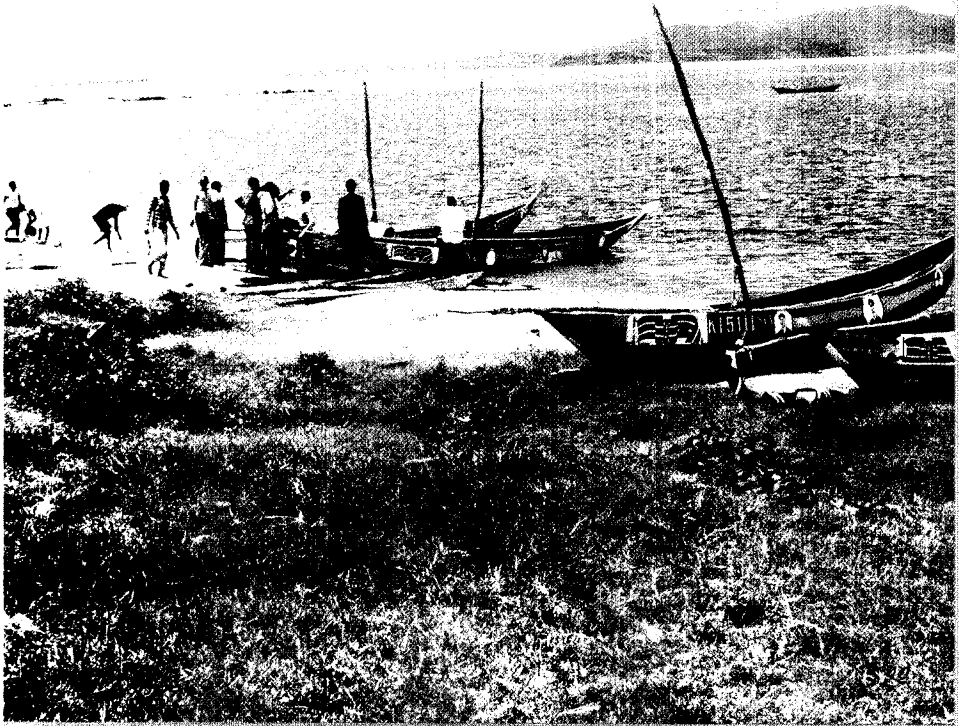
# Limnology and hydrology of Lake Victoria

Ruud C. M. Crul



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# Limnology and hydrology of Lake Victoria

Comprehensive and Comparative
Study of Great Lakes
UNESCO/IHP - IV Project M-5.1

Ruud C. M. Crul

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# Preface

Rivers and lakes around the world are often shared by several countries. Experience shows that it is much easier to reach consensus on the common development, management and utilization of these international water bodies when there is an agreed physical and hydrological description.

In the framework of the Fourth Phase (1990–1995) of UNESCO's International Hydrological Programme, a special theme (Theme M-5) was devoted to 'hydrological and water management aspects of international water systems' with the objective of preparing material on hydrological, ecological and water management aspects of international rivers and lake basins.

Project M-5 was in particular devoted to the 'comprehensive and comparative study of great lakes' with the overall objective of bringing together knowledge obtained over the last 15 years on the hydrology and limnology of specific lakes, starting with the Great Lakes of Africa, which constitute the most important freshwater reserves on the African continent.

Three main lakes, namely Lakes Victoria, Tanganyika and Malawi, were selected for the preparation of monographs, to be followed by a comprehensive report on their similarities and differences.

It was decided to start with this monograph on Lake Victoria, for which all available documentation on hydrology and limnology was gathered and analysed. The large bibliography of Lake Victoria compiled during the course of the project is being published separately within UNESCO's series 'Technical Documents in Hydrology'.

Project M-5–1 was implemented with the collaboration of the African Great Lakes Working Group of the International Limnological Society (SIL), in collaboration with their professional and official contacts in the East African countries around the Great Lakes.

We are grateful to Dr. F. C. Roest, from the International Agricultural Centre of Wageningen, Netherlands, convenor of the African Great Lakes Working Group of SIL, for the supervision of the book's preparation and of course to Dr. R. C. M. Crul for his major contribution to the project.

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# Foreword

This final version of the monograph on the Limnology and hydrology of Lake Victoria is one of the activities of the project 'Comprehensive and Comparative Study of Great Lakes (1992–1995)', a project of the fourth phase of the International Hydrological Programme (1990–1995) of UNESCO (UNESCO/IHP - IV Project M-5.1).

The overall objective of this project is to bring together the knowledge obtained during the last 15 years on the hydrology, limnology and pollution of the African Great Lakes Victoria, Tanganyika and Malawi in order to contribute to the overall aim of the UNESCO IHP IV M-5 project to prepare material on hydrological, ecological and water management problems encountered in shared water bodies.

The African Great Lakes Working Group of the International Limnological Society (SIL) has collaborated with UNESCO in implementing the various activities of the project.

The output of the project will be monographs on the individual Lakes Victoria, Tanganyika and Malawi and a comprehensive report on the similarities and differences between them. Together with workshops in 1993 and 1995 to discuss and finalize these draft monographs with the hydrologists and limnologists of the African countries concerned by the project, the reports will contribute to reaching a consensus on the hydrological and limnological description of these international water systems. Consequently, it will be easier for the riparian countries to reach an agreement for the use, development, planning and management of these lakes.

