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Aquatic Sciences

Overview Article

Environmental assessment of the East African Rift Valley lakes

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Abstract. An assessment of the East African Rift Valley lakes was initiated by the United Nations Environment Programme (UNEP) with funding from Global Environment Facility as part of the Global International Waters Assessment (GIWA). The purpose of GIWA was to produce globally comparable assessments and examine stresses on international waters: marine, coastal and fresh; surface and groundwaters. The assessment of the East African Rift Valley lakes was undertaken from the perspective of water quality and quantity, associated biodiversity and habitats, their use by society and societal causes of the regionally identified issues and problems. Assuming intrinsic values of aquatic ecosystems, the assessment of social perspective focused on human use of water and considered the incremental costs of measures to encourage sustainable development. The assessment identified the major concerns facing the East African Rift Valley lakes.

By and large, pollution and unsustainable exploitation of fisheries and other living resources emerged as critical concerns attributable to human activities. East Africa has a very high concentration of humans and economic activities. Pollution is from uncontrolled discharge of wastes directly into the lakes. Unsustainable exploitation of fisheries and other living resources is caused by over-fishing, destructive fishing practices, and introduction of non-native species that affect the composition of the native communities, resulting sometimes in the collapse of certain species and dominance by resilient ones. Loss of biodiversity also was identified as a major concern; and the issues of excessive by-catch and discards are also relevant. Trawling using undersized mesh-nets for target species and indiscriminate fishing gear or poison is serious, in most cases resulting in indiscriminate catches, including juvenile fish. Given the transboundary nature of the issues identified in this assessment, appropriate multilateral policy and institutional arrangements need to be established in East Africa to address the main concerns of these large lakes. Riparian countries must pay attention to the regional management of these transboundary water bodies, and appropriate planning of human population sizes and their settlement, land-use and waste disposal to control pollution. Although East African lakes contribute relatively little emission of greenhouse gases, there is a need to reduce the rate of deforestation and even restore cleared areas since forests serve as sinks of greenhouse gases towards mitigating adverse climatic changes.

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Key words. Rift Valley lakes; pollution; over-exploitation; habitat modification; biodiversity loss; transboundary diagnostic analysis; causal chain analysis; policy options.

Introduction

The large lakes of East African Rift Valley (Fig.1) are unique natural resources that are heavily utilised by their bordering countries for transportation, water supply, fisheries, waste disposal, recreation and tourism. The population density is high and heavily concentrated near the lakes (Cohen et al., 1996). Densities vary considerably among lake watersheds, ranging over 100/km^2 for the Victoria basin to <1/km^2 for some regions around Lake Turkana (Cohen et al., 1996). The large lakes as well as many smaller freshwater bodies (wetlands and rivers) in the region are, consequently, under considerable pressure from a variety of interlinked human activities. Overfishing, siltation from the erosion of deforested watersheds, species introductions, industrial pollution, eutrophication and climate change are all contributing to a host of rapidly evolving changes occurring in these lakes that seriously threaten both their ecosystem function and overall diversity (Hecky and Bugenyi, 1992). For example, the extinction of several hundred species of haplochromine cichlid fish in Lake Victoria following the introduction of the Nile Perch, a large voracious predator, ranks as the largest single recorded vertebrate extinction attributable to specific human actions on earth (Johnson et. al., 1996).

The boundaries of the East African Rift Valley Lakes (EARVL) span a range of latitude from 4°35′N to 14°30′S and a north-south distance of over 2100 km (Spigel and Coulter, 1996). It runs from the northern end of Lake Turkana basin down to the southern tip of Lake Malawi/Nyasa basin and includes the natural habitat and associated human communities found within the rift valley and on the adjacent escarpments as well as tributary catchments originating on the surrounding plateau. It encompasses regions of the following countries: Ethiopia, Kenya, Uganda, Tanzania, Rwanda, Burundi, Democratic Republic of Congo (DRC), Zambia, Malawi and Mozambique. The main lakes in the region include Victoria, Tanganyika, Malawi, Turkana, Albert, Edward, George and Kivu. These tropical lakes comprise the African Great Lakes eco-region (WWF SARPO, 2001). However, each lake lies within its own separate drainage basin, with its own assemblage of endemic organisms, most notably the cichlid fish species-flocks. The lake basins exhibit a variety of types, including the very deep, elongated and steep-sided troughs of Lakes Tanganyika and Malawi, and the more nearly circular, relatively shallow basin of Lake Victoria with its highly complex, indented shoreline (Spigel and Coulter, 1996). Each lake differs substantially with respect to limnology, catchment dynamics and human impacts (Bootsma and Hecky, 1993).

For the purpose of the Global International Waters Assessment (GIWA) assessment, the following lakes that are characteristic of most of the transboundary waterbodies in the region were selected: Lakes Turkana, Victoria, Tanganyika and Malawi. These four are the largest of the East African Rift Valley lakes and are among the oldest in the world – they are classed as Ancient Lakes (Brooks, 1950). Lakes Victoria, Tanganyika and Malawi, in particular, are well known as the homes to literally thousands of species of endemic fish and invertebrates (individual species in almost all cases are restricted to a single lake), exciting the interest of evolutionary biologists and ecologists.

Climatic setting

Diurnal fluctuations in temperature and wind circulation at local to meso-scales dominate the regional climate and weather in the tropics, in contrast to higher latitudes where diurnal cycles are much less pronounced than seasonal fluctuations (Hastenrath, 1991). Within equatorial East Africa, the large-scale thermal pattern is horizontally rather uniform (East African Meteorological Department, 1970), although appreciable contrasts occur at a smaller scale as a consequence of the pronounced topography (Hastenrath, 1984). The subtropical high pressure areas are situated about 20 to 30° north and south of the Equator and are important controls of the climate of tropical Africa (Boucher, 1975). These subtropical high pressure belts tend to move north during the northern summer and south during the southern summer, and the outflow of air from their centres is reduced during summer months as a consequence of thermal heating. Thus, much of the region experiences a bimodal seasonal distribution in rainfall, with maxima occurring in the two transition seasons – there is a third maximum that usually occurs in July or August in large areas of Kenya and a few other regions (Nicholson, 1996). Seasonality is unimodal in the northern and southern extremes of the region, with a maximum occurring during the high-sun season of the respective hemisphere (Nicholson, 1996).

Large-scale tropical controls, including several major convergence zones, are superimposed upon regional factors associated with lakes, topography and maritime influence – as a result, the climatic patterns are complex and change rapidly over short distances (Nicholson, 1996). The interannual variability in rainfall is remarkably coherent throughout most of eastern Africa despite the markedly complex climatic patterns, and the largest portion of this variability is accounted for by the “short

