Hydrobiologia **488:** 81–88, 2002.
D.M. Harper, R. Boar, M. Everard & P. Hickley (eds), Lake Naivasha, Kenya.

Magnetic susceptibilities of lake sediment and soils on the shoreline of Lake Naivasha, Kenya

R.R. Boar[1,*] & David M. Harper[2]
[1]*School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, U.K.*
[2]*Department of Biology, University of Leicester, Leicester LE1 7RH, U.K.*
**Author for correspondence. E-mail: r.boar@uea.ac.uk*

Key words: environmental magnetism, *Cyperus papyrus*, soil erosion, buffer zones, RAMSAR

Abstract

On steep, unvegetated slopes, sands (particle sizes 0.063 to 2 mm) and gravels (2–64 mm) erode from the shoreline of Lake Naivasha (Kenya) and enter the lake basin. This occurred freely where fringing papyrus *(Cyperus papyrus)* swamp had been cleared in favour of landing jetties or agriculture. Gravel-sized particles have been recovered up to 60 m offshore and sands to 80 m. In an area where papyrus was undisturbed and the swamp margin was 52 m wide, gravel did not enter the lake and sands penetrated to around 35 m. Large particles are much easier to trace to source and to manage than the finer silts and clays (<0.63 μm) that form the bulk of Lake Naivasha's sediment. The pattern of mass specific magnetic susceptibilities for the <63 μm fraction of lake sediment around the southern shoreline of the lake suggests that fine particles enter open water directly from the shoreline and are not transported from the lake's only perennial inflow, the River Malewa in the north. Such particles originate from a hinterland that supports high intensity horticulture and are therefore a potential source of contamination. Mean $\pm$ SD susceptibility (χ_{lf}) immediately offshore papyrus fringe was $0.49 \pm 0.08 \times 10^{-6}$ m^3 kg^{-1} compared with higher values of $1.33 \pm 0.14 \times 10^{-6}$ m^3 kg^{-1} where there was no papyrus barrier ($P < 0.0001$). The value for five sites in the middle parts of the lake was $0.45 \pm 0.02 \times 10^{-6}$ m^3 kg^{-1} with $1.38 \pm 0.10 \times 10^{-6}$ m^3 kg^{-1} near the mouth of the River Malewa. The results of this study are evidence, therefore, that conservation of a continuous papyrus margin of about 50 m width is a priority for intercepting particulate material.

Introduction

Lake Naivasha is a shallow freshwater lake in southern Kenya (0° 45′ S and 36° 20′ E) with a surface area that has fluctuated around 150 km^2. The only perennial inflow to the north of the lake, the River Malewa, drains a largely volcanic catchment of 1730 km^2. The other main river of the drainage basin, the Gilgil, distributes into irrigation ditches about 5 km north of the lake shore and does not flow directly into the lake. The Karati River to the northeast is an ephemeral stream that flows into Lake Naivasha on about 100 days each year. Several other small ephemeral streams, mostly along the southern shore, carry storm runoff toward open water during heavy rains. With an average mean daily flow of around 20 m^3 s^{-1} recorded between April 1994 and March 1995 (P. Obade, pers. com.), the River Malewa is likely to contribute by far the major part of Lake Naivasha's external supply of suspended and dissolved materials. Lake Naivasha has no surface outflow. The lake itself lies in a shallow basin dominated by Tertiary and Quaternary pyroclastic and lacustrine deposits and slope varies between about 1° and 48° over a 2000-m belt around the shore.

Annual rainfall in the area averages 680 mm (1951–1982) and annual evaporation is about 1865 mm (1966–1982; Åse et al., 1986). Lake Naivasha is a RAMSAR site of international importance for wildlife conservation, supports a local fishery and supplies water for arable agriculture, and geothermal power generation and horticulture.

Although the lake has international conservation status, its ecology is compromised by cultivation of its immediate shoreline, particularly in the south and in the northern part of the lake where large tracts of papyrus (*Cyperus papyrus* L.) swamp have been cleared for intensive agriculture. Undesirable influences of shoreline development on the ecology of the lake include: changes in water chemistry in the direction of increases in nutrient status (Harper, 1992); losses in lake volume due to water abstraction (LNRA, 1999; Becht & Harper, 2002); loss of papyrus swamps (Boar et al., 1999) and, introduction of alien fish (Muchiri & Hickley, 1991), crayfish and water plants (Harper et al., 1995). Potential influences of shoreline development include soil erosion and transport to the lake basin of soil particles on which pesticides; nutrients, particularly phosphorus and other agrochemicals may be adsorbed.