# Acknowledgements

Thanks are expressed to all people who assisted in the preparation of this monograph.

Several scientists who worked and work on Lake Victoria, provided me with papers on the lake of which some were still in review: F. Witte, R. H. Lowe-McConnell, R. E. Hecky, A. Lema, A. T Grove, S. Nicholson, H. A. Bootsma and J. T. Lehman. I thank R. H. Lowe-McConnell, R. E. Hecky, F. Witte, F. W. B. Bugenyi, F. G. Whoriskey and H. Zebidi for their useful comments on the first draft. I thank F. Witte for the permission to use several maps which were originally prepared by HEST for a handbook of a regional seminar in 1989. Finally, I am indebted to F. C. Roest for guidance, discussions and advice in the course of preparing this overview.

# Introduction

Lake Victoria, Lake Tanganyika, Lake Malawi and the other African Great Lakes are of crucial socio-economic importance to the nutrition and welfare of their riparian populations (Ntakimazi, 1992). The lakes are major sources of fish protein, reservoirs of freshwater and avenues of transportation. They have a great tourism potential and offer possibilities for the development of trade between the riparian countries. Recently the oil industry has shown interest in exploring a wide area of Eastern and Central Africa and some of the concession agreements include the African Great Lakes (Baker, 1992). Besides their socio-economic value to the riparian populations, the lakes have also a high scientific value to mankind as a whole due to their high biodiversity and an intrinsic value because of the exceptional sceneries and wildlife in and around the lakes.

Human activities in the African Great Lakes and their catchments and exploitation of the lake resources may easily damage the lakes and their resources. The threats to the lakes are diverse and include eutrophication and/or pollution caused by untreated domestic, industrial and agricultural effluents, by oil exploration, transport and recreational activities; lake level changes and siltation due to deforestation of the watersheds; and reduction of fish stocks because of overfishing and/or the introduction of exotic fish species. There are even indications of acid rain over tropical Africa (Andreae, 1991). Therefore it is necessary to carefully manage the lake resources and their catchment areas (Lowe-McConnell *et al.* 1992).

Lake Victoria is, like all other African Great Lakes, a shared water body. Mutual consultations and coordination of action between the lacustrine states are urgently needed. Only then may comprehensive programmes of scientific research supported by the international community provide the necessary background to the riparian states to take measures for the conservation of the lake.

One of the disciplines involved in lake research is limnology, including hydrological research. At present, limnology covers a very broad field including aquatic, atmospheric, terrestrial, subterranean and even marine ecology (Frey, 1990). Even the past has become a subject in limnological research. Records of changes in water and nutrient budgets, productivity, eutrophication, species composition and abundance in lakes have been left in the sediments. Paleolimnology focuses on these sedimentary records in order to gain insight into the past metabolic states of lakes. And paleolimnological studies also help us to understand how lakes are functioning at present.

In the past fifty years, limnology has made great advances in Europe and North America, and has developed from a mainly descriptive discipline to a highly sophisticated science. Knowledge on lake limnology has been reviewed by Ruttner (1953), Hutchinson (1957, 1967, 1975), and Wetzel (1975, 1983) and on river limnology by Hynes (1972), Whitton (1975) and Davies & Walker (1986).

An important area in limnology since the 1950s has been eutrophication, the process of excessive nutrient loading of natural waters by effluents resulting from man's activities, e.g. domestic sewage, industrial wastes and run-off water containing agricultural fertilizers. Eutrophication has caused major problems in temperate lakes in industrialized countries, e.g. the Laurentian Great Lakes in North

America (Vollenweider, 1968; National Academy of Science, 1969; Likens, 1972; Hutchinson, 1973). Toxic pollution is another important subject of limnology. Pesticides, PCBs, heavy metals and other substances of industrial wastes have contaminated areas, including lakes, far from the source of the pollutants. In the last decade, limnologists in Norway and subsequently in North America discovered that acidification of lakes resulted from acid deposition of industrial wastes from the atmosphere. These phenomena clearly demonstrate the close interrelation between lake, watershed and atmosphere.

During the last fifty years limnological methods have developed as a result of new technologies and advances in science. Many physical and chemical parameters of water can now be measured, if necessary continuously, with sophisticated instruments, and recorded by and stored in computers. Large data sets collected in this way can be accurately analysed by statistical computer programmes. All this advanced research has only been possible thanks to significant financial inputs of governments and industries in the developed countries, and has been mainly focused on temperate waters.

In sharp contrast with this sophisticated research in temperate waters the limnological studies of tropical waters have so far been more of a descriptive nature. Research activities have been restricted due to limited financial budgets of most national research institutes in developing countries in the tropics and in a number of cases research was only possible with help of United Nations and other funding agencies assisting African countries in the rational exploitation of their natural resources.

African inland waters have been the subject of limnological research since the late 1920s and 1930s when the first major expeditions were carried out (Beadle, 1981). Textbooks which provide much information on the limnology and ecology of (African) tropical fresh waters and the African Great Lakes are Beadle (1974, 1981), Welcomme (1979, 1985), Serruya & Pollingher (1983), Taub (1984), Payne (1986), Coulter (1991) and VandenBossche & Bernacsek (1990*a*, 1990*b*, 1991). A database on the inland fisheries resources of Africa containing basic limnological data from the latter FAO publications has been developed by the FAO Fisheries Department (Crul, 1992*a*).