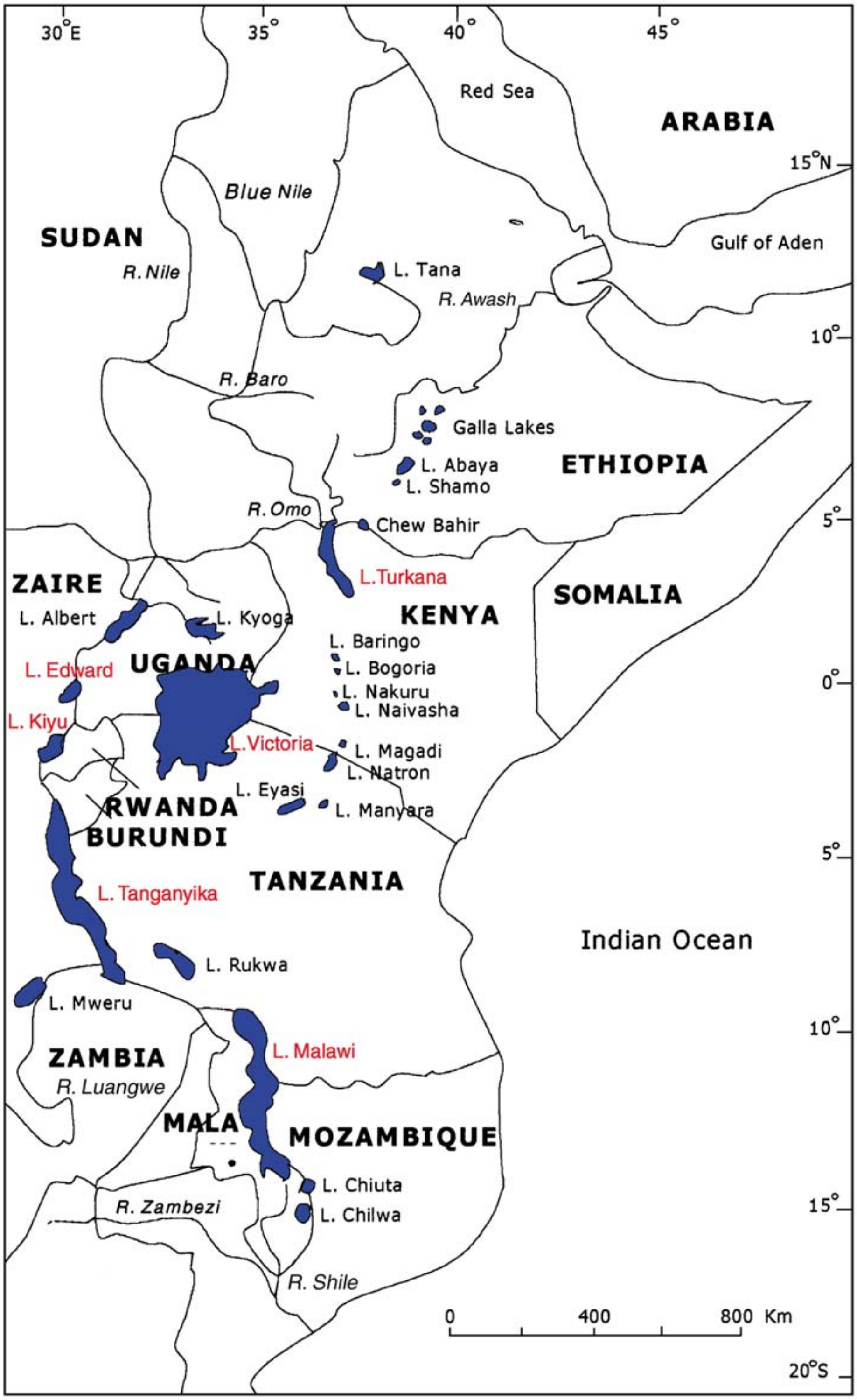

Figure 1. East African lakes (from Nyamweru CK, 1983).

rains" season in October-December (Nicholson, 1996). The rainfall variability in the region shows strong teleconnections to the rest of Africa and to the global tropics (Nicholson, 1996). Rainfall in eastern Africa is strongly quasi-periodic, with a dominant timescale of variability of 5 to 6 years that is particularly influenced by El Niño Southern Oscillation (ENSO)-induced changes in the *"short"* rain period in October-November (Nicholson, 1996). Rainfall variability is closely linked to both ENSO and sea surface temperatures (SST's) in the Indian and Atlantic Oceans, and it tends to be enhanced in East Africa during ENSO years (Ropelewski and Halpert, 1987; Ogallo, 1989).

Description of the lakes

Lake Turkana

Lake Turkana is located in the Great Rift Valley in the arid northwestern part of Kenya at about 3°N, 36°E (Fig. 1). Most of the lake lies in Kenya, but part of the Omo River (which supplies about 90% of water to the lake; Ferguson and Harbott, 1982) delta lies in southwestern Ethiopia. Lake Turkana is the largest closed-basin lake in the East African Rift, and loses water mainly by evaporation. It can be considered as the "arid region end-member" of large rift valley lakes and an important modern analogue for ancient rift environments in Africa and elsewhere (Halfman et al., 1989). The age of Lake Turkana is given a conservative estimate of 4.3 Ma (by K-Ar and ^{40}Ar/^{39}Ar methods), which is recorded from the lowermost tuff bed within the Koobi Fora basin (McDougall, 1986).

The lake surface area is about 6,750 km^2 and the catchment area is 130,860 km^2. The average depth is 35 m while the maximum depth is 115 m. The lake is moderately saline (2.5‰), alkaline (pH = 9.2), and is well mixed by strong diurnal winds (Yuretich and Cerling, 1983). Measurements of dissolved O_2 (Hopson, 1982) indicate that in the northern half of the lake, even near the bottom, the water is at about 70% of oxygen saturation levels. The principal ions are Na^+, HCO_3^-, and Cl^-, with relatively low concentrations of Ca^{2+}, Mg^{2+}, and SO_4^{2-} (Halfman et al., 1989). In the north, salinity is seasonally reduced through mixing with dilute Omo River floodwaters. Its high alkalinity promotes rapid equilibration of CO_2 with the atmosphere (Peng and Broecker, 1980). The water has a residence time of about 12.5 years. The euphotic zone is about 6 m, and the lake is always turbid (Kallqvist et al., 1988). Yuretich (1979) observed that sediment plumes up to 100 km long extend southward from the Omo River delta during flood seasons. An annual cycle of stratification was observed in 1988: stable stratification from March to May and complete circulation in June to July (Kallqvist et al., 1988). For the rest of the year there is partly restricted vertical mixing with a temperature gradient of 1 to 2 °C from the surface to the bottom at 70 m (Kallqvist et al., 1988).

Lake fauna is little modified with a low level of endemicity and few cichlids (Lowe-McConnell, 1995). It has a Nilotic riverine fauna (Lowe-McConnell, 1995). Some 48 species of fish have been identified in the lake, of which 30 are widespread Sudanian types, 8 have restricted distributions and 10 are endemic (Hughes and Hughes, 1992); 36 occur in the lake and 10 are confined to the inflowing Omo River (Lowe-McConnell, 1995). The dominant phytoplankton are the blue-green alga *Microcystis ceruginosa* and the green alga *Botryococcus braunii*, while in Ferguson's Gulf *Anabaenopsis arnoldii* (blue-green alga) is dominant (Kallqvist et al., 1988). The zooplankton is dominated by protozoans in terms of numbers, but by crustaceans in terms of biomass (Hughes and Hughes, 1992). The reason for Turkana's world-wide fame as the purported 'cradle of mankind' is the find of early hominids, including remains of various australopithecine species, *Homo habilis, Homo erectus* and *Homo sapiens* (Finke, 2001).

Lake Victoria

Lake Victoria (lying 0° 21′N – 3° 0′S) is, by area, the second largest lake in the world and the largest in Africa. It is perched high (1134 m above sea level) on the African craton between the western and eastern rift valleys (Johnson et al., 2000). The water balance is dominated by rainfall on the lake, evaporation, and River Nile outflow, with river inflow making a minor contribution (Spigel and Coulter, 1996). More than 80% of the water is derived directly from rain onto the lake surface, and evaporation from the lake itself accounts for a significant amount of its annual rainfall (Johnson et al., 2000). The age of the Lake Victoria basin is estimated at 400,000 years, based on the seismically determined total thickness of the sediments (60 m) and assuming modern sedimentation rates and the effects of compaction (Johnson et al., 2000).

Covering a surface area of roughly 68,800 km^2, Lake Victoria is almost twice the size of Lakes Tanganyika (32,600 km^2) and Malawi (28,800 km^2). Its catchment area is 184,000 km^3. The lake is relatively very shallow, with a maximum depth of 68 m (Johnson et al., 2000) compared to Tanganyika and Malawi whose maximum depths are 1470 m (Capart, 1949; Tiercelin and Mondeguer, 1991) and 700 m (Johnson and Ng'ang'a, 1990), respectively. Lake Victoria has a flushing time of 140 years and a residence time of 23 years (Bootsma and Hecky, 1993). Surface water temperatures are between 24 and 28 °C (Ochumba, 1996), and evaporative cooling during the dry season is important in the heat balance and mixing regime (Talling, 1966). Temperature profiles measured in Lake Victoria show a lack of well-defined mixed layers and seasonal thermoclines; the temperature gradients tend to be more diffuse, and horizontal variability greater than in Lakes Tanganyika and Malawi (Spigel and Coulter, 1996). Measurements carried out in the Kenya sector of the lake show that anoxic water occurs below a depth of 35 m, with the oxycline at 10 to 50 m (20 to 30 m for most of the year) (Ochumba, 1996). Sporadic upsurges of the oxycline to depths as shallow as 10 m in the open lake have been associated with fish kills (Ochumba, 1996).

