Executive Summary

Water Quality Report for the SADC/GEF Lake Malawi/Nyasa Biodiversity Conservation Project

Introduction

Lake Malawi/Nyasa is one of the largest and oldest lakes on earth. It is bordered by the countries of Malawi, Mozambique and Tanzania, which share responsibility for its management. The lake is a valuable resource for the riparian peoples, providing abundant water for domestic uses in a water scarce region, providing essential and cheap protein through its fisheries, facilitating transportation, attracting tourism, contributing to hydroelectric energy production, and providing recreational and aesthetic opportunities. The lake is also home to more species of fish than any other lake in the world, over 90% of which are endemic to the lake. This biodiversity, which is the product of evolution within this lake in the past, is also important to the lake's future. The sustainability of this biodiversity and the manifold resource uses in this vast international waterway are the issues which led to the development and implementation of the SADC/GEF Lake Malawi/Nyasa Biodiversity Conservation Project. The project recognizes that good water quality is a necessary requirement for all the current resource uses, including biodiversity maintenance. Other Great Lakes in the world, especially Lake Victoria in Africa, provide object lessons that great size alone offers no insurance against loss of biodiversity and degradation of the other beneficial uses of the lakes. There is no need to learn another lesson in Malawi/Nyasa. In all these other lakes, degradation of water quality has been recognized as contributing directly to the loss of fish habitats and the deterioration of other uses of the aquatic resource. Maintaining good water quality is therefore critical to the future of biodiversity in Malawi/Nyasa as well as to the economic well being and health of the riparian peoples and nations.

This report summarizes studies conducted with funding from part of the Canadian International Development Agency (CIDA) contribution to the SADC/GEF project. The Freshwater Institute of the Canadian Department of Fisheries and Oceans was the responsible implementing agency. The report provides information on current water quality conditions, evaluates the sensitivity of the lake and its inputs to water quality change, and assesses, where evidence exists, whether the water quality of the lake may already be changing.

There may be over 700 species of fish, nearly all within the family of Cichlidae, in Lake Malawi/Nyasa. An important activity of the SADC/GEF project is the continuing effort to identify new species and confirm current biological nomenclature. These haplochromines challenge scientific understanding of how so many species successfully coexist in one ecosystem, and their conservation and maintenance will similarly challenge management. What is clear about these fishes is that they have finely divided the habitats available in the lake through a variety of complex adjustments in their morphologies, coloration, behaviour and life histories. Most of the haplochromine species are living near or on the bottom in shallow waters inshore. Rocky areas are especially species-rich. They extract food, either directly or indirectly, from the benthic algal communities which occur there. The areal extent of these benthic algal communities is controlled by light penetration for photosynthesis. The fishes also require good light conditions for visual recognition during mating and territorial defense. Light penetration in the lake is controlled locally by suspended sediments from river plumes and lakewide by phytoplankton abundance which absorbs light for photosynthesis. Therefore, changing abundance of suspended sediments and phytoplankton will directly affect the habitat space of the diverse haplochromines. For the continued success of these fishes, the fine adjustments and adaptations to their environment presume that the environment will not change abruptly and/or significantly. Changes in the environment involving species introductions and water quality in Lake Victoria brought about dramatic losses in biodiversity. Therefore, the safest assumption to make about the water quality and habitat requirements of these species is that conditions should remain similar to what they are now. The safest course for management is to take an **ecosystem approach**, such as that embraced in North American Great Lakes, to the maintenance of species and their habitats. A major task of this water quality report therefore has been to characterize the current water quality of the lake and its major water inputs as crucial elements of the ecosystem which has produced and maintained the exceptional biodiversity.

There are three major factors controlling the nutrient chemistry of the productive mixed layer (above 100 m depth): river inflows, wet and dry deposition from the atmosphere, and mixing with deeper nutrient rich waters, including the permanently stratified, nutrient rich and anoxic waters below 200 m depth. Each of these water sources contributes significant amounts of nutrients to sustain algal productivity in the upper mixed layer, but each of these sources differ in the proportion of different nutrients, and increasingly contaminants, they contribute to the mixed layer, and they differ in their sensitivity to human activities.

Rivers most directly connect human activity in catchments with the lake as they receive uncontrolled byproducts of human, agricultural and industrial wastes, and soil erosion. Increasingly it is appreciated that the atmosphere is having its chemical composition changed by human activity at all scales from local to regional to global. The atmosphere also bears a burden of uncontrolled waste products from human activities, and in a large lake like Malawi/Nyasa where nearly 60% of the water input occurs as rainfall on the lake's surface, the changing atmospheric chemistry can quickly find expression in the lake.

The deep water of the lake was formed in the past decades and is out of equilibrium with current conditions at the surface. It is nutrient rich as it receives sediment nutrients which are regenerated and mix back into surface waters after a long delay. This deep water is an important input of nutrients to the surface. Because of the lake's large volume and the slow exchange between deep water and surface waters, changes in the chemistry of rivers and atmospheric deposition may not become immediately apparent in the lake. However, by the same virtue, the remediation of deleterious water quality changes in the lake will also be a slow process. Consequently it is most important to monitor the rivers and atmosphere closely as they are the inputs which are most sensitive to changing conditions, and they represent new inputs to the lake.

On a lake-wide basis, eutrophication (a term for excess nutrient enrichment causing overabundant phytoplankton growth) is the most serious water quality threat to the maintenance of healthy and diverse benthic fish communities. Also of concern, especially for the predaceous fishes, is contamination by toxic compounds used in agriculture and industries. Consequently this study has addressed which factors now control phytoplankton growth in Malawi/Nyasa and has reviewed evidence for change in those factors. For the very first time, a comprehensive survey has been completed on persistent contaminants in the rivers, the atmosphere and biota of the lake. These surveys will provide important information on baseline conditions in 1996-98, against which future change can be evaluated. These results have relevance to human health issues as well as biodiversity, given the significance of the lake and biota in supplying water for domestic use and food for consumption.

River flows and water quality

Rainfall and river discharge are highly seasonal in the Malawi/Nyasa watershed. The single rainy season, usually beginning in late November/December and extending through March, follows a prolonged dry period of little or no rain when many rivers nearly cease to flow. Rainfall and river discharge are highest in the more mountainous northern region, and under natural conditions the northern catchments dominate the input of sediments. However, population growth and agricultural development have been proceeding most rapidly in the less mountainous southern catchments, especially on the Malawi side, and the most significant changes in river quality from natural conditions may be expected there.

