the Naivasha basin, attempt to provide an explanation for Naivasha's freshness and test Kilham & Hecky's hypothesis.

Study area

Geology and soils

The geology of the area is described by Thompson & Dodson (1963) and Noble & Ojiambo (1976). The following account is based on their work.

The Naivasha basin (Fig. 1) lies between the two flanks of the Eastern or Gregory Rift Valley, with the Aberdare mountains and Kinangop plateau on the east and the Mau Escarpment on the west. The lakes lie between Njorowa Gorge and the Eburu Mountains. Evidence from a sediment core (Richardson & Richardson, 1972) and from raised strandlines (Washbourn, 1967), document higher lake levels during the Holocene when surface outflow through Njorowa Gorge occurred.

The volcanic rocks consist of tephrites, basalts, trachytes, phonolites, ashes, tuffs, agglomerates and acid lavas (rhyolite, comendite and obsidian). Craters, fumaroles, hot springs and steam vents are found in several places in the south-eastern and south-western regions.

The lake beds are mainly composed of reworked volcanic material or subaqueously deposited pyroclastics and organic matter produced locally. The structures of the area comprises faulting on the flanks and in the floor of the Rift Valley and slight folding in the Njorowa Gorge. Slight non-conformities are present in the lake beds and can most clearly be seen along the Malewa River drainage.

Ongweny (1973) described the soils occupying the floor of the Rift Valley from Naivasha to Lake Baringo as light grey or brown to pinkish non-calcareous soils. In the high areas of the catchment there are non-calcareous black or grey soils overlying yellow-brown compact subsoils with iron concretions. The soils in the Aberdare mountains and the Kinangop plateau, where the Malewa River originates, are high altitude, young soils with predominantly montmorillonite clays (Rachillo, 1977). In the Rift Valley the soils along the north shore above the lake are generally high in exchangeable Na^+ and K^+ (Makin, 1967). The clay-sized fraction is amorphous and mostly dispersed under the prevailing alkaline conditions. This results in a stable soil which is not susceptible to cracking when dry. The upper layers leach quickly, with an accumulation of $CaCO_3$ typical of the soils in semi-arid regions of Kenya. The soil at the lake edge is less alkaline and more liable to crack during drying (Gaudet, 1977).

Climate and vegetation

The climate is warm and semi-arid (East African Meteorological Department, 1964) Air temperatures are moderate with monthly means varying from 15.9 to 18.5°C. The combination of warm temperatures, low relative humidity and low rainfall make January and February the months with the highest evaporation. Breezes are common in the morning but afternoon winds (11–15 km h^{-1}) are typical. Winds usually come from the south; the importance of easterly and westerly components is dependent on the month. Average rainfall near the lake has a muted bimodality with a main pulse in April and
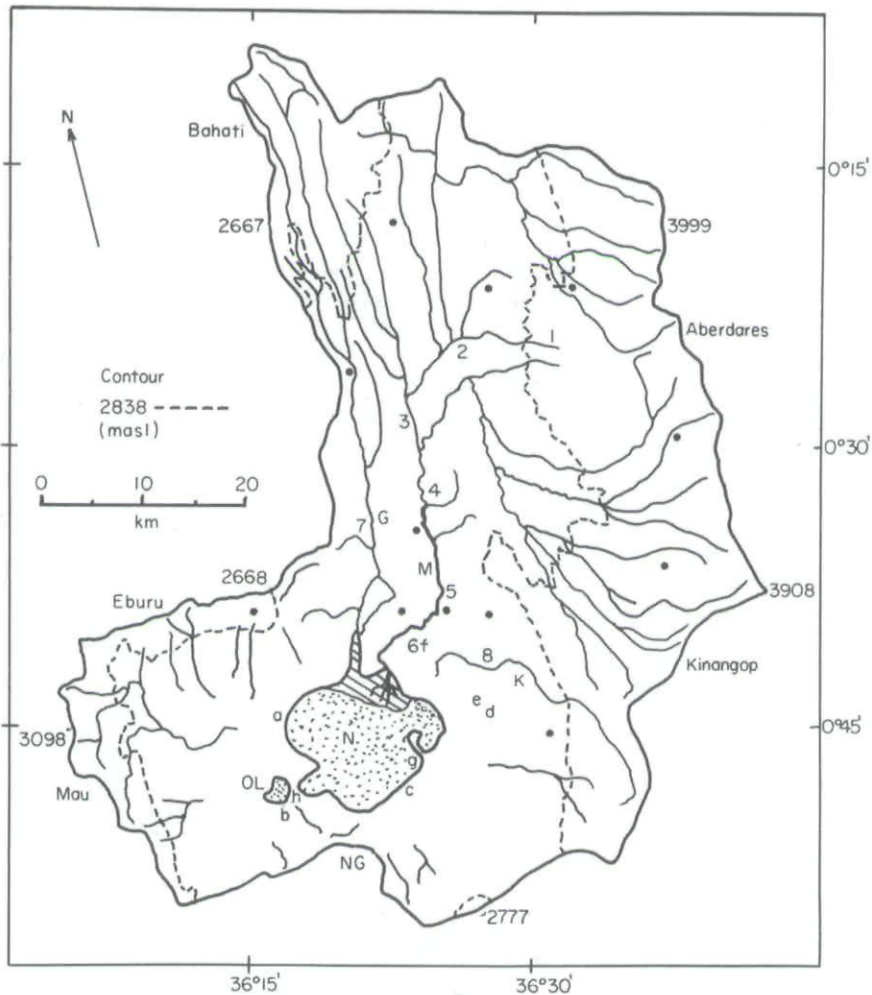
FIG. 1. Naivasha drainage basin. Lake Naivasha (N); Oloidien Lake (OL); Gilgil River (G): Malewa River (M) with six river stations indicated (1–6); Karati River (K). Evaporation station: Naivasha WDD (d); Rainfall stations near lakes: Korongo (a); Kongoni (b); Longonot (c); Naivasha DO (e); K.C.C. (f). Additional rainfall stations throughout the watershed are indicated by solid circles (●). Level gauges at (g) and (h); Njorowa Gorge (NG). River staff gauges at 6, 7 and 8.

May and a minor pulse in November. Irregularities from this pattern are common, as the local rainfall in the area of the main lake is erratic. The highlands surrounding the drainage basin receive more rain than the lakes and valley floor and provide most of the water that maintains the lakes.

The Naivasha basin falls in the Ecological Zone IV of Pratt, Greenway & Gwynne (1966), a zone in which upland *Acacia* woodland is common. The northern parts of the basin, near the origin of the Malewa River, are bordered by submontane tropical evergreen forest. The slopes of the Rift Valley above Naivasha are covered by tropical grassland which grades into bushland typical of the Rift Valley floor. As the Malewa flows along the valley it passes through riverine forests and, about 5 km north of the main lake, it is bordered by papyrus (*Cyperus papyrus* L.) before finally entering North Swamp. The main lake lies directly in an *Acacia xanthophloea* Benth. woodland, with trees up to 35 m tall. The lake-side flora is quite diverse and complicated (108 spp.) and has been described in detail by Gaudet (1977).

Much of the drainage basin is used as

ranchland with some forest clearance and farming in the north on the mountain slopes. The lake area has become an important area for intensive vegetable production under irrigation.

Lake basins

The Naivasha basin contains four topographically distinct bodies of water. The boundaries of the four regions were determined by the tectonic faulting and volcanic activity associated with the formation of the rift valley. The deepest region lies in a volcanic crater in part bounded by an exposed rim called Crescent Island but confluent with the main lake (Fig. 2). The distinctiveness of the depression called Oloidien Lake depends on the water level in the basin. During the first third of this century the width of the connection with L. Naivasha varied from about 100 to 1000 m, and the region was called a bay. During the high water levels in the 1960's a 100-m wide connection occasionally existed and in 1965 a boat channel was dug which maintains contact with L. Naivasha unless its level falls below 1888.4 m above sea level. Gently sloping sides (Fig. 3) and the shallowness of the basin make the area of open water in the main lake, and the areas covered by papyrus and lagoons, sensitive to water level. About 4 km west of the main lake there is a 14 ha soda lake in a volcanic crater.

Daily records of lake level were initiated in 1909 and show repeated fluctuations [Sikes, 1936; Kenya Ministry of Works (Hydrology), 1958, 1964]. Up to 1975 the last major fluctuation was a 5.1 m increase from 1961 to 1964. Subsequently, the level has remained high but had a net decline with yearly oscillations associated with rainy and dry seasons (Fig. 4). The gently sloping northeast section of the main lake contains extensive beds of *Ceratophyllum demersum* L. and has been isolated in the past by papyrus reefs. Along the western and eastern shores of the main lake are shallow lagoons that
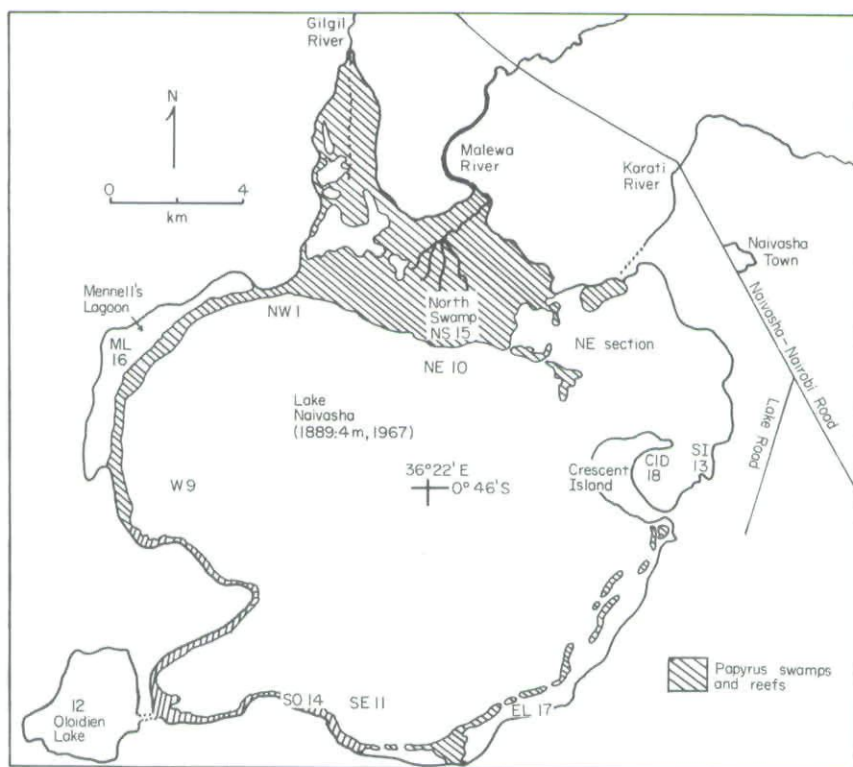

