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from Action
to Theory

Lake Naivasha, Kenya: Ecohydrology to guide the management of a tropical protected area

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Abstract

The present ecological and hydrological state of Lake Naivasha, a tropical freshwater Ramsar site, is reviewed from existing research. The ecology of the lake was formerly regulated by ecohydrological control exerted on the inflowing hydrochemistry by the continuous fringing papyrus, with a full swamp on the inflow rivers' delta. The ecology of the lake since that time has been severely disrupted by alien (or exotic) species invasions, particularly the Louisiana crayfish *Procambarus clarkii*. Lake-wide papyrus degradation has also been occurring since about 1980, following a lake level decline of up to 3m through agri-industrial abstraction. The river Malewa, which previously ran through a swamp, now runs directly into the lake, bringing high silt and nutrient loads in wet seasons, making the lake eutrophic.

It is suggested that sustainable management of the lake should focus upon three ecohydrological objectives - control of abstractions to achieve hydrological balance, physical restoration of the former North Swamp and the control of illegal fishing. The latter would enable the commercial fishery returns to maximum sustainable yield so that large *M. salmoides* (large mouthed bass) individuals once again impose a 'top-down' control upon *P. clarkii*, and the crayfish itself be copmmercially exploited.

Key words: *Procambarus clarkii*, *Cyperus papyrus*, Ramsar site, wise use, water resources, integrated water management.

1. Introduction

Freshwater resources are scarce in Kenya, an equatorial, semi-arid country where many rivers are seasonal. Its two major standing waters are the eastern shore of Lake Victoria and Lake Naivasha in the floor of the Rift Valley. The latter is the freshest of a chain of lakes, most of which are very alkaline (Fig. 1). It is endorheic, but fresh, because its catchment area includes land on the eastern escarpment rising over 3000 metres, resulting in its main inflow river, the Malewa, being rain-supported and permanent (Becht, Harper 2002 and references therein). The lake also has underground outflow seepage and geochemical and biochemical sedimentation of salts (Gaudet, Melack 1981).

The natural ecological state

The lake, being close to Nairobi, was used for recreation by residents and visitors to Kenya, leading to reports in tourist guidebooks that qualified the lake for 'one of the world's top 10 bird-

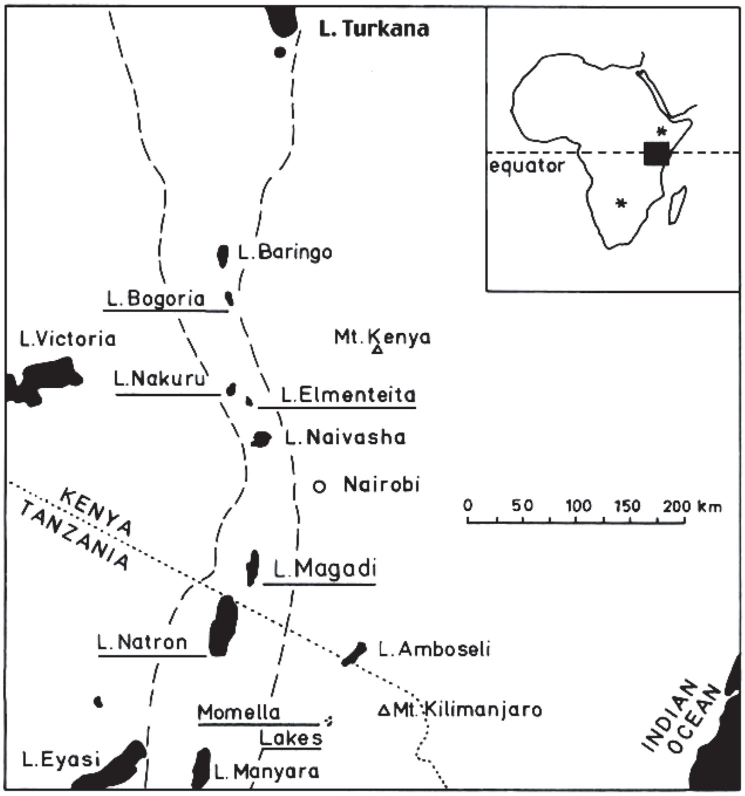

Fig 1. The Eastern Rift valley showing the lakes on the valley floor. Soda lakes are underlined, so that the rarity of freshwater ones is apparent (from Harper *et al.* 2003).

watching sites' and 'the most beautiful of the Rift Valley lakes' (Williams 1967). Such abbreviated descriptions barely do justice to an ecosystem as spectacular as this; the concluding words from Willcock (1974) perhaps enable one to imagine the spectacle:

"Naivasha is perhaps unsurpassed in its softness and beauty by any other of the lakes in the Rift. Here the beauty is not just in the landscape, but in the whole wild world that awakens and returns to sleep every day. In the golden sunlight of an African morning, there is dew on the grass and occasional patches of frost, too. The purple lotus flowers of the water lilies are not open yet. There is not a sound except a fussing of coots around the lily pads. The wide lily beds silently tremble and lift above the backs of fish searching for crustacea, snails and larvae on the ceiling of their green underworld. Then a black crake tiptoes out of the papyrus and a paid of African pochard plane in, wings set and paddles down, scratching the glossy surface with their landing. Gradually, the lake assumes the throbbing vitality of the daytime.

The hour of greatest beauty is the one just before nightfall. Dusk on the equator is a rapid dimming. Long before the light goes down, the purple lotus flowers of the lily beds have closed again. Yet a Naivasha sunset grows its own blooms. Skeins of egrets, ducks, geese and pelicans blossom against the purpling dusk that clings to the Rift Valley walls. And a million tree frogs tune up to sing their nocturne."

Early uses of the lake

The lake's water has always had value to humans, despite it having an unstable hydrology (Richardson, Richardson 1972; Vincent *et al.* 1979). At several times in the past one thousand years it was reduced to almost nothing and those periods are thought to have coincided with social disruption (Verschuren *et al.* 2000). In pre-colonial times it lay within the area occupied by nomadic Masaai pastoralists, who used it as a dry season refuge for their cattle from up to 300 km to the north and south, sharing it with wildlife, both those resident on the plains and those migrating between the higher ground to west (Mau forest) and east (Aberdare mountains).

In colonial times it supported small farms around its shores, growing citrus fruits, alfalfa and fattening cattle, supported by lake water irrigation. There was economic interest in the lake's water balance, driven by a desire to utilize the "available" freshwater for towns further afield. Colonial hydrologists estimated the potential 'safe' yield at approximately 10-year intervals over 60 years (Sikes 1936; Tetley 1948; Brind, Robertson 1958; Oestergaard 1974; Anon 1984), during which time the lake level varied about 10-fold in area and 3-fold in average depth by the natural climatic instability.