The Malawi Water Department routinely monitors flows in all the major rivers of Malawi. In the water years of 96-97 and 97-98, using analytical laboratory facilities established at Senga Bay and at the Freshwater Institute in Winnipeg, Canada, a wide range of water quality parameters including all the major forms of nutrients were measured. The full data base of all completed analyses resides at the Senga Bay laboratory. Data on concentrations of nutrients and suspended sediments were combined with flow data from the Water Department to calculate yields of sediment and nutrients to Lake Malawi/Nyasa. Rivers were sampled from weekly to monthly. Unfortunately very few (in Tanzania) or no samples (Mozambique) were collected from rivers in the other countries during this period. But given the similarity of geology and land use activities, extrapolations to unsampled catchments were made on the basis of the historical contribution of the unsampled catchments to total flow to the lake. This is the first time that sampling was accomplished of the whole flow year on Malawian rivers. The only prior effort to estimate nutrient inputs from the lake catchment was based on a single sample for chemistry from each catchment during a survey done in 1983.

The estimated inputs of the critical nutrients, nitrogen (N) and phosphorus (P), from rivers are much higher than previously estimated. Phosphorus inputs from all rivers are three times higher than previously thought, while nitrogen is six times higher. The cause of the previous underestimation is the high variability in suspended sediment loads. Suspended particulate forms of phosphorus and nitrogen account for 90% and 80% respectively of the total load of these elements. Concentrations of sediments change rapidly with flow conditions and the single sampling in 1983, which was done late in the dry season, could not characterize this variability. The annual yield of sediments and nutrients was strongly dependent on flow conditions in any water year. For example, in the very high flows of 1997-98 the yield of suspended sediments from the Linthipe catchment was nearly 50% higher than in 1996-97. However, there was no statistical relationship between discharge and concentrations of the various parameters. River flows early in the rainy season carried much higher concentrations of sediment and nutrients than similar flows late in the rainy season. This was likely due to the flushing out of debris from the prolonged dry season and to soil loss from the cultivated and planted fields prepared for the beginning of the rains. Extensive cultivation within a catchment is a factor causing well- populated catchments to have higher than expected yields of sediments and nutrients, a phenomenon which is well established around the globe. Flow variability is also a measure of catchment land surface disturbance. The Linthipe River had the highest coefficients of variability of flow by the two different assessment techniques applied while the other southern catchments, in general, had higher coefficients than the more northern catchments where forests and soils are less impacted by agricultural development.

The extrapolation of flows and concentration data from monitored to unmonitored rivers leaves uncertainty as to actual yields in those catchments. Therefore a range of annual yields for sediments and nutrients are provided giving high and low estimates. The rivers supplied 0.26 to 0.40 g P m^{-2} y^{-1} and 2.0 to 4.5 g N m^{-2} y^{-1} to the surface of Malawi/Nyasa. Due to their heavy loads of suspended phosphorus, rivers are the largest source of total P to the lake (although the atmosphere is also an important source). **Of the rivers monitored, the southern rivers Linthipe and Dwangwa are the largest riverine contributors of N and P to Malawi/Nyasa. These rivers also have the most variable flows and significant outputs of nitrate and sulfate. Nitrate release is characteristic of catchments losing vegetative cover while sulfate is yielded from wetlands when they are drained and disturbed. The most disturbed southern catchments are exhibiting higher suspended sediment, total phosphorus and total nitrogen concentrations which are 10, 5 and 9 times higher respectively than concentrations in rivers with less extensive agriculture and land clearance**. Extensive agriculture and land clearance have been documented to have these effects world-wide and the results from Malawi rivers are consistent with other studies. If the northern catchments begin to experience similar degrees of settlement, their catchment responses may be even greater because of the greater elevations and rainfall which provide the kinetic energy to mobilize suspended loads through soil erosion. Only good soil conservation and catchment management practice can reduce the increased loads to the lake which further settlement and agricultural expansion will yield.

The behaviour of rivers when they enter the lake reduces the contribution that the rivers could make to surface waters. Many of the rivers actually enter the lake cooler and more dense than the lake and consequently "plunge" until they encounter cooler water of similar density in the lake. This plunging diverts the carried loads below the mixed layer. On average, in monitored rivers, over 50% of the entering flows may dive to a depth greater than 50 m. The northern rivers, which have catchments with steeper relief and offshore areas, exhibit this behaviour more than the southern rivers, with the average depth of penetration in the north being well in excess of 50 m and as high as 124 m in the case of the North Rumphi. This plunging behaviour will provide some protection in the short term to increasing sediment and nutrients loads as they will be diverted to deeper water. However as the deep waters are affected by these increasing loads, the return to surface waters via vertical mixing in the lake will eventually occur after some decades. The most disturbed southern rivers, e.g. the Linthipe, on average, contribute most of their load to the surface mixed layer on entering the lake and will have more immediate effects on surface waters.

The sediment loads should be monitored in the rivers entering the lakes. Measuring suspended solids loads can be done at low cost, and there are good predictive relationships between total suspended solids and concentrations of total phosphorus, total nitrogen and total organic carbon. Therefore, monitoring suspended solids will provide information on nutrient loading by rivers. The Water Departments in the riparian countries in conjunction with a suitable analytical laboratory in Malawi, such as the one at Senga Bay, could cost-effectively monitor the rivers to evaluate the need for of the efficacy of soil conservation and catchment management practices in the Malawi/Nyasa basin. This study of the quality of the rivers has been able to infer qualitative relationships between geographic factors such population density, loss of forest cover and agricultural activity and the response of rivers such as increased flow variance, river chemistry and sediment and nutrient yields. Ongoing research by the Centre for Earth Observation Studies will develop a quantitative GIS database on these basin characteristics which will test these qualitative inferences and develop GIS based models which can predict the consequence of future basin developments on the quantity and quality of river flows and their effects on the lake.

Atmospheric deposition

Rainfall directly on the lake surface provides nearly 60% of the total input of water. The large surface area of the lake also receives “dry” precipitation in the form of dust and volatile gases e.g. ammonia. The possible input from the atmosphere can be visually appreciated by comparing the extremely hazy (smoky) atmosphere of the dry season with the clear views of the rainy season. There has been one previous study on precipitation chemistry in Malawi in 1990-91 at a lakeshore site near Monkey Bay. Since September 1995, rainfall chemistry and potential dry deposition have been monitored at the Senga Bay laboratory. Because of the need to analyze these samples soon after collection unless appropriate preservatives are added, it is difficult to operate an extensive network without an investment in human resources and analytical resources which were beyond the current project. However, some samples were collected from Nkhata Bay and Kyela. Because of the potential importance of the atmospheric flux to the lake, the Senga Bay station is continuing to operate its monitoring of atmospheric deposition. It is also possible to compare the results from this station with the previous one-year effort at Monkey Bay.