The first major meeting on African limnology was held in Nairobi in 1979 (Symoens *et al.* 1981). In 1989 an International Symposium on Resource Use and Conservation of the African Great Lakes was held in Bujumbura (IAC, 1990; Lowe-McConnell *et al.* 1992) and in 1993 a symposium on the Limnology, Climatology and Paleoclimatology of the East African Lakes was held in Uganda (Johnson *et al.* 1993).

As limnology evolved in temperate regions from the beginning of this century, so a theoretical framework was developed from studies of temperate lakes. Tropical lakes have attributes, especially in the biogeochemical cycles of nutrient elements, that make them quite different from temperate lakes, and therefore they may not function the same way as temperate lakes (Kilham & Kilham, 1989, 1990). Lewis (1987) made an attempt to identify the features of tropical lakes that are likely to provide the most productive basis for comparison with temperate lakes.

Limnological and hydrological research will provide information on the important physical, chemical and biological events occurring in the lakes. First, limnological research is important for fisheries management. It helps elucidate the factors that determine the numbers, biomass and distribution of fish populations, such as current velocity, water temperature, dissolved oxygen and nutrient availability and food sources. Limnological data may also be used for estimating potential fish production, although the use of predictive models for African inland waters is still restricted due to the scarcity and unreliability of basic limnological and fisheries data (Crul, 1992*b*). Second, water quality research is an important tool for controlling and monitoring pollution of the lakes.

Limnological research has its application in human health control. Water plays an important role in disseminating a large number of important human diseases. In addition to many bacterial diseases (e.g. cholera, typhoid and paratyphoid) there are several widespread parasitic diseases, such as bilharzia, malaria, and river blindness, linked to water.

Furthermore, hydrological research is essential for planning the use of the available water resources for power generation, irrigation, domestic and industrial use, and transport.

As long-term data sets of basic physical and chemical parameters are not available for most African Great Lakes, an alternative for gaining information about long-term trends in tropical lakes is the examination of cores of lake sediments. Paleolimnology, the multidisciplinary science that uses physical, chemical and biological information preserved in sediments, has great potential for the African Great Lakes. The lakes are among the oldest on earth and sediments thickness may be up to 2–6 km in some of them. As sedimentation rates for these lakes are between 0.2 and 5 mm/year, the records are resolvable to decades or in some cases even to years (Johnson *et al.* 1990). The sediment records provide important information on the climatic history of East Africa (Johnson *et al.* 1993).

## Section I

# Research on Lake Victoria

## *a review*

# 1

# The importance of the lake to the region and the role of hydrological and limnological research

## RESOURCE USE

### Water availability

Lake Victoria, the largest lake in Africa (68,800 km$^2$) is the most important fresh water resource for the people living in its vicinity. The lake forms, together with Lake Kyoga and Lake Mobutu Sese Seko, an estimated reservoir of 3,200 km$^3$ of fresh water (Kite, 1981). The sole outlet of Lake Victoria is the River Nile leaving the lake near Jinja (Uganda), flowing through the Lakes Kyoga and Mobutu Sese Seko and contributing on average 14 % of the flow in the combined White and Blue Niles as measured at Aswan (Hurst, 1952). The flow of the Nile is relatively constant due to the natural regulatory effect of the three equatorial lakes. Changes in the water balance of the lakes are of major importance not only to the riparian countries, but also to the countries north of these lakes, Sudan and Egypt, which receive water from the Upper Nile basin besides the Blue Nile from Ethiopia. In addition to increased damage to lake-shore interests in Kenya, Uganda and Tanzania, large fluctuations in lake level result in variations in flow of the Nile which is of major importance to Egypt, a densely populated country totally dependent on the continued flow of its largest river for drinking water, irrigation and water for power generation. Significant jumps in flow of the river are related to higher water levels in the Lakes Victoria and Mobutu (WMO, 1974). Increases in River Nile flows during 1960–1964 and 1977–1980 were clearly related to the rise in level in Lake Victoria in those periods (Kite, 1981). International agreements between Egypt and Uganda and between Egypt and Sudan were concluded as early as 1929. Regulation of the Nile has been a major issue since the early decades of this century to all the countries concerned (Kite, 1984). Water from the lake is used for irrigation purposes in all three countries.

### Fisheries

Fishing and related post-harvest processing have been a very important economic activity in and around Lake Victoria, and a rapidly growing population of more than 8 million people in its catchment area (Figure 1.1) depends on the lake fisheries as a source of protein. After the introduction of gill nets in Lake Victoria in 1905, catches of the endemic fish species gradually declined due to the increased fishing effort, as observed for the period 1905 to 1928 by Graham (1929). A further increase of fishing effort during the 1940s with the use of illegal undersized, mesh sizes and the introduction of nylon nets and outboard motors in the 1950s resulted in overfishing and a sharp reduction in the catches in the inshore areas (Craig, 1992).