The lake's biodiversity was initially studied by U.K. scientific expeditions in the first two quarters of the 20th Century (Jenkin 1929, 1936; Beadle 1932) and its ecosystem functioning by Kenyan-based scientists in the third (Gaudet 1976a, b, 1977a, 1977b; Siddiqui, 1977, Gaudet, Melack 1981). This analysis of the functioning of the ecotone (called the 'drawdown zone') showed how the vegetation, in particular the dominant swamp species *Cyperus papyrus*, papyrus, regulated the incoming materials, particularly soluble and particulate nutrients, according to classic ecohydrological principles (Zalewski 2002). High quantities were delivered by the incoming rivers

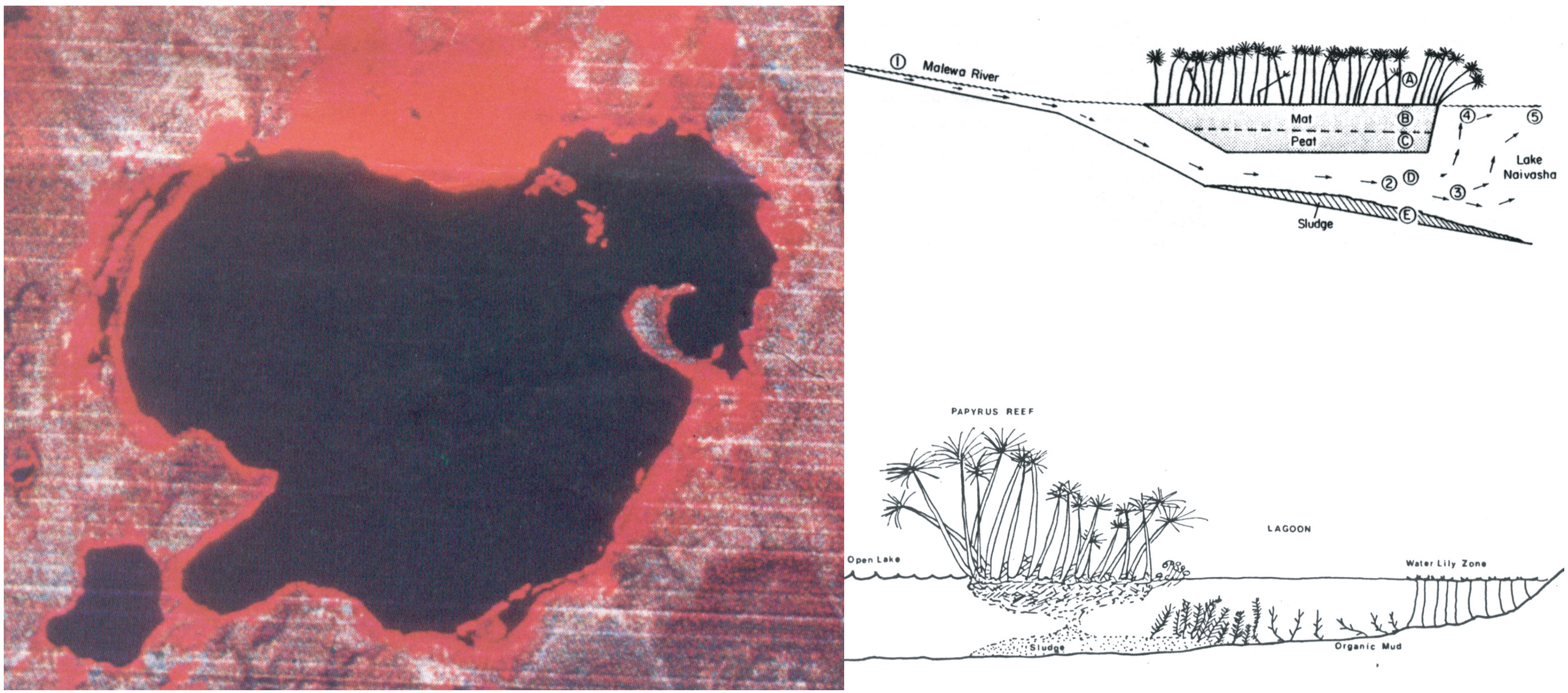

Fig 2. Lake Naivasha, showing the former dimensions of the 'North Swamp' in January 1979 (from Gaudet, Falconer 1982) from a Landsat image and diagrammatic representation of the ecohydrological processes that maintained an oligotrophic lake up to this time (From Gaudet 1977b).

during the wet seasons to a large papyrus swamp in the north which encompassed the delta of all three main rivers (Fig. 2). The swamp trapped the sediments, incorporated much of the nutrients into plant and microbial biomass, losing nitrogen by denitrification in the swamp mat, then releasing (over a much longer time-period) soluble and organic-bound nutrients into the submerged- and floating-leaved aquatic plant zones and ultimately the open water.

Anthropogenic changes in the 20th Century

A commercial fishery had been opened in the lake in the second half of the 20th Century after several earlier introductions of piscivorous American large-mouthed bass (*Micropterus salmoides*) and herbivorous east African native *Tilapia* species (Harper *et al.* 1990; Hickley, Harper 2002). The former is believed to have exterminated the only native species, a small endemic tooth-carp, *Aplocheilichthys antinorii*, by the 1960s, representing the first detectable impact (following the introductions) on the lake's ecology by humans.

By the time that the endemic fish had disappeared, the first of several endemic species had arrived, by chance. *Salvinia molesta*, a floating fern originally from South Africa, named 'Kariba Weed' because of its dramatic impact upon the new reservoir of that name in the same decade, was recorded in the shallow lagoons

The nature of agriculture around the lake began to change as the final quarter of the 20th Century started (Harper *et al.* 1990). The erstwhile small farms had given way to approximately 100 km^2 of irrigated horticulture by 1995 (Johnson *et al.* 1999) in large units, with output (flowers and vegetables) air-freighted to Europe. The cultivated area had doubled by the start of the 21st Century (Becht, unpubl.). This land use change, visually dramatic in itself, brought even greater social changes - the ten-fold rise in population of horticultural estate workers and their dependents to a quarter of a million.

The exotic arrivals continued with the deliberate introduction of *Procambarus clarkii* in 1970 (Lowery, Mendes, 1977a,b; Oluoch 1983, 1990), followed by the arrival of *Eichhornia crassipes* in 1988.

Conservation initiatives

In the early 1990s an organisation of riparian land-owners (which already existed to settle disputes between members whose land ownership ends at the 1906 lake level contour but who have a legal right to temporarily cultivate lake bed below this), articulated the environmental concern about these changes (Enniskillen 2002). They commissioned two consultants' reports to summarise all the scientific knowledge about Lake Naivasha and its conservation status (Goldson 1993; Khroda 1994). The Association's subsequent lobbying, using the scientific knowledge recently accumulated (Harper *et al.* 1990; Harper *et al.* 1995) led to the lake being declared Kenya's second Ramsar site in 1995 (Ramsar, 1997). The Association changed its constitution and name to become the Lake Naivasha Riparian Association (LNRA), followed by the production of its management plan with a strategy for its implementation and Codes of Conduct for each industry using lake water (LNRA, 1999). Its organizational work was recognized by the award of the Ramsar Prize in 1998. The Ramsar management process is now in the hands of the Lake Naivasha Management Implementation Committee (LNMIC), incorporating the legal Ramsar management agents (Kenya Wildlife Services), LNRA and local stakeholders.

Conservation management issues

The most important issue risking the conservation value of the lake, is perceived to be excess water use, leading from an insufficient understanding of the water balance. At the conclusion of the 20th Century the demands for freshwater were intense, not just for potable water as envisaged half a century earlier but also for intensive irrigation (about two thirds of the demand) and in the Olkaria Geothermal Power Station, which generates around 15% of Kenya's power and is the largest single user of lake water (about one third). The total calculated yield of freshwater from the lake plus its catchment from these three uses (potable, horticulture and power) in the late 1980s-early 1990s was estimated by Goldson (loc. cit.) to be 37, 39 and 15 x; 106 m^3 ann^{-1} respectively, a total of 91 x 106 m^3 ann^{-1}. Since 1992 water has also been abstracted in the catchment from the Turasha, main tributary of the Malewa, for supply to Nakuru and Gilgil, towns to the north (as well as many informal abstractions from all streams in the catchment for rural domestic and farm use). There is currently (mid-2004) no basin- or even lake-wide monitoring of abstractions, although the new, democratic, Government of Kenya (in office from January 2003) has created a National Environmental Management Authority (NEMA) and will create Water Management Authorities, using legislation passed in 1999 (Environmental Management and Co-ordination Act) and 2002 (Water Act).