The lithosols and solentz soils around the southern shore of the lake are derived from volcanic ashes and other pyroclastic rocks (e.g. tuff and pumice) formed during recent volcanic activity (Kenya Soil Survey, 1982). A survey of the geochemistry of sediments from inflowing rivers (Tarras-Wahlberg, 1998) using X-Ray fluorescence analyses, has shown that river sands from the lower River Malewa contain around 9% haematite (Fe_2O_3). The ferrimagnetic content of the material is thus high and the natural magnetic content of catchment soils likely, therefore, to be detectable using standard methods in environmental magnetism (Smith, 1999). Organic sediments formed from primary production within lakes have very low, or sometimes negative magnetism and are thus likely to be quite distinct from sediment containing iron-rich minerals that may have eroded from lake catchments (Dearing, 1999). Environmental magnetism has been used since the mid 1970s to separate the origins of lake sediments and to trace their actual origin from known source domains (Thompson et al., 1975; Dearing, 1979; Oldfield et al., 1989; David et al., 1998). However there are other influences that complicate, and can invalidate, interpretation. For example, magnetic properties of materials vary with particle size (Thompson & Morton, 1979) and with variations in the size and shape of crystals (Maher, 1988). A particular feature of lake sediments is that in conditions of low redox potential, iron dissolution may occur and so reduce magnetic signatures (Hilton & Lishman, 1985). Conversely, authigenic iron sulphides (e.g. greigite) might be formed (Hilton, 1990) or iron nodules (magnetosomes) may be formed through intense bacterial activity (Snowball, 1994) and may enhance magnetic signatures significantly. Casual observations of sediment in Lake Naivasha over the period 1993–1998 suggest, however, that lake sediment is always oxic and that reduction of iron is not, therefore, a dominant process. This means that particles that have eroded from the immediate shoreline and that have entered the lake are likely to have retained largely unaltered magnetic properties.

This work set out to discover: (i) if sediment in the lake's littoral zone receives soil that has eroded from the lake shore; (ii) if magnetic properties of such sediment can be used to distinguish it from material that has come from the main inflowing river and, (iii) the extent to which papyrus swamp intercepts finer size classes of soil that, potentially, carry contaminants into the lake. The wider aim of the work is to help establish quantitatively the role of papyrus in trapping particulate material that may be moving from the immediate shoreline into the lake's basin.

Methods

Samples of topsoil were taken at 50-m or 10-m intervals along three transects of 420 m, 575 m and 920 m from upland (1960 m.a.s.l.) to the lake edge on the southern shore of Lake Naivasha (water level 1890 m.a.s.l.) during August 1998, (Fig. 1). One year later, samples of surface lake sediment were taken with an Ekman grab at intervals of up to 30 m to extend the three transects into the open lake. Transects were chosen to represent areas with a high risk of soil erosion where continuous papyrus swamp was present on the lake shore; areas of similarly high erosion risk, but with a discontinuous papyrus fringe and an area of low erosion risk. Erosion risk was taken as high on slopes with a gradient of greater than 30° with shrubs *(Tarchonanthus camphoratus* L. and *Acacia drepanolobium* Sjøstedt) and very sparse (c.1°) cover by ground vegetation and low where gradients were low (c. 1°) with continuous ground cover (*Cynodon* sp. and other grasses, *Senna didymobotrya* (Fresen.) Irwin & Barneby and *A. xanthophloea* Benth.)

Additional samples of lake sediment were taken at the waterward edge of papyrus swamp in 16 other sampling areas distributed around the lake, from five sites in the middle of the lake and, to represent the drainage catchment of the inflowing river, from two sites at the mouth of the River Malewa and four areas further south of the inflow. Samples were taken around the mouth of the River Malewa since it is possible that minerals from the inflow could have been transported and then redistributed along the southern shoreline.

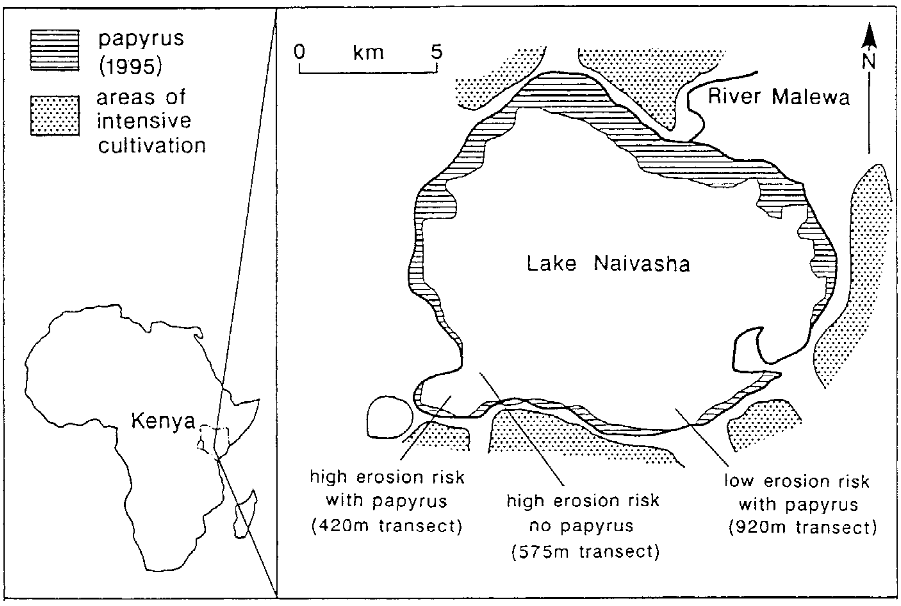

Figure 1. Schematic map of Lake Naivasha, Kenya, showing the locations of three sampling transects. Transect lengths are not shown to scale.