FIG. 2. Lake Naivasha and Oloidien Lake. Sampling stations: Main lake (W9), (NE 10), (SE 11); Oloidien Lake (12); North Swamp (NS 15); Mennell's Lagoon (ML 16), East Lagoon (EL 17); Crescent Island Basin (CID 18). Seepage meters in lake SI 13, SO 14, NW 1, ML 16, EL 17.
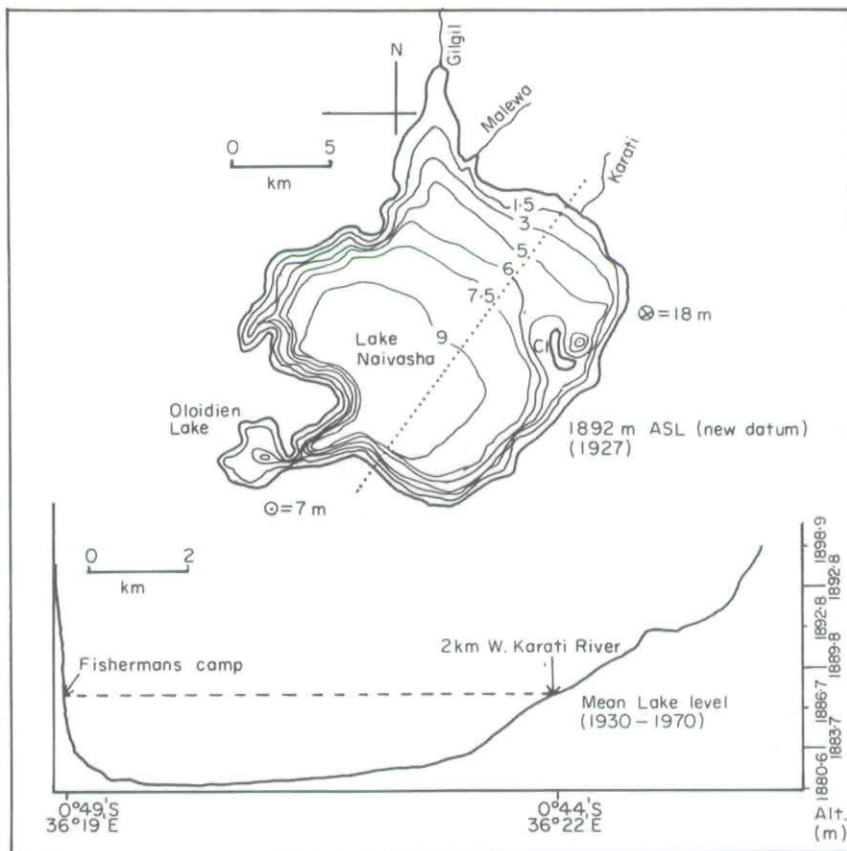
FIG 3. Bathymetric map of Lake Naivasha and section showing gently sloping northeastern area. (The cross section was provided by Dr M. Litterick.)

remain isolated from the main lake by papyrus reefs (Fig. 2) except during occasional periods of very high water. Vincent, Davies & Beresford (1979) have found a highly significant correlation between levels of the main lake and rainfall at highland stations in Kenya with a periodicity of about 7 years.

The rivers and swamps

Perennial flow is maintained in the Malewa River (1730 km² watershed) by rains on the Aberdare mountains and Kinangop plateau. Rains on the Bahati highlands keep perennial flow in the Gilgil River (420 km² watershed) to at least the 2100 m contour but consumption for irrigation and natural losses often eliminate the flow before the lake is reached. The Malewa River accounts for about 90% of the river discharge into L. Naivasha. Flows in the Karati

River and the numerous stream courses on the Eburu range and Mau escarpment (1240 km² watershed) are seasonal and often do not reach the lake as surface water. Only the Malewa and Gilgil Rivers are discussed in this paper. Both of these rivers enter the papyrus swamp on the northern side of the lake and pass under this large swamp for several kilometres before reaching the lake. The water under the swamp is diluted during the rainy season by river water and may receive inflow of lake water during the dry season. The major portion of the northern swamp consists of a floating mat of *Cyperus papyrus* L. rhizomes, roots, debris and humus. Interspersed among the papyrus plants and debris are pockets of water which may be continuous after a heavy rain but are isolated for most of the year. Within the swamp, mixing of the surface and bottom waters occurs, but because the mixing is incomplete the upper
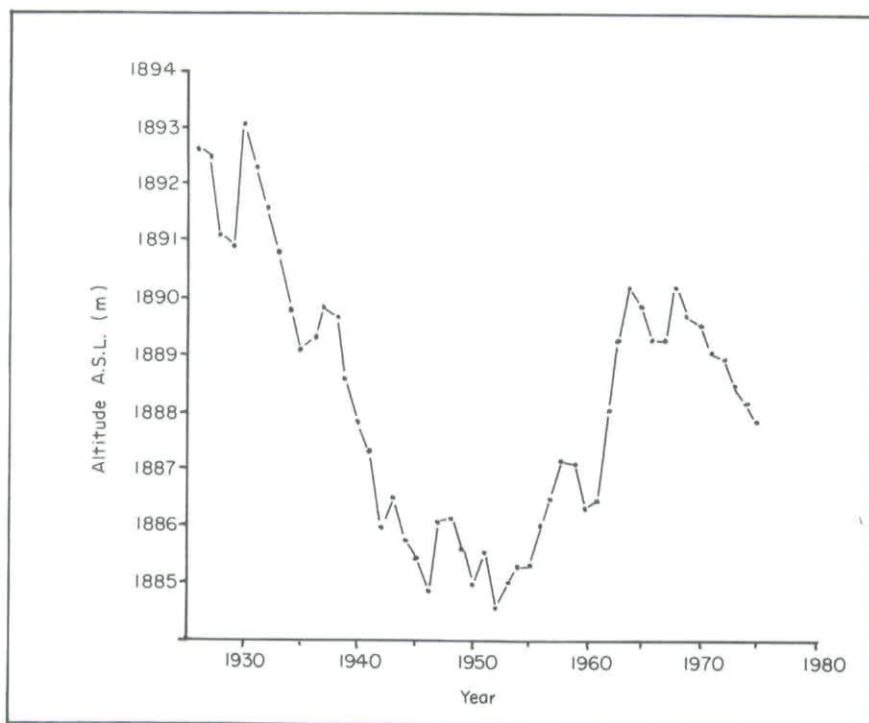
FIG. 4. Annual mean lake levels.

water is usually chemically different from the water near the bottom.

The lakes

Seasonal variations in water temperatures near the bottom of the lakes are slight (18.9–22.0°C) and daily heating and cooling raises and lowers the temperature by only a few degrees near the surface (Melack, 1979). Complete vertical mixing occurs almost every day, and well oxygenated water is usually present from top to bottom (Melack, 1979). The pH values in L. Naivasha (8.6), Oloidien L. (9.2) and Crescent Island Crater (8.4) are alkaline.

Methods

Sample collection

Water samples were collected from seven locations within the Naivasha basin from March 1973 to November 1975, using a Van Dorn or Ruttner sampler in the open water and rivers and a Dussart bottle fastened to a pipe in the swamp. Samples were stored in polyethylene bottles.

Collecting stations are shown in Fig. 2 and described in Table 1. Additional water samples were collected along the Malewa River at five stations (2–6 in Fig. 1) at the end of a dry season (14 February 1976) and at six stations (1–6, Fig. 1) during a rainy season (10 October 1975).

One rainwater sample was collected on the eastern shore of the main lake in a plastic container lined with clean aluminum foil (11 September 1974). Rain samples were also collected at ten stations on a transect from Kericho in the western highlands across the Rift Valley to Thika north of Nairobi in April and August, 1977. The samples were taken using a plastic funnel and a 2.5-l glass bottle set out for a month at each station. Occasionally the bottles overflowed but generally the bottle was less than full. All samples represent a composite sample of dry and wet precipitation. The collectors were located inside standard Meteorological Department compounds in open field stations or near forests. The samples were stored in plastic bottles at room temperature. Pentachlorophenol was added to the April samples as a preservative, but not the August samples. In addition, two samples from each of three stations (Nairobi,

TABLE 1. Location, dates of sampling, area (km^2), volume (m$^3 \times 10^6$), mean depth ($\bar{Z}$, m), and maximum depth (Z_m) of each compartment (December 1974)

Compartment	Sample dates	Sample location	Area	Volume	$\bar{Z}$	Z_m
River (1)	Mar 1973–Apr 1975	Malewa (4.8 km) and Gilgil (9.5 km) N of swamp	—	—	—	—
Swamp bottom (2)	Apr 1974–May 1975	30 m inside North Swamp from lake	11.7	11.7	1.0	2.0
Swamp surface (3)	Apr 1974–May 1975	30 m inside North Swamp from lake	11.7	11.7	1.0	1.0
Main lake (4)	Mar 1973–Apr 1975	500 m off W side, 200 m off SE and NE sides	145	680	4.7	7.3
Lagoon (5)	Mar 1973–Apr 1975	Mennell's Lagoon (W) and East Lagoon (E)	4.5	4.5	1.0	3.0
Crescent Island (6)	Mar 1973–Apr 1975	Middle of depression	2.1	23	11	17
Oloiden Lake (7)	Mar 1973–Nov 1974	400 m off S shore	5.5	31	5.6	8.4

Kericho, Lower Kabete) were collected in plastic collectors by the Meteorological Department (Kenya) and analysed for that Department by the International Meteorological Institute, Stockholm.

Two samples of runoff were collected on the western shore shortly after a heavy rain-storm. Seepage samples were collected in seepage meters (Lee, 1977) placed around the lake perimeter in shallow water. Analysis of water flowing into the meters was carried out as for lake water (see below), but seepage-out water was assumed to be chemically similar to water near the bottom of the southern part of the main lake (SO 14 in Fig. 2) where seepage-out was found to occur.