The high demand for fish led to the introduction of exotic species into Lake Victoria. The tilapias *Oreochromis niloticus*, *O. leucostictus*, *Tilapia zillii* and *T. rendalli* ('melanopleura') were introduced during the 1950s and 1960s and eventually replaced the indigenous species (Craig, 1992). The Nile perch found his way into Lake Victoria in the early 1950s, by unofficial and official means, before the results of a pilot experiment carried out in Lake Kyoga in the 1950s to determine the advisability of stocking Lake

Victoria with the fish, were available (Craig, 1992). Recent research revealed that the Nile perch from Lake Victoria differs taxonomically from *Lates* species collected elsewhere, including *L. niloticus rudolfianus, L. niloticus longispinus, L. albertianus, L. macrophthalmus* and *L. niloticus niloticus* (Harrison, 1991).

The introduced species resulted in increased commercial catches. In 1989 the lake produced over 500,000 tonnes of fish, predominantly Nile perch (63%), dagaa (*Rastrineobola argentea*) (19%) and Nile tilapia (9%) (Gréboval & Mannini, 1992). Provisional estimates for the years 1990 and 1991, as official data are not yet available, would indicate that catches have been levelling off (Gréboval & Mannini, 1992). The ecosystem is still largely unstable and the level at which the fish production of the lake will stabilize is simply not predictable. The management of the Nile perch fishery is therefore seen as an utmost priority (Gréboval & Mannini, 1992). Predation by Nile perch and competition with introduced tilapias have caused a severe decline, and in some cases total disappearance, of native species (Ogutu-Ohwayo, 1992).

Fish has always been a important source of food for the people around the lake. The increased production of table fish from 44,000 to 405,000 tonnes between 1975 and 1989 must have had a significant impact on the food availability around the lake basin and also to more distant urban centres in the three countries (Gréboval & Mannini, 1992). The presence of Nile perch drastically changed the nature of fishing operations, fish processing and marketing. The total value of production at market level has been estimated at US$ 270 million for 1989 (Reynolds *et al.* 1992). In Kenya and Tanzania the value of production increased by 500% and 750% respectively between 1985 and 1990 (Gréboval & Mannini, 1992).

In Kenya a new industrial, large-scale fishing trade with export of fillets to overseas markets has developed in the last decade in addition to traditional, local, small-scale fishing. In 1991 exports of fillets from Kenya reached over 10,000 tonnes, representing a value of US$ 20 million (Gréboval & Mannini, 1992). In both Uganda and Tanzania, exports of fish so far involved mostly trans-border trade to Zaire, Rwanda and Burundi, but a recent survey by Van der Hoeven & Budeba (1992) estimated the total Nile perch exports from Tanzania at 35,000 tonnes, representing about 18% of the total national catch for this species. Exports have grown substantially in the last five years, as overseas trade in 1987 represented less than 5% of the total production (Gréboval, 1989). The growing export trade is now becoming a matter of great concern, because the production of the filleting industry in Uganda and Tanzania, where new plants are being built with capacities up to 50,000 tonnes, will have severe consequences for the local market in terms of fish availability and fish prices (Gréboval & Mannini, 1992).