Particle size analysis was carried out on lake sediment and soil samples from the transects. Magnetic analyses have been carried out on the < 63 μm fraction (silts and clays) of all lake samples and on soil samples from the high erosion risk transect where there was no shoreline papyrus. For particle size analysis, 100 ml of each lake sediment sample was wet sieved into four size classes: >2000 μm (gravel); 2000–500μm (very coarse and coarse sand); 500–250 μm (medium sand) and 250–63 μm (fine and very fine sand). Each fraction was dried and weighed to the nearest 0.001 g. Replicate 100-ml bulk samples were dried and weighed and the mass of the <63 μm fraction calculated by difference.

Magnetic analyses were carried out on the <63 μm size fraction of topsoils and lake sediment of five extra replicate samples taken in each sampling area and dried for subsequent sieving. Samples of 10 cm^3 of the $<63\mu$m fraction were weighed in plastic pots to the nearest 0.0001 g. Their magnetic susceptibility was measured in a weak magnetic field (0.1 mT) at 0.46 kHz (low frequency, lf) and 4.6 kHz (high frequency, hf) on a Bartington MS2B single sample dual frequency sensor. Low frequency mass specific magnetic susceptibility (χ_{lf}), in units corrected for variations in bulk density (m^3 kg^{-1}) and percentage mass specific frequency dependent susceptibility ($\chi_{\text{fd}}\%$) were calculated according to Walden (1999a).

Further magnetic analyses were carried out to correct for variations in magnetic behaviour due only to variations in the content of ultrafine material within samples. Samples were first demagnetised by tumbling them at 80 mT in a Molspin AF (alternating field) demagnetiser. This was carried out inside a magnetic shield that reduces the Earth's magnetic field to near zero. Samples were then fixed in one position relative to the coil and remagnetised in an applied alternating field (0.08 mT) so that they acquired an anhysteretic remanent magnetism (ARM). The remanence of the acquired magnetism was then measured (Am^{-2} kg^{-1}) immediately in a Molspin Spinner and values corrected to mass specific ARM (χ_{ARM}) in m^{-3} kg^{-1}. The method for this followed Walden (1999b).

Results

The particle size analysis of sediments along the southern shoreline shows the permeability of the shoreline to different size classes of particles (Fig. 2) and a marked effect of removal of papyrus swamp on the movement of topsoil into open water. Where the risk of soil erosion was high, gravel-sized particles entered the lake from its shoreline and were found at up to 60 m offshore, but only where papyrus had been removed (Fig. 2a). Gravel was not found in the lake where a 52-m fringe of papyrus was present (Fig.

