*Hydrobiologia* **488:** 27–41, 2002.
*D.M. Harper, R. Boar, M. Everard & P. Hickley (eds), Lake Naivasha, Kenya.*




# Geochemical and physical characteristics of river and lake sediments at Naivasha, Kenya

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*Key words:* Lake Naivasha, sediment stratigraphy, sediment geochemistry, metals

**Abstract**

Prior studies on Lake Naivasha relevant to understanding sediment dynamics include a bathymetric map, a paleolimnological study of fossil invertebrate assemblages in lake sediment, an overview of lake level fluctuations throughout the 20th century, and identification of a dynamic assemblage of macrophyte zones that has responded both to these changes in lake level and to more recent, alien species. Sediment samples collected from the rivers systems and the lake were examined physically and chemically. River sediment characteristics reflect geology and geomorphological processes in the catchment, whereas lake sediment stratigraphy has responded to past lake level changes. Such changes have caused significant changes in aquatic vegetation assemblages. Present day sediment dynamics in the lake are governed by the presence of river point sources in the north and wave-induced re-suspension, such that sediments introduced by rivers are transported in easterly and southerly directions, and are eventually deposited in the eastern, central and southern parts of the lake. Sedimentary deposition is also occurring in northern areas that once were protected by papyrus swamp vegetation but now only have a narrow fringe, highlighting the important role of swamp vegetation in filtering out suspended particulates and thereby controlling water quality in the lake. Geochemical analyses of river and lake sediments indicate that they represent fairly undisturbed background conditions. Higher-than-expected concentrations of cadmium, iron, nickel and zinc found in both river and lake sediment are likely to derive from volcanic rocks and/or lateritic soils found in the lake catchment.

## Introduction

Lakes are strongly influenced by the natural and human characteristics of their catchments. River sediment in low order channels derive from a plethora of hillslope and channel sources in the upstream catchment (Bowie & Mutchler, 1986). During downstream transport, sediment from different sources will mix and, therefore, investigations of the geochemical and physical characteristics of river sediment may provide evidence of processes occurring in the entire catchment. As a consequence, stream sediment sampling has long been used as a tool to prospect for metalliferous mineral deposits, and it is generally accepted that such surveys provide more representative and cost effective results than surveys of soils or vegetation (Levinson, 1980).

Geochemical surveys of river sediment are increasingly being used also in environmental investigations, and applications include:

(i) assessments of environmental impacts, as sediments' contaminant concentrations downstream of industrial, agricultural or other human activities often are elevated (Darnley et al., 1995);
(ii) human and animal health studies as geologically controlled deficiencies/excesses of certain nutrients/toxins in water and/or food products may

cause health problems (Fordyce et al., 1996); and

(iii) to provide a geochemical baseline against which any future pertubations may be appraised (Williams et al., 2000).

Similarly, investigations of lake sediments can also be used in environmental surveys. When rivers enter a lake, the decrease of velocity results in sediment deposition. Investigations of geochemical changes with sediment depth may, thus, provide indications of changes in the characteristics of sediment input with time. Such investigations may therefore be used to determine both the character of contamination and, if sedimentation rates are known, changes in contaminant loading with time (Nicholson, 1996).

Environmental applications of geochemistry often investigate metal contamination, and it is generally acknowledged that metals in their dissolved ionic state control direct toxic effects (Förstner, 1983; 1988; Stumm & Morgan, 1996). However, metals in aquatic systems are usually predominantly associated with sediment (Förstner, 1983; Windom et al., 1991). Therefore, the concentration of metals in sediment is generally a more sensitive and accurate indicator of contamination of an aquatic system, compared to the concentration of dissolved metals (Carelli et al., 1995). It is also recognised that sediment-bound metals have the potential of changing to the ionic state (Willford et al., 1987). Investigations of sediment geochemistry is, thus, directly relevant to assessing the possibility of toxic effects of metal contamination. Furthermore, as metals are present in much higher concentrations in sediment than in water, the analysis of sediment is comparatively easy to perform and, therefore, less costly, enabling more samples to be analysed, and a greater geographical coverage.

The interpretation of sediment geochemistry data is, however, not without its problems. In rivers, different morphological units often have quite different geochemical characteristics, resulting from physical sorting processes within the stream bed (Ladd et al., 1998). Similarily, metals are often found preferentially concentrated in the finer fraction of sediment (Förstner, 1983). Consequently, care needs to be taken to ensure that the same or at least similar morphological units and size fractions are sampled in order for results from different rivers or even reaches of the same river to be comparable (Ladd et al., 1998). Further, whereas environmental criteria for water have been established for a varity of purposes, including the protection of aquatic life, attempts to elaborate similar criteria for sediment have been less succesful. It is difficult to determine to what extent potentially harmful elements in sediment are, or may become, available for biological uptake. Consequently, environmental criteria for sediment are generally seen to be of limited value due to variations through time and space in the conditions that determine bioavailability (Darnley et al., 1995; Maher et al., 1999). Non-statutory systems for sediment quality guidelines have, nevertheless, been developed in a number of countries, including Canada and Sweden.

Studies of the input of nutrients and other material from the Naivasha catchment to lake have been undertaken by Gaudet & Melack (1981), Harper et al. (1993), Harper et al. (1995), Everard et al. (2002), and Kitaka et al. (2002). None have yet investigated lake and river sediments. The aims of the study were: (i) to investigate the geochemical and physical characteristics of river and lake sediments, (ii) to investigate the sediment stratigraphy of the lake, and (iii) to assess the implications of (i) and (ii) in informing of how to best manage Lake Naivasha and its catchment.

## Study site description

### *Water level and vegetation changes*

The water level and aquatic vegetation of Lake Naivasha changes continuously (Becht & Harper, 2002), and such fluctuations will have significant effects upon sediment characteristics. The lake was first described in the writing of European explorers in the 1880s but its earliest record is that according to local tradition, there was a period immediately before the arrival of the first Europeans when the lake was almost completely dry (Åse et al., 1986). Towards the end of the 19th century, writings by European travellers indicate that the lake's level was continuously rising until 1895, when a maximum lake level of 1896 m above sea level was reached. This historic high water level is some 4–5 m higher than any level reached since that time. Levels then declined around the turn of the century, so that when continuous recordings commenced in 1908 the level was 1890 m (Åse, 1987). Thereafter, the records show a progressive decline in lake levels during the 1920s and 1930s, culminating in a historic (recorded) low of 1882 m in 1946. The lake level remained low until about 1956, whereafter it rose to an intermediate level of 1887 m in 1980 (Åse et al., 1986). Lake level declined progressively during the following decade, rising rapidly by 1 m in May 1988, declining for a decade then rising by 3 m in 1997. Both these latter events were following heavy rains associated with the ENSO climatic phenomenon (see Becht & Harper (2002) for details of lake level changes).