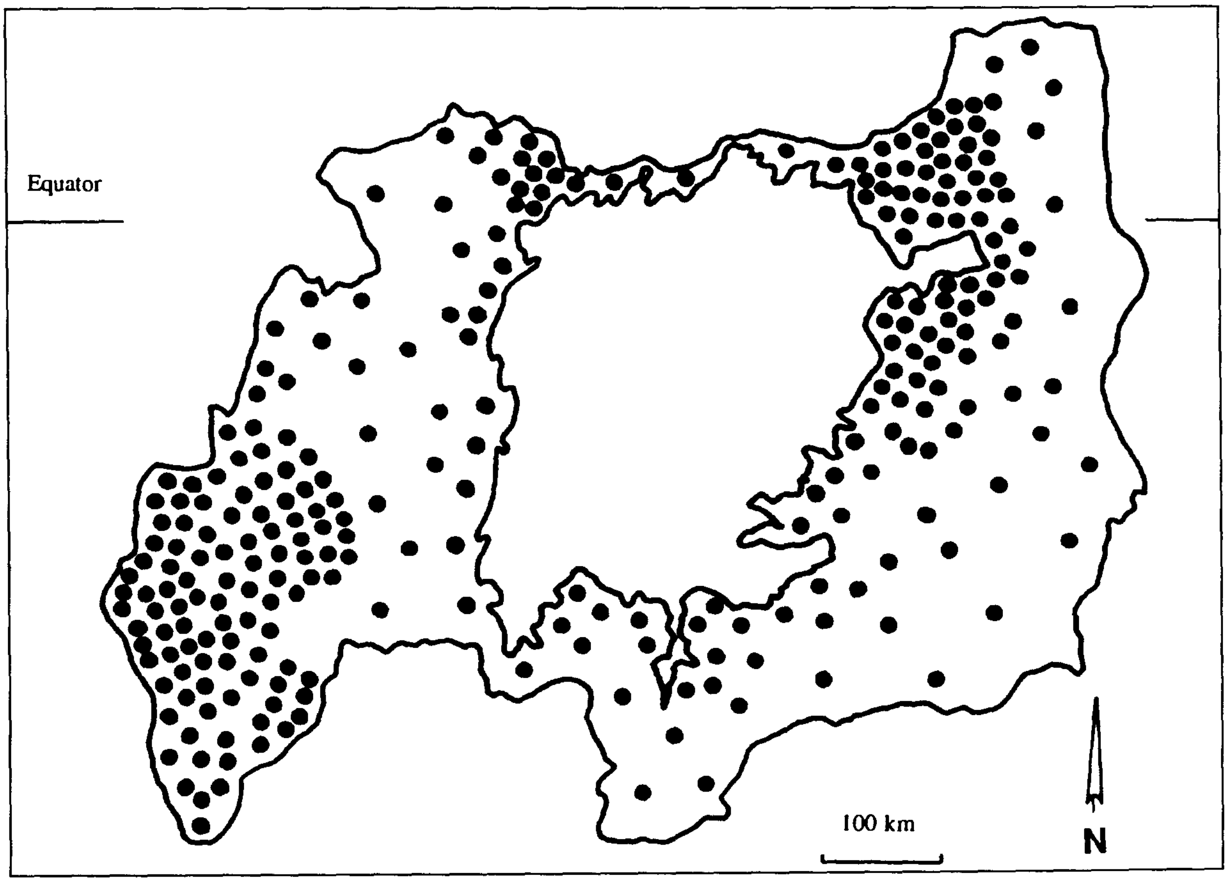

**Figure 1.1** Population density in the catchment area of Lake Victoria. Each dot represents 100,000 persons (Redrawn after Bootsma & Hecky, 1993)

### Transport and power generation

The lake has been an important means of transport since the Arabs put their sailing dhows on its waters in 1880 (Moorehead, 1960). With wagon ferry terminals at selected port installations, the lake is a link between the northern railway network in Kenya and Uganda and the southern railway network in Tanzania. From a number of ports on the lakeshore the East African Railways and Harbours corporations transported more than 500,000 passengers and 500,000 tonnes of goods in 1972, with the ships ranging from 1,000 to 1,500 metric tonnes. In order to maintain their port facilities the East African Railways and Harbours Corporations are interested in the variations of the water level of the lake (Krishnamurthy & Ibrahim, 1973).

Since 1954 hydro-electric power has been produced at the Owen Falls Dam near Jinja. The station with a capacity of 150,000 kW is working on the run of the river principle. A minor power installation is the Kikagati plant on the Kagera River. The hydropower schemes require knowledge of the discharge of the rivers concerned.

## MAJOR ENVIRONMENTAL ISSUES

### Changes in the ecosystem

Lake Victoria has undergone large changes in its chemistry and biology during the last decades, for example, a reduction in number of species and population sizes of endemic fish species, possible changes in the thermocline/anaerobic boundary, increases in chlorophyll concentrations in near-shore waters of Uganda, and a tenfold reduction in the Si concentration in the epilimnion (Kilham & Kilham, 1990; Bugenyi, 1992; Hecky, 1993; Mugidde, 1993). The introduction of the Nile perch undoubtedly attributed to a reduction of stocks of endemic species and a decline in biodiversity. For the other changes several hypotheses exist: the increased global transport of $SO_x$ and $NO_x$ to Lake Victoria (Hecky & Bugenyi, 1992; Hecky, 1993), changes in the trophic structure after the introduction of Nile perch and Nile Tilapia (Ogutu-Ohwayo, 1992; Witte *et al.* 1992*a*; Goldschmidt *et al.* 1993) and climate change (Hecky, 1993). The infestation of the water hyacinth (*Eichhornia crassipes*) which has recently occurred in Lake Victoria, poses an urgent problem (Thompson, 1991*a*).

### Pollution

Lake Victoria has become a depository for waste. Pollution is increasing with the rapid population growth in the lake basin area, resulting in a deterioration of the water quality. This means worsened health conditions, the spread of water-borne diseases, and reduced benefits to riparian population from using the lake as source of drinking water or for fishing. Pollution of the lake is caused by a variety of things. In Kenya, pollution is of particular concern, since agricultural activities, agro-based industries and urban centres in the Kenyan catchment, which covers an area of almost 50,000 km$^2$, adversely affect the water quality of the rivers draining into Lake Victoria, thus contributing to the eutrophication and contamination of the lake (Vidaeus & Schneider, 1992). The Entebbe and Kampala areas of Uganda and the Mwanza area in Tanzania have also been identified as areas with serious pollution problems due to sewage discharges and industrial effluents containing toxic and oxygen-demanding substances (Bugenyi & Balirwa, 1989; World Bank, 1992). In Tanzania an additional pollution issue deals with the gold rush occurring east and south of Musoma and west and south of Mwanza, where settlements have grown in the last several years to 6,000 people and mercury used to recover gold is released into the environment (World Bank, 1992).

Land use in the catchment and riparian zone of the lake plays an major role in the pollution process. Increased pressure on land in the three countries has led to high rates of deforestation, resulting in increased soil erosion and high loads of silt and nutrients being transported through rivers into the lake, contributing to its eutrophication. Wetlands bordering the lake are being converted into agricultural land or land for industrial use and are therefore increasingly unable to act as natural filters for nutrients and silt, to provide breeding and nursery grounds for many fish species and to play an important role for bird life.