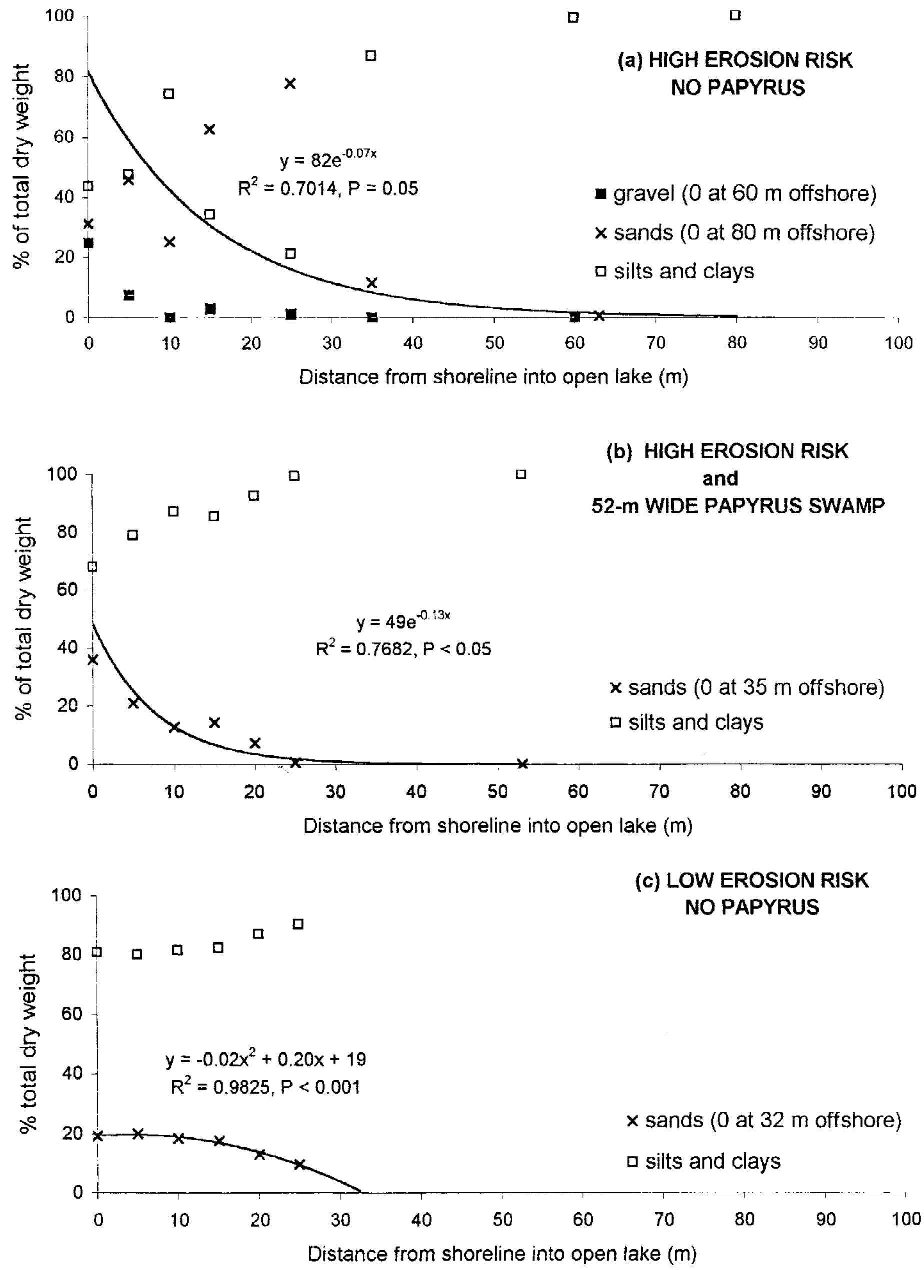

Figure 2. Particle size distributions in lake sediment from three transects along the southern shore of Lake Naivasha, Kenya, during 1998. Transects begin at the lake's shoreline and papyrus had been removed from the shorelines of (a) and (c).

2b). Sands penetrated much further (up to 80 m) into open water where fringing swamp had been removed. Where the risk of soil erosion was low (Fig. 2c) sands penetrated to about 30 m offshore. The difference made by papyrus in high risk areas was thus the interception of gravel and a reduction in the lakeward spreading of sands. The control area, with no papyrus and at low risk of soil erosion, did not contribute gravel to open water but did contribute sands to the predicted c. 30 m. In this area, sands contributed about 20% of the dry weight of sediment on the immediate shoreline. The most disturbed sampling area (Fig. 2a) appeared to contribute much larger loads of sand (and

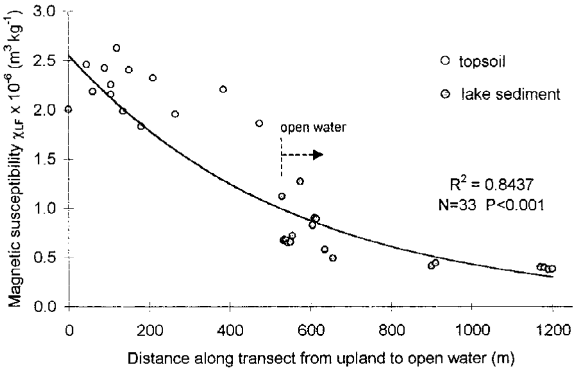

Figure 3. Mass specific magnetic susceptibility of silts and clays ($<63\ \mu$m) in topsoil and lake sediment along a transect from upland into Lake Naivasha, Kenya where marginal *Cyperus papyrus* swamp had been removed from the lake's shoreline. The lakeward end of the same transect is shown in Figure 2a.

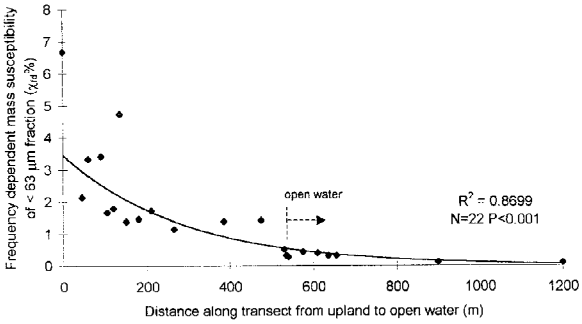

Figure 4. Frequency dependent mass specific magnetic susceptibility of silts and clays ($<63\ \mu$m) in topsoil and lake sediment along the transect shown in Figure 3.

gravel) than either of the other two sites although the material penetrated little further into open water.