Two additional threats to the lake and its biodiversity, in addition to abstraction, are perceived by conservation agencies and the public (IUCN 2002). These are the human population growth

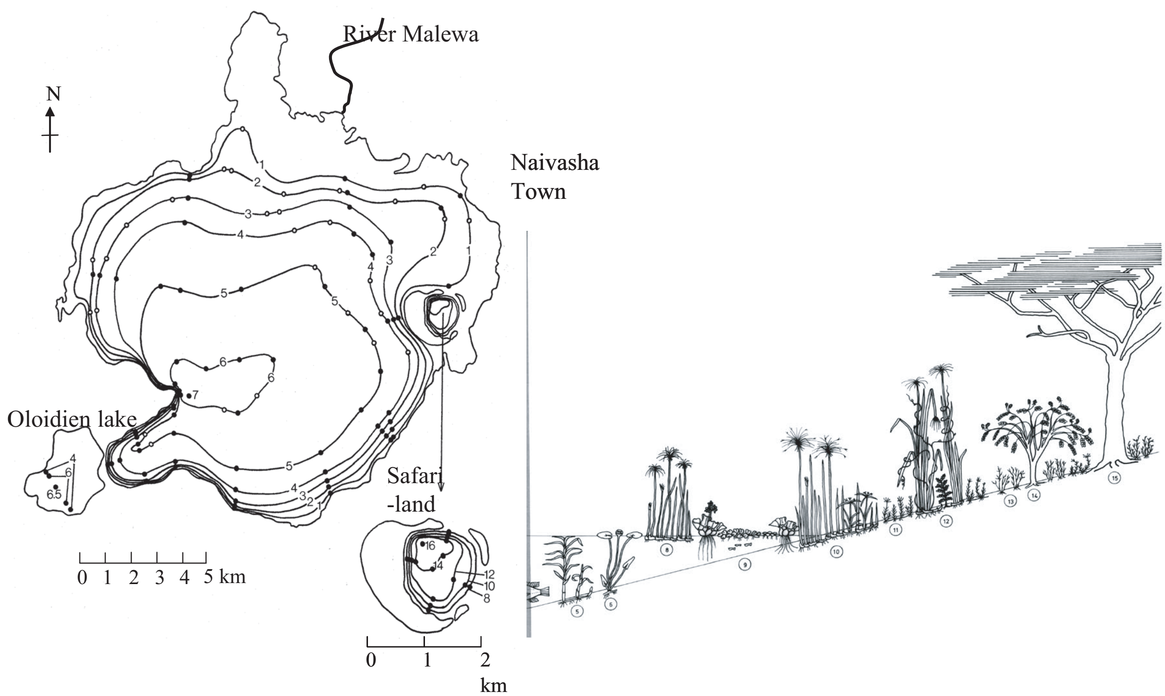

Fig. 3. The bathymetry of the lake in 1991, showing the extent of the shallow littoral zone, together with a cross-section through the whole drawdown zone (ecotone) (from Hickley *et al.* 2002 and Harper, Mavuti 1996).

leading to physical pressure on the shores and the untreated waste water flowing into the lake from industries and settlements. No mention is made of alien species in either the IUCN summary of Naivasha (IUCN 2002) or the Kenya Government's first report to Ramsar (Ramsar 1999), although the risk of alien invasive species is recognised widely (McNeely 1997; Howard, Matindi 2003) and earlier publications had highlighted the risk of ecosystem disruption at Naivasha from them (Harper *et al.* 1990; Goldson 1993). The perceptions of abstraction and pollution as the major threats to the lake are fuelled by media articles, in Kenya and UK, which focus on the most extreme events and people, making stark contrasts between Kenyan and European living standards (Lawrence 2003).

The role of ecohydrology as a guide to future lake management

The aim of this paper is to review the existing scientific evidence, in order to evaluate the relative risk of each of the 21st Century threats to the integrity of this Ramsar-staus lake-wetland ecosystem. It is particularly important that the risks to the ecosystem are accurately evaluated and managed, because Lake Naivasha is one of the few examples in the world of a wetland which is of international importance for biodiversity conservation yet at the same time of high economic importance to the nation (horticulture is currently the second-highest foreign exchange earner, and power generation is from Africa's sole geothermal station). It thus potentially epitomises 'Wise Use' leading to 'Sustainable Development', especially in the light of the closer links between the activities of Ramsar and the UNESCO Man and the Biosphere (MAB) programme recently developed (Ramsar 2002). A proper understanding of the ecosystem is important in the context of the Millenium Ecosystem Assessment (Anon 2003a).

Ecohydrological principles potentially have a major role to play in attempting to manage the lake sustainably. Almost all of the impacts are felt primarily in the shallow littoral, which formerly encompassed three vegetation zones that moderated external inputs of sediment and pollutants from the inflowing rivers (see below) in a classic demonstration of ecohydrological functioning. Sustainable management would enable the use of phyto-technologies to re-create the ecotone structure and mitigate the (now far greater) external impacts.

2. Methods and study area

The work described here is a case-study built up from a number of publications, where each describes the methods used to collect the data more fully. Lake hydrology has been calculated from levels daily recorded by a flower company and maintained by the LNRA (Becht, Harper 2002). Water chemistry was measured using standard methods described in Kitaka *et al.* (2002), Kitaka; Harper, Mavuti (2002) and Hubble, Harper (2002). Measurements of papyrus and cross-sections of river channel were taken by tape and theodolite; identification of plants by Agnew (1974) and Beentje (1994). Location and size of plant communities was studied by GPS locations converted to scale mapping.

Naivasha lies about 80 kilometres south of the equator and 100 kilometres north west of Nairobi. The lake, at 1890 metres altitude, is the highest of the Kenyan Rift Valley lakes (Harper *et al.* 1990). It has a surface area of between 100 and 150 km^2 caused by fluctuating lake; Some water characteristics have varied over time as a consequence, conductivity is between 250 and 400 µS cm^{-1} for example. The water is moderately soft with carbonate/bicarbonate alkalinity between 3.4 and 7.2 meq dm^{-3}, with Na^+ and Ca^{2+} as major cations and a pH range from 7.3 to 9.2 (Talling, Talling 1965; Kilham 1971; Gaudet, Melack 1981; Harper *et al.* 1995). Short-term changes relate more to climate; surface temperature varies between 18 and 26.5°C for example, but the diurnal variation is greater than the seasonal (D.M. Harper, unpubl.).

The lake is shallow, at all hydrological states. Thus its ecotone, (which is the same as its drawdown zone (Gaudet 1977b)), is a substantial proportion of its area (Fig. 3). The landward edge of the zone, extends to the highest lake level achieved in the last decade of the 19th century. This is naturally occupied by an *Acacia xanthophloea* woodland with trees up to 35m tall. This gives way to a rooted *Cyperus papyrus* zone, in water at high lake levels but on dry land at low levels. The zone of recent lake level decline is, depending on the time since last inundation, bare mud quite quickly colonised by sedges, rushes, grasses and then flowering plants dominated by the family Compositae (Gaudet 1977b). The flora is diverse; Gaudet described 108 species from 43 plant families.

3. Results : causes of the 21st century ecosystem condition

Impact of Abstractions

The only available estimate of the quantitative effect of abstractions comes from the post-1980 deviation of recorded lake levels from lake levels which had been modelled using hydrological records (river discharge, gauging) collected earlier in the 20th Century (Becht, Harper 2002) and which matched measured lake levels prior to 1980 (Fig. 4). There are no direct data. The model suggests that the lake was 3.5 metres lower than it would have been naturally in late-1998, just prior to the last major level rise caused by the heavy 'El Nińo' rains over eastern Africa.

These anthropogenic impacts on lake hydrology since about 1980 have not caused the lake to exceed the range of fluctuation shown naturally, best illustrated in the first two thirds of the 20th Century. The early colonial scientific expeditions that visited the lake during that period, did not report a lake impoverished in species other than in the fish community, where only the single species of native, endemic, fish was found. Successive lake level fluctuations in the early 20th Century resulted in bands of germinated *C. papyrus* on different level rises, which enabled Gaudet (1977b) to explain the wetland plant species richness on the basis of this unpredictable water rise and fall leaving a mosaic of different wet habitats. There is thus no evidence that lake level fluctuations alone risk biodiversity loss, and no evidence that the present abstractions are greater than the past, natural, fluctuations. Becht's model suggest that the current abstraction level will lead to the lake level equilibrating (because as lake size declines evaporation decreases) at about 30km^2, one third of the present (2003) and one fifth of the recent maximum (e.g. late 1970s) size (Becht, Higgins 2004).