The vegetation of Lake Naivasha is, in turn, influenced by changing lake levels. Beadle (1932) provided the first scientific description of the lake's vegetation. At that time, during a period of declining lake levels, papyrus (*Cyperus papyrus*) formed an extensive floating swamp in the whole northern part of the lake, north of an east–west horizontal line along the northern edge of Crescent Island (known colloquially as the North Swamp). Elsewhere varying widths of it fringed the lake and formed a multitude of small, mobile islands. Various submerged macrophytes and the blue water lily (*Nymphaea nouchalii* var. *caerulea*) grew in shallow lagoons inside these papyrus islands. To the lakeward side, as water deepened, the floating-leaved followed by dense beds of submerged macrophytes formed clear zonation. This pattern was consistent throughout the water level changes up to the mid-1970s. Thereafter, it underwent dramatic and continuous changes. The driving forces behind these changes have been various anthropogenic influences, including the introduction of alien species of animals and plants (Harper, 1984; Tarras-Wahlberg, 1986; Gouder et al., 1998), and the clearance of lakeside lands for intensive agriculture, (Harper et al., 1990).

*Lake bathymetry*

Åse et al. (1986) provide a bathymetric map of the lake referring to a lake-surface of 1889 masl (reproduced as Fig. 1). The map shows that the lake may be divided into three semi-separate basins: the main lake basin, the Crescent island crater in the east and Lake Oloidien in the south. The main lake is characterized by a smooth flat relief with a maximum depth just off Hippo Point in the southwest. The flat bottom topography contrasts sharply with the hilly topography of the surrounding land, indicating that the lake basin is filled with large amounts of sediments (Åse et al., 1986). A shallower area in the northern end of the lake is interpreted as a deltaic sediment accumulation deriving from the inflows of the Gilgil, Karati and Malewa rivers. At the time of the survey by Åse et al. (1986), the deltaic feature coincided closely with the papyrus-dominated North Swamp. A feedback process is, thus, indicated in which the shallow delta area provides a preferred habitat for papyrus whilst at the same time the papyrus swamp functions as a sediment trap and protects the delta from wave erosion and, in turn, promotes delta development.

*Lake sedimentology*

Verschuren (1996) conducted stratigraphic and geochronological analyses of three sediment cores taken from the main lake. He noted that sedimentation patterns in the lake vary due to the effects of wind-induced re-suspension and re-deposition of sediments, and the presence of river point sources of sediment in the north. As a result, two of the cores sampled did not represent longer periods of undisturbed sedimentation. In the central part of the lake, however, he sampled what was interpreted as a complete and uninterrupted sequence of sediments deposited during the 20th century, non-conformably overlying sediments dating back as far as the 16th–17th centuries. In this core, he identified four main units: Unit 0, Unit I, Unit II and Unit III.

- **Unit 0**, found at the base of the core at 114–105 cm depths, was a peat horizon with abundant fragments of *Cyperus papyrus* and *Ceratophyllum*. Verschuren interpreted it as representing a period when a low lake level transformed the lake into a shallow, fragmented wetland overgrown by a papyrus swamp. A radiocarbon age of 290 $\pm$ 50 years of sediments directly overlying this horizon indicates that Unit 0 was laid down, not during the mid 19th century lowstand but during an earlier event in the 16th–17th century.
- The clayey muds of **Unit I**, between 105 and 82 cm, was interpreted as being composed of sediments laid down during low to intermediate water levels between the 16th–17th century and the end of the 19th century.
- **Unit II** sediments, between 82 and 44 cm, were interpreted as being laid down during high lake levels in the late 19th and early 20th century. At 48–58 cm there was a black layer with a significant admixture of coarse partially decomposed papyrus material. The unit's black color was imparted by the decomposed papyrus fragments, and the unit was interpreted as representing sedimentation in shallow areas near papyrus stands, which grew on exposed mudflats, created as lake levels decreased in the 1920s and 1930s.
- Lake levels declined in the 1920s, 1930s and 1940s and reached a lowstand of 1881.5 masl in 1946.

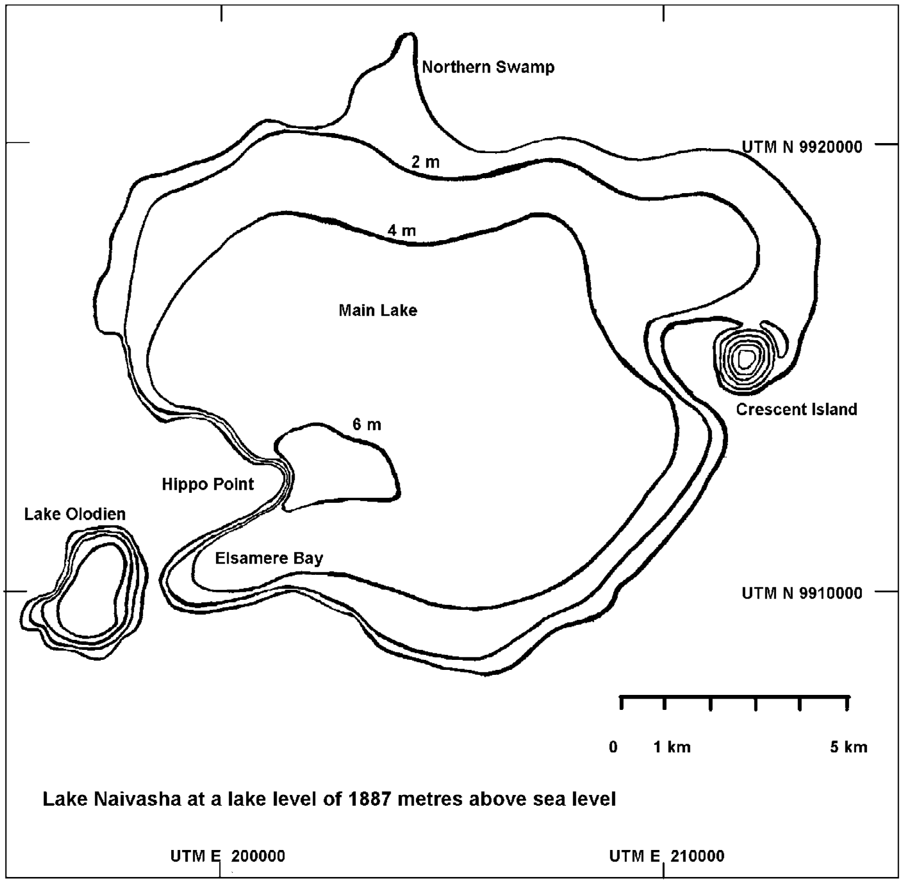


*Figure 1.* Bathymetric map of Lake Naivasha. Water depth contours are drawn at 2-m intervals. The lake contour represents a water level of approximately 1887 m above sea level, (adapted from Åse et al., 1986).