Much of the lake margin is swampy: islands of *Cyperus papyrus*, with its typical associates, detach from the fringing swamps (Hughes and Hughes, 1992). The current phytoplankton community is dominated by the cyanobacteria *Cylindrospermopsis* and *Planktolyngbya*, and the diatom *Nitzchia* (Komarek and Kling, 1991; Hecky, 1993; Kling et al., 2001). Zooplankton consists of abundant copepods and cladocerans (Branstrator et al., 1996). As recently as the 1960s, Lake Victoria supported an endemic cichlid fish species flock of 500+ species (Seehausen, 1996), but these have progressively disappeared from the catches to become poorly represented today. The losses are attributed to habitat degradation in the catchment, introduction of exotic species (particularly Nile perch) and heavy fishing pressure (Ogutu-Ohwayo, 1990; Witte et al., 1999).

Lake Victoria has, in recent history, acted as an evolutionary laboratory for one of the most diverse flocks of fish species on earth (Witte et al., 1992; Lowe-McConnell, 1997; Johnson et al., 1996). The lake has also undergone enormous environmental changes within the last 40 years or so. We now know, for example, that nearly half of the lake floor experiences prolonged spells of lack of oxygen (anoxia) for several months of the year compared to four decades ago when anoxia was sporadic and localised (Talling, 1965; Hecky, 1993; Hecky et al*.*, 1994; Ochumba, 1996). Similarly, algal biomass is almost five times greater in the surface waters today than reported in the 1960's (Mugidde, 1993), indicating higher rates of photosynthesis. Also, transparency values have decreased up to three-fold, and the silicon concentration has gone down ten-fold (Hecky and Bugenyi, 1992; Hecky, 1993; Lehman, 1996). Through the early/mid 1980s, catches of traditional fish species in Lake Victoria started declining due to the resurgence and extraordinary abundance of Nile perch (*Lates niloticus)* which had been introduced in the lake during the mid and probably late 1950s (Ogutu-Ohwayo, 1990). These and other related environmental changes, arising out of natural or anthropogenic causes, have significantly impacted Lake Victoria's fish populations (Cohen et al., 1996).

Lake Tanganyika

Situated between the latitudes of 03°20′ and 08°48′S and the longitudes of 29°03′ and 31°12′E, Lake Tanganyika is an elongate lake. The current configuration of modern Lake Tanganyika was achieved about 450,000 years ago, although the proto-lake started forming at about 12 Ma (Tiercelin and Lezzar, 2002). It consists of two major basins, northern and southern, separated by a complex, block-faulted structure known as the Kalemie shoal. Major border faults have further delineated these two major basins into several sub-basins (Tiercelin and Mondeguer, 1991). Geologic processes have, to a large extent, determined the shoreline substrates around the lake. Of the 1,838 km shoreline perimeter, 43% is rocky substrate, 21% is mixed rock and sand substrate, 31% is sand substrate and 10% is marshy substrate (Coenen et al., 1993).

Lake Tanganyika, with an approximate surface area of 32,600 km^2 and volume of 18,940 km^3, contains 17% of the Earth's free fresh water (statistics from Hutchinson, 1975; Edmond et al., 1993; Coulter, 1994). At 673 km along its major axis, Tanganyika is the longest lake in the world and ranges from 12 to 90 km in width with a shoreline perimeter of 1,838 km (statistics from Hanek et al., 1993). A catchment area of 220,000 km^2 feeds the lake (Coulter, 1994). The lake's average depth is 570 m, with a maximum depth of 1,320 m in the northern basin and 1,470 m in the southern basin (Coulter, 1994), making it the world's second deepest lake after Lake Baikal. Lake Tanganyika is fed by numerous small rivers and two major rivers, the Rusizi draining Lake Kivu to the north, and the Malagarasi draining Western Tanzania south of the Victoria Basin (Hughes and Hughes, 1992). Only a single outlet, the Lukuga River, drains Lake Tanganyika, although the flow of this river has changed directions in historical times (Beadle, 1981). The temperature and pH of surface waters vary between 23–28 °C and 8.6–9.2, respectively (Coulter, 1994). Most of Tanganyika's water loss is through evaporation. Only 6% of water input to Tanganyika leaves at its outlet, which was totally blocked when the lake was explored by Europeans (Bootsma and Hecky, 1993). Calculations from Lake Tanganyika's water budget suggest a water residence time of 440 years and a flushing time of 7,000 years (Coulter and Spigel, 1991; Bootsma and Hecky, 1993). Lake Tanganyika is stratified into an oxygenated upper layer (penetrating to about 70 m depth at the north end and 200 m at the south end) and an anoxic lower layer, which constitutes most of the lake water volume (Beauchamp, 1939; Hutchinson, 1975; Coulter and Spigel, 1991). Stratification is permanent (meromictic), that is, the oxygenated and anoxic layers generally do not mix annually, although wind-induced upwelling results in some mixing at the lake's southern end (Coulter and Spigel, 1991).

The lake's morphology, a steep-sided rift cradling a deep anoxic mass and capped by a thin oxygenated layer, has profound implications for the distribution of organisms in Lake Tanganyika. *Cyperus papyrus*, *Phragmites* *mauritanus* and *Typha domingensis* dominate the delta swamps, while *Potamogeton* species are the predominant macrophytes around much of the shoreline. Occasional rafts of *Nymphaea caerulea* and *N. capensis* occur in shallow sheltered bays (Hughes and Hughes, 1992). Most of Lake Tanganyika's water mass is uninhabited by higher organisms. Fish are limited to the upper oxygenated zone. Lake Tanganyika hosts 250+ cichlid species parsed between several subflocks (Snoeks et al. 1994). However, unlike the other African Great Lakes, Lake Tanganyika also hosts species flocks of non-cichlid fish and invertebrate organisms, including gastropods, bivalves, ostracods, decapods, copepods, leeches and sponges (Coulter, 1994). More than 600 of these species are endemic to the Tanganyika Basin, i.e., they are not found anywhere else (Coulter, 1994). Because of the steeply sloping sides of the Tanganyika basin, benthic organisms (which rely on the substrate for at least some aspect of their life cycle) are limited to a thin habitable ring fringing the lake perimeter which extends sometimes only tens of meters offshore. Coulter (1991) makes the following delineation: littoral zone – from shore to 10 m depth; sub-littoral zone – from 10 m to 40 m depth; benthic zone – from 40 m to the end of the oxygenated zone.

Lake Malawi

Lake Malawi (9°30′ to 14°40′S, 33°50′ to 33°36′E) is located in the southern end of the Great Rift Valley system, which fractured the ancient plateau of eastern Africa (Bootsma and Hecky, 1999). The process of rifting was accompanied by regional uplift (Tiercelin and Lezzar, 2002), reinforcing the dramatic topography created by graben formation. Consequently, the lake is surrounded by mountains with highest elevations to the north where the mountains rise over 2000 m above the lake's surface, and lower elevations to the south (Beadle, 1981; Johnson and Ng'ang'a, 1990). A broad asymmetric lake basin prefiguring the northern part of Lake Malawi was formed at about 8.6 Ma, resulting from faulting associated with initial volcanic activity in the proto-Rungwe volcanic province (Ebinger et al., 1989; 1993). At about 3.6 Ma, a major expansion of lacustrine conditions in the Lake Malawi Basin is recorded from the fossiliferous Chiwondo Beds (Bromage, 1995), as a consequence of a wetter climate in Central and Eastern Africa during the Mid-Pliocene (Tiercelin and Lezzar, 2002). The age of the lake, in its present configuration, is uncertain. Most authors (Fryer and Iles, 1972; Crossley, 1979; Owen et al., 1990) estimate the age of the lake to be about two million years.