The dry weight of sediment that was not accounted for by sand or by gravel was much finer ($<63\ \mu$m) silts and clays. Figure 3 shows that the mass specific magnetic content of the $<63\ \mu$m size fraction of topsoils and sediments fell more than fourfold ($P < 0.001$) from upland to lake bed along a 1200-m transect from an eroding upland to lake sediment. Particle sizes of the lake sediments on this transect are shown in Figure 2a. The water's edge was 575 m from the start of the transect, and the average $\pm$ SD mass specific magnetic susceptibility of fine sediment sieved from seven lake sediment samples taken at 5-m intervals within 35 m of the edge was $0.83 \pm 0.26 \times 10^{-6}$ m^3 kg^{-1}. At 575 m, magnetic susceptibility reached its peak of $1.28 \pm 0.04 \times 10^{-6}$ m^3 kg^{-1}. This sampling site was thus taken to represent extreme erosion of the shoreline with values higher ($P < 0.01$) than the mean value in the five sites sampled in the middle of the open lake ($0.45 \pm 0.02 \times 10^{-6}$ m^3 kg^{-1}).

The data in Figure 4 help show whether the origin of the sediment sampled along the southern shoreline was from material eroded from the immediate catchment or if it was transported from the northern part of the basin. Large values for frequency dependent susceptibility are typical of material that has been weathered little, and low values suggest that soil minerals have undergone physical and chemical weathering. Figure 4 thus suggests that products of soil weathering had been transported down slope and accumulated on the lower slopes and shoreline of the sampling site. Frequency dependent susceptibility reached almost 7% on the upper slopes and fell to between 1 and 2% on lower slopes. Values varied quite closely with distance along the transect ($R^2 = 0.87$, $P < 0.001$), suggesting that material on lower slopes had originated from higher ground.

Since magnetic susceptibility depends upon grain size as well as the concentration of magnetic minerals within samples, magnetic analyses that correct for grain size had to be carried out. Figure 5 shows the results of ARM analysis on samples from the transect. The importance of Figure 5 is that, after correction for variations in ultra-grain size, the pattern is very similar to the pattern shown in Figure 3. On Figure 5, ARM values are shown also for samples taken from the edge of open water at five other sites on the southern shore where, in contrast to the sampling transect, the papyrus fringe was undisturbed. The mean $\pm$ SD ARM (χ_{ARM}) of sediment from these five sites ($2.53 \pm 0.56 \times 10^{-3}$ m^3 kg^{-1}) was lower ($P < 0.01$) than along the sampling transect and was the same as sediment sampled from the middle of the lake basin. Together,

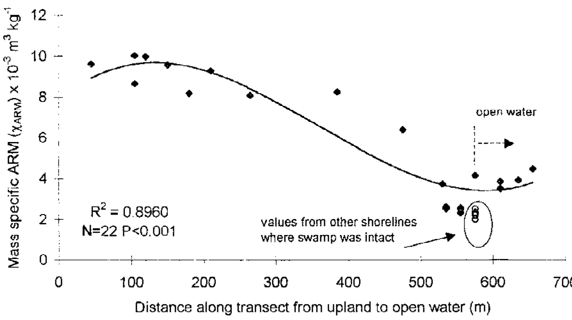

Figure 5. Mass specific anhysteretic remanent magnetisation (χ_{ARM}) of silts and clays ($<63\ \mu$m) in topsoil and lake sediment along the transect shown in Figure 3 extending the transect to 655 m into the lake.

these results indicate that papyrus forms a barrier to the entry of fine particles from the shoreline.

Figure 6 is based upon values for the magnetic susceptibility of all the sediments that were sampled and shows that the strongest present-day magnetic susceptibility of sediment in the lake basin is at the mouth of the River Malewa and the weakest toward the middle of the lake. If the middle of the lake basin is taken to represent a background concentration for the lake (of $<0.50 \times 10^{-6}$ m^3 kg^{-1}), then magnetic susceptibilities well above background occurred along the southern shore where papyrus was absent and where the risk of soil erosion was high. Sediment with high magnetic concentration in the north of the lake appeared to reflect inputs from the River Malewa, rather than from the much smaller Karati. Patches of relatively high magnestism along the western shores of the lake may be associated with very steep shoreline gradients in these areas.

Discussion

A papyrus margin of 52-m width formed an effective barrier to the movement of gravel from the southern shore of Lake Naivasha into open water and appeared also to reduce to around half the rate of entry of sands. The pattern of results for these larger particles thus shows that clearance of swamp in areas at high risk of soil erosion results in transport of topsoil into the lake. However, it is the entry of smaller particles that is the more likely to influence the ecology of lake sediments and, potentially, the water column.