The transition to **Unit III** sediments at 44 cm were interpreted as marking this return to lower lake levels. Near the transition of Unit II and III, Verschuren noted the presence of a thin, light felt horizon, dated at 1941 ±7 years, composed of numerous needle shaped diatoms. The mechanism of formation is unclear, though Verschuren speculates that its origin could be either a result of mass sedimentation of diatoms triggered by unfavorable conditions during low lake levels, or the sedimentary redistribution and associated aggregation of previously deposited diatoms. Above this level, Unit III consisted of a fairly homogenous organic, clayey mud indicating that the depositional environment has remained similar over the past 40 years. The sedimentation rate in the main lake during this time was estimated at about 1 cm per year.

## Methods

Sampling was undertaken during the dry season in July/August 1997 and during October 2000.

Sediment samples from rivers were collected from sixteen river sites during the dry season, between 19th July and 7th August 1997. Sample sites were selected in low (first to third) order reaches to represent the overall characteristics of river sediments in the entire lake catchment (Fig. 2). During this time, the Karati river contained water in isolated pools only. The samples were taken with an Ekman grab from active, oxygenated, mid-river sediments at sites where the channel is straight and the flow fairly rapid (with the exception of the Karati samples, which were taken from standing pools of water and sample S10, taken from the Turasha dam in the Malewa catchment). At each site, about 1 kg of sediment was collected in two to three grabs and these were subsequently mixed. A subsample of approximately 150 g (wet weight) was retrieved from the master sample. This subsample was subsequently wet sieved through a 2-mm mesh (discarding the +2 mm fraction), and air dried at approximately 40 °C.

The sample were then divided in two, and one subsample was investigated under the microscope (×10 magnification) in order to determine grain size, angularity and sorting in accordance with tables provided in Pettijohn (1975). The other sub-sample was sent for analysis of bulk and trace geochemistry by X–ray Fluorescence spectrometry (XRF) at the Anglo American research Laboratories in Johannesburg, South Africa.

Care was taken to avoid cross sample contamination and all equipment used were thoroughly cleaned, first in river water and then in de-ionised water. The accuracy and repeatability of the sampling procedure and the XRF analysis was checked by sampling and analysing the sediment from one site in duplicate.

Sampling of lake sediment was performed by using a sediment corer in 1997, and by using an Ekman grab in 2000.

Eighteen lake sites were sampled during 5–18 August 1997. Sediment cores were collected in 110-cm long Perspex tubes, attached to a single-drive piston corer, which was deployed from a small boat. The location of sample sites was fixed by using a handheld Garmin GPS 12, Global Position System. The exact sampling locations are shown in Figure 3. The cores were extruded and described with regards to their physical and biological character and appearance. Each stratigraphic unit identified was described in detail.

Two cores were selected for geochemical analysis, one from the central lake (no. 12) and one in the Northern swamp (no. 9), close to the outflow of the Malewa river. One sample of 50–100 g (wet weight) was collected from each of the stratigraphic units identified in the two cores, making a total of 10 samples. Care was taken to take these samples from the centre of the core, so as to avoid cross-sample contamination. The samples were kept cool in a refrigerator before being sent for geochemical analysis at the Anglo-American research laboratories in Johannesburg, South Africa. The analysis was performed by plasma emission spectroscopy (ICP-AES) following digestion in aqua regia. The accuracy and repeatability of the sampling and analysis was checked by sampling and analysing one stratigraphic unit twice. Seven lake sediment samples were retrieved during the period 20–24 October 2000. At each site, about one kilo of sediment was collected in three grabs, which were subsequently mixed. A subsample of approximately 150 grams (wet weight) was retrieved from the master sample. This subsample was air dried at approximately 40 °C, and thereafter kept cool in a refrigerator before being sent for analysis of Loss on Ignition (LOI) and metal content at the Leeds University School of Geography's laboratories in the UK. The metal analysis was performed by plasma emission spectroscopy (ICP-AES) following digestion in aqua regia. Again, the accuracy and repeatability of the sampling and analytical procedure was checked by sampling and analysing one sample twice.

The evaluation of sediment analysis was carried out by comparison of the observed major and minor element sediment concentrations with global averages for shale (Turekian & Wedepohl, 1961; Mason & More, 1982), and Environment Canada's provisional sediment quality guidelines for the protection of aquatic life (Environment Canada, 1995). The latter assume 100% bioavailablity for sediment-bound metals which, in turn, make them possibly over protective (Williams et al., 2000). Further, caution must attend comparisons between river and lake sediments as the analytical procedures differ.

## Results

### *River sediment description*

Site descriptions are provided in Table 1, together with a sediment description and a linkage to RHS sites examined by Everard et al. (2002). Sediment characteristics differ markedly between the three rivers sampled, reflecting the hydrological, topographic, and geological differences in their catchments.

Sediment in the Karati is generally immature (i.e., poorly sorted and angular in nature), reflecting the fact that the river's gradient beneath the Kinangop Plateau is steep and that it flows only during the rainy season, providing little time for sorting and abrasion. As a consequence of the episodic nature of the river's flow, Karati sediment contain both fine particles (clay and silt) and coarse material (gravel and coarse sand).

Sediment in the Gilgil system is different from that of the Karati. Everard et al. (2002) demonstrate that the topography of the Gilgil system is more gentle than the Karati, with few rapids. The flow of water in the Gilgil system are also perennial. Consequently, the sediments found at Gilgil sampling sites are mod-

*Table 1.* Descriptions of the sampling locations, the physical characteristics of the sampled sediment and the analysis performed