Lake Malawi is the fourth deepest inland water body in the world with its greatest depths (700 m) extending below sea level. It is the ninth largest by area and the fourth largest body of freshwater on the globe. The lake surface area is 28,000 km^2 and the catchment area is 126,500 km^2 (Bootsma and Hecky, 1993). As in Lakes Victoria and Tanganyika, the water balance is dominated by rainfall on the lake and evaporation (Spigel and Coulter, 1996). Very little water leaves the lake via the Shire River at its southern end. The flushing time is 750 years and the residence time is 140 years (Bootsma and Hecky, 1993). Surface water temperatures of the open lake range from 23 °C in the cool windy season to 28 °C in the warm season (Eccles, 1974). By virtue of its tropical setting the lake is permanently stratified thermally (Eccles, 1974). Below 250 m the temperature is constantly between 22.5 °C and 22.75 °C (Gonfiantini et al., 1979), but above that depth there is a seasonal cycle of stratification. Lake Malawi possesses a well-defined mixed layer and seasonal thermocline that strengthens during the wet season (Austral summer) and then weakens and deepens due to evaporative cooling and wind mixing during the south-wind season (Eccles, 1974; Spigel and Coulter, 1996). The influence of biogenically induced stratification from dissolved solids and gases, though minor, is significant in the lake (Wüest et al., 1996). The surface waters are well oxygenated, but the oxygen content decreases as depth increases until the waters become anoxic between 170 and 210 m depth (Bootsma and Hecky, 1999). Seasonal upwelling at the southern end of the basin is thought to play an important part in nutrient and production cycles (Spigel and Coulter, 1996).

The lake supports a large number of endemic cichlids (over 300 species), many of which have limited distributions within the lake, e.g., almost all islands support unique populations of rock-dwelling cichlids (Hughes and Hughes, 1992). The cichlid fish communities of the inshore regions are the richest, most diverse, most stenotopic, and hence the most vulnerable to fishing pressure (Ribbink, 2001). Swampy banks along the lake shore are covered by hygrophilous grasses, including *Panicum repens*, *Sacciolepis africana* and *Vossia cuspidata*, while some bays are fringed by reed swamps with carpets of the free-living *Pistia stratiotes* on quiet shallow water (Hughes and Hughes, 1992). The prominence of *Planktolyngbya tallingi* in the southern region of the lake, where it has replaced the previously dominant *Plantolyngbya nyassensis*, is indicative of increasing nutrient availability and poorer light conditions (Bootsma and Hecky, 1999). Zooplankton comprises primarily copepods and cladocerans, together with the larvae of chaoborid flies (Hughes and Hughes, 1992).

Lake Malawi is renowned for its fabulous biodiversity, especially among the numerous cichlid fishes, the haplochromine subfamily being particularly species-rich and nearly completely endemic. Malawi has more species of fish than any other lake in the world with the actual number of species still to be determined. The existence of this biodiversity has attracted international interest and together with other resource use of this international lake has led to the implementation of the SADC/GEF Lake Malawi Biodiversity Conservation Project. At a more fundamental ecological level, these fishes are a scientific wonder as they have made many adaptations to the habitats available in the lake, especially in regard to how they extract food resources from the lake. They challenge science with basic questions such as what limits the number of species in an ecosystem and why are some ecosystems so species-rich while others are poor.

Methods

The conceptual framework that GIWA uses is Transboundary Diagnostic Analysis (TDA), consisting of interrelated components. Detailed scoping of environmental and socio-economic impacts of water-related issues under present and future (2020s) conditions (Phase I) provides a strong base for more in-depth investigations, namely, causal chain and policy options analysis (Phase II). In the first phase of the assessment addressed in this paper, we undertook the following activities: 1) assessment of environmental and socio-economic impacts under present conditions; 2) assessment of likely environmental and socio-economic impacts under future (2020s) conditions and; 3) assessment of overall (time-averaged) impacts and priorities for further analysis. It does not include the causal chain and policy options analysis that represents the second phase of the assessment that is currently on-going. The assessment follows a prescribed methodology[1], which, though subject to many criticisms, allows for the systematic inter comparison of the world's international waters.

The assessment was undertaken by evaluating the present environmental situation (natural and socio-economic) and taking into account "scenarios of future conditions (2020s) based on projections of demographic, economic and social changes associated with the process of human development". The GIWA framework investigates 22 key issues within five areas of major concern (Table 1). Nested within each of these 22 key issues (Table 1) are clearly defined environmental criteria for ascribing impact scores[1] that range from 0 (no known impact) through 1 (slight impact) and 2 (moderate impact) to 3 (severe impact). A second set of criteria defines the impact scores ascribed to socio-economic impacts, again on a scale ranging from 0 to 3. The detailed criteria for determining the impact score for the issues can be found in the GIWA Methodology Handbook for Scaling and Scoping[1]. The socio-economic impacts are diverse and are divided into three groups: 1) economic impacts, 2) health impacts, and 3) other social and community impacts. Within each of these three groups, one has to consider the following criteria for the impacts score (scale 0 to 3): (1) size of economic/public sectors/community and number of people affected (very small, small, medium, large), (2) degree of impact (cost, output changes, etc.) or severity (minimum, small, moderate, severe), and (3) frequency and duration of impact (very occasional/very short term to continuous/long term). All impacts are considered to be negative, unless a positive sign is placed before the prescribed score to indicate positive impacts.

The GIWA Methodology Handbook provides a comprehensive, but not exhaustive, list of the possible impacts under each of the major concerns, which are then evaluated and weighted according to their importance for the sub-region. The environmental and socio-economic impact scores for the present and future (2020s) are then integrated using a clearly defined procedure to come up with an overall time and impact averaged score for each of the major concerns. The overall time and impact averaged score (Table 2a) is that upon which the discussion below is based.

Results and discussion

A summary of total scores for environmental concerns affecting the four lakes and the ranking of major concerns are presented in Tables 2a and 2b, respectively. The concerns are all inter-linked, although the strength and mode of the linkages vary according to the unique environmental, social, economic and health characteristics of each specific lake basin. In the discussion below, emphasis is placed on the top two ranked major concerns (Tables 2a,b) as these are the concerns that are primarily being addressed in the on-going causal chain and policy options analysis exercise.

Freshwater shortage

Emerging findings of this assessment show that Lake Turkana basin faces severe freshwater shortage. The freshwater shortage is mainly due to modification of stream flow (Table 1). Along the Omo River (supplying 90% of water to the lake) in Ethiopia, there has been an extensive increase in small irrigation schemes diverting water from Lake Turkana. For example, in the Lower Omo Valley in Ethiopia (rainfall 300 mm/year), fodder and food crop production depends almost entirely on seasonal floodwater from the River Omo and recession farming in the old river channels (Kay, 2001). Alexander (1990; in Haack and Messina, 2001) estimates the Omo River discharge has been reduced by 50% because of these activities. Due to climate change and to the exten-

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[1] GIWA Methodology Stage I: Scaling and Scoping. Guidance to the Methodology and its Use. 10th July 2001. http://www.giwa.net/methodology/RevScalScop_Meth_10July2001.PDF

Table 1. GIWA environmental concerns and issues considered in the Assessment.