At around 10%, the magnetite content of sediment in Lake Naivasha is high (Tarras-Wahlberg, 1999) and this was reflected in this work by values for magnetic susceptibility that were high for lake sediment. The magnetic susceptibility of topsoil from the Lake Naivasha catchment was around $2\chi_{\mathrm{lf}}\ 10^{-6}$ m^3 kg^{-1} and so at the upper end of published ranges of between 0.01 $\chi_{\mathrm{lf}}\ 10^{-6}$ m^3 kg^{-1} to 10 $\chi_{\mathrm{lf}}\ 10^{-6}$ m^3 kg^{-1} (Dearing, 1999). Magnetic susceptibility appears, therefore, to form a good basis for tracing the transport of fine material into the lake. Since the magnetic strength of eroded materials may be altered by both diagenetic and authigenic processes, the reliability of the method would be reduced if there were evidence of these from the lake. Since Tarras-Wahlberg (1998) did not find ferrimagnetic minerals (such as greigite) and negligible rates of phosphorus release from lake sediment have been measured (N. Kitaka pers. com.), it is unlikely that ferrimagnetic minerals of catchment origin were transformed significantly during their residence in the lake's sediment.

Variations in frequency dependent susceptibility between 1% and 10% are accepted as interpretable in terms of extent of soil weathering with lower values typical of more weathered material. This means that the range of values from 0.1% to 7% in topsoil taken from the main sampling transect probably does indicate that the magnetic content of the material was washed down slope rather than formed *in situ*.

At the five sites where papyrus swamp was intact, values for ARM were significantly lower that where papyrus formed a continuous barrier. Thus, both magnetic susceptibilities and remanence measures have indicated that silts and clays have entered open water directly from the southern shoreline and have not been transported from the inflow of the River Malewa.

The ecological implications of the results involve potential increases in the rate of sediment accumulation in the lake. Rates of sedimentation may be reconstructed using environmental magnetism as well as a variety of methods in paleolimnology. Paleolimnological approaches may include analysis of the diatom record and of zooplankton and other invertebrate remains. Such methods have been used in separate basins within Lake Naivasha (Verschuren et al., 1999). Using stratigraphic and geochronological analyses of sediment cores from the middle of Lake Naivasha, Verschuren (1999) estimated that the linear sedimentation rate in the middle of the lake is around 1 cm per year (0.1 g dry matter cm^{-2} yr^{-1}) and that the depositional environment has been relatively stable over the last 40 years. On the basis of the present study, such stability is unlikely to persist, at least at eroding lake margins, given the penetration of sands into open water where shoreline papyrus has been removed. The actual areal extent of papyrus swamp, although fluctuating naturally with lake level, has been in a period of net decline over the last 40 years with the area changing from 48 km^2 during 1960 to 14 km^2 in 1995 (Boar et al., 1999) with a recent estimate for 1999 based upon maps made from aerial photographs of only 8 km^2 (R.R. Boar, unpublished data). Moreover, in his recent study of the geochemistry of sediment cores taken in the south-eastern part of Lake Naivasha and thus in the same part of the lake as the main transect in this study, Tarras-Wahlberg (1999) has estimated a sedimentation rate of 3 cm per year which is much higher than elsewhere in the lake. Nutrients may accumulate also as a result of increases in external

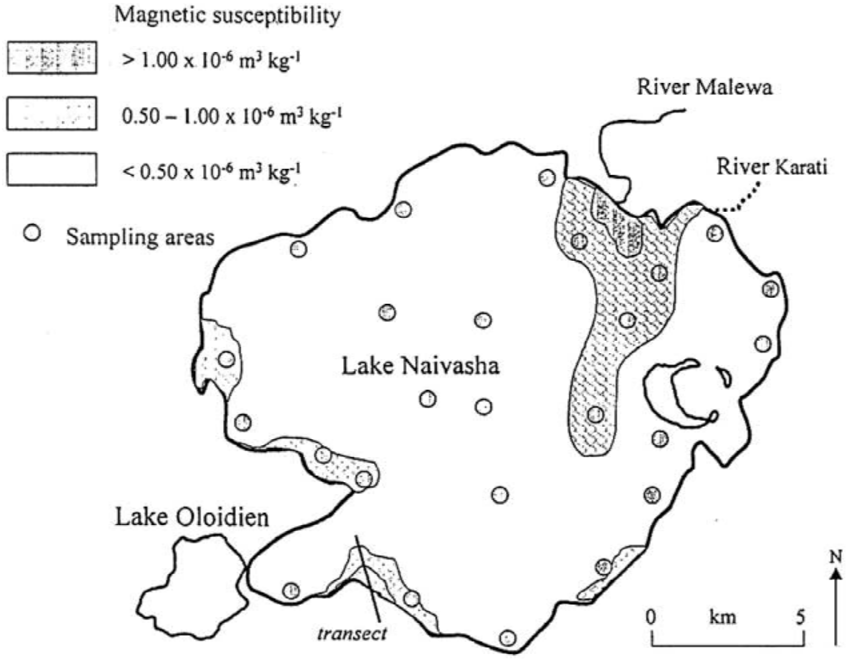

Figure 6. Mass specific magnetic susceptibility of silts and clays (<63 μm) in surface sediment sampled around the shoreline of Lake Naivasha, Kenya, during 1999. The position of the transect referred to in Figures 3–5 is shown.