In 1990-91 dry deposition was found to exceed wet deposition of nitrogen and phosphorus by a factor of 12 even though on an event basis rainfall yielded, on average, 3 times the daily flux of dissolved inorganic nitrogen and phosphorus as the mean daily rate of dry deposition. The long dry season amplifies the significance of dry deposition in the annual budget. The 96-98 data concur with the earlier data in regards to the importance of dry deposition (which in 96-98 had similar or higher event fluxes than wet deposition), but the ability of the most recent study to access sufficient water for more analyses has increased the measured concentrations of dissolved organic and particulate forms of nitrogen and phosphorus. The estimated contribution of phosphorus from the atmosphere has increased to 0.24 g P m^{-2} y^{-1} from 0.05 g P m^{-2} y^{-1} with most of this increase accounted for by better estimates of dissolved organic and particulate forms of phosphorus. Estimates of total nitrogen loading from the atmosphere are also higher by nearly 80%, again because of better estimation of dissolved organic and particulate N. The best estimates now are 2.0 g N $m\text{-}^{2}$ y^{-1}. **Although comparable or somewhat lower than the riverine input of these nutrient elements, it is noteworthy that the loading of <u>dissolved</u> forms of N and P from the atmosphere are**

substantially higher than in the rivers where particulate forms dominate. For example, the inorganic forms of nitrate, ammonia and phosphate which are most readily taken up by plants occur at 4-5 times higher concentrations in the atmospheric deposition than in the rivers. The organic dissolved compounds also are often more readily available to the biota and have more immediate effect on plant growth.

The dissolved organic and particulate forms of N and P in the atmospheric deposition most likely originate from the surrounding land surfaces and vegetation cover. This is confirmed by the high deposition rates of potassium and calcium relative to sodium which confirms that land surfaces are the source of the solutes. The prolonged dry season and the agricultural practices of the region likely contribute to the relatively high atmospheric loading of dissolved organic compounds. Domestic cooking, heating, and land clearance all rely on burning, and are all potentially contributory to the atmospheric loading of N and P. It is not possible at this time to determine whether atmospheric inputs are higher than they used to be or whether they are increasing, because there are no long-term data on precipitation chemistry from the region to compare. Similarly the sampling is very limited spatially with only two lakeshore locations analyzed and interpreted. More monitoring stations (especially from the open lake) and longer-term monitoring are needed to answer such questions. But, given the result of this study that atmospheric inputs of N and P are of similar magnitude as river inputs and may be more immediately available, a regional monitoring programme and initiation of regional discussions on air quality may be crucial to maintaining the good water quality of Malawi/Nyasa. An international effort in this regard would be appropriate because many atmospheric contaminants can travel long distances from their sources and the solution to controlling or reducing atmospheric inputs may actually lie outside the immediate Malawi/Nyasa basin.

Vertical Mixing and Upwelling

Mixing of the deep waters of the lake into surface waters is continuously occurring, and this is the third source of water and nutrients to the productive surface layer. The deep waters have high concentrations of N, P and dissolved silica (essential for diatom growth), but the importance of this nutrient-rich reserve depends on the rate of physical mixing which can bring the deep waters to the surface. Previous work using tritium (a fallout product of atmospheric weapons testing of the 1950's and early 1960's) had estimated a relatively high rate of deep water renewal which in turn led to estimates of nutrient loading from this source which dominated estimates of P and silica loading to surface waters. In this study, another man-made product, chlorofluorcarbons (CFC's) from freon (a refrigerant gas now banned in many countries) has been used to estimate the rate of deep water renewal in Malawi/Nyasa. Some of the CFC's are inert (do not undergo chemical reaction), and the history of atmospheric contamination around the globe is well known. Therefore their rate of invasion into deep lake water is dependent on physical mixing within the lake. Application of this technique which quantifies the trace amounts of CFC-12 in Malawi/Nyasa can be used to estimate the rates of exchange between the surface layer of the lake (epilimnion) and next deepest water layer (metalimnion) and between the metalimnion and hypolimnion (deepest water layer). These layers are bounded by discrete breaks in the concentration of the CFC's and other thermal and chemical properties at depths of approximately 100 m and 220 m.

The results of the modeling of the distribution of the CFC's estimate that rates of exchange between the three layers are much slower than previously thought. **The exchange between the epilimnion and metalimnion is 50% of the previous values while the exchange between the hypolimnion and metalimnion is only 25% of the previous value. The slower exchange rates will proportionately reduce estimates of nutrient loading from the deep water to the surface and thereby make other water sources such as the atmosphere and the rivers much more important in determining the nutrient concentrations in the upper mixed layer**. Consequently the water quality of the mixed layer will be more dependent on inputs which may be altered by human activity. The difference from earlier estimates of deep water renewal may reflect real differences in mixing process over the past 20 years because of climatic variation, or it may simply result from the increased sensitivity of the analyses and the passage of time. Full three-dimensional modelling of the physics of the lake would be necessary to investigate the possible effects of climate change while further analytical verification of the mixing rates will be pursued using other tracers such as tritium.

Using tracers to estimate rates of vertical exchange can only yield multi-year averages of water exchange. It also cannot discriminate among the actual physical processes which drive the exchange. There are at least three processes, upwelling, entrainment of deeper water and turbulent mixing, which actually drive the exchange of water between layers. Thermistor chains were installed in Malawi/Nyasa to allow evaluation of the relative role of these three processes in driving exchange. Upwelling is likely the strongest of these three processes driving exchange between the metalimnion and epilimnion. Malawi/Nyasa is remarkable for the persistence of southerly winds which, together with the orientation of the lake, allow prolonged and surprisingly steady movement of surface waters from south to north. This prolonged wind-driven movement produces a steady upwelling in the southern part of the lake and especially in the southeast arm. Although the importance of this phenomena has been recognized for many years, for the first time we have been able to estimate it quantitatively using models of physical flow based on wind, measured at lakeshore locations, physical modeling of temperature structure recorded at thermistor chains, and nutrient profiles acquired at the thermistor chains on a monthly basis. **Upwelling dominates vertical water exchange in the southern end of the lake for months at a time, being up to 100 times as effective as turbulent mixing in introducing deeper water into the surface waters.** The nutrient loading rates from southern upwelling are one to two orders of magnitude higher than the mean loading rates calculated for the whole lake from the CFC modeling of exchange but the upwelling is restricted to a small portion of the lake's surface. The high rate of nutrient loading provided by the southern upwelling system sustains the higher rates of fish production in the southern part of the lake. These estimates of nutrient loading by upwelling should allow upper limits to be placed on fish production (and managed yield) in the southern part of Malawi/Nyasa.