| Sample (RHS number*) | Sampling date | Location description and land use | River morphology | Sample description | XRF analysis |
|---|---|---|---|---|---|
| s1 (9576) | 19 Jul 97 | River pool near bridge over the Karati. Near small village (10 huts). Mix of natural vegetation and small scale agriculture (maize). Pool used for washing | No continuous water flow. Relatively steep gradient with gravelly riverbed. Channel width of 2–4 m and depth of 0.3 m (in pool) | Sandy, clayey silt<br>suba – subr<br>m-p sorted | |
| s2 (no RHS) | 19 Jul 97 | Pool at upper part of a deep gorge near bridge over the Karati. Near small village (30 huts). Pastures and small scale farming (beans). | No continuous water flow, Steep gradient with gravelly riverbed. Channel width of 2–3 m, and depth of 0.8 m (in pool) | Sandy, clayey silt<br>subs – subr<br>m-p sorted | |
| s3 (9575) | 19 Jul 97 | At bridge over the upper Karati on the Njabeni – south Kinangop road. Near two farmhouses. Pastures, small-scale farming | No continuous water flow. Steep gradient with gravelly riverbed. Channel width of 2 m and depth of of 0.4 m (in pool) | Gravelly, clayey sand<br>a<br>m-p sorted | Y |
| s4 (No RHS†) | 19 Jul 97 | Upstream of bridge over Karati on the Naivasha–Nakuru highway. Pastures and extensive watering of cattle | No continuous water flow<br>Gentle gradient and smooth riverbed. Channel width of 3 m, and depth of 0.15 m (in pool) | silty sand<br>subr – suba<br>m sorted | Y |
| s5 (9579) | 20 Jul 97 | Downstream of bridge over the Gilgil on the northern Lake road. Dense acacia vegetation, 20–100 m wide, pastures. | Small rapid at bridge, otherwise gentle gradient and smooth riverbed. Channel width of 5 m, and depth of 0.5 m | silty fine sand<br>suba – subr<br>w-m sorted | |
| s6 (No RHS†) | 20 Jul 97 | Downstream of bridge over the Malewa on the Naivasha-Nakuru highway. Near Naivasha town, extensive settlements. Washing and bathing downstream | Gentle gradient. Slow flowing water. Channel width of 10–12 m, and depth of 0.5 m | slightly silty sand<br>subr – r<br>w sorted | |
| s7 (9571) | 20 Jul 97 | At bridge over Little Gilgil at the Pembroke school. Euphorbia and eucalyptus woodland. Acacia woodland downstream. Small village nearby (50 houses). | Smooth and gentle gradient. Grassed banks. Channel width of 1 m, and depth of 0.1 m | fine sand<br>subr<br>m sorted | Y |
| s8 (9574) | 21 Jul 97 | Upstream of bridge over Malewa. Dense acacia woodland. Watering place for cattle. | Mainly smooth with gentle gradient. Small rapid below sampling area. Channel width of 20 m, and depth of 0.5 m | fine sand<br>suba – subr<br>m sorted | Y |

*Table 1.* Continued

| Sample (RHS number*) | Sampling date | Location description and land use | River morphology | Sample description | XRF analysis |
|---|---|---|---|---|---|
| s9 (9573) | 21 Jul 97 | At pumpsation just upstream of Malewa's confluence with the Turasha. Small scale farming (maize) and acacia woodland | Fairly smooth gradient but with intermittent small rapids. Channel width of 16 m, and depth of 0.4 m | Fine sand<br>suba – subr<br>m sorted | |
| s10 (9572) | 24 Jul 97 | At small bridge over the Turasha dam reservoir. Small scale farming (maize) and acacia woodland | Reservoir dam with submerged macrophytes and floating vegetation | Sandy silt<br>subr – suba<br>w sorted | Y |
| s11 (9570) | 24 Jul 97 | At bridge over Gilgil, 3 km east of Gilgil township, Pastures | Smooth and gentle gradient. Grassed banks. Channel width of 2–4 m, and depth of 0.4 m | Sandy silt<br>subr – suba<br>w-m sorted | Y |
| s12 (9568) | 24 Jul 97 | At small bridge downstream of bigger bridge over the Malewa on the Ol Kalou road, east of Ol Kalou, Pastures | Smooth and gentle gradient. Grassed banks. Channel width of 5–6 m, and depth of 0.7 m | fine sand<br>suba – subr<br>m sorted | |
| s14 (9582) | 25 Jul 97 | On the Karati at the Delamere farm, next to fence by the northern swamp. Pastures and near Buffalo/cattle watering place | No continuous water flow. Gentle gradient with grassed banks. Channel width of 1–2 m, and depth of of 0.1 m (in pool). | silty clay<br>r<br>w sorted | Y |
| s15 (No RHS)< | 25 Jul 97 | Gilgil river on the farm of Mr A. Simpson. Farmland and pastures, near cattle watering location | Smooth and gentle gradient. Channel width of 1–2 m, and depth of 0.1 m (in pool). | clayey, sandy silt<br>s – mr<br>m sorted | Y |
| m1 (9577) | 7 Aug 97 | Eastern fringe of Gilgil papyrus swamp, on Merula farm, swamp/wetland vegetation for > 50 m each side | River fringed by shallow pools of water with abundant papyrus and salvinia. Channel width of 5m, and depth of 1 m | silty clay<br>r – sr<br>w sorted | Y |
| m3 (9569) | 7 Aug 97 | Southern part of Merula farm, at cattle watering place near small farm village (~10 houses) | Gentle gradient, steep grassed bands. Channel width of 15 m, and depth of 1.5 m | silty sand<br>subr<br>m-w sorted | Y |

Notes: *RHS site numbers and background data are referred to in Everard et al. (2002).
† Neither of these sites are an RHS site, but both are close to Malewa RHS site 9581 (KARI farm). < This is not an RHS site, but is upstream of RHS site 9579 and formed the upper limit of bird survey stretch in Everard et al. (2002).
Sample description: a – angular; r – rounded; w – well; m – moderately; p – poorly
Note: XRF–X-ray fluorescence – major and trace geochemistry.