Concern I: Freshwater shortage		
1	Modification of stream flow	An increase or decrease in the discharge of streams and rivers as a result of human interventions on a local/regional scale (see Issue 19 for flow alterations resulting from global change) over the last 3–4 decades.
2	Pollution of existing supplies	Pollution of surface and ground fresh waters supplies as a result of point or diffuse sources.
3	Changes in Water table	Changes in aquifers as a direct or indirect consequence of human activity.
Concern II: Pollution		
4	Microbiological	The adverse effects of microbial constituents of human sewage released to water bodies.
5	Eutrophication	Artificially enhanced primary productivity in receiving water basins related to the increased availability or supply of nutrients, including cultural eutrophication in lakes.
6	Chemical	The adverse effects of chemical contaminants released to standing or marine water bodies as a result of human activities. Chemical contaminants are here defined as compounds that are toxic or persistent or bioaccumulating.
7	Suspended solids	The adverse effects of modified rates of release of suspended particulate matter to water bodies resulting from human activities.
8	Solid wastes	Adverse effects associated with the introduction of solid waste materials into water bodies or their environs.
9	Thermal	The adverse effects of the release of aqueous effluents at temperatures exceeding ambient temperature in the receiving water body.
10	Radionuclide	The adverse effects of the release of radioactive contaminants and wastes into the aquatic environment from human activities.
11	Spills	The adverse effects of accidental episodic releases of contaminants and materials to the aquatic environment as a result of human activities.
Concern III: Habitat Modification		
12	Loss of ecosystems or ecotones	The complete destruction of aquatic habitats. For the purpose of GIWA methodology, recent loss will be measured as a loss of pre-defined habitats (see Appendix I) over the last 2–3 decades.
13	Modification of ecosystems or ecotones	Modification of pre-defined habitats (see Appendix I) in terms of extinction of native species, occurrence of introduced species and changing in ecosystem function and services over the last 2–3 decades.
Concern IV: Unsustainable exploitation of fisheries		
14	Over exploitation	The capture of fish, shellfish or marine invertebrates at a level that exceeds the maximum sustainable yield of the stock.
15	Excessive bycatch and discards	By-catch refers to the incidental capture of fish or other animals that are not the target of the fisheries. Discards refers to dead fish or other animals that are returned to the sea (lake).
16	Destructive fishing practices	Fishing practices that are deemed to produce significant harm to marine, lacustrine or coastal habitats and communities.
17	Decreased viability of stocks through contamination and diseases	Contamination or diseases of feral (wild) stocks of fish or invertebrates that are a direct or indirect consequence of human action.
18	Impact on biological and genetic diversity	Changes in genetic and species diversity of aquatic environments resulting from the introduction of alien or genetically modified species as an intentional or unintentional result of human activities including aquaculture and restocking.
Concern V: Global Change		
19	Changes in hydrological cycle and ocean circulation	Changes in the local/regional water balance and changes in ocean and coastal circulation or current regime over the last 2–3 decades arising from the wider problem of global change including ENSO.
20	Sea (lake) level change	Changes in the last 2–3 decades in the annual/seasonal mean sea (lake) level as a result of global change.
21	Increased UV-b radiation as a result of Ozone depletion	Increased UV-B flux as a result of polar ozone depletion over the last 2–3 decades.
22	Changes in ocean CO_2 source/sink function	Changes in the capacity of aquatic systems, ocean as well as freshwater, to generate or absorb atmospheric CO_2 as a direct or indirect consequence of global change over the last 2–3 decades.

Table 2 a. Summary of total scores (overall time and impact averaged score) for environmental concerns and issues affecting the East African Rift Valley Lakes.

Major concerns	Lake Turkana	Lake Victoria	Lake Tanganyika	Lake Malawi
Freshwater shortage (I)	3 (2.6)	1 (1.2)	1 (0.9)	2 (2.0)
Pollution (II)	3 (2.4)	2 (2.1)	2 (2.1)	2 (2.4)
Habitat and community modification (III)	3 (3.0)	2 (1.5)	2 (2.4)	3 (2.8)
Unsustainable Exploitation of Resources (IV)	1 (1.0)	2 (1.9)	2 (2.4)	3 (2.8)
Global Change (V)	2 (2.2)	1 (1.3)	2 (1.5)	1 (1.4)

Key: 0 = no known impact; 1 = slight impact; 2 = moderate impact; 3 = severe impact.

Table 2 b. Ranking of the five major concerns assessed in the East African Lakes.

Rank	Major concerns			
	L. Turkana	L. Victoria	L. Tanganyika	L. Malawi
1	III	II	III	IV
2	I	IV	IV	III
3	II	III	II	II
4	V	V	V	I
5	IV	I	I	V

Major concerns: Freshwater Shortage (I); Pollution (II); Habitat and Community Modification (III); Unsustainable Exploitation of Fisheries and Other Living Resources (IV); Global Change (V).

sive land use changes in the region, particularly in the Omo River catchment, the amount of freshwater entering Lake Turkana has declined steadily over the years (Haack and Messina, 2001). Development of the large Turkwel River dam also has significantly impeded the flow of freshwater in the Turkwel River (flows for most of the year and drains into the west shore of the north basin), and this has negatively impacted the fisheries in Ferguson's Gulf. Ferguson's Gulf on the west shore is now an enclosed lake because lowered lake levels have exposed the inlet bottom (Haack and Messina, 2001).

Freshwater shortage has only slight impacts in Lakes Victoria, Tanganyika and Malawi (Table 1). We consider that the freshwater shortage in Lake Victoria, most of which is due to pollution of existing supplies, is driven principally by pollution. This issue, therefore, is tackled in more detail in the pollution section below. There is little modification or diversion of Tanganyika's influent water supply; dams and irrigation channels are not common in influent rivers (Odada et al., 2002). However, increasing land use particularly in the north is affecting the quality of river water, and there is a significant loss of wetlands in some areas (e.g., Burundi) (Odada et al., 2002). The very large volume of Lake Tanganyika (and Lake Malawi) may provide a temporary buffer against deterioration of water quality (Spigel and Coulter, 1996). Several significant fish kills have, however, been reported in localised areas of Lake Tanganyika, especially in Bujumbura and Kigoma Bays (Odada et al., 2002). In Lake Malawi, catchment disturbance through land clearance has resulted in greatly increased sediment loads (Tweddle, 1992), and diversion of water for irrigation in some rivers has resulted in reduced flow. The Dwanga River, for example, is completely closed off during the dry season and diverted to sugar cane fields (Cohen et al., 1996). Pollution of existing supplies does occur in some heavily populated river basins and localised shoreline areas (Odada et al., 2002).

Pollution

The East African Rift Valley lake basins have a dense human population (see review) and high economic activities, with the exception of the Lake Turkana basin. Consequently, direct discharge of raw/untreated wastes from industries, domestic and urban sources into the lakes contribute to various forms of pollution, i.e., eutrophication, microbiological, suspended solids, sedimentation, and pesticides residues leached from soils and agricultural plantations. Maintenance of a high standard of water quality in the lakes is of considerable economic concern for human consumption (domestic, industrial, agricultural uses), public health, and lake ecosystem health (Cohen et al., 1996). The following sources of pollution were identified: microbiological, eutrophication, chemical, suspended solids, solid waste and oil spills, all resulting from human activities (Odada et al., 2002).

The principal pollution problem in Lake Turkana is that of suspended solids. An increased population pressure in the drainage basin of the Omo River in Ethiopia has caused increased soil erosion by removal of the vegetative cover for fuel and conversion to agricultural lands (Haack and Messina, 2001). Imagery from Landsat and other remote sensors clearly show the heavy sedimentation flow into the lake (Haack and Messina, 2001). There is a slight impact of eutrophication as indicated by an increased abundance in epiphytic algae and the presence of various species, e.g., *Microcystis*, *Oocystis*, *Anabaenopsis* and *Surirella* sp. (Kallqvist et al., 1988), due to nutrient influx associated with suspended solids input.

In Lake Victoria, pollution is a major problem. From the catchment, there are (i) the diffuse pollution sources such as agricultural – silting and agrochemicals which increase biological oxygen demand (BOD) and fertilise the lake; and (ii) the point pollution sources including industrial-waste water effluents and solid wastes, domestic sewage, and organic and microbial loads (Kansiime and Bugenyi, 1996; Kansiime and Nalubega, 1999). Microbiological pollution, eutrophication and chemical pollution are the most important issues in this major concern and occur over a significant proportion of the Lake Victoria basin. All these pose many problems of an economic, social and/or health nature. Microbial pollution is a large problem with many incidences of epidemics of cholera, dysentery and intestinal problems (Odada et al., 2002). There are major urban centres located near the lake, such as Kampala and Entebbe in Uganda, Bukoba and Mwanza in Tanzania, and Kisumu in Kenya. Large sectors of these and other urban-periurban centres either do not have or are poorly served by a public sewerage system; raw sewage is discharged directly into the lake (Nriagu, 1992). Domestic biological oxygen demand (BOD) exceeds industrial loads in all regions (Scheren et al., 2000). Pollution has also been reported in feeder rivers and streams (Wandiga and Onyari, 1987). The use of agrochemicals is increasing in the lake basin where there are large scale farms of coffee, tea, cotton, rice, maize, sugar, and tobacco (Ntiba et al., 2001). In the industrial sector, the polluters include breweries, sugar refineries, soft drink and food processing factories, oil and soap mills, leather tanning factories, mining companies, etc. (Ntiba et al., 2001). Beer brewing, pulp and paper production, tanning, fish processing, agro-processing and abattoirs discharge raw/untreated waste to feeder rivers and lakes (Wandiga and Onyari, 1987; Ntiba et al., 2001).