Factors controlling algal growth

Water clarity is one of the most notable and noticeable features of Malawi/Nyasa. Objects are readily seen in depths of up to 20 m from the surface. The constituents which limit clarity in lakes such as dissolved humic substances, suspended mineral sediments and planktonic algae are currently present in low concentrations over most of the lake except in the vicinity of river plumes. Relatively low contributions from the watershed, along with the great depth of the lake, currently limit the concentrations of humic substances and sediments in the lake, but a combination of factors control algal growth. In Lake Victoria, eutrophication (nutrient enrichment) and food web changes have greatly altered the abundance of phytoplankton which now control light penetration, and have reduced water clarity by a factor of five since the 1920's. Experimental and observational studies were undertaken in Malawi/Nyasa to determine what factors are currently controlling phytoplankton abundance and thereby maintaining excellent water clarity.

Chlorophyll concentration is indicative of phytoplankton biomass and is the most important light absorbing compound present in all algal cells. The distribution of chlorophyll is remarkably uniform in time and space in the mixed layer of Malawi/Nyasa, seldom deviating from ~1 $\mu g\ l^{-1}$. This relative constancy is remarkable among lakes and indicates that concentrations of phytoplankton are closely controlled most of the time. Factors which can control algal abundance and growth can be classified as physical, chemical or biological. Examples of physical control are temperature and light which is essential for photosynthesis. Because temperature is continuously high and falls within a very narrow range, it unlikely to affect algal growth directly. However, temperature will affect nutrient supply through its control of vertical mixing. Surface light varies more than temperature over the year but is relatively high compared to temperate lake systems. An important feature of tropical lakes which affects the availability of light to a phytoplankton cell which cannot control its depth in the mixed layer is the depth of the mixed layer. Tropical lakes have deeper mixed layers than temperate lakes of similar size because of their warm hypolimnions which reduce the density difference between surface and deep waters. Therefore, the high clarity of Malawi/Nyasa is offset, at least in part, by the depth of mixing, especially during June through August when the surface mixed layer is deepened by the cool, dry southeast winds. Chemical control of phytoplankton growth is possible, with nitrogen and phosphorus most often being the elements in shortest supply and therefore likely to limit growth. Biological control can arise from grazing of cells which in the extreme can drop algal populations to very low numbers or can maintain numbers if grazing rates are nearly equal to specific growth rates of phytoplankton. In Malawi/Nyasa the populations of grazers can persist continuously because seasonal changes are muted and not as likely to limit and reduce animal activity as in lakes in temperate climates.

Concentrations of dissolved inorganic nutrients are low in Malawi/Nyasa and have been thought likely to control phytoplankton abundance and growth. Soluble reactive P concentrations are frequently less than 1 $\mu g\ l^{-1}$ while inorganic nitrogen concentrations are less than 14 $\mu g\ l^{-1}$, and frequently these nutrients are undetectable by standard chemical methods. Dissolved silica is usually between 300 and 600 $\mu g\ l^{-1,}$ concentrations which can limit growth of some species of diatoms including species of the large *Aulacoseira* common in Malawi/Nyasa. Although low, the ambient concentrations of N and P do not seem to be immediately controlling growth rates of the algae. **Physiological indicators of nutrient status which are sensitive to deficiencies of nitrogen and phosphorus and therefore indicative of nutrient limited specific growth rates do not indicate strong deficiency for these nutrients by the phytoplankton community in Malawi/Nyasa**. Sensitive radioassays for phosphate availability also did not indicate that phosphate concentrations were immediately limiting growth of the algal community. Nitrogen fixation by blue green algae such as *Anabaena* is, which is indicative of N deficiency, is often undetectable or occurring at very low rates except at some inshore locations. If inorganic nitrogen were strongly limiting phytoplankton growth, then higher rates of fixation would be expected as would greater abundances of these nitrogen fixing species. The composition ratios of the suspended materials are high enough to indicate that P and N may be limiting, but the high ratios may be influenced by non-living organic carbon or may also indicate a selection for algal species which grow well under low nutrient conditions and with high C:P and C:N optimum ratios.

Experiments were done to try to isolate the factors which can control phytoplankton abundance. The experiments altered the light availability, increased the concentrations of nutrients available to the phytoplankton and/or removed large grazers from the incubated samples. The experiments were done in three different seasons: 1) near the end of dry season (November), 2) the rainy season (February) and 3) the onset of maximal seasonal mixing (June). **These experiments show that all three factors, light exposure, nutrient concentrations and grazing, contribute to the maintenance of low phytoplankton biomass and weak nutrient demand in all seasons with their relative importance varying among the seasons**. The alteration of any of these three factors altered the nutrient status of the experimental treatment and sometimes led to substantial increases or decreases in phytoplankton abundance. Higher light exposures and higher nutrient concentrations generally favored algal growth. Removal of large grazers resulted in more complex responses sometimes leading to increased algal abundance (probably because of reduced grazing pressure), and sometimes leading to declines (as a result of increased activity of micrograzers or loss of a source of regenerated nutrients). **Of the three factors, only nutrient concentrations are likely to be altered directly by human activities. Nutrient enrichment usually led to increased biomass but only after passage of two to four days. The delay suggests that the ambient phytoplankton community could not respond initially because of the need to shift metabolically in order to use the higher nutrient concentrations added, or that phytoplankton species originally present at low abundance accounted for increased growth achieved by the end of the experimental period**.

Phytoplankton populations in Malawi/Nyasa are strongly regulated by a mix of light limitation, nutrient concentration and grazing. If one of these controlling factors is relaxed the others quickly come into play keeping algal biomass within a narrow range of low concentrations and consequently water clarity high. Currently in Malawi/Nyasa these factors change most rapidly as the shoreline or a river mouth is approached. Shallower depths nearshore reduce mixing depths and increase light exposure until turbidity and algal growth reduce light penetration. The nearshore zone can also be a source of higher nutrient concentrations, especially near rivers in the rainy season when nutrient inputs are high. In these situations phytoplankton growth can exceed the response time of the grazing animals and algal blooms can develop. When algal blooms develop in Malawi/Nyasa at present, dissolved inorganic nitrogen compounds are likely to be depleted before phosphorus, and extreme nitrogen deficiency can develop. This nitrogen deficiency and excess phosphate favours the filamentous, nitrogen fixing blue-green algae such as *Anabaena*, and other species such as *Cylindrospermopsis,* which are undesirable and can even become toxic to humans and domestic animals, as well as fish and wildlife. These nitrogen fixing blue-green algae now dominate Lake Victoria for much of the year and concerted efforts should be made to prevent their becoming similarly dominant in Malawi/Nyasa. **Deforestation and intensive agriculture are increasing nutrient inputs to the lake and also lowering the nitrogen to phosphorus loading ratio. Therefore the current trend in nutrient loading from the watershed and airshed would increase algal abundance and shift the composition of the phytoplankton community towards filamentous nitrogen-fixing blue-green algae. Increased phytoplankton abundance will result in decreased light penetration while greater abundance of noxious blue-green algae will negatively affect many beneficial uses of the water by biota and humans.**