## LIMNOLOGICAL AND HYDROLOGICAL RESEARCH

Most of the limnological research of the last decade has been undertaken by limnologists of the national fisheries research institutes: the Uganda Freshwater Fisheries Research Institute (UFFRO) at Jinja, the Kenya Marine and Fisheries Research Institute (KMFRI) at Kisumu and the Tanzanian Fisheries Research Institute (TAFIRI) at Mwanza. In recent years limnological research has been supported by projects financed by development agencies (e.g. International Development Research Centre (IDRC) in Uganda and Tanzania) and executed in cooperation with researchers of limnological institutes, universities and non-governmental organizations in Europe and North America (e.g. Haplochromis Ecology Survey Team (HEST), Leiden State University in Tanzania; the Freshwater Institute (Canada) in Uganda and Kenya, Kinneret Limnological Laboratory (Israel) and the New England Aquarium (USA) in Kenya).

The regular occurrence of fish kills in Lake Victoria has been a very important issue since the early 1980s. These fish kills are the cause of considerable loss of exploitable fish in inshore bays and gulfs in Kenya. Limnological research revealed that this massive dying is caused by anoxic conditions resulting from sudden destratification of the water column and plankton blooms (Ochumba, 1988; Ochumba & Kibaara, 1989). Recent limnological research in Uganda and Kenya has primarily focused attention on the eutrophication of the lake (Hecky, 1993).

In August 1992 a Workshop on 'People, Fisheries, Biodiversity and the Future of Lake Victoria' was held in Jinja. Summarizing current and recent research of limnology, ecology, and socio-economics of the lake and its catchment in some 50 presentations (Anon. 1992*a*), scientists from Uganda, Kenya, Tanzania, Europe, Israel, Canada and the U.S.A. concluded that the limnology and environment of Lake Victoria are undergoing rapid change and that this will have serious implications for the fisheries of Lake Victoria and result in a deterioration of the social and economic welfare of its riparian population (Anon. 1992*b*; Kaufman, 1992). Resolutions in this Workshop underscored the urgent need for understanding current changes in limnology of the lake and include the development of a general ecosystem model, the improvement of the understanding of the controls on oxygen distribution and levels, of the food web alterations and its effects on water quality and lake productivity and the determination of the energy flows of the two major trophic pathways based on new algal production and on detritus. Furthermore, it was recommended that a research and management programme for the fringing wetland and forest habitat should be undertaken and that special attention should be given to the explosive growth of the water hyacinth in the lake (Anon. 1992*b*; Kaufman, 1992).

Research on the pollution of the lake and its catchment has become increasingly important in recent years. Pollution studies in Kenya have been carried out by the University of Nairobi and KMFRI (Meadows, 1980; Onyari, 1986; Wandera, 1986; Onyari & Wandiga, 1989; Ochieng, 1992) and in Uganda by UFFRO (Balirwa & Bugenyi, 1988; Bugenyi & Balirwa, 1989).

Recent hydrological research on Lake Victoria has mainly focused on the assessment of the different components of the water balance in order to predict changes in water level and the flow of the Nile (WHO, 1974, 1981; Kite, 1981, 1982, 1984; Piper *et al.* 1986).

## REGIONAL ENVIRONMENTAL MANAGEMENT OF LAKE VICTORIA

Lake Victoria is a shared water body. Resource use by one of the riparian countries impacts the activities of the other countries. Regional cooperation in environmental management of the lake basin is currently being envisaged with the assistance of UNEP and the World Bank in order to harmonize management objectives and to provide a framework within which to resolve user conflicts and transboundary issues (World Bank, 1992).

Management of water availability, water quality and lake pollution is only possible with a improved scientific understanding of the limnology and hydrology of the lake and of the effect of anthropogenic activities on the lake environment. This requires regional collaboration and coordination of limnological and hydrological research.

# 2

# History of limnological and hydrological research on Lake Victoria

## GEOGRAPHICAL EXPLORATION AND THE EUROPEAN DISCOVERY OF THE LAKE

The first scientific research on Lake Victoria goes back to the expeditions to find the sources of the Nile, which constituted the first hydrological research on Lake Victoria. A compelling book on the explorers and conquerors of the sources of the Nile was written by Moorehead (1960) and has been used as the main reference for the following short historical overview. The European discovery of Lake Victoria was made by two German missionaries, Johann Krapf and Johann Rebmann, from a missionary post in Rabai near Mombasa. They were the first Europeans to see the mountains of Kilimanjaro (1848) and Kenya (1849) respectively. In 1855 they produced, together with another missionary, J. J. Erhardt, a map showing a large inland lake called 'Uniamesi Sea'. At the same time there were local reports from Arab slave and ivory traders of two large lakes 'Ujiji' and 'Nyanza' and a third lake, 'Nyasa' further south. The Royal Geographical Society in London became interested and supported an expedition by Richard Burton and John Hanning Speke to investigate the reports of the lakes and their relation with the Nile river. They decided to start from Zanzibar and approached the lakes from the East African coast, and with this expedition the period of the Central African exploration began. In 1858 they first discovered 'Ujiji', the present Lake Tanganyika. During the expedition they heard about another lake further north and John Speke left Burton in Kazeh, now called Tabora (Tanzania) and reached the southeast end of the second large lake, which he named after Queen Victoria. (The Gulf that he discovered was later named after him.) In 1862 John Speke and James Grant found the outlet of Lake Victoria near Jinja. Later in 1875 Stanley circumnavigated Lake Victoria by canoe in two months (the first lakewide survey) and confirmed Speke's hypothesis that it was one great lake with a single outlet at Ripon Falls (near Jinja). He started his trip near Mwanza, sailed directly to Ripon Falls along the east side of the lake and returned along the west side to Mwanza. In the years following that trip other expeditions were made to or passed through the lake. In 1884 the Scottish explorer Joseph Thompson made a journey through Masailand and reached the north-eastern shore of Lake Victoria east of the Ripon Falls. In 1889 Stanley and Emin Pasha (Eduard Schnitzer) returned from the latter's camp near Lake Albert along the south-west shore of Lake Victoria via Kazeh to Bagamoyo on the East African coast near Zanzibar.