Impact of human population increase

The recorded human population of the town of Naivasha and the lake hinterland has increased ten-fold over the past three decades as employment opportunities have become available in the very labour-intensive horticultural industry; from 7000 in 1969 to 35 500 in 1989 and 67 000 in 2002 (Lahmeyer 2002). The actual population is, in 2004, widely estimated to be about 250 000. The industry employs about 25 000 labourers (Enniskillen, 2002). Many of these live close to their work with their families on the southern side of the lake; three unplanned settlements have grown along this shoreline, and together with two major villages on horticultural farms which house their staff and the housing compound of geothermal power employees and associated company staff; there are six distinct, new, settlements that have grown in the past two decades. The number of inhabitants is not recorded in them, but it is at least 50 000 people in total. There are no waste treatment facilities beyond pit latrines and no piped water supply to the overwhelming majority of those. The lakeshore immediately below the unplanned settlements is degraded where access is possible (Fig. 5) by the pressures of demand for washing,

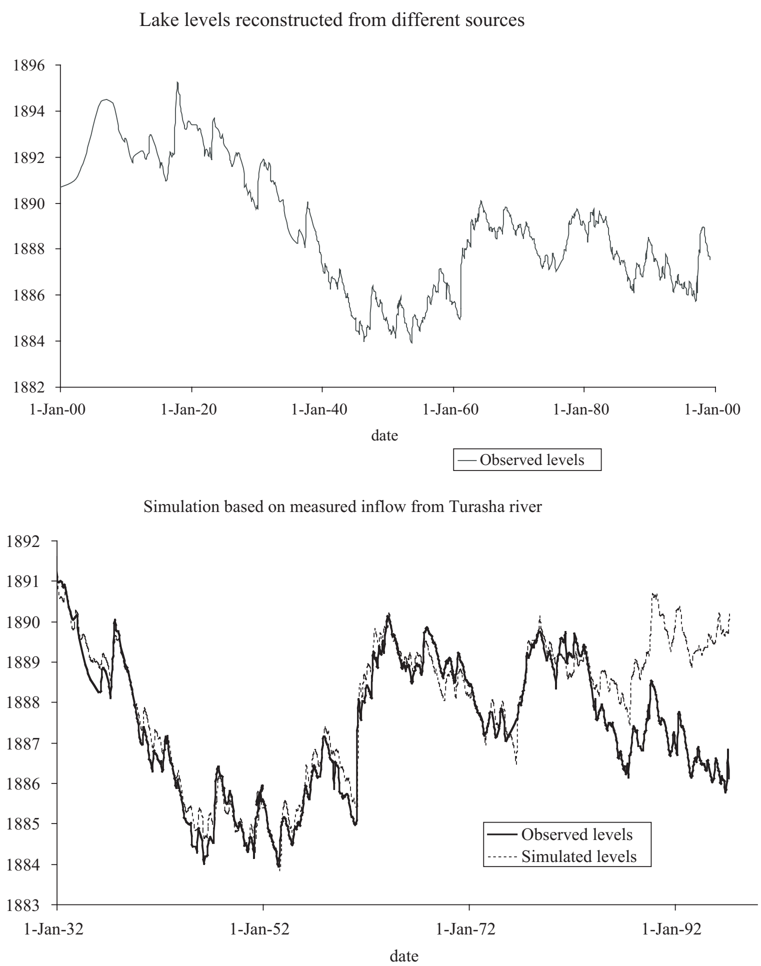

Fig 4. Lake level throughout the 20th Century, together with modelled lake level which shows, in the final quarter of the 20th Century, the deviation post-1980 of model from actual (from Becht, Harper 2002).

domestic stock watering and laundry. The total length of lakeshore affected in this way is not large however, because private ownership (almost all the shoreline) is not sympathetic to such activities. Nevertheless, the clearance of fringing *C. papyrus* was shown to permit the penetration of coarser sand and gravel particles over 50 metres into open lake - two times further than occurred with a fringing buffer (Boar, Harper 2002). Untreated human wastes could be seen in drains flowing under the South Lake Road from one settlement leading to a part of the lakeshore whose *C. papyrus* fringe had been cleared for cultivation, in December 2002 (D. M. Harper, unpubl.). Experimental catches of two out of three of the commercial fish species, *Tilapia zillia* and *Oreochromis leucostictus*, were significantly higher off papyrus-fringed shores than off degraded shores (Hickley *et al.* 2004a in press).

The human population increase has also been responsible for the overall decline of the commercial fishery at the lake, due to over-fishing by illegal men and methods (Hickley *et al.* 2002; Hickley, Harper 2002; Hickley *et al.* 2004a in press). The extent of fish removal has been impossible to quantify, but both subsistence/local consumption as well as larger scale organised poaching occurred in the late 20th Century (D. M. Harper, unpubl.). The impact on the legitimate fishery was such that the catch records for the past decade have been around one third of the estimated sustainable yield (Hickley *et al.* 2002). The lake community (including representatives of fisherman) agreed to a total fishing ban, initially for a trial period of 12 months in 2001-2, policed both by the government Fisheries Department staff and privately-funded 'task-force' personnel. Now there is a closed season of 3 months each year, but poaching continues to be a major problem (S. Higgins, unpubl.).

The urban area of Naivasha, of 70 000 people on the north-eastern shores of the lake, has a sewage-collection system for only part of its area; the other part has open drains which carry waste during heavy rains. The sewage treatment works in 2003 had been non-functioning however, for about a decade. In the low-lake conditions of the past decade (paradoxically exacerbated by abstractions, see above), the urban edge is several hundred metres away from the water (Fig. 6) because the lake is very shallow in its northern half, so untreated waste and partially-treated sewage effluent seep into the former lake-bed soils prior to reaching the lake in surface flow (D.M. Harper, unpubl.). The lake is contaminated with E.coli (Mwachiro *et al.* 2001), which, although not exceeding the WHO guidelines for drinking water, indicates human waste contamination. There is no evidence of localised enrichment of shallows (Kitaka 2001) and the sandy volcanic soils probably provide a good 'tertiary treatment' mechanism for sewage. Nevertheless, a real tertiary treatment, in the form of an artificial wetland, is being planned, using design methods successfully proven elsewhere in Kenya (Raymer 2001).

Fig. 5. An example of *C. papyrus* degradation on the shoreline immediately below a human settlement, on the south shore of the lake.

Lake-wide decline in *Cyperus papyrus*

The lake ecotone as a whole has shown a serious decline in area covered by *C. papyrus* in the past three decades (Boar *et al.* 1999; Everard, Harper 2002; Hickley *et al.* 2004a in press) (Fig. 7). The greatest area was formerly known as the 'North Swamp' at the mouth of the main inflowing rivers, Malewa and Gilgil (Gaudet 1977a; Gouder *et al.* 1998). This has now almost entirely disappeared, yet most of the area is on a single large ranch, Marula, in private ownership rarely visited by unauthorised people, so human pressure alone cannot be responsible for the swamp's decline. Neither can water level decline alone; *C. papyrus* clumps are not uncommon in the lakeside grounds of private houses, where they were stranded at the last very high lake level in 1982-3, 4 metres higher than the 1997 low and have grown healthily since that time (D.M. Harper, unpubl.).