Evidence of recent changes in water quality

This study has highlighted a number of possible changes which may take place in the water quality of Malawi/Nyasa. The lack of previous long term data makes it difficult to state definitively how fast changes may be taking place in the lake or even if demonstrable change has occurred. Previous studies have been restricted in time or spatial coverage and often used different methodologies and considered different aspects of the ecosystem. The very earliest ecological observations on the lake pre-date this century when floristic records of the algae were first published. Therefore comparisons of the algal flora of the lake extend over a century, a long enough period to look for temporal change due to increasing human activities. But quantitative study of the phytoplankton with acceptable modern methods began only in 1980 and even then was limited to the area around Nkhata Bay. Lake-wide study of this community did not begin until the 1990's, and so it does not offer much time to detect rates of changes in quantitative aspects of this community. The sediments of the lake do continuously accumulate materials falling from the water column. Therefore the sediment record can be examined to look for changes in output of the ecosystem to the sediments. Paleolimnological analysis works best for algal remains and nutrients which leave abundant traces in the sediment; other ecosystem components such as zooplankton and fish leave fragmentary fossil records by comparison. The historical record of algal species occurrence has been examined to see if there is evidence in the algal community of any significant additions to the flora in the past century. Also the record of sedimentation over the past century has been examined in two sediment cores one in the northern portion of the lake and one in the south to see if changes in rate or composition of the sediment may have occurred.

Historical analyses of the records of phytoplankton flora of Malawi/Nyasa revealed only a few changes, but the ones which have been recorded create concern. It must be emphasized that this analysis is restricted only to the larger species of algae which should have been caught in the nets which were used for algal study prior to 1960. Many small forms of phytoplankton which can now be sampled in the lake would pass through such nets and therefore no decision can be made about their presence or absence prior to 1979 when quantitative analysis began. The filamentous chlorophytes of the *Mougoetia/Oedogonium* complex are an example of a large new species occurring since the 1960's which had not been reported earlier in this century. These filamentous greens are not prominent in plankton. **The prominence of *Planktolyngbya tallingi* in southern regions of the lake, where it has replaced the previously dominant *Planktolyngbya nyassensis,* is indicative of increasing nutrient availability and poorer light conditions. The reported occurrence of *Cylindrospermopsis raciborski,* nitrogen-fixing filamentous blue-green, which is often a climax species in highly eutrophic situations and which has toxic forms, is also cause for concern.** In recent years

Anabaena blooms have become a repetitive occurrence especially inshore in the vicinity of the Linthipe River in March-April at the end of the rainy season and has provided visible evidence (which would have been difficult to overlook in earlier years) of possible nutrient enrichment. Although *Anabaena* blooms are reported in the earlier literature, they then occurred only in October-November. The co-occurrence of the dinoflagellate *Peridinium* with the *Anabaena* bloom in at least one of the recent blooms is also worrisome as both taxa have forms that can produce phycotoxins.

Although changes in the phytoplankton community composition may yet appear minor, they are indications that greater changes may follow. Interpretation of such changes is now greatly hampered by the qualitative, fragmentary and discontinuous availability of earlier studies. In Lake Victoria fully quantitative analysis of the phytoplankton did not occur until after dramatic changes had occurred in which the phytoplankton community which had been dominant for centuries changed within decades to a eutrophic assemblage dominated by potentially toxic blue-green algal species. **At mininum, these recorded changes in Malawi relative to earlier observations, and the evidence of the quantitative changes in the algal community recorded in the sediment require the installation of an algal monitoring programme as part of an integrated ecosystem monitoring initiative.** Not only will such a programme identify undesirable trends in water quality from indicator species, but it will also warn of toxic algal blooms which should be linked to consumption advisories. Such programmes are now routine in the Baltic Sea, in the Laurentian Great Lakes and in the coastal oceans around the world.

Taxonomy and biodiversity studies should be applied to all elements of the food chain, not only to fish which are themselves dependent on healthy and productive algal communities. It is essential that attention is paid to the changes that are occurring at the bottom of food chain (where changes can occur rapidly because of the high rates of population turnover) in order to protect and manage the top. A programme of algal study and monitoring can refer to the early few records which are an invaluable asset as reference checks against which recent and future data comparisons can be made. But such a programme should be extended to sediment trap collections which are an efficient method to detect changes from year to year.

Sedimentation rates were quantitatively evaluated on two sediment cores from below 200 m depth, one taken near the Songwe delta and one in the south near the Dwangwa delta. The northernmost core near the Songwe delta was also visibly laminated because of highly seasonal sediment input and minimal sediment mixing by biota in the permanently anoxic hypolimnion. This annual lamination allowed an independent check on sediment ages assigned by radioisotopic techniques. The higher mean rate of sedimentation post 1850 was measured in the northernmost core which receives higher inputs of eroded mineral sediment because of the steeper relief and greater rainfall in the north. **Between 1900 and 1960, rates of biogenic sedimentation were quite similar at the two core sites, with the biogenic sediments being more diluted by mineral sediment inputs at the northern site. However, the northern and southern sites recorded quite different histories since 1960. The northern site has experienced somewhat reduced sedimentation in the last three decades, especially during the 1980's when a drier climate reduced river flows in Malawi. However, since 1960 at the southern site sedimentation increased by as much as 50%. At the northern site, dry weight sedimentation rates are dominated by terrigenous, detrital material, and therefore rates change in response to natural variation in runoff from the catchments. In the south, the recent increase in sedimentation is largely accounted for by biogenic sedimentation especially of diatoms and organic matter which have been stimulated by the higher rate of nutrient input recorded in the core.** Other studies in this report indicate that the southern catchments of the Malawi/Nyasa basin are changing and yielding heavier loads of sediment and nutrients than would have been expected under natural conditions. This inference has been substantiated by the direct measurements of sedimentation in sediment traps in the lake where the most southerly trap records higher rates of dry weight and nutrient sedimentation than the trap farther north.

The post 1960 sedimentation rates and composition of the sediment from the cores are consistent with the current sediment trap data indicating greater rates of diatom sedimentation and phosphorus inputs in the southern region of the lake at present. These results are also consistent with greater catchment disturbance through land clearance and more extensive agriculture in the south. The more southerly trap also had the highest seasonal rates of sedimentation which occurred in the rainy season.