Nutrient loads to the lake are associated mainly with atmospheric deposition (natural and biomass burning) and land runoff (agriculture), and these together account for about 90% of phosphorus and 94% of nitrogen input to the lake (Scheren et al., 2000). Eutrophication has increased drastically within the last three decades due to high levels of nutrients (Hecky, 1993). Algal blooms have increased since the 1960's (Mugidde, 1993). The blue green algae, known for causing hypoxia conditions as well as being potentially toxic, are now dominant and occasionally lead to fish kills (Kling et al., 2001). All these have contributed to the degradation of river and lake water quality for habitat and drinking use (Wandiga and Onyari, 1987; Ntiba et al., 2001). The certain population increase will increase demand for freshwater resources, leading to greater pressure to modify stream/river flows. The governments of the region and international agencies such as GEF and the World Bank have provided funds to water quality assessments with a view to mitigating the pollution of existing supplies.

Pollution (particularly suspended sediment, chemical and eutrophication) is a threat to Lake Tanganyika because the basin's population is rapidly increasing and little legislation exists to protect the environment (Odada et al., 2002). Currently Burundi, with the largest population density and the most industries in the basin, poses the greatest pollution threat (Odada et al., 2002). Increased deforestation and, consequently, erosion in the catchment has caused an increase in suspended sediment entering the lake through streams, with highest impacts in the northern basin (Cohen, 1991; Tiercelin and Mondegeur, 1991). Kigoma Bay, Tanzania shows early warning signs that eutrophication should be a cause for local concern (Chale, 2000). Currently the effects of pollution in Lake Tanganyika seem to be buffered by the enormous size of the reservoir (Odada et al., 2002).

Suspended solids and eutrophication are the primary pollution issues in Lake Malawi. The likely factors influencing increased sediment deposition (Calder et al., 1995) and nutrient input (Bootsma and Hecky, 1999) in the southern catchments are deforestation, increased agriculture, erosion and biomass burning. The environmental degradation is driven by the need to sustain the growing population. The prominence of *Planktolyngbya tallingi* in the southern region of the lake (where it has replaced the previously dominant *Plantolyngbya nyassensis*) and the reported occurrence of *Cylindrospermopsis raciborski*, a filamentous blue-green which is often a climax species in highly eutrophic situations and which has toxic forms, are indicative of increasing eutrophication (Bootsma and Hecky, 1999).

Loss and modification of habitats

Loss and modification of aquatic ecosystems is a phenomenon capturing high attention in today's conservation measures (WWF SARPO, 2001). Over the past four decades, East African lakes have witnessed diminishing of wetlands by draining them for other purposes. This concern was rated as moderate to severe in Lakes Turkana, Tanganyika and Malawi (Tables 2 a and 2 b).

At the Omo River of Lake Turkana, there has developed a highly complex and spatially fluctuating floodplain and delta (Haack and Messina, 2001). Landsat imagery has provided information on the extent of the deltaic growth (particularly significant since 1979) but fails to provide clarification as to what are the land covers and land uses on these new areas (Haack and Messina, 2001). Examination of a variety of space-borne imagery including hand held shuttle photographs, Landsat MSS, colour composites, and a 1994 SPOT panchromatic image illustrated the growth to be a function of both changing water levels in the lake and increased sedimentation (Haack and Messina, 2001). Aquatic vegetation has developed on the emerging delta. The expansion of the delta wetland is potentially maintaining or increasing the biodiversity of fauna and flora, both locally and regionally (Haack and Messina, 2001). On the other hand, the productive soil, lush vegetation and availability of water is also attracting permanent human populations, most likely in conflict with flora and fauna (Haack and Messina, 2001).

In Lake Tanganyika, comparisons between recent biodiversity surveys and lake-wide ecological studies by Belgian expeditions in the 1940s, revealed that many sites had been transformed within the past forty years (Odada et al., 2002). The littoral zone of Lake Tanganyika includes sandy, rocky, mixed sandy-rocky and mud substrates. With increasing sedimentation, many rocky substrates have been transformed into mixed sandy-rocky substrates or even completely sandy substrates (Odada et al., 2002). The structure of fish communities has changed over time as well, with some populations of cichlids and molluscs going locally extinct during the past 30 years (Odada et al., 2002). Alin et al. (1999) have shown that increased sediment inputs to the lake have, to varying degrees, negatively affected species richness, density and abundance of fish, molluscs and ostracods. The floodplains of the Rusizi River are extensively cultivated, and the extensive wetlands associated with the river and its tributaries are grazed by cattle in the dry season when large areas of wetlands are burned (Hughes and Hughes, 1992). Significant loss of wetland has been noted, e.g., in Burundi (Odada et al., 2002).

Cattle grazing and agricultural activities (sugar and cotton growing under irrigation) are common in the marginal areas of the Shire Swamps in the lower part of the Shire River that supports one of Malawi's most important fisheries (Hughes and Hughes, 1992). For example, the Dwanga River is completely closed off during the dry season and diverted to sugar cane fields; the river was originally an important locality for potamodromous fish runs – these spawning runs have now ceased completely with the annual diversion (Tweddle, 1992). Habitat degradation of rivers and overfishing threaten riverine and potamodromous fish species (Tweddle, 1992; Ribbink, 2001). The Bua River (the largest river to enter the lake from the Malawi side) fishes, e.g., *Opsaridium microlepis*, have been largely eliminated from Malawian waters through a combination of siltation and fishing pressure (Cohen et al., 1996). The habitats of the inshore regions support the richest, most diverse and most stenotopic cichlid fish communities (Ribbink, 2001). The rocky shores harbour a wealth of invertebrates (e.g., harpacticoid copepods, chironomids, ostracods), molluscs and the crab *Potamonautes lirrangensis* while sandy shores support an almost entirely different invertebrate fauna (copepod and ostracod Crustacea, the *prawn Caridina nilotica*, chironomid larvae, gastropods, bivalve Mollusca) (Hughes and Hughes, 1992). These communities are under threat from sediment inundation of the habitats (Odada et al., 2002) and overfishing (Ribbink, 2001). Although no studies have been done, anecdotal comments suggest that seine netting has reduced substantially the vegetated regions, and hence the amount of habitat for use as nurseries and for species that are adapted to living among macrophytes (Ribbink, 2001).

Much of the Lake Victoria margin is swampy. Islands of *Cyperus papyrus*, with its typical associates, detach from the fringing swamps (Hughes and Hughes, 1992). Elimination of swamps through water diversion or damming is likely to cause declines in diversity of indigenous fish through habitat loss, destruction of refugia and faunal mixing (Chapman et al., 1992). Continuous cropping of papyrus could have serious ecological effects, including the loss of large quantities of nutrients removed with the harvested papyrus biomass that would otherwise be recycled (Muthuri et al., 1989). The losses in cichlid fish species diversity are partly attributed to habitat degradation (Ogutu-Ohwayo, 1990; Witte et al., 1999), leading to increased lake sedimentation, turbidity and pollution through activities such as agriculture, harvesting of wetland resources, etc. (Odada et al., 2002). Lake Victoria is believed to have been invaded by water hyacinth in the late 1980s (Freilink, 1991), through the Kagera River (Twongo, 1996). The weed thrives in bays and inlets which are sheltered from strong offshore and along-shore winds: have flat or gently sloping, relatively shallow shores (rarely deeper than 6 m), and have a muddy bottom rich in organic matter (Twongo, 1996). From satellite imagery, it has been observed that nutrient-rich sediment plumes originating from agricultural runoff and the low-lying, deforested riparian zones and other areas surrounding the lake are feeding the water hyacinth (Wilson et al., 1999). Its spread has disrupted fishing activities, transportation, and has threatened the functioning of various lakeshore-based installations such as water purification and hydroelectric power plants (Twongo, 1996). Proliferation of the water hyacinth leads to reduced oxygen levels, and hence reduced floral and faunal diversity (Kudhongania et al., 1996). A study in Lake Victoria (Uganda) has shown that, in the vicinity of the water hyacinth, fish species number, biomass and diversity are reduced, the former two significantly (Willoughby et al., 1996).