loading of sediment to the lake. A recent phosphorus budget shows that at least 70% of the external load of phosphorus to Lake Naivasha is associated with particulate material (N. Kitaka, pers. com.), some of which may enter from the shoreline rather than from inflowing rivers.

The importance of conservation of papyrus swamp is thus twofold; to capture particulate material, and to intercept dissolved materials that enter the lake from its margins. Although a swamp margin of about 50 m does, to an extent, buffer the lake against entry of particulates, such a margin may be insufficient to remove or transform nutrients or other ions that are dissolved in swamp throughflow. There is some evidence for this from a transect through a 50-m wide swamp in Lake Naivasha in that neither electrical conductivity of standing water nor the size or density of papyrus stems changed with distance from the shore to open water (Boar et al., 1999). This is in contrast to much larger papyrus swamps where important changes in nutrient chemistry occur in through flow under floating papyrus mats (Gaudet, 1979).

There is potential for transport of other contaminants (such as pesticides) to open water where silts and clays eroded from intensively cultivated shorelines enter the lake. However, the extent to which contaminants adsorbed onto silts and clays would be transferred to higher trophic levels is limited in Lake Naivasha since the benthic community is patchy (J.E.P.C. Darlington, pers. com.) and in some years sparse (Clarke et al., 1989), and none of the members of the lake's species-poor fish community are benthivorous (Muchiri et al., 1994). The biological community of Lake Naivasha has simplified over the past decades. There have been large-scale losses in cover by submerged water plants that have corresponded to nutrient enrichment as well as disturbance by introduced Louisiana crayfish (*Pracambarus clarkii* Girard), water hyacinth (*Eichhornia crassipes* (Mart) Solms) and salvinia (*Salvinia molesta* Mitchell). The future of the lake's ecology would appear, at least in part, to depend also upon rates of soil erosion in the catchment and the conservation of papyrus swamp.

Conclusion

The main outcome of this work has been to show that, in the absence of papyrus, fine silts and clays are transported into the main basin of Lake Naivasha directly from its shoreline. Where the shoreline is cultivated intensively, any contaminants adsorbed onto such particles would be transported also. Papyrus swamps of at least 50-m width appear to form an effective barrier to gravel and to reduce to at least 50% the distance that sands penetrate into the lake. Such a buffer zone would not necessarily absorb nutrients or other dissolved salts. Until the width of papyrus needed for adequate nutrient buffering is quantified for Lake Naivasha, conservation of a minimum papyrus margin of 50 m that is continuous and not broken must be a priority for continuing lake management.

Acknowledgements

The fieldwork was funded by the Earthwatch Institute, Boston, U.S.A. and Oxford, England. Earthwatch volunteers on Team IV, 1998 and Team V, 1999, collected and helped prepare samples and thanks are due also to Mr Ruben Kamau Chege. Sampling was carried out with the permission of the Osieran Development Company, Mrs A. Root and The Elsa Trust. Magnetic analyses were carried out in the School of Environmental Sciences, UEA with the help of Mr Tom Mutch and Prof. Barbara Maher. We are grateful to our colleague Prof. Ken Mavuti at the University of Nairobi. The research was authorized by the Office of the President of the Government of Kenya under permit no. OP 13/001/12C46.

References

Åse, L-E., K. Sernbo & P. Syrén, 1986. Studies of Lake Naivasha, Kenya, and its drainage area. Forsk. Naturgeogr. Inst. Stockholm University 33: 1–77.

Boar, R. R., D. M. Harper & C. S. Adams, 1999. Biomass and its allocation in *Cyperus papyrus* in a tropical wetland, Lake Naivasha, Kenya. Biotropica 31: 411–421.

Clark, F., A. Beeby & P. Kirby, 1998. A study of the macroinvertebrates of Lakes Naivasha, Oloidien and Sonachi, Kenya. Rev. Hydrobiol. Trop. 22: 21–33.

David, C., J. A. Dearing & N. Roberts, 1998. Land use history and sediment flux in a lowland catchment, Groby Pool, Leicestershire, U.K. Holocene 8: 383–394.