This indicates that the increased sedimentation rate since 1960 recorded at the southern site is a result of increased sedimentation during the rainy season which links the post 1960 increase to increased inputs from the catchments during the rainy season. These interpretations are based on a minimum number of cores and one year of sediment trapping, and more of the cores collected during this study should be analyzed to confirm these serious conclusions about land use and sedimentation in Lake Malawi. Sediment trapping will be extended for at least another year with support from a grant from the U.S. National Science Foundation. Ongoing studies by the Centre for Earth Observation Studies will analyze and quantify the relationship of these changes in river quality and sedimentation to land use in the southern catchments**. Therefore it is recommended that at least five more sediment cores be analyzed to confirm the conclusions about increased sedimentation and for trends in contaminants entering the lake. A water quality monitoring programme should also be established directed primarily at measuring the sediment loads carried by the rivers in order to provide early warning of catchment degradation and soil loss.** Completion of the CEOS land use and basin characteristics database is an essential requirement to complete the chain of evidence linking increased sediment and contaminant input with land use and will be a useful management tool to guide corrective or preventative action. The development of GIS models relating land use and human activities to water quality characteristics will allow assessment and forecasting of consequences of different catchment development scenarios.

The nutrient budget for Lake Malawi/Nyasa

The quantification of all the major nutrient inputs and outputs has been achieved for the first time on an African Great Lake. Within the assumptions that have to made about the extrapolation of the data and steady state conditions (which need not be the case in such a large lake with long response times), the resulting balance is remarkably good when the possible error terms are considered. **The studies on the riverine input and atmospheric deposition indicate that they are of approximately equal magnitude for both nitrogen and phosphorus. If only dissolved nitrogen and phosphorus inputs were considered, then the atmospheric source would be dominant for both nutrients because the riverine contribution is overwhelmingly of particulate forms of N and P originating from soil and detrital particles in the catchment.** The immediate effect of the riverine load on the mixed layer is reduced because a significant fraction of the nutrient load carried by rivers (especially northern rivers) may be diverted below the upper mixed layer, due to the greater density of river water. In contrast, the entire atmospheric loading of nutrients will be available to the biota in the mixed layer.

Deep water renewal is a much less important source of nutrients than prior estimates suggested, but it is still a very important source for phosphorus and silica. The rate of deep water renewal estimated in this study from the invasion of anthropogenic CFC's is only one-third that previously estimated. This has the result of reducing nutrient inputs to the surface mixed layer by a comparable factor. However, even with this reduction in the rate of input of nutrients from deep water, this source is still extremely important for phosphorus and dominates the dissolved silica budget. **The deep water supplies as much phosphorus to the epilimnion as the rivers and atmosphere combined while supplying up to two times as much dissolved silica as those other sources. In contrast, the deep water makes a relatively small contribution of nitrogen to the mixed layer because denitrification at the oxic-anoxic interface at around 200 m removes nitrogen from the aquatic nitrogen cycle.** This loss of nitrogen may be balanced by nitrogen fixation in surface waters, which currently is not well quantified for the pelagic zone. The deep water supplies nitrogen and phosphorus at an extremely low ratio of approximately 2:1. If it were not for the higher loading ratios from the atmosphere , approx. 18:1, and the rivers, approx. 25:1, the mixed layer of the lake would have an extreme nitrogen deficit and nitrogen-fixing algae would dominate the algal community as they do in Lake Victoria.

When all sources of total nitrogen and total phosphorus are considered the loading ratio of these two nutrients is low, being 18.7 for the whole lake and 10.5 for the epilimnion. The algae of the lake require these critical nutrient elements at an average of 16: 1. When loading ratios are as low as those observed, then nitrogen limitation can favor the proliferation of nitrogen-fixing blue-green algal species which can fix atmospheric nitrogen to balance the nitrogen with the phosphorus supply. Currently such fixation appears to be minimal because the atmosphere and catchments provide sufficient nitrogen to balance the low N:P water provided from the deep water. However, the loading ratios of these sources is also low relative to global data and in fact may be moving towards lower values. Soil erosion in particular lowers N:P ratios. For example, the most disturbed river sampled, the Linthipe, has an N:P ratio of only 10:1 well below the average for riverine inputs. If other rivers become more like the Linthipe, then the lake will begin to experience strong nitrogen deficiency and the algal community will have to shift towards species which can fix atmospheric nitrogen. A similar depletion often occurs for silica during eutrophication because the loading of silica from the catchment does not match the increased loading of phosphorus. The rate of silica burial may have increased in the southern region of the lake by a factor of 2.5 since 1960 (if the results of the core analyses are typical) in response to an 85% increase in phosphorus deposition. This accelerated burial of biogenic silica, if not matched by increased input of dissolved or available silica, will lead to a silica depletion in Malawi/Nyasa which will also favour the proliferation of blue-green algae as phosphorus which formerly was sequestered through diatom sedimentation and burial will remain available in the mixed layer for utilization by the blue-greens. There is some evidence that silica depletion has already occurred in surface waters, because current estimated burial rates of silica in Malawi/Nyasa cannot be sustained by input rates. Dissolved silica concentrations in the lake should be monitored to determine if the lakes silica reserves are indeed declining.

The present study has significantly increased previous estimates of phosphorus loading to the mixed layer from the atmosphere (factor of 3) and from rivers (factor of 4) but reduced the estimated flux from deep water by a factor of 3. The estimate of total P loading to the mixed layer from all sources is little changed, but the importance of atmospheric and riverine sources is much greater. Consequently, the lake will be more responsive to increased catchment and atmospheric sources and therefore to anthropogenic modifications of the land surface than formerly appreciated. Nitrogen inputs from rivers are also three times greater and atmospheric inputs nearly 70% greater than former estimates. These higher inputs currently prevent a strong nitrogen deficit from developing on a lakewide basis, but the lake remains in a critical situation with regard to its nitrogen budget. Increasing dominance by nitrogen fixing blue green algae remains highly probable if current trends continue. The deep water remains the primary source for dissolved silica and therefore the silica budget is not as sensitive to watershed alterations as the phosphorus budget. If phosphorus loading continues to increase, silica depletion may occur as it has in Lake Victoria. But because the silica reserve in the deep water of Malawi is much greater than that present in Victoria prior to eutrophication, the depletion will take much longer in Malawi. The residence time of nitrogen and phosphorus in the mixed layer remains on the order of 2 to 3 years so that the mixed layer will come to steady state with a changed loading regime in approximately eight years. Although the estimate of residence time is little changed from previous estimates the sensitivity to watershed change is much greater than formerly recognized. **There is evidence from the river quality studies that deforestation and land use in highly settled catchments can increase the yield of nutrients by a factor 3 to 5. If such changes occurred in all the catchments, then the lake would be very different than its current condition. A dynamic model of nutrient loading rather than the static budget approach is required to make more precise estimates of the consequences of land use practices on Malawi/Nyasa. But it can be said with certainty that management actions to preserve the lake's water quality must be taken soon to avoid potentially dramatic changes early in the next century.**

Contaminants

The study accomplished the first measurements of a broad range of persistent pollutants in Malawi/Nyasa air, water, sediments and biota. As such, they allow an assessment of the current state of contamination of the ecosystem and assessment of risks for biota and people. In the future these results will provide a valuable baseline against which trends can be determined and assessment made of the likely impact of proposed developments or pesticide usage. Some of the results are preliminary because additional samples and blanks need to be analyzed.. Although results are limited for organochlorines in air and water and some current use non-chlorinated pesticides, some preliminary conclusions can be drawn from them:

1. PCBs (polychlorinated biphenyls) appear to be important contaminants of Lake Malawi surface waters and air. PCB levels are below method detection limits (<100 pg/L) at 40 and 80 m depth in the lake. Future work needs to more thoroughly investigate sources of these PCBs.