Laboratory procedures

All samples except the rain water were filtered through Whatman's No. 1 paper and stored at room temperature. Filtration did not affect the solute content of the water in any significant way except for sulphate. Gaudet (1979) has shown that filtration results in lower total sulphur levels, therefore the sulphate levels reported in the present work are probably low.

Conductivity (K_{25} as μS cm^{-1}) was measured with a conductivity bridge on unfiltered water (to the nearest 5%). Sodium and potassium were determined by emission spectroscopy using an atomic absorption spectrophotometer (to the nearest 3%). Calcium and magnesium were measured by EDTA titration with glyoxalbis and eriochrome black indicators (Golterman, 1969; to the nearest 2%). Carbonate and bicarbonate were determined (to the nearest 7%) by titration

with 0.05 M HCl (Golterman, 1969). Chloride and fluoride were measured (to the nearest 2%) by using a specific ion electrode. Sulphate was measured (to the nearest 2%) by titration of excess barium with EDTA after ion exchange (Golterman, 1969). Silicate was determined colorimetrically with zinc chloride reduction of molybdate complex (Golterman, 1969; to the nearest 4%).

Cations in rain were determined by atomic emission (Na, K) and absorption (Ca, Mg) on a 250-ml aliquot taken down to dryness at 80°C and then taken up in 5 ml of 4M HCl. Total S was determined on a dried 20-ml aliquot by reduction and subsequent titration of the sulphide using dithizone (Beaton, Burns & Platau, 1968; limit of detection 5 μg l^{-1}). Chloride was determined at the International Meteorological Institute by titration with an alcoholic solution of mercuric salt using diphenylcarbazone indicator and photometric determination of the end point. This technique has a limit of detection of 2.5 μg l^{-1}.

Determination of hydrologic and chemical balance terms

Rainfall was calculated as the mean monthly total from five stations around the lakes (Fig. 1) and evaporation was recorded from pan evaporation at one station (d in Fig. 1). In Kenya, Edwards & Waweru (1975) found a close agreement between values for pan evaporation and the value(s) for Penman evaporation from open water, E$_o$. They show that average annual evaporation rates from Lake Victoria, obtained by mass transfer (1481 mm) or water balance

(1473 mm), were very similar to evaporation from class A pans at Kericho (1474 mm). Accordingly, in our water budgets we did not use any pan factors. Evapotranspiration from the North Swamp was estimated by multiplying open water evaporation by 0.6, because Rijks (1969) found that papyrus swamps in Uganda lost only 60% compared to open water. The local use of lake water for irrigation was not monitored; it was estimated from records of the maximum yearly allotments of water by the Ministry of Water Development, Nairobi. River discharge based on daily readings of staff gauges in channels of known cross-section was calculated as monthly total discharge at three stations (6, 7, and 8 in Fig. 1). Lake levels were taken as close as possible to the first day of the month at a station near Crescent Island (g in Fig. 1) and at a station in Oloidien Lake (h in Fig. 1). Surface (or sheet) runoff was estimated from the amount of water found in local drains and channels after a heavy rain.

The following components of the hydrologic budget (shown schematically in Fig. 5) were determined each month during 1973, 1974 and 1975; E_p = pan evaporation, monthly total; E_L = lake evaporation (E_p); P = average rainfall, monthly total; I_1 = surface runoff (0.55% of lake side rainfall) into main lake; I_2 = river discharge, monthly total; I_3 = rainfall on North Swamp (P × 11.7 km²); I_4 = rainfall on main lake (P × area calculated from level on first day of each month); I_5 = rainfall on lagoons (P × 4.5 km²); O_1 = evapotranspiration from swamp (E_L × 0.6 × 11.7); O_2 = evaporation from main lake open water (E_L × area calculated from level on first day of each month); O_3 = evaporation

from lagoons (E_L × 4.5); S_L = monthly change in storage of main lake (level on the first day minus the level on last day); C_L = potential change in storage, $\sum_1^5 I_i - \sum_1^3 O_k$; I_6 = seepage into main lake (i.e., $S_L - C_L$ when $C_L > C_L$); O_4 = seepage out and use for irrigation (i.e., $S_L - C_L$ when $C_L > S_L$); water balance for main lake = all inputs minus all outputs, $\sum_1^6 I_i - \sum_1^4 O_k$; I_7 = surface runoff into Oloidien Lake (OL); I_8 = rainfall on OL (P × area calculated from level on first day of each month); I_9 seepage into OL (calculated as above); O_5 = evaporation from OL (E_L × area calculated from level on first day of each month); O_6 = seepage and use for irrigation from OL (as above); S_o = change in storage of OL (as above).

To estimate the solute balance for L. Naivasha the following quantities were calculated each month for 1973 and 1974 (insufficient analyses were available for 1975): M_1 = component mass in rain ($\sum_3^5 I_i$ × conc. in Appendix 1); M_2 = component mass in runoff (I_1 × conc. in Appendix 1); M_3 = component mass in discharge (I_2 × monthly concentrations in rivers); M_4 = component mass in seepage-in (I_6 × conc., in Appendix 1); D_1 = component mass in seepage-out and use for irrigation (O_4 × conc., in Appendix 1); C_m = potential change in storage of components, $\sum_1^4 M_i - D_1$; S_m = change in storage of components (lake vol. of previous month × conc. present in water at that time) – (lake vol. of present month × conc. present in water during present month); M_5 = component mass released each month from sediments (i.e., $S_m - C_m$, when
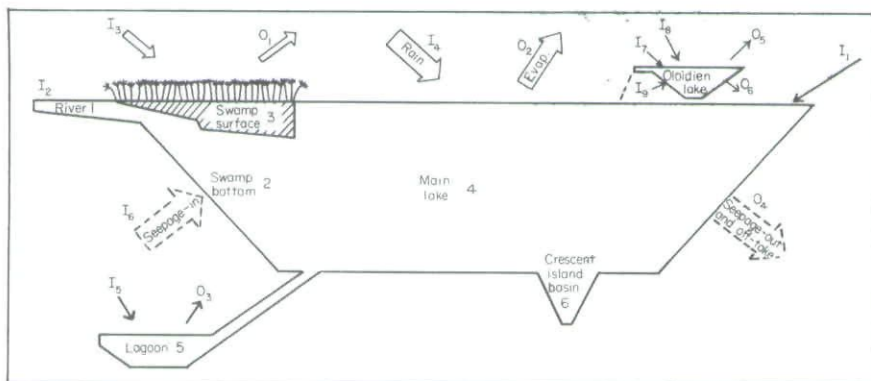

FIG. 5. Schematic diagram of water inputs, outputs, and compartments. See Methods for definitions of terms.

TABLE 2. Hydrologic balances ($m^3 \times 10^6$) for Lake Naivasha and Oloidien Lake

	Naivasha			Oloidien		
Surface runoff	0.6	0.7	0.4	0.0	0.0	0.0
River discharge	90.8	204.0	260.5	—	—	—
Rainfall	106.1	114.2	77.1	3.6	3.8	2.7
Seepage-in	37.0	42.3	50.8	4.1	6.0	7.0
Total input	234.5	361.2	388.8	7.7	9.8	9.7
Evapotranspiration	14.3	13.2	13.3	—	—	—
Lake evaporation	309.5	276.0	278.2	11.3	10.1	10.1
Seepage-out	17.6	36.6	78.3	0.0	0.6	0.0
Irrigation off-take	7.0	14.0	15.0	—	—	—
Total output	348.4	339.8	384.8	11.3	10.7	10.1
Change in storage (calc. by balance)	− 113.9	+ 21.4	+ 4.0	− 3.6	− 0.9	− 0.4
Change in storage (calc. from level change)	− 113.9	+ 21.4	+ 4.0	− 3.6	− 0.9	− 0.4

$S_m > C_m$); D_2 = component mass taken up each month by sediments (i.e., $S_m - C_m$ when $C_m > S_m$); Chemical balance = all inputs minus all outputs,

$$\sum_1^5 M_i - \sum_1^2 D_k.$$

In some cases monthly analyses of river and/or lake waters were missing, in which case they were estimated from previous months. Insufficient analyses were done for Oloidien Lake to calculate monthly budgets. We have grouped all exchange processes between water and sediments into two components: sediment uptake (D_2) and sediment release (M_s). Lerman & Brunskill (1971) suggest that the errors in estimates of exchanges between sediments and water, when calculated as the difference between inputs and outputs, can easily be 20–30%.

Results

Water balance and seepage

River discharge, lake level changes in Naivasha and Oloidien, evaporation, and rainfall data for the period 1973–1975 are summarized in the annual water balances for the main lake and Oloidien Lake (Tables 2 and 3); complete data sets are available from the authors. The water balance is predominantly controlled by river discharge, rainfall and evaporation (Table 2). A detailed description of water tables and directions of seepage in the north-east section of the main lake, based on recent work, is shown in Fig. 6. These general directions of seepage were confirmed by our seepage-meter readings (Table 4). Seepage-in occurred in the meters set along the north-east and north-west shores, whereas seepage-out was detected along the south and south-east shores. The seepage flux rates (Table 4) can be applied only to near-shore regions because seepage-in usually decreases logarithmically from the shore toward deeper water (McBride & Pfannkuch, 1975; Lee, 1977; Lock & John, 1978). The annual rates of seepage were calculated as the residual term of the hydrologic balance (Table 2); they include the suite of unquantified errors associated with each component of the budget (cf., Winter, 1978).