Unsustainable exploitation of fisheries and other living resources

Overfishing ranks high as a major concern in Lakes Victoria, Tanganyika and Malawi (Tables 2a, b). In Lake Turkana, reduced fish landings due to collapse of the tilapia fisheries in the mid-1980s and marketing problems led to fisheries being much less profitable (Kallqvist et al., 1988). The quantity of fish landed today is less than 3% of total fish catches in Kenya (Ikiara, 1999).

The East African Rift Valley lakes are famous for their rich and diverse populations of endemic species of fish and invertebrates and account for about 74.7% of total annual catches in the freshwater within East and Central Africa (FAO, 1998). Exploitation of fisheries in major inland water bodies has reached the optimal scientifically calculated levels according to recent studies. Some fish are in state of decline due to growth in the human population and introduction of more destructive fishing methods (Shumway, 1999; FAO, 2000; Bwathondi et al., 2001). In 1978, fish catch in Lake Victoria was estimated at 100,000 tons as compared to 300,000 – 500,000 tons in 1999 (World Bank, 1996). In addition to impacting biodiversity by altering the population and community structure of fish stocks and food webs, overfishing and fishing with destructive methods have negative repercussions on the socio-economic circumstances of riparian communities through loss of jobs and livelihoods (Odada et al., 2002). Factors affecting different fish stocks, particularly in view of changes in composition, are related to introduction of exotic species.

In 1955, the Nile Perch was introduced to Lake Victoria from Lake Kyoga. During the early 1980s the Nile Perch exploded in numbers causing serious predatory impacts on the Lake's native species. (Ogutu-Ohwayo, 1990). The population of haplochromines was collapsing due to these introductions. Therefore, the loss of biodiversity is considered a critical issue in the East African Rift Valley lakes. Trawling using undersized mesh nets for target species and indiscriminate fishing gear or poisons are considered serious and in most cases result in indiscriminate catches, including juvenile fish. Although the Nile Perch fisheries produces about 300,000 metric tons of fish per annum in Lake Victoria (FAO, 1998) – a market that technically did not exist prior to its introduction in 1955, there are concerns that this income generation is not benefiting the local people who, in the first place, have lost their favourite species, and secondly, the Perch is harvested for foreign markets. This is one reason why fish consumption has declined and there is concern about malnutrition in the Lake Victoria region (Kaufman, 1992). Lake Victoria supports 30 million people that directly or indirectly rely on the fishing trade; loss of fisheries has serious socio-economic implications for this population.

Lake Tanganyika is currently undergoing similar problems of excessive fishing. UNDP (1994) reported that excessive harvesting was diminishing certain fish stocks in this lake. Several studies have suggested that commercial fisheries already have drastically reduced the fish stocks. Burundi once hosted a large industrial fishing fleet, but by the early 1990s they could no longer make a living and all the vessels were dormant or had been sold to companies in Congo or Zambia (Petit and Kiyuku, 1995). Pearce (1995) calculates that the fishing effort in Zambia had tripled by the early 1990s and catches had been decreasing since 1985. These efforts have apparently affected the community structure of the stocks in Zambia. Initially the catch was 50 percent sardines, 50 percent *Lates* (Coulter, 1970), whereas since 1986 the catch has been 62–94 percent *Lates stappersi*. The fishery has evolved from a six-species fishery (two sardines, four *Lates* spp.) to a single species fishery (*Lates stappersi*).

Overfishing does not occur throughout Lake Malawi, and the deep pelagic waters of the lake are probably under-exploited (Ribbink, 2001). However, deep-water demersal communities (between 50–100 m depth) are harvested by offshore trawlers in particular and have shown changes in species composition and standing stock, but nearshore, shallow demersal communities are under the greatest pressure (Ribbink, 2001). At the southern end of the lake, fishing has resulted in reduced fish size, smaller catches, and possibly reduced biodiversity. The potamodromous fishes are subjected to heavy fishing pressure when adults congregate on their spawning runs up river; simultaneously, degradation of rivers negatively affects breeding success and recruitment so that populations of several species are in decline and many are threatened (Tweddle, 1992; Ribbink, 2001). As in Lake Tanganyika, the impact of ornamental fishing on population and community structure could be considerable as these rare and exotic species are extracted at the highest possible number because of the high mortality rates in shipping (Odada et al., 2002). Declining fish yields and catches per unit effort, as well as disappearance of certain fishes from the catches (while the number of people involved in fishing continues to grow), suggests that present levels of exploitation are not sustainable, at least in some parts of the lake (Ribbink, 2001).

Global change

Lake Turkana is sensitive to climate change as a result of its arid setting, topographically closed basin (i. e., no outlet), and a high dependency on Omo River inflow. Lakes Victoria, Tanganyika and Malawi are also extremely sensitive to climate change as their water balances are dominated by rainfall on the lakes and evaporation, with river inflow and outflow making minor contributions (Spigel and Coulter, 1996). The level of Lake Turkana has varied by 20 m within the past century alone (Owen et al., 1982). In lakes Victoria, Tanganyika and Malawi, relatively small changes in rainfall and evaporation may lead to shifting between open- and closed-basin status as has happened in historical times for Lake Tanganyika (Spigel and Coulter, 1996) and Lake Malawi (Beadle, 1981; Owen et al., 1990). For example, Lake Tanganyika's outflow was totally blocked when Europeans explored it in the early 1900s (Bootsma and Hecky, 1993). Lake Malawi had a low stand between 1500 and 1850 AD (^{210}Pb dates) (Owen et al., 1990) and in 1915 AD when outflow via the Shire River ceased; outflow resumed in 1935 AD after the lake level had risen 6 m (Beadle, 1981). A modelling study of Lake Malawi (using a fixed forest cover value of 64%) shows that rainfall variation is sufficient to explain the lake level changes over the past century (1896 to 1967) irrespective of changes in land use, evaporative demand or in the hydraulic regime of the lake (Calder et al., 1995). Deforestation has, however, resulted in increased runoff to the lake: model predictions for the period 1967 to 1990 (based on a linear decrease in forest cover from 64 to 51%) agree well with observed annual and seasonal changes in lake level (Calder et al., 1995). Without the decrease in forest cover, the predicted lake level would have been about 1 m lower during the southern Africa drought of 1992, and this would have accentuated the adverse impacts of the drought on lake transport, hydroelectric power generation, and lakeside tourist developments (Calder et al., 1995).

It has been established that levels of the East African lakes have fluctuated significantly during the Quaternary period. Many lacustrine sediment records covering the last glacial maximum and Holocene period show that between 15,000 and 10,000 yr BP, many lakes including the large but relatively shallow Lake Victoria were desiccated, while others such as Tanganyika and Malawi had significantly lower lake levels. Several lake level lowerings of large magnitude have also been recorded in the east African lakes during the Holocene. Seismic profiling in Lake Turkana shows a major erosional unconformity at ca. 60 m depth, indicating that the lake was 60 m lower than present, and is believed to have occurred between 13,000 and 10,000 yr BP (based on a sedimentation rate of 0.3 cm yr^{-1}) (Johnson et al., 1987). Lake Turkana subsequently rose rapidly and achieved open lake status at approximately 9,500 yr BP, standing at about 70 m above the present day lake-level (Butzer, 1980). Regressions in Lake Turkana occurred at 7,500 (a 60 m lowering of lake level – Owen et al., 1982), 4,500 yr BP (Halfman et al., 1992) and 4,000 yr BP (a 30 m lowering of lake level – Owen et al., 1982), respectively. From about 400,000 years BP, the Lake Victoria basin seems to have experienced several major climatic events which included the lake drying up and most recently has seen the present Lake Victoria arising from a dry landscape about 14,600 years ago (Johnson et al., 2000). Seismic reflection data suggest that Lake Tanganyika was divided into three hydrologically, chemically and biologically distinct paleolakes during lake low stands between 150,000 and 50,000 years ago (Scholz and Rosendahl, 1988). Low levels were recorded in Lake Tanganyika between 21,700 and 12,700 yr BP, with minimum levels at 18,030 ± 230 yr BP, identified by maxima in *Gomphonema* and other benthic diatoms (Gasse et al., 1989; Haberyan and Hecky, 1987). However, for the past 2,800 years, lake levels have been relatively stable, fluctuating between 765–775 meters above sea level for most of this time (Cohen et al., 1997). There is evidence suggesting that Lake Malawi was almost 400 m lower than present about 25,000 years ago (Scholz and Rosendahl, 1988), and that its level has been 100–200 m lower than present several times in the past few thousand years (Scholz and Rosendahl, 1988; Owen et al., 1990).