2. There is evidence from air measurements that lindane (γHCH) and dieldrin (or its precursor aldrin), as well as possibly heptachlor, endosulfan, and DDT, are currently being used in the region. Analysis of the remaining air samples would help to clarify the trends observed in the Feb.-June 1997 sampling period.

3. **Unlike many water bodies in the Northern Hemisphere, the direction of flux for current use compounds such as lindane and dieldrin is from the atmosphere into the water, suggesting that the lake has yet to reach equilibrium with these compounds**. By contrast Lake Malawi appears to be degassing PCBs similar to what is observed in the Laurentian Great Lakes, although additional measurements are needed to confirm this because of high blank values.

4. Several current-use non-chlorinated pesticides and herbicides which are considered to be non-persistent and biodegradable were detected in Malawian rivers. The concentrations of these pesticides were below well accepted water quality guideline limits for these compounds. However guidelines have not been set for several of the compounds detected. The combined effect of rapid degradation in both tropical soils and runoff waters, as well as volatilization following application at tropical temperatures, may reduce the amount of these pesticide found in surface waters in Malawi.

Concentrations of potentially toxic metals were made on surface sediments collected from a large number of spatially distributed samples. Comparisons can be made between the measured concentrations of some heavy metals (mercury, cadmium, lead, copper, zinc, and arsenic) in the sediments and the Canadian guidelines currently under development to protect freshwater organisms. These Sediment Quality Guidelines are concentrations of metals in sediments that have rarely been observed to cause effects, such as reduced growth or reproduction, in sediment-dwelling organisms. Higher concentrations of metals that frequently have harmful effects on aquatic organisms are called Probable Effect Levels. It is recognized that these Canadian guidelines may be inappropriate for Lake Malawi. Nonetheless, in the absence of local guidelines, the comparison is instructive. **Copper and zinc were the only metals observed to exceed Sediment Quality Guidelines in Lake Malawi sediments in 14 of 21 and 1 of 21 samples respectively. The remaining metals were at concentrations that are not expected to have effects on aquatic organisms. The actual risk associated with the higher than expected copper concentrations would require further study**. Fifteen sediment cores were also collected from Lake Malawi between October 30 and November 5, 1997 at sites ranging in depth from 63 to 613 m. Analyses of these cores have not been done because of lack of funds, but would provide valuable information on whether inputs of metals (and other pollutants like DDT) to the lake are changing. It is anticipated that future analyses of these cores will furnish that information and permit calculation of input budgets for metals and a number of organic contaminants.

Concentrations of persistent pesticides, PCBs and mercury in most fish from Lake Malawi are low. DDT is the most predominant organochlorine found in these fish, and was found at the highest concentrations in fish high in lipid and in the top predators of the lake. Concentrations of persistent organochlorines in a scale/fin eater (*G. mento*) and a fungi-eater (*Docimodus evelynae*) were low and indicated that fish with unusual dietary habits did not have a greater risk of accumulating contaminants than fish with more common feeding habits. Concentrations of total DDT in fish from Lake Malawi are considerably lower than levels found in fish from other East African lakes. Lipid is a significant predictor of organochlorine concentrations in fish from Lake Malawi with the offshore, pelagic fish tending to be fattier and therefore also more contaminated than the nearshore fish we analyzed.

Biomagnification of these persistent contaminants is often observed as their elimination from tissues is often much slower than their uptake from food. Therefore fish and animals feeding higher up the food chain are generally more contaminated than those feeding lower. Trophic position (as determined by the stable isotope ratio, $\delta^{15}N$, of the flesh) is also a significant predictor of organochlorine levels in the food web from Lake Malawi. Based upon the slope of this relation, DDT accumulates at the same rate in this tropical food web as we have observed previously in temperate and arctic food webs. DDT is accumulated at a greater rate (slope of DDT versus $\delta^{15}N$) through the offshore than nearshore food web, and this is likely due to the higher lipid content of the offshore top predators.

Information on consumption rates are needed to assess whether contaminants in the fish may have human health impacts. It seems unlikely that organochlorines would have any health impacts because a person would have to consume more than 3 kg of fish each day to exceed the recommended intake of these contaminants. However, mercury is a potential problem for humans since considerably less of some fish species can safely be consumed (e.g. 150 g of mpasa (*Opsaridium microlepis*) and 140 g of ncheni (*Rhamphochromis* spp.) for pregnant women and children). The levels of organochlorines and mercury found in Lake Malawi fish are not likely to have detrimental impacts upon fish-eating wildlife.

Conserving the Lake Malawi/Nyasa Ecosystem

The marvelous biodiversity of Malawi/Nyasa evolved with no assistance from people, but its future is highly interwoven with the people just as their future is highly dependent on maintaining the many beneficial uses of the lake. The low numbers of people in the lake's catchment for all but its most recent history made it impossible for them to have any effect on the properties of the lake, its watersheds or its fisheries. This is no longer the case. This report has found a number of recent changes in Lake Malawi/Nyasa which can be related to the activities of the growing human populations in its catchment. The future of the water quality of the ecosystem is now in the hands of the people of the basin. Active management of the human activities is now required if the lake is to retain its desirable aspects and beneficial uses. Maintaining the biodiversity of the fishes will require an ecosystem approach which recognizes that people are the most critical component. People can affect the fish populations in a variety of ways from directly catching fish, to changing the nutrient and sediment fluxes from catchments, to using pesticides to maintain health and increase crop yields. A management plan to conserve the biodiversity must recognize the complex interrelationships within the ecosystem, the dependence of fish on their habitat and how people's activities can modify all these aspects. Sustaining the biodiversity of Malawi/Nyasa will require a motivated and knowledgeable population which recognizes that their own welfare is intimately connected to that of the lake. The farthest farmer in the most remote part of the catchment has a role to play as does the fisherman living at the shoreline. Natural science can illustrate and quantify the interrelationships and the roles of the peoples of the basin, but science alone cannot guarantee the future of the lake. ***Therefore the first priority for successful conservation of Lake Malawi/Nyasa is the adoption of the ecosystem approach for management and strategic planning and a directed educational effort should be undertaken to explain its significance to the people in the catchment.***