The evidence now suggests that *C. papyrus* decline over the past two decades has been caused by the combination of lowered lake levels with human destruction, direct and indirect. It occurs in 4 phases:

1. The process is initiated by lake level decline, which causes ground water table decline. This is most apparent in the former North Swamp where the Malewa and Gilgil inflow. Recent lake level decline (and probably also more severe flood events due to deforestation of the upper catchment) has been followed by downcutting of the Malewa river channel through the alluvial sediments of its delta to separate swamp from groundwater (Fig. 8). The Gilgil no longer flows directly into the lake because of abstraction for agriculture but disappears into small swamps around the riparian boundary, several kilometres away from the present lake level (Everard *et al.* 2002a).
2. The decline in water table through the 1980s and 1990s then made the former lakebed soils dry and more easily accessible to buffalo (*Syncerrus cafer*). Herds of a few hundred of these live in a few large ranches of the Malewa delta area, particularly Marula, the largest, bounded on its eastern side by the river as it flows down to the lake. The herd was confined in the delta area, but now (at low lake levels) can move freely around the northern three-quarters of the lake, along the grassland on former lakebed. *S. cafer* break down the structure of the swamp to obtain the green stems and flower heads of *C. papyrus*, up to 4 m above the ground, and in doing so leave paths which, in the drier surface sediment, remain permanent.
3. These paths are then followed by other animals such as zebra (*Equus burchelli*), waterbuck (Kobus ellipsiprymnus)) and even giraffe (*Giraffa camelopardalis*) on the landward edge (D. M. Harper, unpubl.). Individuals of these species graze off new shoots, which would otherwise enable the *C. papyrus* clumps to photosynthesise and survive until re-flooded.
4. The increased light availability then enables climbing plants, particularly of the family Convolvulaceae, and creeping grasses such as *Pennisetum clandestinum* (Kikuyu grass), to overgrow the *C. papyrus* clumps, by now just

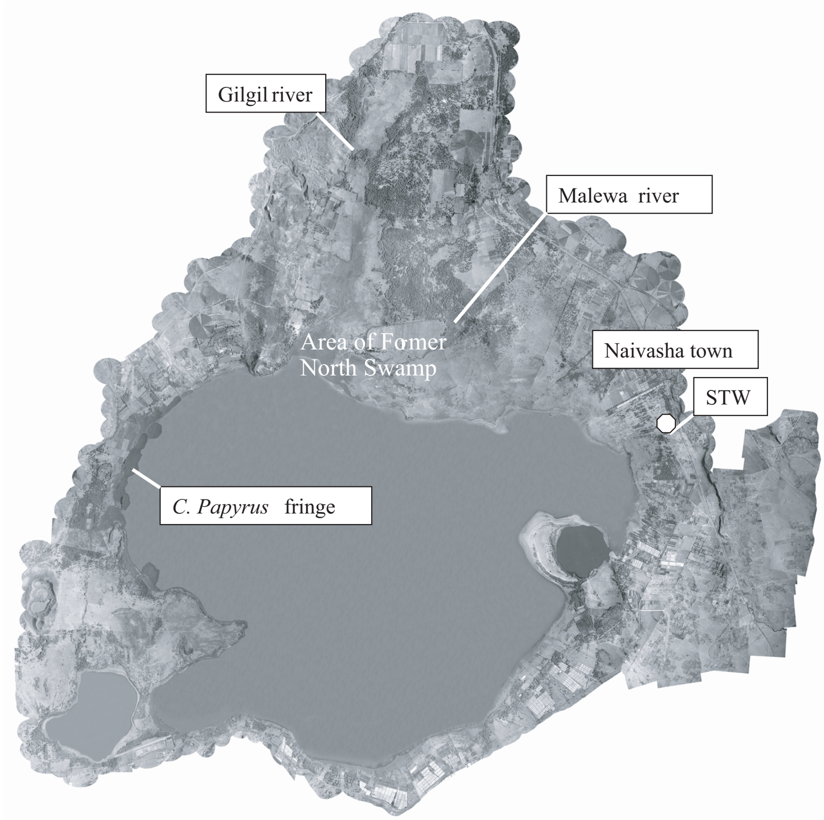

Fig 6. Composite aerial photograph made November 2001, taken for the Lake Naivasha Riparian Association. The urban area of Naivasha with its Sewage Treatment Works, the course of the river Malewa and the end of the river Gilgil, together with the former North Swamp are shown. The lake-wide extent of *C. papyrus* loss is apparent from the dark nature of the fringe in the largest continuous location where it largest remains intact, along the western shoreline. The almost total absence of any *C. papryrus* in the north can be compared with the image in Figure 2.

mounds 1-2 m high 1-2 m apart in what becomes an open, hummocky, grassland.

These processes are natural, and undoubtedly occurred at low lake levels in the past, such as the first half of the 20th Century and earlier, but then would have been reversed at each stage by water level rises flooding the paths and revitalising *C. papyrus*. There are three main differences between this century and the last, though:

1. The number of *S. cafer* counted on Marula in the monthly game counts run by the Nakuru Wildlife Conservancy for KWS has increased three-fold - from a few hundred in the early 1990s to a peaks of 1500 (Nakuru Wildife Conservancy, unpublished). It is believed that the buffalo are being forced down from the Eburru hills in the west (with the increase of people, cultivation and forest destruction) and these are living permanently in the northern riparian area (Higgins, Root, unpubl.).
2. The area of *C. papyrus* has been severely reduced by agriculture/horticulture (Fig. 7) such that these, albeit natural, processes occur to a far smaller area of swamp, so are more damaging, particularly since they are likely to be three times as frequent.
3. The lake edge *C. papyrus* is now subject to repeated human damage, even in areas where human access on land is limited such as the large ranches at the Malewa delta and the western shoreline. This is because fish poachers, and even legal fishermen, make overnight camps at the lake edge; fires spread through dry swamp readily (Fig. 9). Sometimes fires have been deliberately used to facilitate clearing of swamp for cultivation on the landward side of a buffer strip (the LNRA guidelines recommend only a 50 m buffer strip between water and cultivation). Domestic stock and herdsmen can wander almost without hindrance around the lake edge at the current low lake levels. Herdsmen cut *C. papyrus* flower heads for fodder, particularly in drought when grazing is sparse. So where freely accessible to herds of domestic stock (such as close to Naivasha town in the north), the *C. papyrus* has all died and the landscape is just one of close-grazed humps.

The net result is that *C. papyrus*, as a functioning swamp ecotone, protecting both lake shal-