TABLE 3. Rainfall and runoff in Malewa River watershed

	1973	1974	1975
Average rainfall on watershed (mm)*	693	836	789
Runoff from watershed via Malewa River (mm)	52	118	151
Runoff as percentage of rainfall	7.5	14.1	19.1

*Calculated by two axis method (Bethlahmy, 1976) based on fourteen stations.
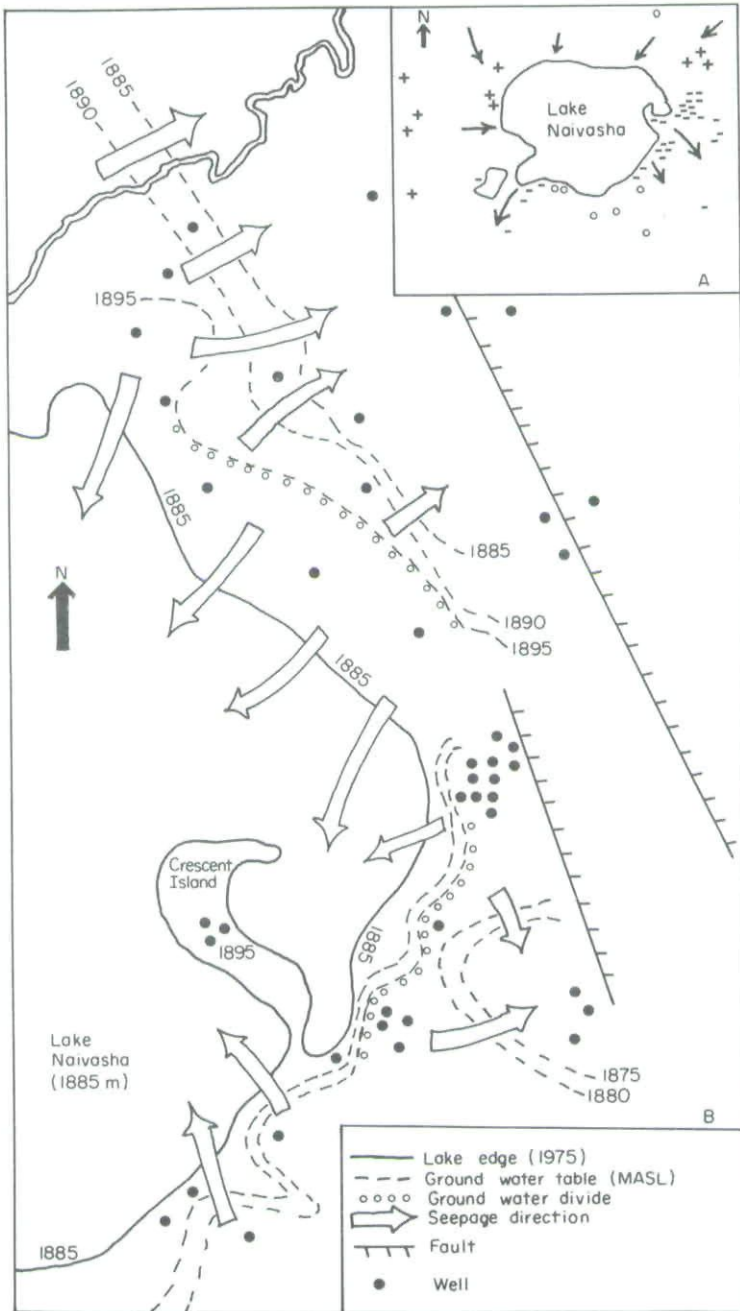
FIG. 6. Map of water seepage based on Thompson & Dodson (1963). Borehole water above (+), below (−), or at same level (o) as main lake (Inset A). Detail of water tables in the NE section of the main lake (after VIAK, 1974, unpublished) (B).

TABLE 4. Location of seepage meters and seepage flux rate for Lake Naivasha. Seepage meters cover 0.26 m^2

	Meter location*	Distance from shore (m)	Depth (m)	Dates	Mean seepage (ml day^{-1})
East	SI-13	30	1.8	4 Oct–3 Dec 1977	+275
Southeast	EL-17	10	1.7	16 Nov–28 Nov 1978	−318
South	SO-14	10	2.0	16 Oct–4 Nov 1977	−380
West	ML-16	20	1.2	15 Oct–10 Nov 1977	+473
North	NW-1	10	1.0	28 Jan–11 Feb 1978	+ 36

*See Fig. 2

Solute inputs to standing waters

Surface runoff and seepage. Chemical analyses of two surface runoff samples and of water collected in seepage meters are listed in Appendix 1. The analyses referred to as seepage-out samples were done on collections of near-bottom lake water. The surface runoff contained considerably higher proportions of potassium, calcium and magnesium than the seepage, river or lake water.

Atmospheric precipitation. Chemical analyses of precipitation collected on two transects across the rift valley and one collection at L. Naivasha are listed in Appendix 1. The difference between the total charges of cations and anions of the weighted means indicates there were un-measured ions and/or analytical errors of up to 29% of the means. Hydrogen ions are not included in the charge balance calculation because so few pH measurements are available.

Riverine solute transport. The Malewa and Gilgil Rivers are dilute (Table 5) and contain a predominance of bicarbonate (Appendix 1). In the Malewa River sodium and calcium are the major cations, while in the Gilgil River sodium is the major cation. The chemical composition of the Malewa River varies seasonally from its head-waters to its mouth (Table 6). At the end of one dry season a gradient of increasing concentration from stations 1–6 occurred for all major ions except chloride. On the other hand, during a wet season no regular trend in concentration existed. The peak at station 3 may have been caused by the input of more saline water between stations 2 and 3 and subsequent dilution by the Turasha River between stations 3 and 4.

The relationship between discharge and chemical composition was tested using regression analysis (Table 7). There was a very significant relationship between conductance and discharge ($r^2 = 0.84$; $P<0.001$) and between the concentration of two major components of conductance, ie. bicarbonate ($r^2 = 0.74$; $P<0.001$) and sodium ($r^2 = 0.61$, $P<0.001$) and discharge.

Chemical weathering. The Malewa River drains predominantly trachytes, tuffs and welded tuffs but its headwaters begin in the strongly alkaline lavas and olivine basalts that

TABLE 5. Conductance (K$_{25}$, μScm^{-1} at 25°C), total ionic content and charge and balance as per cent of difference between cations and anions for the seven compartments. n is the number of samples

Compartment	K$_{25}$	Total inonic content (mg l^{-1})	(m-equiv. l^{-1})	Charge balance (% difference)	n
Malewa River	120	122	2.57	10.5	20
Gilgil River	131	138	2.87	10.1	9
Swamp bottom	243	217	5.14	5.2	22
Swamp surface	329	289	6.92	3.0	22
Lake Naivasha	363	329	7.89	2.8	21
Lagoons	432	367	8.85	2.7	29
Crescent Is. depression	457	394	9.35	2.1	11
Oloidien Lake	983	831	19.43	7.5	13

TABLE 6. Chemical composition (mg l^{-1}) and conductance (K_{25}) along the Malewa River from origin (N) to mouth (S) at stations shown in Fig. 1.

Date	14 February 1976					10 October 1975					
Discharge ($m^3 s^{-1}$)	0.81					20.80					
Season	End of dry season					Wet season					
Stations	2	3	4	5	6	1	2	3	4	5	6
K_{25}	48	58	80	98	121	89	72	174	66	72	78
Na	3	4	6	7	9	12	9	21	8	7	8
K	2	3	4	5	5	2	2	10	2	3	3
Ca	4	4	6	8	9	11	7	11	7	8	7
Mg	0	1.2	4.4	7.9	10.1	3.0	2.6	7.6	4.8	10.8	5.3
HCO_3	22	23	53	65	85	61	43	97	58	58	46
SO_4	8	7	7	10	11	33	20	31	15	15	13
Cl	7	6	5	7	7	7	8	10	7	7	8
F	0.1	0.2	1.0	1.5	2.0	—	—	—	—	—	—
SiO_2	4	4	5	9	7	23	21	25	22	24	24

form the Aberdare and Kipipiri ranges. Because the specific weathering rates of these rocks are not known we compared the weight ratios of K, Ca, Mg, SO_4 and Cl to Na in known examples of the major rocks from the Eastern Rift Valley (Saggerson, 1970) with the weight ratios in the Malewa River (Appendix 2).

Although there is no detailed petrologic map of the Naivasha basin, it is possible to estimate, from Saggerson's (1970) geological map of the Eastern Rift Valley, the areal extent of the major rock-types in the Naivasha basin: 70% trachytes, tuffs and welded tuffs; 10% rhyolites and obsidians; 10% strongly alkaline lavas from central volcanoes (e.g., basanite, nephelinite, phonolite); 5% mildly alkaline lavas from central volcanoes (e.g., olivine basalt, quartz trachyte, welded tuff, kataphorite trachyte, soda rhyolite, obsidian); 5% basalts and olivine basalts. Thus,

the second and third columns in Appendix 2 represent the predominant rocks.

Differences in quality of sediments and water chemistry

Plagioclase feldspar is common in the sediments of most regions and microcline and orthoclase occur in L. Naivasha, Oloidien Lake and Crescent Island basin. These feldspars are all detrital phases and are common in most earth surface environments.

Sediment samples from the Malewa River were mainly amorphous material with a trace of poorly crystallized montmorillonite. Trace amounts of the latter were also detected in the sediments under the North Swamp, but montmorillonite was not detected in any other region. Vermiculite and chlorite were detected near the shore in L. Naivasha and in lagoon sediments.

The regional differences in the concentration of dissolved solutes is illustrated in Fig. 8 and summarized in Appendix 1. On the basis of the water analyses, stability field diagrams were constructed for sodium, potassium, calcium and magnesium (Fig. 7). The diagrams indicate that if the waters were in equilibrium with minerals, they would be in equilibrium with kaolinite, Ca-zeolite (leonhardite), Mg-montmorillonite and K-feldspar (microcline).