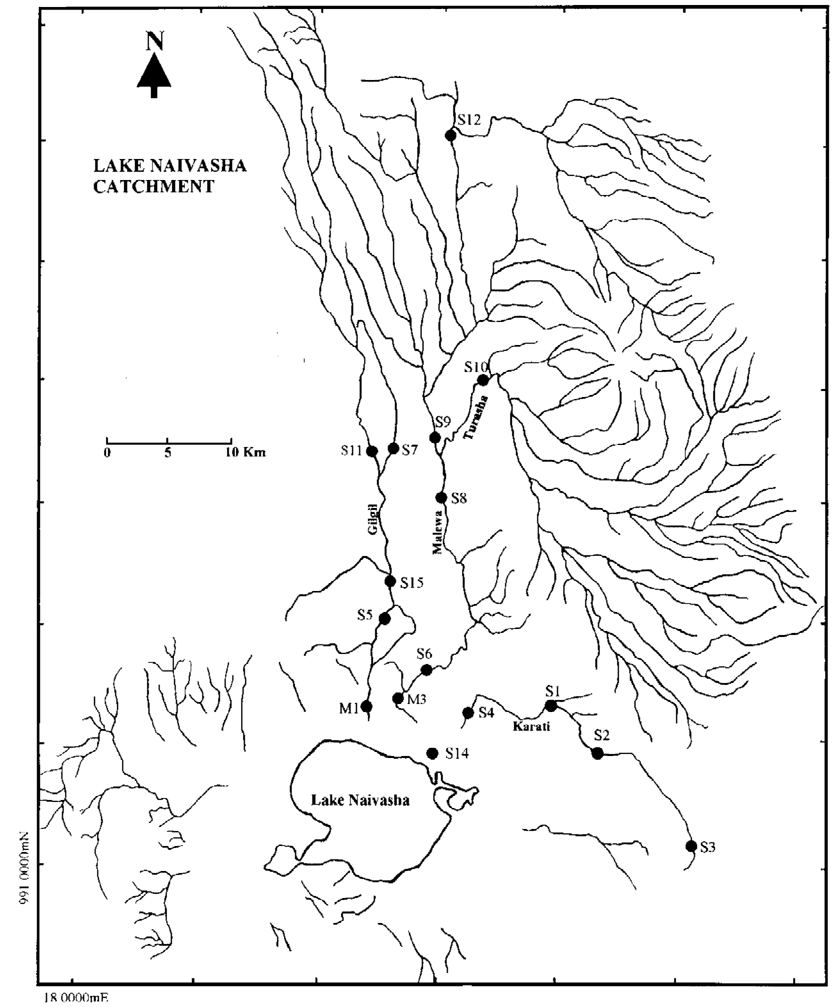


*Figure 2.* Sample site locations in the river sediment survey.

erately to well sorted, and the individual grains are sub-rounded to rounded. Since the flow of the Gilgil is relatively slower and more gentle, the sediment is generally fine (fine silt or clayey silt).

Sediments in the Malewa system represent an intermediary stage between the poorly sorted and angular sediment of the Karati and the fine, well-sorted sediment of the Gilgil. This follows from the upper reaches of the Malewa being steep and similar to those of the Karati (although these upland reaches were not sampled in this study), whereas the lower reaches are similar to the Gilgil. Compared to the Karati and the Gilgil, the Malewa is, furthermore, a more forceful river. Consequently, the sediment in the lower reaches is, though generally well-sorted, coarser-grained than those of the Gilgil.

*Lake sediment description*

The lake stratigraphy is conveniently divided into six sub-areas: central lake, delta front, northeast, northwest, southeast, and southwest. These divisions are not absolute, as differences between areas are gradational. The division reflects differences in water depth and long term sediment dynamics, and serves to make both analysis and presentation of results more effective.

The *Central Lake* sub-area occurs in the centre of Lake Naivasha with depths of 5–6 m. The general stratigraphy of the four cores corresponded to that suggested by Verschuren (1996), and is summarised in Table 2 . A thickness of 10–20 cm of sediments in the central lake sub-area, interpreted as being laid down during the past 10–15 years, gives a current sediment-

*Table 2.* Idealised stratigraphic section of the central Lake Naivasha basin

| Depth of interface | Type of sediment and interpretation |
|---|---|
| 0 cm | *Brown, organic mud*<br>Trace macrophytes and papyrus, and trace diatoms.<br>Interpreted as sediment laid down during the last 10–15 years during which time papyrus rafts have been more or less completely absent from this part of the lake.<br>**Distinct contact** |
| 10–20 cm | *Light brown, organic mud*<br>Abundant macrophytes and papyrus and trace diatoms.<br>Interpreted as sediments laid down during progressive increasing water levels from about 1950 to 1980. A few cm thick layer of *yellowish brown diatomaceous felt* may in places be present at the base of this unit. Together with the unit above they seem to correspond to Unit III of Verschuren (1996).<br>**Gradational contact** |
| 40–50 cm | *Black rooty and diatomaceous mud*<br>Abundant macrophytes, papyrus and abundant diatoms.<br>Interpreted as sediments laid down during a progressive lowering of water levels in the early $20^{th}$ century when papyrus stands were continuously germinating on exposed mudflats. Probably corresponding to Unit II of Verschuren (1996).<br>**Distinct non-conformity** |
| 70–75 cm | *Dark brown peaty mud*<br>Abundant macrophytes, papyrus and diatoms.<br>Interpreted as sediment laid down during low lake level stand of the mid $19^{th}$ century. Probably truncated by a period when the lake may have been completely dry. Probably corresponding to Unit I of Verschuren (1996).<br>**Distinct non-conformity** |
| 80–90 cm | *Black Peat*<br>Abundant papyrus and trace macrophytes.<br>Hard and massive peat laid down when the whole lake must have been a shallow, fragmented wetland overgrown with papyrus. Probably corresponding to Unit 0 of Verschuren (1996) and thus laid down during $16^{th}$ to $17^{th}$ century. |

ation rate of about 1 cm per year. The upper 40–50 cm appears to have been laid down conformably. Below this level, two distinct non-conformities, caused by erosion during times when lake levels were low, were identified. A distinct horizon of yellowish brown, diatomaceous felt was identified at the base of the light brown, organic mud in cores 10 and 15 only. The fact that this unit was not noted in all cores indicates that the unit is not continuous over the whole central basin. An explanation for the unit's formation must therefore be sought in a process that was not basin-wide. A system of smaller sub-basins, each with its specific salinity and water quality conditions, situated within a larger wetland, may have created conditions for the mass mortality and subsequent sedimentation of diatoms in some basins but not others. A similar situation, albeit at a larger scale, occurs in the present day where water quality, and hence diatom assemblages, vary somewhat between the three sub-basins of the main lake, that is the Main Lake, Oloidien Bay and Crescent Island crater lake (Verschuren, 1996).

The *Delta front* sub-area occurs along the lakeward fringe of the North Swamp, at depths up to about 1 m. The deltafront sub-area is dynamic where sedimentation patterns are sensitive to changes in water level, changes in location of river inflows and the extent of swamp vegetation. Consequently, sediments in the area are an heterogeneous mix of massive brown clays, sandy mud, organic mud and peat horizons.

The *Northeast* sub-area, at depths of about 1–3 m, contains sandy muds derived from the river inlets. These sediments are continuously being reworked and re-suspended by wave action. Below these active sediments are stiff grey clays, interpreted as having formed from the previous aerial exposure and mineralization of lacustrine sediments, and brown clays which are interpreted as representing deltaic mudflat deposits.

The *Northwest* sub-area, depths of 2–3 m, contains sediments which appears to correspond to the upper three units of the central lake stratigraphy with two brown organic mud units overlying a black rooted mud unit.

Core 11 was situated only about 3 km west of the Malewa outflow. Nevertheless, there was no evidence of material directly derived from the river in this core. It is therefore indicated that river sediment input is, subsequent to being introduced to the lake, transported in an easterly direction only.

The *Southeast* sub-area, together with one core taken about 4 km further north, 2.5 km west of Crescent Island (core 5), but included in this group because of its stratigraphic similarity, appear to correspond to the upper four units of the central lake stratigraphy with brown organic mud units above a black or dark brown rooted mud unit over a dark brown peaty mud.