It is particularly pertinent that during the late Holocene when natural forcings and boundary conditions were similar to today, climate variability often exceeded anything that is seen in modern instrumental records (Oldfield and Alverson, 2003). The fact that persistent droughts, well beyond the range of those recently experienced, have been common in the past, suggest that there is a high possibility of their occurrence in the future (Oldfield and Alverson, 2003). Global warming will lead to higher temperatures estimated to be between 0.2 and 0.5 °C per decade for Africa (Hulme et al., 2001). The major effects of climate change on African water systems will be through changes in the hydrological cycle, the balance of temperature, and rainfall (IPCC, 2001). Lake Victoria, for example, is now one-half a degree (°C) warmer than in the 1960s (Hecky et al., 1994; Bugenyi and Magumba, 1996), in harmony with changes in surface temperature at tropical elevations above 1000 m worldwide. Warming temperatures in the region will cause greater heating in surface waters than in deep waters in the meromictic Rift Valley lakes, and this could reduce vertical exchange of deep waters with surface waters and reduced loading from the higher nutrient concentrations in those deep waters. Vollmer et al. (2002) have documented a recent reduction in the ventilation of the deep water of Lake Malawi which has also reduced nutrient loading from the hypolimnion (Bootsma and Hecky, 1999). Reduced nutrient loading could lead to lower biological production in those deep lakes. Although current climate scenarios project small increases in tropical temperatures, small changes in temperature and water balance can dramatically alter water levels, as well as mixing regimes and productivity (IPCC, 1996). High temperatures would increase evaporative losses, especially if rainfall also declined (IPCC, 1996). Minor declines in mean annual rainfall (10–20%) for extended periods would lead to the closure of the African lake basins even if temperatures were unchanged (IPCC, 1996). There is also likely to be an increase in the frequency and or severity of extreme events such as El Niño. Severe droughts and floods would adversely impact the socio-economic activities and livelihoods of the inhabitants of the lake basins. For example, the El Niño phenomenon in 1997–1998 saw water levels rise by 1.7 m (Lake Victoria), 2.1 m (Lake Tanganyika) and 1.8 m (Lake Malawi) (Birkett et al., 1999). The widespread heavy rainfall and flooding produced adverse wide-ranging agricultural, hydrological, ecological and economic impacts in east Africa (Conway, 2002).

Summary and conclusion

The assessment (Odada et al., 2002) has revealed the environmental concerns facing the East African Rift Valley lakes and their catchments. All the five GIWA concerns are important in the region, but by following the GIWA criteria and methodology for the assessment the following emerged as priority concerns: pollution, unsustainable exploitation of fisheries and other living resources, and modification and loss of habitats due to human activities. The population of the region was estimated to be 52 million in mid 1990's (Victoria – 53%, Tanganyika –12%, Malawi – 11% and Turkana – 3.8% (Cohen et al., 1996), but is expected to double within the next two decades (World Bank, 1999). Many African countries are today experiencing water stress, and it is projected that many more will shift from a water surplus state to a water scarce state by 2025 due to increase in population alone (IPCC, 2001).

The lakes water quality and ecology will continue to be degraded due to increasing efforts in activities such as agriculture, deforestation, transportation and regional economic development within the lake catchments that result from increasing population. The lakes have been found to be more vulnerable than originally thought because of their long retention time, accelerated catchment degradation, population pressure, and complex internal hydrodynamic processes (Duda, 2002). Efforts at mitigation of sedimentation, population, eutrophication and biodiversity loss in lakes will be much more difficult if implemented in the future, rather than now. For example, in Lake Victoria, pollutants tend to accumulate rapidly, but even 100 years after cessation of pollution, the concentration in the lake would still be about 15% of the original input (Bootsma and Hecky, 1993). In deeper lakes such as Lake Malawi, concentration of pollutants increase considerably slower than in Lake Victoria, but its subsequent elimination from the lake via outflow is also considerably retarded (Bootsma and Hecky, 1993). The threat of petroleum and other types of spill looms large in Lakes Victoria, Tanganyika and Malawi as these products are increasingly being transported across the lakes (Odada et al., 2002). Already, there have been serious accidental spills, e.g., of DDT in Kigoma harbour (Alabaster, 1981) and fuel oil leakages in Mpulungu harbour, although DDT is no longer used except near the shoreline in the Zambian side of the lake (Cohen et al., 1996). Petroleum exploration is being undertaken west of Lake Tanganyika – if oil were discovered and produced in the region, risks of oil spills would arise from well accidents, cross-lake transport and harbour spills (Cohen et al., 1996).

Against the backdrop of increasing riparian human population and rural-urban migration coupled with lack of management strategies and interventions for sustainable use of the lakes and their catchments, the lakes will increasingly be vulnerable to change as their capacities to maintain the current ecological balances are systematically reduced as critical thresholds for sustainable use are exceeded. Future scenarios of possible lowered lake levels in the long-term would result in, among others, changes in salinity of the lake water and loss of littoral habitats. Such scenarios would have adverse impacts on food webs and fisheries, biodiversity, transportation, freshwater availability, agriculture and hydroelectric power generation. In addition, present-day and future human impact is bound to cause dramatic environmental changes followed by significant biodiversity loss in the lakes over a very short time frame, less than a few dozen years (Martens, 2002). Excessive sedimentation as well as excessive exploitation of fisheries would lead to a loss of biodiversity in the lakes and incrementally reduce their economic resource value (Kaufman, 1992; Tweddle, 1992; Cohen et al., 1993, 1996; Beeton, 2002). For example, the apparent cichlid extinction of hundreds of species in Lake Victoria was caused by the combined effects of the introduction of an alien predator (the Nile Perch in 1955), increasing eutrophication (Hecky, 1993; Seehausen et al., 1997; Wanink and Witte, 2000), and overfishing (Kaufman, 1992). Continued degradation and unsustainable use of the resources of Lakes Malawi, Tanganyika, Victoria and others have major implications not only for their globally significant biological diversity but also for tens of millions of people depending on them for survival (Duda, 2002). Thus integrated transboundary catchment – water resource management strategies and interventions need to be implemented for sustainable use of the lakes, and to help maintain their natural hydrological and ecological balance (Beeton, 2002).

It is evident from these emerging issues, that there are inter-basin commonalities in issues linked to shared resources for common survival; first is inland freshwater, forests functioning as water catchment areas, and soils and rocks which play important roles in storage of underground water. Humans depend on a process network of water, soil and predictable climate for food production using solar energy. While issues of global climate change are cross-cutting throughout the African Rift Valley region, resource use patterns that bear a reflection on the emerging issues give a sense of direction on how to tackle them with respect to commonalities among the various lake basins within the Rift Valley region.

There is need, therefore, to focus on regional management of the quality and quantity of the following: freshwater availability and utilisation, sustainable utilisation of freshwater for food security and trade, appropriate planning for human size and their settlements, land use, and waste disposal to control pollution which will in the long term reduce habitat and ecosystem modification. Although the East African Rift Valley lakes contribute minimal emissions of greenhouse gases, there is still need to reduce the rate of deforestation and even restore cleared areas since forests serve as sinks for greenhouse gases, mitigating adverse climatic changes. Due to the fact that the issues identified are transboundary, appropriate multilateral policies and institutional arrangements need to be created to help shape the common future of the East African Rift Valley lakes.

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