## THE FIRST SCIENTIFIC INVESTIGATIONS

Emin Pasha, a German doctor of medicine, appears also to have been a good naturalist and ornithologist. During a twelve-year stay on the Nile north of Jinja he sent out thousands of birds and animals and thousands of specimens of plants of the region to museums and scientific societies of Europe. He also made records of bird migration, rainfall and geology of the country. In 1890 he left Bagamoyo again together with zoologist Franz Stuhlmann to return to his camp near Lake Albert. On his way back he founded the town of

Bukoba on the western shore of Lake Victoria. Upon his return to the shore of Lake Albert he found his camp in total disorder. He went on into the Congo, where he was killed in 1892 by a group of Arab slavers. He was the first pioneer naturalist combining the pure geographical exploration and scientific research in the fields of biology, geology, medicine and anthropology.

At this time, when most of the geographical problems had been solved, European scientists were becoming interested in the exciting new, virgin area of tropical Africa. The first scientific expeditions in the region were those of J. W. Gregory, a Scottish geologist who worked in the East African Rift Valley and J. E. S. Moore's expeditions to Lake Tanganyika in 1894 and 1897, which can be regarded as the foundation of tropical African limnology (Beadle, 1981).

## LIMNOLOGICAL AND HYDROLOGICAL RESEARCH

Limnological investigations of Lake Victoria and other East African lakes evolved from rather short-term investigations in the beginning of the century mainly focused on collecting specimens and carrying out simple physical measurements, to more extended physical and chemical measurements, and finally to the foundation of research institutes on the shores of the lakes which permitted prolonged investigations and the use of research vessels.

Regular measurements of water level have been recorded since 1902 at Kisumu (Graham, 1929) and the first bathymetric survey of the lake was completed in 1900 (Whitehouse, 1902). Stuhlmann, the zoologist who accompanied Emin Pasha on his trip to Lake Albert in 1890, was in 1892 the first collector of algae from Lake Victoria at Bukoba and later several others followed (Talling, 1986).

Before the Second World War the first and only systematic biological research on Lake Victoria was the Fishing Survey of Lake Victoria in 1927–1928 by Michael Graham (Graham, 1929). In Appendix 3 of the report the physiography of Lake Victoria is described with information on geography, geology, the climate of the region and some physical and chemical characteristics of the lake, and in Appendix 8 an outline of the ecology of Lake Victoria is given. Limnological observations on physical characteristics and a study on zooplankton of Lake Victoria were carried out during the Fishing Survey of 1927–1928 by Worthington (1930, 1931).

After the Second World War newly founded research institutes and universities in the three territories around the lake (Uganda, Kenya and Tanganyika) became increasingly important for limnological research on the lake.

In 1947 the East African Fisheries Research Organization (EAFRO) (later the East African Freshwater Fisheries Research Organization (EAFFRO) and presently the Uganda Freshwater Fisheries Research Institute (UFFRO) at Jinja (Uganda), was the first research organization established under the East Africa High Commission and focused on inland fisheries in East Africa. This organization, with R. S. A. Beauchamp as its first director, advanced to a large extent the knowledge of Lake Victoria and other East African inland waters and their fisheries. In 1975 substations of EAFFRO were established in Kisumu (Kenya) and Mwanza (Tanzania). The station at Kisumu is now the Kisumu Laboratory of the Kenya Marine and Fisheries Research Institute (KMFRI). In Tanzania the substation first was renamed the Freshwater Fisheries Research Institute (FFRI). Presently it is a substation of the Tanzanian Fisheries Research Institute (TAFIRI).

In 1949 another organization was established under the East Africa High Commission with its headquarters in Kisumu (Kenya): the Lake Victoria Fisheries Service (LVFS). It became responsible for fishery production and management in the lake and had vessels based in Entebbe, Kisumu and Mwanza.

The only major centre for higher education at that time was Makerere College at Kampala which was to become the first university in East Africa. Several departments of the university became involved in lake research. In Kenya departments of the University of Nairobi, the second university in the region, were involved in limnological research in the Kenyan waters of Lake Victoria, predominantly of the Nyanza Gulf. In Tanzania, the Tanzania Fisheries Research Institute (TAFIRI) and departments of the third university in the region, the University of Dar-es-Salaam, have been responsible for limnological research on the lake. Finally, the Fisheries Departments of the three countries, although mainly involved in fisheries, have carried out some studies.

An important contribution to the limnology of Lake Victoria and African limnology in general has been made by the Freshwater Biological Association (FBA) of the UK. Starting with R. S. A. Beauchamp, the first director of EAFRO, who spent several years on the lake, and the first Director of the FBA, E. B. Worthington, who was already working on the lake in 1927, past and present members of FBA have been engaged in limnological research on Lake Victoria (Fryer & Talling, 1986).