Dearing, J. A., 1979. The Use of Magnetic Measurements to Study Particulate Flux in Lake-Watershed Ecosystems. PhD thesis, University of Liverpool, U.K.

Dearing, J. A., 1999. Holocene environmental change from magnetic proxies in lake sediments. In Maher, B. A. & R. Thompson (eds), Quaternary Climates, Environments and Magnetism. Cambridge University Press: 354 pp.

Gaudet, J. J., 1979. Seasonal changes in nutrients in a tropical swamp: North Swamp, Lake Naivasha, Kenya. J. Ecol. 67: 953–981.

Harper, D. M., 1992. The ecological relationships of aquatic plants at Lake Naivasha, Kenya. Hydrobiologia 232: 65–71.

Harper, D. M., C. Adams & K. M. Mavuti, 1995. The aquatic plant communities of the Lake Naivasha wetland, Kenya: pattern, dynamics and conservation. Wetland Ecol. Manage. 3: 111–123.

Hilton, J., 1990. Greigite and the magnetic properties of sediments. Limnol. Oceanogr, 35: 509–520.

Hilton, J. & J. P. Lishman, 1985. The effect of redox changes on the magnetic susceptibility of sediments from a seasonally anoxic lake. Limnol. Oceanogr. 30: 907–909.

Kenya Soil Survey, 1982. Exploratory soil map and agro-climatic zone map of Kenya, 1980. Exploratory Soil Survey Report No. E1, Kenya Soil Survey, Nairobi: 56 pp.

LNRA, 1999. Lake Naivasha Management Plan. The Lake Naivasha Riparian Association (LNRA), P.O. Box 1011, Naivasha, Kenya: 77 pp.

Maher, B. A., 1988. Magnetic properties of some synthetic submicron magnetites. Geophy. J. Royal Astron. Soc. 94: 83–96.

Muchiri, S. M. & P. Hickley, 1991. The fishery of Lake Naivasha, Kenya. In Cowx, I. G. (ed.), Catch Effort Sampling Strategies: their Application in Freshwater Fisheries Management. Fishing News Books, Blackwell Scientific Publications, Oxford: 382–392.

Muchiri, S. M., P. Hickley, D. M. Harper & E. North, 1994. The potential for enhancing the fishery of Lake Naivasha, Kenya. In Cowx, I. G. (ed.), Rehabilitation of Freshwater Fisheries. Fishing News Books, Blackwell Scientific Publications, Oxford: 348–357.

Oldfield, F., B. A. Maher & P. G. Appleby, 1989. Sediment source variations and lead-210 inventories in recent Potomac Estuary sediment cores. J. Quat. Sci. 4: 189–200.

Smith, J. P., 1999. An introduction to the magnetic properties of natural materials. In Walden, J., F. Oldfield & J. P. Smith (eds), Environmental Magnetism: a Practical Guide. Technical Guide, No. 6, Quaternary Research Association, London: 5–34.

Snowball, I. F., 1994. Bacterial magnetite and the magnetic properties of sediments in a Swedish lake. Earth Planet. Sci. Lett. 126: 129–142.

Tarras-Wahlberg, H., 1998. Investigations of Sediment Geochemistry in Rivers in the Lake Naivasha Catchment. University of Leicester/Earthwatch Institute Report: 11 pp.

Tarras-Wahlberg, H., 1999. Investigations of Sediment Stratigraphy and Sediment Geochemistry of Lake Naivasha, Kenya. University of Leicester/Earthwatch Institute Report: 14 pp.

Thompson, R. & D. J. Morton, 1979. Magnetic susceptibility and particle-size distributions in recent sediments of the Loch Lomond drainage basin, Scotland. J. Sed. Petrol. 49: 801–811.

Thompson, R., R. W. Battarbee, P. E. O'Sullivan & F. Oldfield, 1975. Magnetic susceptibility of lake sediments. Limnol. Oceanogr. 20: 687–698.

Verschuren, D., 1999. Sedimentation controls on the preservation and time resolution of sedimentary climate-proxy records from shallow fluctuating lakes. Quaternary Science Reviews 18: 821–837.

Verschuren, D., C. Cocquyt, J. Tibby, C. N. Roberts & P. R. Leavitt, 1999. Long-term dynamics of algal and invertebrate communities in a small, fluctuating tropical soda lake. Limnol. Oceanogr. 44: 1216–1231.

Walden, J., 1999a. Magnetic susceptibility. In Walden, J. F. Oldfield & J. P. Smith (eds), Environmental Magnetism: a Practical Guide. Technical Guide, No. 6, Quaternary Research Association, London: 35–62.

Walden, J., 1999b. Remanence measurements. In Walden, J., Oldfield F. & J. P. Smith (eds), Environmental Magnetism: a Practical Guide. Technical Guide, No. 6, Quaternary Research Association, London: 63–88.