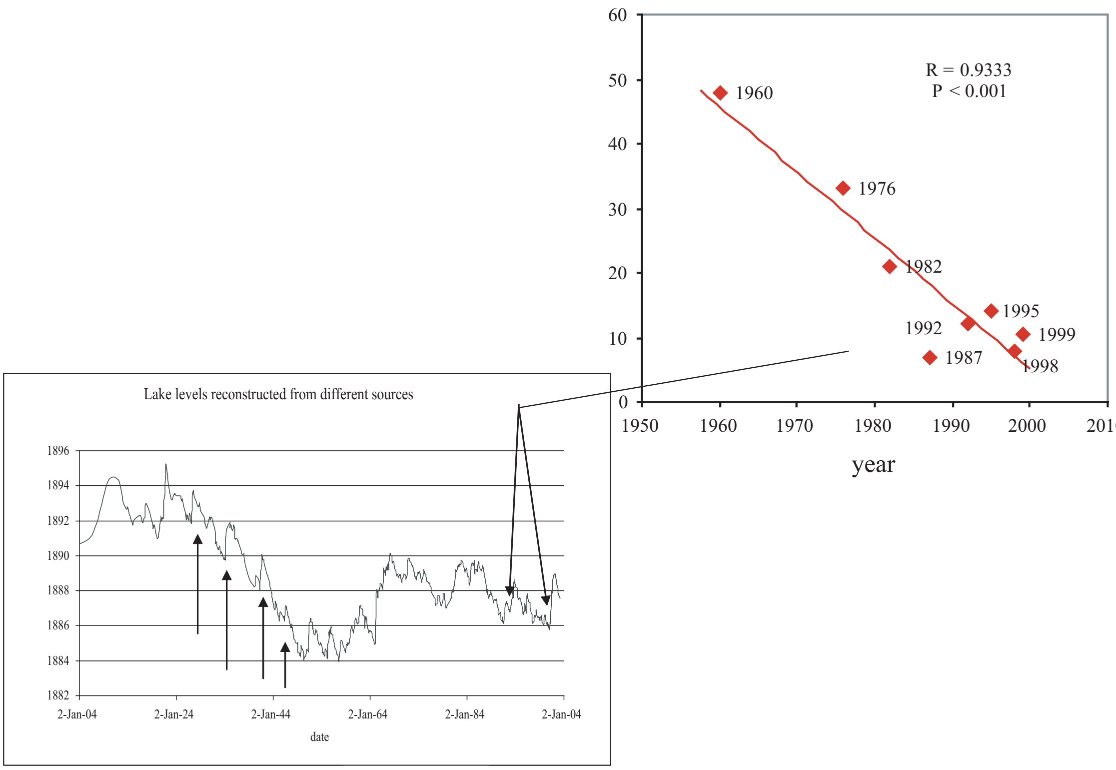

Fig. 7. The area of *C. papyrus* at Lake Naivasha since 1960. Small increases occurred in the past fifteen years, against the general decline, which correspond to two above-average wet seasons that both caused lake level rise, re-flooding former lake bed leading to new germination of *C. papyrus*. It is noticeable that the post-1988 germination covered a greater area than the post-1998 germination, but for a similar area of land flooded.

lows from runoff in the hinterland and the whole lake from the negative inputs of its catchment, no longer exists. This loss has been caused by the combination of lake levels lowered by abstraction for horticulture/industry, combined with the increased pressure of uncontrolled human use of the lake and its shorelines on top of habitat destruction at the lake edge and its hinterland.

Lake pollution from industry/agriculture.

The lake has become eutrophic over the past three decades, as evidenced both by nutrient concentration (Kitaka *et al.* 2002), phytoplankton concentration (Hubble, Harper 2002) and transparency (Harper *et al.* 2002a). It has not become seriously contaminated by any pesticides or other organic compounds measured to date (Gachanja *et al.* 2001; Gitahi *et al.* 2002). There is no evidence from the aquatic community of any selective species loss. For example, there has been no change in the zooplankton community (Harper 1987; Mbogo 2004) that could be a sign of pesticide contamination.

The enrichment can be explained by the combination of the loss of the North Swamp, allowing sediment and soluble phosphorus from the catchment directly into the lake (Kitaka *et al.* 2002) and an increase in the amount of sediment and phosphorus flowing from the catchment (Gaudet 1979 compared with Kitaka *et al.* 2002). The increase has been caused by the greater development of small-scale agriculture in the catchment on the Kinangop plateau, as population has trebled in Kenya over the past 30 years. It is exacerbated by subsistence cultivation, even on steep slopes right down to the river edge (Everard *et al.* 2002b), which has destroyed the riparian zone, as well by use of rivers freely for stock watering throughout the basin (Kitaka 2001).

Any direct loss of water from horticulture, as waste or runoff into the lake, is hidden by this catchment impact. That does not mean it does not occur; some companies have totally destroyed their *C. papyrus* buffer and both cultivate right to the lake edge and use chemical sprays (Fig. 10). It merely means that it has not been detectable in lake water. The biggest horticultural companies are introducing artificial wetlands, which return used water to the lake higher in chemical quality than the water abstracted ('Homegrown' Ltd, unpublished data). This is a recommendation in the Code of Practice for the industry (LNRA 1999) but not yet widely followed.

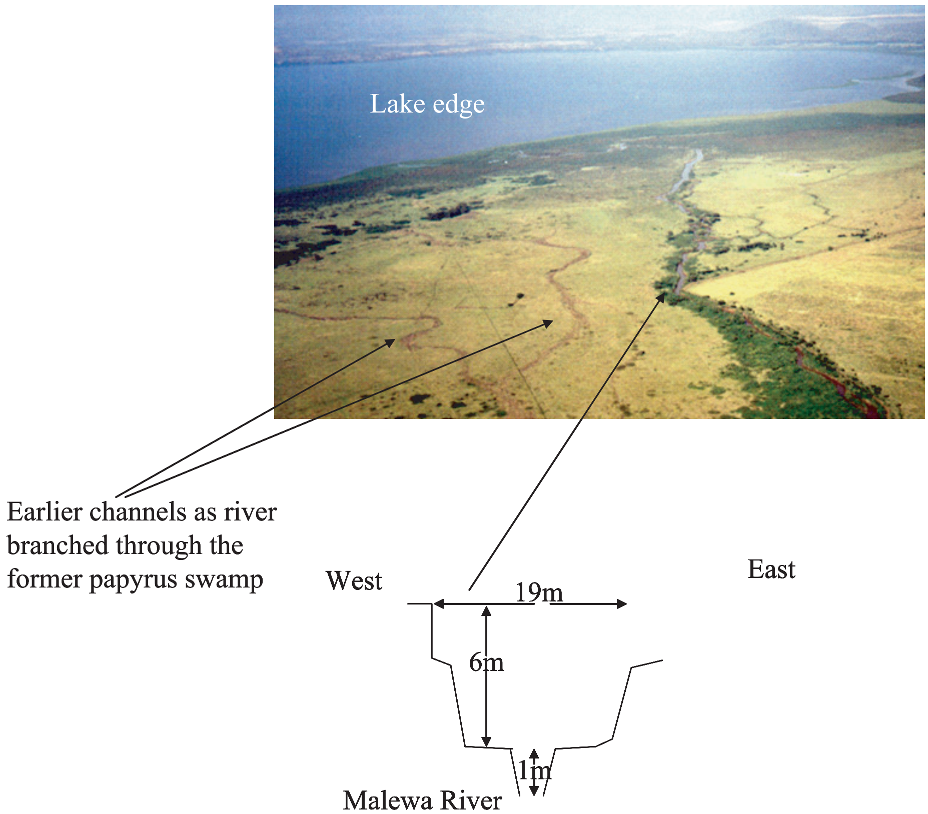

Fig. 8. A cross section of the Malewa river in the former North Swamp area, showing the extent to which the river has cut down through the alluvium during storm events which have occurred during the overall low lake level in the past 2 decades. The low flow channel is a separate, 1 m deep channel, 4m below the bank-full channel.

The real impact of alien invasive species upon the lake.

There is wide perception among international agencies that the problems above are the major ones facing the lake at the beginning of this new Century (Lake Net, 2004). This thinking tends to relegate the impact of alien species to something of the 20th Century to be noted, rather than a current problem to be tackled.

The list of deliberately-introduced and accidentally-arrived aliens at Lake Naivasha stretches back some 80 years, to the first deliberate introduction of large-mouthed bass (*Micropterus salmoides*) at the instigation of the US President Roosevelt, on a hunting visit to Kenya. That species has been blamed for the loss of the only native fish, the endemic small-toothed carp *Aplocheilichthys antinorii*, last seen in the 1960s (Harper *et al.* 1990). The entire commercial fishery is based upon alien species, albeit the others introduced from East Africa (Hickley *et al.* 2002). The most recent alien is the common carp, (*Cyprinus carpio*), first recorded by a fisherman in 2002 but now successfully breeding (Hickley *et al.* 2004b in press) and by early 2004 the dominant species recovered in the commercial fish catches (Fisheries Department, Naivasha, unpublished). This species arrived unannounced when a fish farm in the Malewa floodplain was washed out by the heavy 'El Nińo' rains in 1997 or 98; the first inkling of carp presence was when a fish eagle was observed to catch a small individual (Higgins, unpubl.).