TABLE 7. Values of constants a and b, the coefficient of determination (r^2) and the variance ratio (F) for regressions ($Y = a + b \log_{10} X$) of the chemical composition of Malewa River (Y) on discharge (X), where Y is the chemical concentration in m-equiv. l^{-1} except for SiO_2 (mg l^{-1}) and conductance (μS cm^{-1}) and X is the discharge in $m^3 s^{-1}$; $n = 20$ for each solute

	a	b	r^2	F
Conductance	153	−75	0.84	88.34
SiO_2	13.7	8.1	0.25	5.97
Na	0.48	−0.22	0.61	28.79
K	0.24	−0.04	0.45	14.98
Ca	0.47	−0.17	0.46	15.37
Mg	0.32	−0.16	0.25	5.95
HCO_3	1.39	−0.56	0.74	51.16
SO_4	0.16	−0.07	0.26	6.21
Cl	0.14	−0.04	0.15	3.12

Discussion

Water balance and seepage

The water balance of the main lake is predominantly controlled by river discharge,
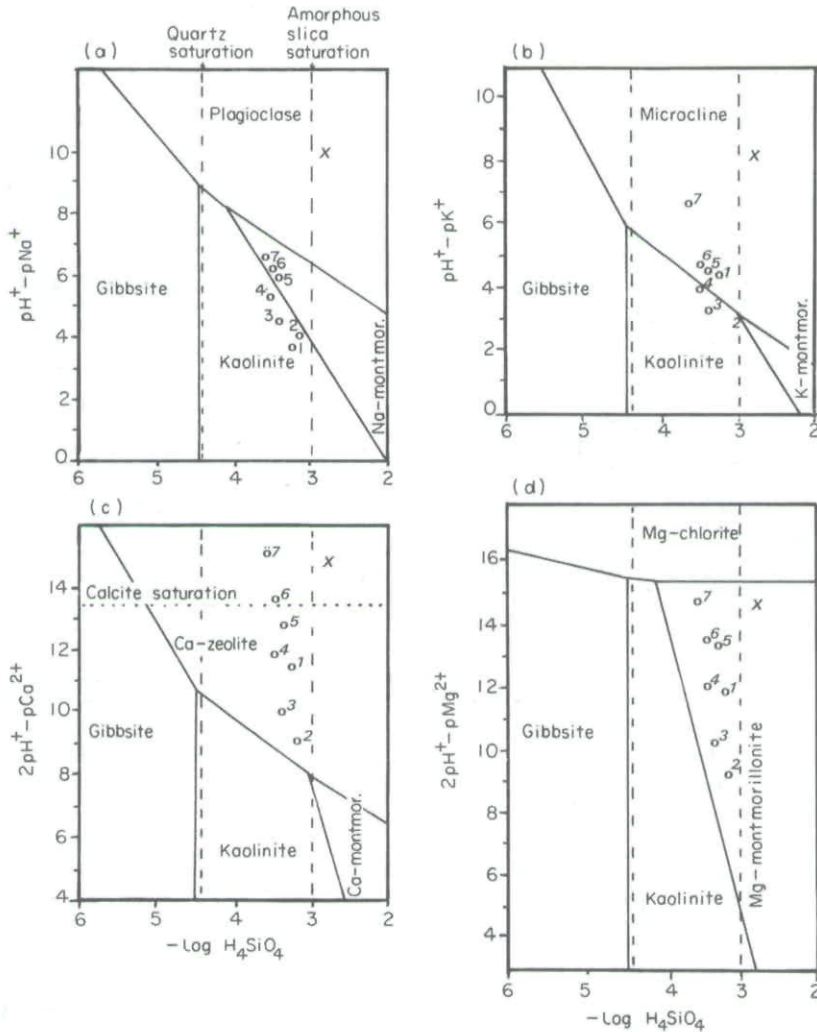
FIG. 7. Stability field diagrams for (a) sodium, (b) potassium, (c) calcium, and (d) magnesium, after Helgeson *et al.*, 1973. Points for closed basin soda lake (*X*) from Stumm and Morgan (1970). Numbered open circles refer to compartments listed in Table 1.

rainfall and evaporation (Table 2). The inverse relationship between lake evaporation and total input is caused by cloudiness and lower air temperatures which accompany high inputs (e.g., in 1974). Conversely, an increase in evaporation occurs during dry years (e.g. 1973) because of the intense insolation (even as the lake area decreased, providing a smaller evaporative surface). There are anomalies in local rainfall with less falling directly on the main lake even during a year when higher rainfall occurs in the catchment (e.g., 1975).

Lake Naivasha lies in a topographically closed basin but is hydrologically a seepage lake, with outflow and a portion of the inflow occurring as groundwater flow. The lake has been called a hydrographic window by Thompson & Dodson (1963): It is '. . . an outcrop of the water-table in an area of internal drainage and only slight runoff. Free underground movement of meteoric waters is allowed by the porosity of pumiceous, scoraceous or ashy beds and other pyroclastics, which constitute about 80 per cent of the known volcanics in the area. The lava flows too are usually well-jointed and often vesicular, allowing free movement to meteoric
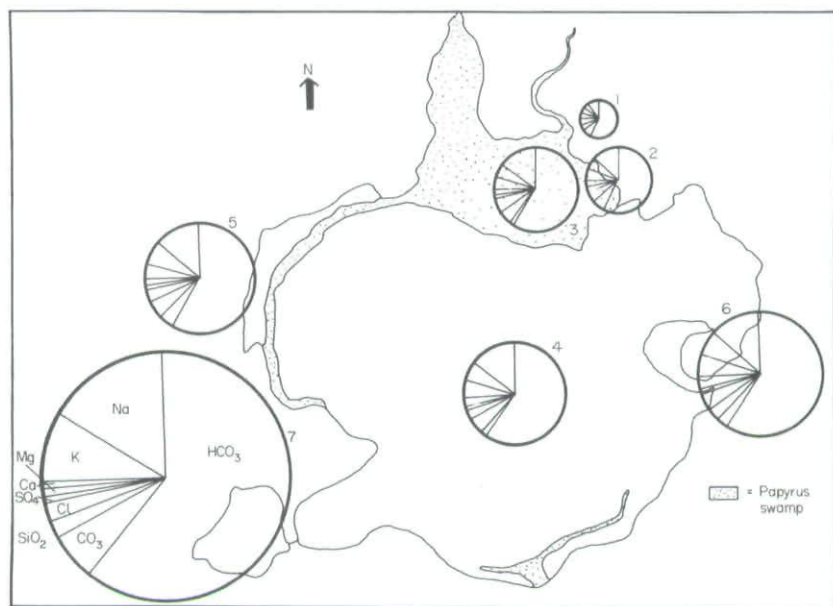
FIG. 8. Schematic diagram showing differences in water quality in the different compartments. Area of circle is proportional to all dissolved solids. Co$_3$ is lacking in compartments 1 and 2.

water. The absorptivity of the Naivasha area is well known, within a few hours after rain most surface water has disappeared'. The early theories proposing the existence of a subterranean river flowing from the main lake have been summarized by Beadle (1932) and Thompson & Dodson (1963). As yet, there is no evidence for such an outlet but there is evidence for seepage. However, compared to river discharge and rainfall, seepage plays a minor role in the main lake water balance, and the lake level fluctuates much as in closed basin lakes. Seepage here refers to water movement in the shallow portions of the littoral zone, especially where soil which has been disturbed by sun-cracking or macrophyte root growth is then inundated.

Water input by seepage occurs in the north-east and north-west sections, and seepage out in the south and south-east sections of the main lake. This was earlier suggested by Thompson & Dodson (1963) based on differences in water level in lake-side boreholes compared to the level in the main lake. These general directions for seepage were confirmed by our seepage

meters. We found that the rate of seepage-in seemed to be related to the amount of rainfall on the catchment. In meter ML-16, for example, the usual daily rate of seepage-in (237 ml day^{-1}) increased by 184% 2 days after a heavy rain-storm in the hills west of this station. This is to be expected because seepage meters in temperate lakes are known to collect more seepage water during rainy periods than dry periods. Downing & Peterka (1978) in Lake Metigoshe, North America, found a significant relationship between ground-water seepage inflow and daily rainfall. Thus the increase in rainfall in the Naivasha watershed (Table 3) resulted in greater river discharge and seepage-in, while evapora-tion from the lake was less; consequently the level of L. Naivasha rose. A rise in lake level, however, also causes flooding of littoral regions and increases water depth, both of which will cause a lake to lose water through its bed. As a result, seepage-out was greater in 1974 and 1975 (Table 2).

Oloidien Lake, unlike the main lake, is almost entirely dependent on seepage.

Atmospheric precipitation

Although precipitation samples were not collected during the same period as our river and lake samples and include a greater area than the Naivasha basin, no other data are available for the rift valley in Kenya. Furthermore, because of the wide geographic spread of the samples, they may be judged as representative of the range of chemical composition of precipitation on the Naivasha basin. However, throughfall was not included in these analyses.

Without additional rainfall data from other parts of eastern Africa and more frequent samples from the Naivasha basin, an evaluation of the sources of the solutes in rain is premature.

Visser (1961) made seventy-eight chemical analyses of rain that fell at Kampala, Uganda, during 1958 and 1959. These remain the only full year of major ion analyses of rain reported for eastern Africa. The median values reported by Visser were similar to our data but the extreme ranges (in parentheses) of his data confound detailed comparisons: Na, 1.7 (0.1–203.1); K, 1.7 (0.1–690); Ca, 0.05; Cl, 0.9 (0.01–8.1); SO_4, 1.8 (0.1–68.9); all as mg. Visser concluded that Lake Victoria and local dust were the principal sources for these solutes.

River discharge

The ionic input from precipitation directly on to the lake is minor compared to the solute contribution from the rivers. The chemical composition of both the Gilgil and Malewa are similar to rivers draining other volcanic regions in east Africa such as the western slopes of the Mau escarpment and the Nkuruman escarpment (Jones, Eugster & Rettig, 1977) and Mt Elgon and Karamoja, Uganda (Viner, 1975).

An important question in regard to African rivers is the supply rate of the different elements, and the relationship of supply rate to rainfall and discharge. For the Amazon River, Gibbs (1972) found that the Cl/Na ratio by weight (1.6) approximated the value of sea water (1.8) during periods of maximum discharge. This supported the hypothesis that both ions were derived principally from rain water during the rainy season. During minimum discharge the ratio gradually shifted to 1.0, and it could then be assumed that the change in ratio was due to an increase in sodium derived from weathering in

the basin because chloride ions have so few sources other than precipitation. On the Malewa River the same general effect is seen if Cl/Na ratios are calculated by weight (Table 8).

It was also possible to directly calculate the percentage of each ion derived from rain falling on the catchment (Table 9). Although net accumulation and year-to-year variation resulted in percentages sometimes exceeding 100, the 3-year mean does show that some sodium and most potassium, sulphate, chloride and magnesium could come from the rainfall on the catchment. Some sodium and most calcium are derived from materials in the basin, while bicarbonate is derived from weathering reactions.

Further evidence for the nature of the relationship between the discharge of the Malewa River and the concentration of solutes is provided by regression analysis (Table 7), where conductance and two major constituents (sodium and bicarbonate) have strong inverse relations with discharge, while magnesium, sulphate and especially chloride show a weak inverse relation. Silica has a weak direct relation with discharge.