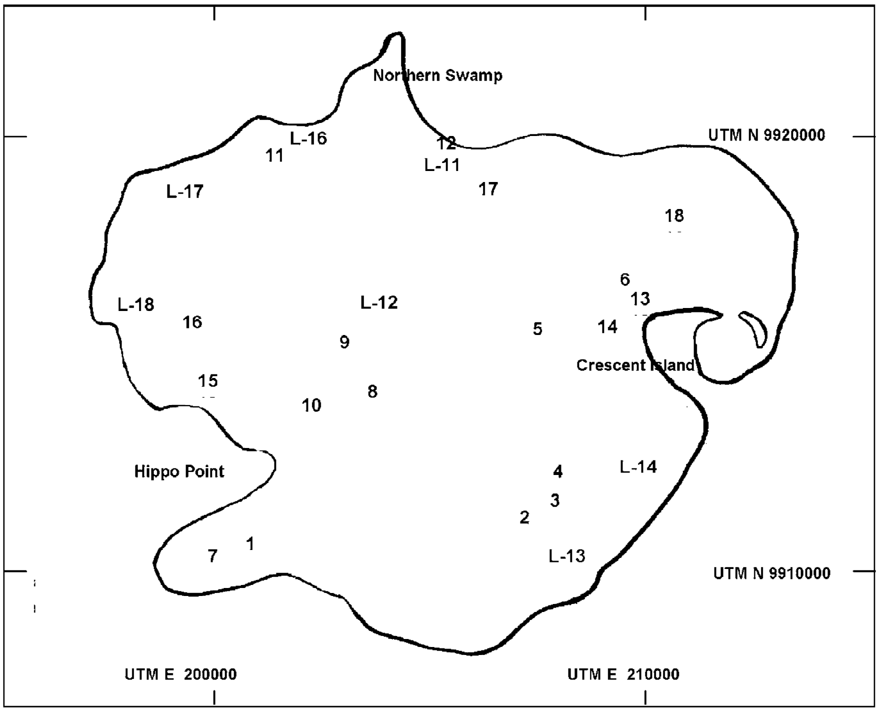


*Figure 3.* Sample site locations in the two lake sediment surveys. Sites in the 2000 survey are identified by the prescript L.

In the *Southwest Bay* sub-area, at depths of 3–4 m, a far greater rate of deposition was evident. The stratigraphies was somewhat different from the central lake stratigraphy. The two cores consisted of organic mud units, interpreted as corresponding to the upper two units of the central lake stratigraphy. However, though both cores were nearly 100 cm in length, neither intersected the organic rich, black mud units laid down in other parts of the lake in early to middle part of this century. Consequently, the sedimentation rate in this relatively sheltered part of the lake appears to be more rapid than in the central part of the lake. A 10-cm thick brown organic mud unit with abundant *Salvinia* and papyrus fragments at a depth of about 40 cm is interpreted as a unit laid from the 10–15 years before the 1987 low level. At this time, both papyrus rafts and *Salvinia* mats were common in this part of the lake (Tarras-Wahlberg, 1986). Such an interpretation leads to a sedimentation rate of about 3 cm per year in this part of the lake, which is considerably more than estimated sedimentation rates in other parts of the lake.

*Present-day sediment dynamics*

Comparisons of the sediment composition at the sediment-water interface of the 18 cores enables an analysis of present day sedimentation patterns.

Near the outflow of the Malewa the surface sediments are either massive brown clay or sandy mud units. The clay is interpreted as a deltaic deposit (a mud flat) which is now actively being eroded by wave action, whereas the sandy mud is material directly derived from the Malewa and Gilgil Rivers. Consequently, the sedimentary regime of the pro-delta area is dominated by erosion and sedimentary transport, rather than sedimentation. Presumably, sedimentation and associated deltaic growth occurs in the reduced areas now protected by swamp vegetation.

The surface sediments in the bay in the northeastern part of the lake and areas directly west and north west of Crescent Island are, like the pro-delta area, dominated by sandy muds and clay units. Consequently, the sedimentary regime here is also dominated by transport and erosion. However, the stiff clays here are not only brown clays (interpreted as deltaic deposits) but also stiff clays that are grey or dark grey in colour. These stiff clays are interpreted as having formed from lacustrine sediments that were exposed to air, such that they became mineralised and oxidised. This may be a consequence of historic low lake levels, and is consistent with the inferences about delta-forming processes based on RHS and other geomorphological observations by Everard et al. (2002). Organic muds dominate the surface sediments collected elsewhere across the lake in this study and, hence, these areas represent depositional sedimentary environments.

*Geochemistry*

Tables 3 and 4 show the results of the geochemical analyses. Lake and river sediments are geochemically similar, and the contents of major and minor elements are mostly comparable to global averages (Table 3). The only noticeable differences between river and lake sediments are that river sediment contain somewhat more $P_2O_5$ and Pb, somewhat less Cu and Ni, and significantly less $SO_3$, than lake sediment. These differences are, with the exception of $SO_3$, less than one order of magnitude and may arise from the different analytical methods used. The higher content of $SO_3$ in lake sediment compared to river sediment is, however, to be expected due to the tendency of animals and plants, more common in the lake compared to the rivers, to concentrate sulphur. This hypothesis is corroborated by the fact that the only two lake sediment samples to have low $SO_3$ concentrations are 12 A and 12 D, both of which represent inorganic clay units.

River sample S10, taken from the Turasha dam in the Malewa catchment, differs from the other samples in that it contains more organic and volatile materials (as indicated by the low total percentage). This reflects, the low energy environment of the dam where fine organic material can settle out to a greater extent than in-stream.

All sediment samples contain elevated levels of $Fe_2O_3$, and the concentrations of 6–13% are considerably higher than the 4% expected in an average shale. The high iron content could either be caused by the bed rock (i.e., the volcanic rocks of the area) being naturally enriched in iron, or caused by the erosion of iron rich lateritic soils, which are common throughout the area.

The content of minor and potentially toxic metals and metalloids are, in comparison to global averages, mostly unremarkable. Exceptions are elevated concentrations of Zn in all samples, Ni in lake sediment and in the Turasha dam sediment, and Cd in two lake sediment samples.

Zinc concentrations are similar in all samples, including samples taken from remote parts of the cathment (e.g., S12 and S3), which strongly indicates that relatively high concentrations are natural in origin. Zinc concentrations vary from 88 to 190 mg $kg^{-1}$, which can be compared to the 'threshold effect level' of the sediment quality criteria, set at 123 mg $kg^{-1}$. The latter assumes however, 100% bioavailability, which is unlikely to be the case, so the Zn levels are not likely to be of concern.