Popular belief has it that the rodent *Myocastor coypu*, released from economically-unsuccessful fur farms higher in the catchment in the 1950s together with the floating fern *Salvinia molesta*, which was first recorded in 1969, were responsible for major changes to the appearance and ecology of the lake, particularly the loss of water lily beds (*Nymphaea nouchalii* var. *caerulea*) so eloquently described by Willcock (1974) (see above), which occurred in the late 1970s. There is no scientific evidence for this: even though *M. coypu* fed upon *N. nouchalii* flowers, its population could not be sustained by them. *M. coypu* died out through starvation and shooting (evidence cited in Harper *et al.* 1990). Individuals have been occasionally reported up to the present day (Joan Root pers. comm.) but the population has not returned.

We now have shown strong circumstantial evidence that the loss of native aquatic vegetation

Fig 9. The western lake shore, showing fringing *C. papyrus* but agriculture behind on former lakebed. The papyrus was burnt a month before this photograph (taken December 2003).

at Lake Naivasha, which includes all native submerged, as well as floating-leaved plants, has been caused by the alien *Procambarus clarkii*, the Louisianan crayfish (Smart *et al.* 2002; Harper *et al.* 2002b). This was deliberately introduced in order to diversify the commercial fishery. It had been introduced to Kenya in 1966 when some individuals were brought from the Uganda Fisheries Department to two dams located at Solai and Subukia, just north of the Naivasha catchment.. In about 1970, 300 *P. clarkii* from Subukia Dam were introduced into the east side of Lake Naivasha. The species thrived, reaching a density of 3 adults m^{-2} within three years (Parker 1974). By 1977 *P. clarkii* was abundant along the eastern shores, moderate on the southern shores and scarce on the western shores. Stocks were spread by riparian owners along the western shores. Commercial exploitation began in 1975, catches of several hundred tonnes per annum of *P. clarkii* were exported live, mainly to Europe (predominantly Sweden and Germany) until 1981 when catches reached a maximum, not subsequently reached, of 500 tonnes (or about 19 million adults).

P. clarkii is a voracious omnivore (Smart *et al.* 2002); periods of its high population density corresponded with the absence of floating and submerged native plants (Gouder *et al.* 1998) and plants returned, through germination from the lakebed sediments, to cover up to 20 km^2 shallow littoral zone after *P. clarkii* population crashes (Fig. 11),. It is likely that the population crashes were caused by the increased susceptibility of *P. clarkii* to predation, as grazing reduced the physical protection offered by submerged meadows. *P. clarkii* in the water forms an important dietary component of predatory fish (Hickley, Harper 2002) and piscivorous aquatic birds such as *Phalocorax* spp (cormorant) (Childress *et al.* 2002) and *Haliaeetus vocifer* (fish eagle) (Harper *et al.* 2002a). In shallow receding lake edges, where there is no cover from stranded aquatic vegetation, *P.clarkii* is readily taken by mammals such as marsh mongoose (*Atilax paludinosus*) and wetland birds such as ibis species (*Bostrychia hagedash* and *Threshkiornis aethiopicus*).The omnivorous nature of *P. clarkii* ensures that it does not run out of food when green plant material is exhausted; individuals feed on invertebrates and detritus (Harper *et al.*, in prep.).

The ecosystem impact of *P. clarkii* is not confined to the plants. The invertebrate population consists mainly of aquatic coleoptera and hemiptera (Clark *et al.* 1989; Clark 1992; Clark, Baroudy 1990). More sedentary taxa, - Hirudinea and insect orders such as Ephemeroptera or Trichoptera - are untypically rare for a tropical freshwater body. Leeches were once so common that yachtsmen picked them off their legs after launching a boat (A. Simpson unpubl.). They dis-

Fig 10. A horticultural company on the south side of the lake, which has destroyed its *C. papyrus* buffer, and cultivates fully right down to the lake edge.

appeared 'in the 1970s' - no resident has been found with an accurate record of when this happened. Only four individual Glossiphonidae could be found in a 6-week search of the entire lake in 1982 and leeches have only been occasionally recorded since then (F. Clark, D. Harper, unpubl). Mollusca are rare when submerged plants are absent, reappearing when they return (e.g. Adams *et al.* 2002).

Three periods of complete absence of native plants (1982-7; 1994-9 and 2003-4) and two periods of plant abundance (1987-93; 2000-02) have now occurred. It appeared initially that the cycle had an approximate 10-year duration (Harper *et al.* 1995), but events in the past five years, not yet scientifically described (Harper, in prep; Foster, in prep), altered this.

The alien floating angiosperm *Eichhornia crassipes*, had first appeared in 1988 (Harper *et al.* 1995). It never grew to serious nuisance proportions, as it has done elsewhere in the tropics (Howard, Matinda 2003) because the altitude of Naivasha means temperatures remain below the plant's optimum, but it still became the dominant species in the lake shallows throughout the 1990s (Adams *et al.* 2002). In the late 1990s it provided a shelter from predation, but not a food source, for *P. clarkii* (Harper *et al.* 2002b, Smart *et al.* 2002) as it formed thick fringes 20-50 metres wide around the lake. The fringe was so thick and so important to *P. clarkii* that commercial crayfish fishermen abandoned trapping in favour of wading waist-deep in the *E. crassipes*, turning plants by hand and picking crayfish into a plastic bucket. Between October and December 2000 however, the *E. crassipes* fringe effectively disappeared coincidentally with a *P. clarkii* population crash, so that by December 2000 few crayfish could be found. In January 2001 dense beds of submerged plants dominated by *Chara* sp. occurred throughout the northern shallows of the lake with only scattered, small floating plants of *E. crassipes* (D. Harper, unpublished). The coincidence of these three events (*E. crassipes* fringe break-up, *P. clarkii* decline, reappearence of submerged plant beds) strongly suggests cause and effect. The fourth piece of circumstantial evidence, that supports the case, is that plants of *E. crassipes* in January 2001, were found extensively damaged by an alien weevil, *Cyrtobagus eichhorniae*, (D. M. Harper, unpubl.) for the first time since it had been introduced as a biological control agent for *E. crassipes* in 1995 (Gitonga *et al.* 2001). Since that time, adult beetles have been found in *E. crassipes* (Harper *et al.* in prep.), suggesting that the control had had an effect, five years after the species introduction. The population of *P. clarkii* recovered during 2002 and 2003 (Givengea 2002; J. Foster, J. Grey, unpubl.) and at the time of writing (2004) there is a population of *P. clarkii* with almost no commercial exploitation, coexisting with small areas of submerged plants in the lake. It is possible, although too early to tell, that this situation might mean *P. clarkii* becoming a less dominant member of the aquatic ecosystem should it be subject to predation from the full range of fish, mammal and bird species known to take it.

The new factor emerging in the lake's ecology is the interaction of carp with crayfish. Carp is feared elsewhere in the world as a most destructive alien fish, because of its ecological impact upon the benthic communities of the lake it enters. In Naivasha, this means competition with crayfish (Grey unpublished), the impact of which remains to be seen.

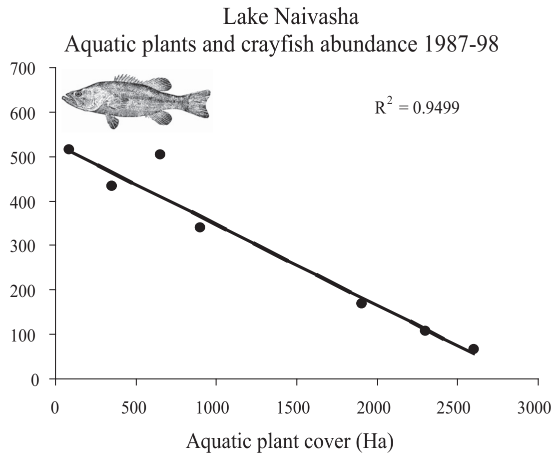

Fig 11. Correlation between density of *P. clarkii* and area covered by submerged plants. *P. clarkii* density is measured in relative terms, as importance in the diet of *Micropterus salmoides* (from Hickley, Harper 2002).