In an ideal dilution model with constant supply rate a 2-fold increase in discharge dilutes the concentration by half. However, for sodium in the Malewa River an increase in discharge of 4.5 times is needed to halve the concentration. The implication of this deviation from the model is that the supply rate is changing for solutes showing strong to moderate inverse relationship to discharge. A second model is that the concentration remains constant as discharge changes. Two mechanisms that can produce this situation are: (a), rapid equilibration between the water and soil through which the water is percolating and (b) the concentration of the solute in the river is at saturation (Golterman, 1975a). The second model does not apply to rain-derived electrolytes, such as chloride, but does apply to those solutes in the Malewa with weak relationship to discharge, such as silica. Evidence for the rapid release of silica when discharge increases is provided by the relationship between the ratio of silica to conductance (SiO_2/Conductance $\times 100 = Y$) and discharge ($m^3 s^{-1} = X$): $Y = 18$ log $X + 9.3$; $r^2 = 1.56$, F $= 15.4$, $n = 20$. This strong direct relationship indicates that the silica concentration increases more rapidly than the

TABLE 8. Discharge and Cl/Na weight ratios for the Malewa River

	Jan 75	Mar 75	Apr 75	Oct 75	Feb 76
Discharge ($m^3 s^{-1}$)	1.7	0.7	0.8	20.8	0.8
Cl/Na	0.4	0.6	0.9	1.0	0.8
% Na from rain on catchment	22	33	48	56	44

*Period of maximum discharge.

concentration of the major constituents of the conductance when the discharge increases.

Although an inverse relation between discharge and total dissolved solids is common, the relations for the individual solutes are often more complex (cf. Johnson et al., 1969). For example, when Likens et al. (1967) pooled data from six watersheds in the Hubbard Brook basin, calcium and magnesium did not show a significant realtionship between concentration and discharge, sodium showed an inverse relationship, while potassium tended to show a direct relationship. In contrast, Johnson & Needham (1966) reported a strong inverse relationship between calcium, magnesium and sodium concentrations and discharge in mountain streams of California. The insensitivity of the silica concentration to changes in discharge is well documented (Davis, 1964; Edwards & Liss, 1973) although not thoroughly understood (Kennedy, 1971). Dissolution of solid phases, biological activity and especially sorption reactions appear to be important regulators of the silica concentrations.

Chemical weathering

The absence of chloride and sulphur in the most common rock-types in the basin (second and third columns in Appendix 2) is evidence that nearly all the chloride and sulphur in the

drainage from the basin is derived from precipitation. In comparing the other possible solutes we chose sodium as a standard for comparison because it is the most conservative, soluble ion found in high concentrations in igneous rock and African waters (Kilham, 1971). Because the ratio of K/Na is greater in almost all the rocks than in the river, the rocks are a probable source of potassium. Although the Mg/Na and Ca/Na ratios are low in the trachytes, welded tuff, phonolites and obsidians, they are high in the olivine basalts, a probable source for these two cations. All the rocks have a high silica content and, because they are volcanic, much of the silica is present in non-crystalline phases which have a relatively high solubility. Thus, the rocks are a probable source of silica in the river. Fluoride is absent in the predominant rock-type, but in Africa there is ample evidence that the rocks are the source of this element (Kilham & Hecky, 1973).

The amounts of dissolved solutes carried by the Malewa River are compared (Table 10) with the solute loads of several well-studied rivers. In order to standardize the data, a ratio of load/precipitation is used. The ratios for the Malewa fall within or close to the range for the other rivers, with the exception of bicarbonate. When compared to Meybeck's (1977) typology of transport by the major rivers of the world, the total dissolved load carried by the Malewa River is similar to the loads carried by rivers with low

TABLE 9. Percentage rain input of solutes discharged by the Malewa River into Lake Naivasha (calculated from rainfall on watershed, mean chemical composition of precipitation and solutes in the Malewa River discharge)

	Na	K	Ca	Mg	HCO_3	SO_4	Cl
1973	87	154	34	99	2	152	172
1974	48	93	21	88	1	122	70
1975*	69	27	21	66	2	79	55
Mean	68	91	25	84	2	117	99

*Based on data for only five monthly readings with seven other months estimated from regression equations (Table 10).

TABLE 10. Dissolved transport by the Malewa River (mean of 1973 and 1974) compared with streams from other regions. Dissolved loads (expressed as kg ha^{-1} year^{-1}) and load/rainfall ratio (using litres of precipitation per ha)

	Malewa River load	(Ratio)	Velen (Sweden)	(Ratio)	Pond Branch (E.Centr.USA)	(Ratio)	Hubbard Brook (NE-USA)	(Ratio)
TDS	91	(11.8)	—		54	(5.5)	150	(11.5)
Na	6.8	(0.9)	9.2	(1.3)	3.5	(0.4)	7.2	(0.6)
K	2.1	(0.3)	2.5	(0.4)	2	(0.2)	1.9	(0.2)
Ca	5.7	(0.7)	11.1	(1.5)	3	(0.3)	13.7	(1.1)
Mg	1.9	(0.3)	3.2	(0.4)	1.8	(0.2)	3.1	(0.2)
HCO$_3$	55	(7.1)	—	(—)	16.7	(1.7)	7.6	(0.6)
SO$_4$	4.2	(0.5)	9.4	(1.3)	3.9	(0.4)	53.8	(4.1)
Cl	2.5	(0.3)	—		4.4	(0.5)	4.9	(0.4)
F	0.3	(0.04)	—		—	(—)	—	(—)
SiO$_2$	12.1	(1.6)	—	19	(1.9)	(1.9)	38.4	(3.0)
Precipitation (mm)	773		720		983		1300	
Reference			Eriksson (1974)		Cleaves *et al.* (1970)		Likens *et al.* (1977)	

runoff, medium relief and warm temperatures, as expected from the characteristics of the Malewa watershed.

The combination of our estimates of the solute load of the Malewa River and our estimates of the contributions of the principal sources of the solutes, allows an approximation of the rates of chemical denudation for the Malewa basin. As Janda (1971) outlines, detailed evaluation of rates of chemical denudation requires reliable analyses of bulk precipitation, the relative contribution of overland flow, interflow and baseflow to river discharge, and an understanding of the chemical reactions that occur as water moves through organic and mineral soils and rocks (see for example, Kennedy & Malcolm, 1977; Likens *et al.*, 1977; Cleaves, Godfrey & Bricker, 1970). Although not so detailed as this outline, our analyses do permit one of the few calculations of chemical denudation for an equatorial watershed. Dunne (1978) reported the first measurements of true chemical denudation in the tropics done in forty-three Kenyan river basins that varied in annual rainfall from 250–3000 mm.

In the terminology of Janda (1971) we made a semi-quantitative computation of the principal denudation and non-denudation components of the river water by assuming that solutes missing or present as only minor constituents in the rocks of the watershed are not important denudation components. Bicarbonate, sulphate and chloride are thus non-denudation components. As is typical for the incongruent solution of aluminosilicate rocks, the atmosphere and respiration of soil biota are sources of bicarbonate (Stumm & Morgan, 1970). A portion of the cations is derived from atmospheric precipitation (Table 11). When denudation and non-denudation components are distinguished in this manner, only 21% of the mean weight of total dissolved solids carried by the Malewa River in 1973 and 1974 was derived directly from the underlying rocks.

Although this result indicates that atmospheric precipitation is an important source of solutes to the Malewa watershed, a different result could emerge if longer-term, more intensive data were available. For example, Johnson (1971) states that the solute budgets for Hubbard Brook showed a much greater contribution from chemical weathering after 6 years than after only 2 years. Furthermore, a portion of the cations in bulk precipitation is derived from terrestrial dust and burning vegetation and can be considered true components of chemical denudation. Although we did not measure the proportion of the atmospheric input derived from local sources, we can apply the approach used by Dunne (1979) to estimate the proportion. If we assume that all the chloride is derived from the ocean and that the amount of the other solutes derived from the ocean retain the same ratio to chloride as in the ocean, we can calculate the oceanic contribution to riverwater concentrations with the equation

TABLE 11. Estimated mean annual solute budget for Lake Naivasha (1973, 1974), expressed as per cent of total inputs and total outputs

	Na	K	Ca	Mg	HCO₃	SO₄	Cl	F	SiO₂
Inputs									
River discharge	11	7	12	21	25	11	10	5	14
Rainfall	0.5	0.9	0.3	0.5	0	1.2	1.4	—	—
Seepage	17	30	13	26	24	7	24	8	12
Sediment exchange*	72	61	79	52	51	81	73	86	74
Outputs									
Seepage	15	11	8	11	16	2	10	9	3
Sediment exchange*	85	89	92	89	84	98	90	91	97

*Residual term calculated by difference after accounting for change in storage in the lake.

$$\frac{[Cl^-]_{river} \, [Cation]_{ocean}}{[Cl^{-1}]_{ocean}} = Cation]_{RE} \qquad (1)$$

The brackets indicate concentrations and RE (rain, evaporation) indicates that the cation concentration in rain has been increased by evaporation. If these values are subtracted from the solute concentrations in the Malewa River, the remainder can be attributed to chemical denudation inclusive of terrestrial dust and vegetation burning. This procedure increases the yield of cations from denudation and the mean weight of total dissolved solids carried by the Malewa River in 1973 and 1974 attributed to chemical denudation is increased to 30%.

Kilham & Hecky (1973) emphasized the importance of chemical weathering of the rocks as the source of major solutes in Lake Naivasha. The incongruent solution of aluminosilicate rocks, such as occur in the Naivasha basin, can be described by a schematic equation from Stumm & Morgan (1970):

Cation Al-silicate + H_2CO_3 + H_2O $\longrightarrow$
    HCO_3^- + H_4SiO_4 + Cation + Al-silicate
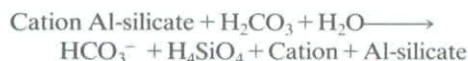
When weathering is evaluated, based on this equation, the bicarbonate is considered as a weathering product, although it is actually derived largely from gaseous CO_2, not from carbonates. Gibbs' (1970) scheme for the control of water chemistry is based on logic similar to Kilham & Hecky's. In fact, Gibbs calculated the contributions from rocks simply as the difference between river discharge and precipitation. When weight ratios of Na/(Na+Ca) and Cl/(Cl+HCO₃) for L. Naivasha and the Malewa River are plotted against their total dissolved solids, both waters fall in the region of Gibbs' scheme where rock dominance is expected.

These perspectives differ from Janda's concern for the actual chemical denudation, and our estimates of the non-denudation and denudation components in the Malewa River discharge are not comparable to Gibbs' calculation of the contribution from rocks. If we do apply Gibbs' method to our data, 80% of the mean weight of total dissolved solids carried by the Malewa River in 1973 and 1974 is attributed to chemical weathering reactions. Bicarbonate accounts for 75% of the weight of solutes derived from the weathering reactions.