Eutrophication in Lake Victoria resulted in proliferation of noxious algae, severe declines in water clarity and increased hypolimnetic oxygen depletion.. Because several forms of nutrients are soluble, and even in particulate form they are readily transported tens of kilometres per day, nutrient enrichment also represents the most significant lakewide threat to the biodiversity of the Malawi/Nyasa. Studies completed for the water quality report indicated that changes may already be occurring in the phytoplankton community which would be indicative of enrichment, including dense algal blooms which appear inshore. Sediment studies and river studies have quantified these changes and concluded they are most severe in the southern areas of the lake. ***Consequently the second priority for water quality conservation is to begin a programme of nutrient management. This water quality study has identified the phosphorus load associated with suspended sediments and airborne phosphorus compounds as the largest external input of phosphorus to the lake. The phosphorus originates from the river catchments, and its mobilization has been accelerated by***

population growth and current agricultural practices. Consequently the development and implementation of good soil conservation and watershed management must also be accelerated, especially in the most densely settled catchments of Malawi, as the most effective means of phosphorus control. Because nitrogen-fixing blue-green algae are already prominent in the lake and because of their ability to make up any nitrogen deficiency imposed by increasing phosphorus loading, priority should be given to phosphorus control from the standpoint of the lake's water quality. Phosphorus control does not mean the discouragement of phosphate fertilizers. Because the fertilizers are tightly bound to soil particles it is the erosion of the soils which must be reduced. Paradoxically, increased of use phosphate fertilizers in conjunction with improved soil and water management and conservation will actually be helpful to the lake by increasing yields from existing cultivated lands instead of bringing marginal lands into cultivation.

Increasing suspended sediment loads are also a threat to biodiversity because they reduce water clarity (and thereby limit benthic algal production), reduce food quality for consumers, eliminate microhabitats for invertebrates and can even clog fish gills at high concentrations. The reduction in water clarity will also affect breeding behaviour and mate selection because of poor visibility. The effects of these suspended loads are more localized than nutrients, although they are transported contemporaneously from watersheds. The strongest effects of the rivers on nearshore, shallow water communities are near the deltas. ***Reduction of soil erosion and transport to Lake Malawi requires that watershed and wetland maintenance and management must be a conservation priority. This means not only the expansion of soil conservation programmes but also whole watershed management which would include the protection of wetlands to retard sediment transport, the maintenance of vegetated streamcourses for sediment and nutrient reduction in surface runoff, and perhaps even the construction of artifical wetlands and small headwater ponds to retain sediments and provide water for irrigation to improve soil quality.*** As mentioned above reduction of soil loss will also have benefits for controlling eutrophication and water clarity. The practice of slash-and-burn agriculture, which can indiscriminately remove vegetation cover, should also be transformed into selective clearing for agriculture and introduction of agro-forestry which will improve water and soil quality.

Toxic compounds, both inorganic and organics, are present in Lake Malawi/Nyasa and its biota, but fortunately all measured concentrations are relatively low. Only mercury concentrations in some fish species are high enough to cause concern for human consumers at present, and none of the measured concentrations pose a risk for the biota.. There is evidence that some of the volatile organic contaminants may already be increasing, primarily being vectored through the atmosphere into the lake, and the rivers are also bringing in current-use pesticides. The "clean" state of the ecosystem at present however is probably more the result of the impoverishment of the agricultural sector than an inherent characteristic of the lake. The lake could become contaminated if usage of pesticides and industrial activity increases. The lesson from the Laurentian Great Lakes is that the source of contamination can be distant from the lake, and that international action is necessary to control the spread of these persistent organic pollutants. Because of the unique limnology of the lake which results in slow flushing, care must be taken to prevent any rise in these toxic compound concentrations. Although several sediment cores were taken to specifically examine whether toxic compounds are increasingly being deposited into the lake, insufficient funds were available to complete these analyses. ***As a priority for conservation, the three riparian countries should press for an internationally funded effort to determine if contaminant concentrations are rising because of atmospheric loadings, and to try to identify sources of such contamination.***

All the actions recommended above are intended to prevent degradation of the water quality of Malawi/Nyasa, but to determine if they are having the desired effect a specific environmental monitoring programme must be put into place. The GEF project has brought the technical elements of such a programme together, but the three countries and international sponsors and donors interested in preserving the biodiversity of this great lake must find a way of maintaining a baseline monitoring programme. ***As a conservation priority it is paramount that an ongoing ecological monitoring programme be put into place to provide an early warning of deleterious changes which reduce beneficial use of the Malawi/Nyasa ecosystem.*** Such a system need not be high cost to be effective and some of it can be conducted by the people of the lake and catchments themselves who have the most to lose from degrading water quality. Ongoing physical studies of the lake's circulation should result in a three-dimensional model which could use basic physical inputs such as winds, solar radiation, air temperature, humidity etc. from the meteorological monitoring system already in place. These three dimensional models can predict movements of river plumes and advected nutrients as well as estimating rates and locations of deep water renewal and loading of dissolved nutrients and contaminants to surface waters. Such a model would be relatively inexpensive to construct and validate because of the excellent data collected by the GEF project. The project is also developing a GIS based model of water quality which will integrate elevation, vegetation cover, land use , population density and climatological features and which will allow forecasting of riverine inputs from current or projected land use patterns. Ongoing lake monitoring would consist of monitoring (at minimum) algal communities, light transparency, chlorophyll, total phosphorus and silica concentrations, and temperature and oxygen profiles. The equipment to operate such a programme are now available. Some staff have been trained for this type of work, and more could be trained to operate programmes at other locations. In the catchment it is recommended that the Water Departments initiate a programme of monitoring suspended sediments to complement existing programmes of flow monitoring. This study has found that a number of key water quality parameters are highly correlated with total suspended sediments in rivers; therefore this single parameter can provide useful information on other nutrient aspects as well. Another low cost initiative would involve local schools located near streams and rivers setting up biomonitoring programmes with GEF assistance. The feasibility of such programmes to provide environmental monitoring has been demonstrated in North and South America, and it has the added benefit of increasing community awareness and action.

The key to successful monitoring is that targets for water quality be set and adopted broadly so that monitoring has meaning in terms of improvement or degradation relative to those targets. The Water Quality studies have generated sufficient understanding of the processes affecting water quality in Malawi/Nyasa and its sensitivities to change that targets could now be set by responsible agencies in the three countries. ***A crucial conservation priority is the establishment by the three riparian countries of a tripartite ecosystem monitoring agency to set water quality and ecosystem targets and to institute on a shared cost basis an integrated monitoring programme for Lake Malawi/Nyasa.*** This agency will insure that the significant changes in the lake will be noted and the management challenge responded to in a timely manner. Never again should the recent history of Lake Victoria be repeated where there was no information for nearly 25 years on the water quality and ecosystem changes which were taking place. The legacy of that neglect will be borne by the people of the Victoria basin for many years to come. The same fate for Lake Malawi/Nyasa must be avoided.