4. Discussion: needs for 21st century restoration

The events described in this paper and the references cited, may be summarised as three phases in the existence of the Lake Naivasha wetland ecosystem:

1. The first phase, existing until 1975-1980, was one in which the natural ecohydrological processes were dominant, even though introduction of alien species had altered the ecological structure by their addition to the food web and subsequent elimination of one endemic species.
2. The second phase, approximately for the 20 years to the end of the 20th century, was one in which the aquatic ecology of the lake became dominated by the alien *P. clarkii*. It controlled the ecosystem structure (the physical structure of the submerged plant meadows and the aquatic invertebrate biodiversity) and to a certain extent the ecosystem function - aquatic primary production was only driven by phytoplankton instead of the combination of phytoplankton/macrophytes of a 'normal' lake (Harper 1990; Hubble, Harper 2002). There is no evidence here that *P. clarkii* caused an ecosystem 'switch' between the macrophyte- and microphyte- dominated stable states which are caused by P-enrichment in eutrophic northern temperate lakes (Jeppesen *et al.* 1997), although the species has been suggested to do so in other small shallow lakes where it has been introduced (Rodriguez *et al.* 2003). Macrophytes have returned on both the occasions that *P. clarkii* density has decreased, which would not have happened had the phytoplankton-dominated state been a stable one excluding light from the lake bottom. This represents the initial loss of ecohydrological buffering capacity in submerged and floating-leaved plant beds. The appearance of carp and the possibility that this second benthic species could further restrict submerged plant regrowth is a very negative start to the 21st Century (Koehn 2004).
3. The third phase, the loss of buffering capacity formerly provided by *C. papyrus* delta and lake-fringe swamp, was growing in impact as the 20th Century closed and now dominates the lake ecosystem processes. This is the reason for continued eutrophication in the lake, driven by land use changes in the catchment. It is potentially the most serious future issue for the lake, because if current over-abstraction continues, the lake will be reduced in size to a third of its present area, a fishery will become non-existent in what then will be a shallow, muddy, alien-dominated muddy pool. Ecohydrological principles can be used in restoration plans aimed at restoring a functional ecotone. The challenges are great but the potential rewards equally so, because, if successful, Naivasha could become a world-famous case-study for ecohydrological principles.

Restoration needs

Cyperus species, in a succession that finishes with *C. papyrus*, germinate readily when former lake-bed soils are wetted after drying. Naturally this happens when a lake level rise quickly follows a fall (Gaudet, 1977a). It last happened lake-wide in May 1988, when a 1 m vertical fall over March-April was followed by a 1-metre vertical rise in May (Harper *et al.* 1995). We suggest that the present state of the lake no longer allows the luxury of waiting on a future lake level rise for this to happen, since it did not happen in 1998 after the rapid rise following the 'El Nińo' rains - the rise in *C. papyrus* area in 1988 was larger than the rise in 1999 even though the areas inundated were similar (Fig 6). This is most likely because of the lower water table level with the bed of the Malewa river in the delta area and the intensive agriculture now practiced around the lakeshores elsewhere. The most important location for *C. papyrus* is at the delta, where its biophysical filtering function is most valuable but no longer operates, so a restoration should be developed there first. We recommend that ecological engineering be planned in the ranches located either side of the Malewa river's entry to the lake, excavating a large number of small, horseshoe-shaped depressions in the alluvial soil, which are subsequently linked to channels from the river to take storm flow. These will fill with water and germinate *C. papyrus* and if they are numerous enough and stay wet, the process of degradation described above will not set in.

The Ramsar protected area is all of Lake Naivasha inside its circumferential lake road, which is a greater area than the legally-defined Riparian land (Enniskillen 2002) because it includes the majority of the cultivated land. Sustainable wise use of this Ramsar wetland is not yet happening at the beginning of the 21st Century, although the LNRA and its partner industries' representatives have established a very sound framework for this to happen. Water abstraction is not collectively controlled, even though forward-thinking enterprises - those which have a direct supply chain to supermarket customers in Europe and are concerned about their reputation - utilise latest technologies to minimise their individual use of water. By contrast, those companies with no environmental conscience (e.g. Fig. 10) are those that do not have a clear customer supply chain, probably because they sell their produce through collective wholesale outlets, such as the Amsterdam flower auction, which makes them anonymous to the customer and consuming society. Loss of *C. papyrus* continues, even though the LNRA guidelines recommend a 50 metre buffer strip between land and water. The forward-thinking enterprises conserve much more than a 50 metre buffer through 'wise use' of wetlands for waste water treatment, but these are only a handful out of approximately 100 horticultural companies around the lake. Government action is promised to control the worst offenders (Anon 2003b), but the seriousness of its control is not yet apparent.

The entire horticultural industry, in tropical countries generally, as well as Kenya in particular, (e.g. Lawrence 2003), is given 'bad press' often for socio-economic rather than biodiversity conservation reasons. Ironically, the most environmentally-conscious companies are the most likely to be attacked, as they have the visible supply chain. Ultimately, environmental and socio-economic considerations make up two legs in the three-legged stool that is true sustainability (Everard, Harper 2002), but negative reports in the press about socio-economic issues are usually made by authors who judge operations in a tropical country by European standards and expectations, implying changes, e.g. in wages, which are impossible to achieve politically or socially over a short time-scale.

The sustainable management of the Lake Naivasha ecosystem, both to enable biodiversity conservation and the future continuation of 'wise use', thus requires movement along a number of routes in parallel. Seven are urgent for ecosystem conservation:

1. Documentation of water abstracted by all users on a record open to public scrutiny so that users comply with their permits, after the re-negotiation of all permits based upon an openly-agreed figure for sustainable abstraction which accepts "water for ecology" and thus defines a minimum-agreed lake area.
2. Successful management of the commercial fishery to primarily curtail poaching, and also seek to - a) keep the population of *M. salmoides* at optimal size to maintain predation pressure on *P. clarkii*, b) minimise the risk of *C. papyrus* fires, c) Maximise the exploitation and marketing of *P. clarkii* and d) actively consider diversifying the fishery with new species (Hickley *et al.* 2002).
3. Prevention of any destruction of *C. papyrus* on any property, adherence to a lakeside buffer zone and its extension to 100 m width, combined with wetland wastewater treatment on all farming enterprises.
4. Development and implementation of plans for restoration *C. papyrus*, particularly in the erstwhile North Swamp at the Malewa delta.
5. Development of conservation awareness in the agricultural community of the catchment by community education programmes, such as are running in the lakes Ol Bolossat (Gichuki 1995) or Bogoria (WWF 2004) catchments to the north, to achieve riparian zone protection and reduction in erosion.
6. A defined policy for the 'riparian zone'. This is the land below the legal limits of private ownership, nominally government-owned but able to be cultivated by those owners of the land contiguous, which is above the limit. The riparian zone will inevitably become larger and more extensive from agri-industrial abstraction demands, whatever the abstraction level finally agreed, particularly in the northern part of the lake. There are huge opportunities here for using ecohydrological principles to protect the water of the future, smaller, lake from the negative influences on land.
7. As a component of the above, there will need to be particular attention paid to conservation of the *Hippopotamus amphibius* population that, at about 5-600 individuals, is at the smallest acceptable limit for the genetic integrity of a population yet the only one of this size in central Kenya. *H. amphibius* requires land areas for nocturnal grazing and water areas for diurnal maintenance of its territorial structure, both of which will come under increasing pressure as lake size declines.

The proposals together address the issues, which would make the lake basin a perfect 'demonstration site' for showing ecohydrological principles in the tropics. The proposals have to use ecosystem properties to sustainably manage Lake Naivasha for both the ecology of the lake and the economy of the region and country.

Without this kind of active ecosystem management, supported by all the diverse stakeholder interests, with a few years the lake will change beyond all recognition, becoming Africa's own "Aral Sea".

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