Nickel levels in sediment are elevated in comparison to the sediment quality guidelines, although considerably lower than the global average shale. Further, the Ni concentrations are considered as only 'somewhat elevated levels', as defined by the Swedish Environmental Protetion Agency (SEPA, 1998). Thus, it may be the case that the Canadian criteria are overly conservative. Nickel is, nevertheless, enriched in basic rocks such as the basalts of the Nyandarua range, which may explain the levels encountered. Further, Ni concentrations are somewhat higher in lake sediment and in the Turasha dam sediment compared to river sediments, indicating that this metal, for reasons unknown, is preferentially enriched in still water sediment compared to active river sediment. Possible anthropogenic sources of Ni include batteries, electroplating and paints. None of these sources appear overly likely in the Lake Naivasha area, which harbours little or no such industry.

The lake sediment samples 9C and 12B contain 7 and 6 mg $kg^{-1}$ Cd, respectively, which is significantly above global average levels and also above the 'probable effect level' of the Canadian sediment quality criteria. There are a number of explanations for these seemingly high concentrations. Firstly, the concentrations are fairly close to the low limit of detection of the analytical method used (2 mg $kg^{-1}$) and therefore analytical error cannot be ruled out. Secondly, cadmium is a common contaminant of rock phosphorus, the major ingredient of chemical fertilisers (Driver et al., 1999). Excessive inputs of Cd into the lake may therefore result from the use and release of chemical fertilisers. Both units represent sediments at depth below the sediment–water interface (39–49 and 8–44 cm, respectively). The high Cd concentrations may thus be a result of Cd being mobilised from the upper oxidising sediments and re-precipitating out at depths where conditions are reducing. Thus a horizon enriched in Cd could be generated from the concentra-

*Table 3.* Concentration of selected major and minor elements in river sediment samples from Lake Naivasha's catchment. Analyses were performed by X-Ray Fluorescence (XRF). Lower totals are caused by organic matter and other volatile material

| Sample | Total | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | $K_2O$ | $Na_2O$ | MgO | $P_2O_5$ | $SO_3$ | CaO | MnO | As | Co | Cr | Cu | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | % | % | % | % | % | % | % | % | % | % | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg |
| S3 | 92 | 57 | 12 | 13 | 3.2 | 2.2 | 0.53 | 0.31 | 0.04 | 0.91 | 0.22 | <10 | <6 | <100 | 2 | 2 | 14 | 150 |
| S4 | 91 | 57 | 13 | 11 | 4.2 | 2.7 | 0.73 | 0.29 | 0.04 | 1.2 | 0.41 | <10 | <6 | <100 | 3 | 7 | 17 | 150 |
| S7 | 91 | 57 | 13 | 12 | 3.6 | 2.0 | 0.81 | 0.20 | 0.03 | 1.7 | 0.38 | <10 | <6 | <100 | 4 | 10 | 19 | 150 |
| S8 | 90 | 55 | 14 | 9.9 | 3.6 | 2.3 | 0.85 | 0.26 | 0.05 | 1.8 | 0.23 | <10 | 8 | <100 | 8 | 11 | 16 | 140 |
| S10 | 83 | 49 | 14 | 11 | 2.0 | 1.1 | 0.84 | 0.54 | 0.08 | 1.6 | 0.31 | <10 | 14 | <100 | 22 | 20 | 12 | 170 |
| S11 | 90 | 58 | 13 | 10 | 3.1 | 1.7 | 0.72 | 0.41 | 0.03 | 1.0 | 0.38 | <10 | <6 | <100 | 5 | 11 | 16 | 150 |
| S14 | 93 | 61 | 14 | 9.3 | 2.6 | 1.4 | 1.0 | 0.31 | 0.03 | 1.6 | 0.23 | <10 | <6 | <100 | 20 | 16 | 12 | 170 |
| S15 | 90 | 61 | 13 | 8.0 | 3.7 | 2.2 | 0.66 | 0.24 | 0.04 | 1.0 | 0.20 | <10 | <6 | <100 | 6 | 6 | 14 | 140 |
| M1 | 89 | 58 | 15 | 9.4 | 2.0 | 0.90 | 0.88 | 0.49 | 0.04 | 0.99 | 0.12 | <10 | <6 | <100 | 19 | 15 | 11 | 190 |
| M1-repeat | 87 | 56 | 15 | 9.3 | 2.0 | 0.90 | 0.86 | 0.28 | 0.04 | 1.0 | 0.14 | <10 | 8 | <100 | 17 | 14 | 11 | 190 |
| M3 | 91 | 55 | 14 | 10 | 3.6 | 2.4 | 0.89 | 0.37 | 0.03 | 2.1 | 0.17 | <10 | 11 | <100 | 7 | 10 | 13 | 130 |
| Average shale[1] | | 58.1 | 15.4 | 4.02 | 3.24 | 1.30 | 2.44 | 0.17 | 0.64 | 3.1 | 0.10 | – | 19 | 90 | 45 | 68 | 20 | 95 |
| Sediment quality criteria for protection of aquatic life[2] | | | | | | | | Threshold effect level: | | | | 5.9 | – | 37 | 36 | 18 | 35 | 123 |
| | | | | | | | | Probable effect level: | | | | 17 | – | 90 | 197 | 36 | 91 | 315 |

[1]Major elements taken from Mason & More (1982) and minor elements from Turekian & Wedepohl (1961). [2]Environment Canada (1996)

*Table 4.* Concentration of selected major and minor elements in lake sediment samples from Lake Naivasha and its catchment. Analyses of lake samples were performed by ICP-AES after digestion in aqua regia