Regional and seasonal differences among the standing waters

The total dissolved solute content increases from a low within the northern papyrus swamp to intermediate values in L. Naivasha, the lagoons and Crescent Island basin and to a high in Oloidien Lake (Fig. 8). Within all these regions sodium and bicarbonate are predominant as is typical in many fresh waters in Africa (Kilham, 1971; Talling & Talling, 1965). In comparing water quality in the different regions of the Naivasha basin, we again used sodium as a standard. In some lakes, such as L. Turkana, this cannot be done because sodium is removed by precipitation in the montmorillonite phase (Cerling, 1977). However, in L. Naivasha there is no evidence for montmorillonite precipitation; also, even though sodium is partially derived from weathering, once in solution in the lake it is highly correlated with the other conservative ion, chloride. Thus, in order to interpret regional differences, ion/Na ratios were computed (Appendix 1). The ratios should remain constant if only dilution and evaporative concentration

cause the differences among the regions. The similar ratios for potassium, chloride and bicarbonate in all the regions indicates that evaporative concentration is the main cause for the differences. The Ca/Na and Mg/Na ratios were slightly lower in Crescent Island basin and much lower in Oloidien Lake than in the main lake. These low ratios, the presence of calcite in the sediments and the fact that both regions are supersaturated with respect to calcite (Fig. 7c) indicate that the precipitation of calcium and magnesium occurred. The disparate ratios of SO₄/Na between the rivers and the standing waters suggests that sulphate was lost in the northern papyrus swamp. According to Gaudet (1979) this depletion is due to sorption onto small particles because very little biological reduction of sulphate occurs in this swamp. In addition, uptake of sulphate by papyrus must occur because sulphur is a component (*c.* 0.6% of dry weight; Gaudet, 1976) of this plant.

Silica is also depleted in the water under the swamp. Again this makes up part of the plant (1.2%; Gaudet, 1979) and uptake would be expected. Stagnation of water under the swamp during the dry season results in deposition of detritus and fine particulate material which is high in silica (Gaudet, 1976) and may be a source of silica during the dry season. Once out of the swamp the silica and sulphur ratios remain low but fairly constant until Oloidien Lake where they both drop to minimum.

Seasonal changes in total dissolved solids, measured as conductivity, occur in each of the compartments (Fig. 9). Throughout 1973 river discharge and rainfall were low. Conductance at this time increased in each region of standing water except for a decline in the lagoon between October and December. During mid-1974 rainfall and river discharge increased and conductance in general declined. There was less similarity of changes among the regions at the
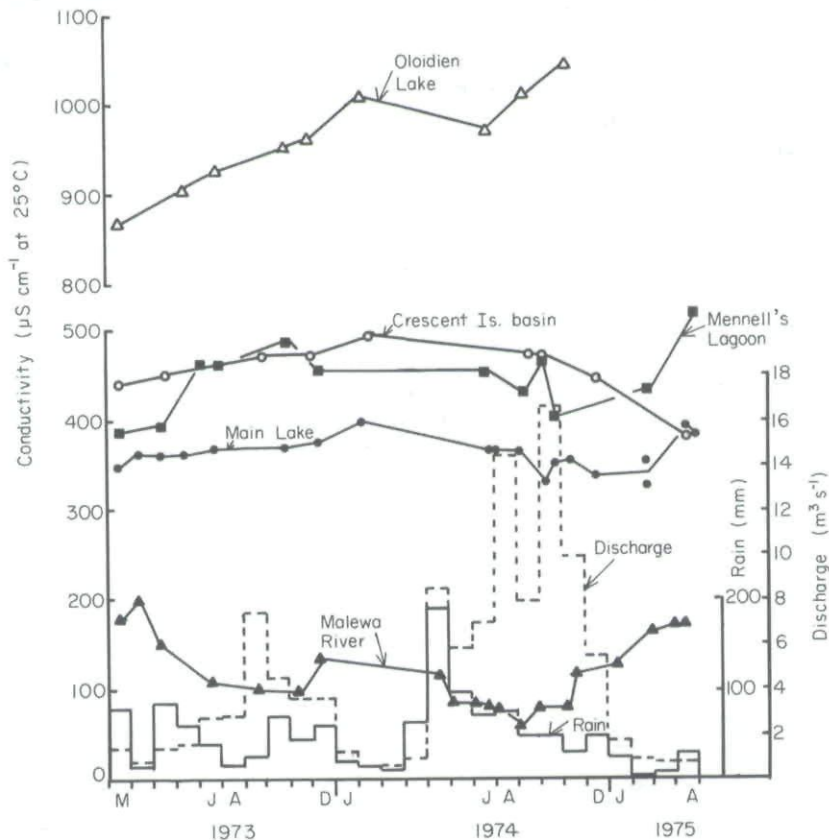

FIG. 9. Seasonal changes in electrical conductance in Lake Naivasha (●), Oloidien Lake (△), Crescent Island basin (○), Mennell's Lagoon (■), and the Malewa River (▲); discharge of the Malewa River (histogram ---), mean rainfall (histogram ———) at the lakeside stations (a–e) Fig. 1).

end of 1974 and in early 1975 and this indicates regional differences in the supply and/or loss of water and/or solutes. These same patterns of change apply to the major ions (although the month-to-month changes of the less abundant solutes were more erratic in part because of analytical errors and differences in the locations of the stations).

Although no single factor is directly correlated with the conductivity changes in the main lake, there is a general trend between seepage and conductance (Fig. 10). It seems that factors other than evaporation have an effect on the salinity of the lake. For example, from the beginning of April 1974 to the beginning of August 1975 there was a lake level decrease of 16 cm and a conductance decrease of 71 μS cm^{-1}. If evaporation had been the only route of water loss, the conductance would have increased during this period. To account for the observed decrease in conductance we suggest that loss of lake water by seepage-out, the addition of water less concentrated than the lake by rain and rivers, and sorption, sedimentation and precipitation reactions in the sediments, are sufficient to override the evaporative concentration expected by a decline in lake level.

Solute budget

From a summary of the inputs and outputs of the main lake (Table 11) it would appear that seepage and river discharge are of secondary importance as inputs. The major route of solute input and output for the lake is sediment exchange, i.e., uptake, exchange and reaction with solids, detritus, biota and interstitial water of the sediments. The actual mechanisms of removal by the sediments would involve a host of reactions depending on the local micro-environment, but some general trends can be noted. For example, The estimated net uptake of silica is 10.7×10^3 tonnes (Table 12). If we assume local diatoms are similar to those in temperate waters, they could contain a range of SiO_2 (0.032–1.250 mg SiO_2 per 10^6 cells), a population doubling time of 5 days and a recycling rate of 50% of the silica (Golterman, 1975b). The 10.7×10^3 tonnes of SiO_2 would support a standing crop of 0.2–6.0×10^{10} cells per m^2. In the main lake a year-round standing crop of 5×10^{10} diatom cells per m^2 would be a reasonable estimate, allowing us to assume that the major uptake of silica in this case is via diatoms. Bicarbonate also shows a large annual
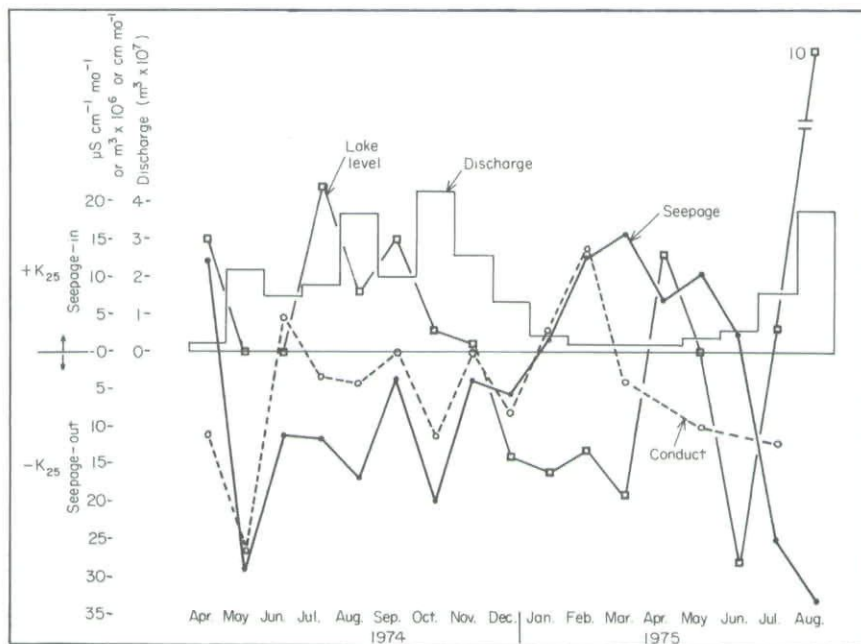

FIG. 10. Monthly changes in conductance (o, μS cm^{-1} month^{-1}) (NE portion of the main lake), lake level ($\square$, cm month^{-1}), seepage-in and seepage-out plus use for irrigation ($\bullet$, m$^3 \times 10^6$) and river discharge (histogram ———, m$^3 \times 10^7$) from April 1974 to August 1975.

TABLE 12. Calculated mean annual sediment uptake and release of solutes in the main lake (tonnes $\times 10^3$)

	Na	K	Ca	Mg	HCO₃	SO₄	Cl	F	SiO₂
Sediment release	7.6	5.1	7.5	1.0	19.1	5.2	4.0	0.8	11.4
Sediment uptake	8.2	7.3	12.8	2.0	48.4	5.1	4.7	0.5	22.1
Net change	0.6	2.2	5.3	1.0	29.3	+0.1	0.7	+0.3	10.7

net uptake of 29.3×10^3 tonnes (Table 12). Bicarbonate uptake, CO_2 exchange, calcite precipitation in certain parts of the main lake, macrophyte uptake and ion exchange could all affect bicarbonate balance.

Some solutes show a small sediment release, e.g., sulphate. This could represent a loss of sulphur by degassing, because a small quantity of H_2S is probably lost from the sediments even though none can be detected by smell.

The most conservative ions, sodium and chloride, show a small net sediment uptake (Table 12). The calcium and magnesium uptake could occur because of (a) incorporation in plant cell walls (algae, and submerged and floating macrophytes), (b) incorporation in hard parts of molluscs, crayfish and fish, (c) deposition as calcite on plant surfaces and in sediments, as in Crescent Island basin. Calcite precipitation may also occur in parts of the main lake not sampled in the sediment mineral assay.