| | LOI % | $Al_2O_3$ % | $Fe_2O_3$ % | MgO % | $P_2O_5$ % | $SO_3$ % | CaO % | MnO % | As mg/kg | Cd mg/kg | Co mg/kg | Cr mg/kg | Cu mg/kg | Ni mg/kg | Pb mg/kg | Zn mg/kg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Core samples (1997) | | | | | | | | | | | | | | | | |
| 9A (0–11cm) | – | 17 | 11 | 0.94 | 0.18 | 0.63 | 0.94 | 0.21 | 2 | <2 | 9 | 9 | 23 | 28 | <5 | 160 |
| 9B (11–39 cm) | – | 14 | 9.0 | 0.65 | 0.16 | 0.70 | 1.1 | 0.22 | 3 | <2 | 8 | 18 | 29 | 41 | <5 | 130 |
| 9C (39–49 cm) | – | 13 | 7.3 | 0.56 | 0.16 | 0.58 | 2.0 | 0.15 | 5 | 7 | 7 | 6 | 9 | 18 | <5 | 110 |
| 9D (49–73 cm) | – | 9.9 | 9.5 | 0.48 | 0.16 | 0.68 | 1.3 | 0.28 | <2 | <2 | 11 | 36 | 17 | 38 | <5 | 88 |
| 9E (73–85 cm) | – | 12 | 7.9 | 0.55 | 0.16 | 0.60 | 0.95 | 0.15 | 2 | <2 | 9 | 30 | 13 | 35 | <5 | 140 |
| 9F (85–101cm) | – | 13 | 7.9 | 0.55 | 0.09 | 0.50 | 0.97 | 0.12 | 2 | <2 | 6 | 22 | 13 | 22 | <5 | 150 |
| 12A (0–8 cm) | – | 11 | 7.3 | 0.48 | 0.11 | 0.05 | 0.67 | 0.15 | <2 | <2 | 10 | 15 | 10 | 19 | 5 | 170 |
| 12A-repeat | – | 11 | 7.5 | 0.50 | 0.09 | 0.05 | 0.67 | 0.15 | <2 | <2 | 11 | 11 | 10 | 18 | 5 | 190 |
| 12B (8–44 cm) | – | 10 | 6.0 | 0.51 | 0.09 | 0.30 | 1.1 | 0.22 | 4 | 6 | 10 | 3 | 16 | 21 | 6 | 160 |
| 12C (44–60 cm) | – | 16 | 7.2 | 0.63 | 0.07 | 0.25 | 0.83 | 0.08 | 4 | <2 | 10 | 7 | 18 | 24 | 7 | 180 |
| 12D (60–73 cm) | – | 19 | 8.6 | 0.70 | 0.07 | 0.08 | 0.60 | 0.06 | 5 | <2 | 11 | 14 | 17 | 22 | 7 | 190 |
| Grab samples (2000) | | | | | | | | | | | | | | | | |
| L-11 | 4.8 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| L-12 | 24 | – | – | – | – | – | – | – | 0.98 | <0.17 | – | – | 15 | 17 | <0.3 | 160 |
| L-13 | 31 | – | – | – | – | – | – | – | 0.84 | <0.17 | – | – | 11 | 13 | <0.3 | 140 |
| L-14 | 20 | – | – | – | – | – | – | – | 0.55 | <0.17 | – | – | 7.4 | 6.4 | 3.7 | 100 |
| L-14-repeat | 20 | – | – | – | – | – | – | – | 0.52 | <0.17 | – | – | 7.6 | 5.7 | 3.7 | 100 |
| L-16 | 26 | – | – | – | – | – | – | – | 0.99 | <0.17 | – | – | 17 | 15 | <0.3 | 180 |
| L-17 | 33 | – | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| L-18 | 39 | – | – | – | – | – | – | – | 0.87 | <0.17 | – | – | 13 | 19 | 3.6 | 112 |
| Average shale[1] | | 15.4 | 4.02 | 3.24 | 0.17 | 0.64 | 3.11 | 0.10 | – | 0.3 | 19 | 90 | 45 | 68 | 20 | 95 |
| Sediment criteria for protection of aquatic life[2] | | | | | | Threshold effect level: | | | 5.9 | 0.6 | – | 37 | 36 | 18 | 35 | 123 |
| | | | | | | Probable effect level: | | | 17 | 3.5 | – | 90 | 197 | 36 | 91 | 315 |

[1]Major elements taken from Mason & More (1982) and minor elements from Turekian & Wedepohl (1961). [2]Environment Canada (1996).

tion of existing natural Cd or, alternatively, through the similar concentration of contaminant Cd. The analysis of surface sediments performed in 2000 does not indicate any significant supply of contaminant Cd from fertilisers. This follows since Cd levels are equally low at sites situated near the big flower farms on the eastern shore of the lake (L-13 and L-14), as at sites near the much less developed western shore (L-16 and L-18). Hence, the relatively high Cd levels encountered are unlikely to be caused by contamination, but rather due to geochemical redistribution of naturally existing Cd. The content of other minor and potentially toxic metals and metalloids is low.

## Conclusions

The description and analyses of Lake Naivasha sediment have provided extensive data on both present and past sedimentation patterns. Importantly, the findings show that natural lake level changes have caused dramatic changes to the lake ecosystem in the past, and that the instability of the lake's ecosystem is in part natural.

At present, sediment dynamics in the lake are governed by the presence of river point sources in the north, the deposition of silt and sand sized material near the river outlets; and wave-induced re-suspension of fine and organic rich sediment in the north, which are transported in easterly and southerly directions and deposited in the lake's central, southern and eastern parts. Deposition of fine, organic rich sediment is also occurring in northern areas that are protected by papyrus swamp vegetation.

The sedimentation rate in the central lake is found to be about 1 cm per year, which is in agreements with a previous estimate (Verschuren, 1996). However, the sedimentation rate in Elsamere Bay in the southwest appears to be higher, at up to 3 cm per year.

In the north-western part of the lake, historic lows in lake levels has lead to the formation of a possibly continuous layer of stiff grey, mineralised clay. This layer will act as an effective water barrier and its existence indicates that ground water recharge in this part of the lake, suggested by among others Åse (1987) may be impossible.

The geochemical analysis of a selected number of sediment samples from the lake and its catchment indicate that the concentrations of Fe, Zn, Cd and Ni sediment are elevated compared to global averages and/or sediment quality criteria. The reasons for the relatively high concentrations are likely to be found in the sediment source materials (volcanic rocks or laterite soils), which are naturally rich in these elements. The concentrations of other potentially toxic elements are low.

Lake Naivasha area is experiencing a period of rapid development with ever-increasing use of land and irrigation water for flower farming and the expansion of the Olkaria hydrothermal plants (Becht & Harper, 2002). In addition to these intensive uses, Everard et al. (2002) note an increasing intensity of subsistence agriculture in the catchment, including widespread poor land management practices. Consequently, it is not unlikely that the lake's catchment may soon be severely affected by impacts related to these developments as well as the pressures of a rising population. In addition to these immediate pressures, the planned construction of a water supply reservoir for the nearby town of Nakuru, that will export a substantial proportion of the river Malewa's water, will have an immediate and large scale affect both on the Malewa River and the lake itself (Harper et al., 1995).

The present study indicates that the river and lake sediment of the Lake Naivasha catchment are still rather pristine, and that anthropogenic impacts are not yet significant. The data obtained may therefore be used as reference values for assessing the possible environmental impacts of future developments around the lake.


## Acknowledgements

This study formed past of the work of the University of Leicester research project at Lake Naivasha, which since 1987 has been authorised by the Office of the President, Government of Kenya under research permit to Dr D. M. Harper no. OP 13/001/12C 46. The project was funded by the Earthwatch Institute, Boston, USA, and Oxford, England. The data collection would not have been possible without the assistance of numerous Earthwatch volunteers. Our sincere thanks go to the numerous colleagues in Kenya in particular Jill & Angus Simpson and Velia Carn.


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