Potassium uptake in the main lake was 2.2×10^3 tonnes. On Lake Chad, Carmouze, Golterman & Pedro (1976) assumed that all of the potassium input to the lake was incorporated into the sediments through macrophytes. On L. Naivasha, with a band of macrophytes 200 m wide (along a 50 km shoreline) and a rate of uptake of 3.7 kg K ha^{-1} (Boyd, 1970) the amount of potassium taken out would be 22.8 g m^{-2} year^{-1}, more than the input of 14.0 g m^{-2} year^{-1} (i.e., 2.2×10^3 tonnes). In these calculations the recycling rate of potassium is not considered. This could be very high, so that macrophyte incorporation may not be the most plausible sink for potassium. It is more likely that potassium along with calcium and magnesium enters into exchange reactions with the sediments. Considering an inorganic sediment-accumulation of 39×10^6 kg year^{-1} (calculated from Richardson & Richardson, 1972 using the 1975 lake basin area) and a cation exchange capacity of 7.3 g kg^{-1} (from lake-edge soils in East Africa; Lind & Visser 1962) each year an increase of at least 1.76 g m^{-2} in the exchange capacity of the sediments would accumulate. Recently, Cerling (1979) found that the measured cation exchange on clay in L. Naivasha water was twice this amount, based on calcium and sodium alone. Older sediments and sorption by organic matter and biota could also be a factor in potassium uptake. Also, we cannot rule out that potassium, though liberated from rocks with difficulty compared to sodium, does exhibit a strong tendency to be reincorporated into solid weathering products, especially clay minerals (Hem, 1970). Such ion removal by diagenesis has been reported in other African lakes, e.g., Lake Chad, which is similar to L. Naivasha in that it also has no surface outflow, is situated in a semi-arid region and contains fresh water. The low salinity of L. Chad is attributed to the dilute inputs of the Chari River and rain, with outputs via seepage and sedimentation (Carmouze *et al.*, 1977; Roche, 1975). The removal of solutes occurs by biochemical sedimentation (incorporation in biota), sorption (clays, organic matter, biota) and geochemical sedimentation (semectites and calcite). The removal of salts by diagenesis, especially of montmorillonites, has been proposed for L. Turkana (Cerling, 1977) as well as L. Chad, but it does not seem likely in L. Naivasha where the clay sediments are quite amorphous.

In conclusion we would explain the freshness of the water of L. Naivasha as due to several factors. A large fraction of the water supplied to the lake comes from dilute rivers and rain. The lake does not lie in a closed basin, but loses water and solutes via seepage. Exchange with sediments both in the pelagic and littoral regions of the lake is a major route for solute movement resulting in a net accumulation of solutes on the lake bottom.

permission to conduct our research and the following departments of the Republic of Kenya for assistance: Survey of Kenya, Ministry of Water Development, Geothermal Laboratory, Kenya Meteorological Department and the Sulphur Group of the Kenya Forestry Research Organization. Special thanks are owed Mr R. Mennell and Ms S. MacIntyre for their help and encouragement, and to Mrs Hopcraft, Mr Maina, Mr Mangan and Mr Mennell for reading our seepage meters. Financial support for JJG's field work came from the Naional Geographic Society, while that for JMM's field work came from U.S. National Science Foundation grants GB 8328X and GB 33310 to D. A. Livingstone. Dr P. Kilham, Dr D. A. Livingstone, Ms S. MacIntyre and an anonymous reviewer improved the manuscript with helpful comments.

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Appendix 1

Columns 1–3

Mean solute composition of surface runoff and seepage (mg l^{-1}). Sandard deviations in parentheses. (1) Surface runoff ($n=2$); (2) seepage-in (east and west, $n=5$); (3) seepage-out (south, $n=10$).

Columns 4–6

Mean ionic composition of rain; standard deviations in parentheses. HCO_3 value is an estimate assuming pH of average rain water is 5.7 in equilibrium with pCO_2 of atmosphere. pH measurements by the International Meteorological Institute were 5.5 and our occasional measurements on fresh collections in 1973 and 1974 were c. 6. Column (a) has units of mg l^{-1}; column b has units of m-equiv. l^{-1}; (4) transect samples ($n=21$); (5) International Meterological Institute samples ($n=6$); (6) weighted mean of column 4 and 5 ($n=27$).

Columns 7–13

Mean concentrations of each solute (column a, mg l^{-1}, column b, m-equiv. l^{-1}). Mean concentrations for rivers are not weighted for discharge. Column c lists specific ion/Na ratios in m-equiv. l^{-1} except for SiO_2 which is expressed as a ratio in mM units. (7) Malewa River ($n=20$); (8) Gilgil River ($n=9$); (9) swamp bottom ($n=22$); (10) swamp surface ($n=22$); (11) Lake Naivasha ($n=21$); lagoons ($n=29$); (13) Cresent Island basin ($n=11$); (14) Oloidien Lake ($n=13$).

Column no.	K_{25}	Na	K	Ca	Mg	CO_3	HCO_3	SO_4	Cl	F	SiO_2
1	152 (84)	8 (0)	16 (11)	16 (12)	4.0 (2.6)	—	92 (11)	10 (5)	8 (4)	1.7 (1.3)	13 (1)
2	415 (39)	44 (3)	31 (3)	23 (4)	10.2 (4.3)	4.4 (3.8)	227 (35)	11 (2)	28 (4)	1.7 (0.8)	47 (3)
3	357 (39)	40 (3)	22 (2)	22 (1)	6.7 (1.3)	11.9 (7.1)	203 (25)	3 (5)	13 (3)	1.3 (0.3)	16 (4)
4a	—	0.59	0.3	0.19	0.27	—	1.2*	0.75	—	—	—
4b	—	0.026	0.008	0.01	0.022	—	0.02	0.016	—	—	—
5a	—	0.36	0.35	0.18	0.07	—	1.2*	0.63	0.41	—	—
5b	—	0.16	0.009	0.009	0.006	—	0.02	0.14	0.012	—	—
6a	—	0.54	0.31	0.19	0.23	—	1.2*	0.72	0.41	—	—
6b	—	0.023	0.008	0.009	0.019	—	0.02	0.015	0.012	—	—
7a	—	9.0	4.3	8.0	3.0	—	70	6.2	4.3	0.4	17.2
7b	—	0.3	0.11	0.4	0.25	0	1.15	0.13	0.12	0.02	—
7c	—	—	0.3	1.0	0.6	—	3.0	0.3	0.3	0.05	0.7
8a	—	16.1	7.4	4.4	2.2	0	75	9.6	3.9	0.8	18.2
8b	—	0.7	0.19	0.22	0.18	0	1.23	0.2	0.11	0.04	—
8c	—	—	0.3	0.3	0.3	—	1.8	0.3	0.2	0.06	0.4
9a	—	26	14	13	4.8	1.8	129	2.9	15	0.9	20
9b	—	1.15	0.36	0.63	0.4	0.06	2.07	0.06	0.36	0.05	—
9c	—	—	0.3	0.9	0.3	0.05	1.8	0.05	0.3	0.04	0.3
10a	—	39	19	15	5.3	5.2	170	3.8	16	1.3	28
10b	—	1.7	0.51	0.75	0.48	0.17	2.72	0.08	0.44	0.07	—
10c	—	—	0.3	0.4	0.3	0.1	1.6	0.05	0.3	0.04	0.3
11a	—	40	20	21	6.4	10.6	192	6.2	14	1.5	34
11b	—	1.77	0.53	1.03	0.53	0.35	3.07	0.13	0.4	0.08	—
11c	—	—	0.3	0.6	0.3	0.2	1.7	0.07	0.2	0.05	0.3
12a	—	43	26	23	6.9	216	14	4.3	17	1.7	30
12b	—	1.87	0.68	1.15	0.57	3.46	0.47	0.09	0.47	0.09	—
12c	—	—	0.4	0.6	0.3	1.9	0.3	0.05	0.3	0.05	0.3
13a	—	52	30	17	7.5	231	15	4.8	17	1.5	36
13b	—	2.27	0.78	0.84	0.62	3.7	0.49	0.1	0.47	0.08	—
13c	—	—	0.3	0.3	0.2	1.6	0.2	0.04	0.2	0.04	0.3
14a	—	125	32	9	6.9	496	43	7.1	32	8.0	44
14b	—	5.5	2.12	0.44	0.57	7.93	1.41	0.15	0.89	0.42	—
14c	—	—	0.4	0.1	0.1	1.4	0.3	0.03	0.2	0.08	0.1

Appendix 2

Elemental composition of rock types occurring in the Eastern Rift Valley. Values expressed as percentages and elements/Na weight ratios calculated from Saggerson (1970). Saggerson sample number in parentheses.

	Malewa River	Quartz trachyte (96)	Welded tuff (202)	Obsidian (78)	Rhyolite obsidian (73)*	Kataphorite trachyte (92)*	Phonolite (111)	Olivine basalt (174)*	Basalt (148)
Na%	—	4.9	4.7	5.0	3.4	4.9	4.9	0.3	3.2
K%	—	3.1	2.3	3.7	3.9	3.9	4.7	0.4	1.3
K/Na	0.5	0.6	0.5	0.7	1.2	0.8	1.0	1.6	0.4
Ca%	—	1.7	1.7	0.20	0.16	0.7	1.3	2.2	5.6
Ca/Na	0.9	0.4	0.4	0.40	0.50	0.1	0.3	8.3	1.8
Mg%	—	0.5	0.2	0.04	0.02	0.2	0.5	18.5	1.4
Mg/Na	0.3	0.1	0.04	0.01	0.01	0.05	0.1	68.4	0.5
S%	—	0	0	0.02	0.01	0	0	0	0
S/Na	0.2	0	0	0.004	0.003	0	0	0	0
Cl%	—	0	0	0.40	0.21	0	0	0	0
Cl/Na	0.5	0	0	0.08	0.06	0	0	0	0
F%	—	0	0	0.17	0.28	0	0	0	0
F/Na	0.04	0	0	0.03	0.08	0	0	0	0
SiO_2%	—	59.2	59.7	70.4	75.6	60.7	57.3	40.7	48.2
SiO_2/Na	1.9	12.1	12.6	14.1	22.4	12.4	11.7	150.7	15.3

*Sample from Lake Naivasha region

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