Lake Victoria has been subject to several hydrological investigations of which the latest is the Hydromet Survey, a cooperative venture between the Nile Basin countries (Burundi, Egypt, Kenya, Rwanda, Sudan, Tanzania, Uganda and Zaire with Ethiopia as observer), the United Nations Development Programme (UNDP) and the World Meteorological Organization (WMO) (WMO, 1974, 1981).

Recent limnological research on Lake Victoria has been carried out by the local research institutes in cooperation with research institutes and universities in Europe and North America, and occasionally Japan, and international organizations such as FAO and UNESCO. Of all inshore waters the bays near Jinja have the longest record of limnological research, having been studied since the late 1940s when EAFRO was founded. Nyanza Gulf has been intensively studied during the last two decades. Research of the last decade has been focused especially on the relations among fish kills, algal blooms and eutrophication. Limnological studies in the Mwanza Gulf started in 1973 (Akiyama *et al.* 1977) and were carried out continuously from 1978 by the HEST/TAFIRI project, although limnological monitoring was more or less limited to those parameters relevant to fish ecology and fisheries. The largest part of the lake, with offshore waters deeper than 60 metres, was first studied in 1927–1928 by Graham (1929) and Worthington (1931) and later more thoroughly by Fish (1957), Newell (1960), Talling (1957, 1966) and Kitaka (1972). Recently, limnological research on a number of offshore sampling stations including underwater observations with a remote-operated Vehicle (ROV) have been carried out as part of the eutrophication research projects in Uganda and Kenya (Kaufman, 1992; Hecky, 1993; Gophen *et al.* 1993; Hecky *et al.* In review).

Over the last 25 years a growing number of African limnologists has contributed to the limnology of Lake Victoria and other East African lakes, resulting in an increasing number of scientific publications on the subject.

In Appendix 1 an overview of expeditions, surveys, limnological research programmes, projects and studies on Lake Victoria is given. References in Appendix 1 may be found in *A Bibliography of Lake Victoria (East Africa)* (Crul *et al.*) published by UNESCO in its Technical Documents in Hydrology series (1995).

## Section II

# Background

# 3

# Geological and climatic history

Work on the historical geography of the Victoria basin started in 1920 with the pioneer geological work of E. J. Wayland, the first director of the Uganda Geological Survey. Work on the basin intensified in the 1950s and 1960s (for references see Bishop & Posnansky, 1960; Bishop & Trendall, 1967; Temple, 1969; Bishop, 1969; and Kendall, 1969).

Kendall (1969), Fryer & Iles (1972), Beadle (1974) and Livingstone (1976) reviewed the various interpretations of the origin of Lake Victoria. Although Lake Victoria is much younger than Lakes Tanganyika and Malawi, it is still one of the oldest lakes in the world.

The African landscapes have been modified over time by earthquakes, vulcanism, rifting and climatic changes. The rivers gradually eroded the land mass and the ancient pattern of drainage – rivers flowing from a higher central region eastward and westward – is still the basis of the continental drainage. In East Africa this drainage pattern began to change following upward earth movements and volcanic activity in Miocene times (starting some 25 million years ago). A wide stretch of land from Eritrea to the Zambezi has been lifted more than 1,000 metres since the Miocene. The two edges have been raised further, forming two Great Rift Valleys (Figure 3.1). Tectonic activities in and near these valleys formed a series of splits in the earth's crust of which some are more than 1000 metres deep and have filled with water.

In this way all the African Great lakes in East Africa except Lake Victoria were formed. The Eastern Rift Valley extends as far north as Israel, where it contains Lake Tiberias and the Dead Sea. Other lakes in the Eastern Rift Valley are the Ethiopian Rift Lakes, Lake Turkana and a number of shallow saline lakes in Kenya and Tanzania. To the west lies the other split, the Western Rift Valley, which comprises from north to south the Lakes Mobutu, Edward, George, Kivu, Tanganyika, Rukwa, Malawi, Chiuta and Chilwa. The shallow basin of Lake Victoria was formed by a gradual sagging of the centre of the lifted stretch.

Lakes existed in the Victoria vicinity in the early Miocene. There is evidence in the form of fossil fish found on Rusinga Island that a lake – named Karunga by Wayland (1931) – (or more probably a group of small lakes) was situated in the northeastern corner of the present Lake Victoria and that the lake (or lakes) eventually dried out or completely drained in the Miocene (Fryer & Iles, 1972). Because of a wide gap in geological evidence between the decline of Lake Karunga (Late Miocene, 16.5 million years B.P.) and the birth of Lake Victoria (Mid Pleistocene, 500,000 years B.P.), we do not have a clear picture of the events in this period (Fryer & Iles, 1972). Interpretation of available data gives the following plausible theory of the genesis of Lake Victoria. The shallow basin of Lake Victoria lies across an ancient east to west drainage system that pre-dated the lake (see Beadle, 1981, Fig. 14.2). The river patterns date from the Miocene and persisted well into the Pleistocene.

It is now thought that the lake owes its origin to elevation of the region which now forms its western margin. A precise dating of the western uplift is not yet possible, but there are indications that the

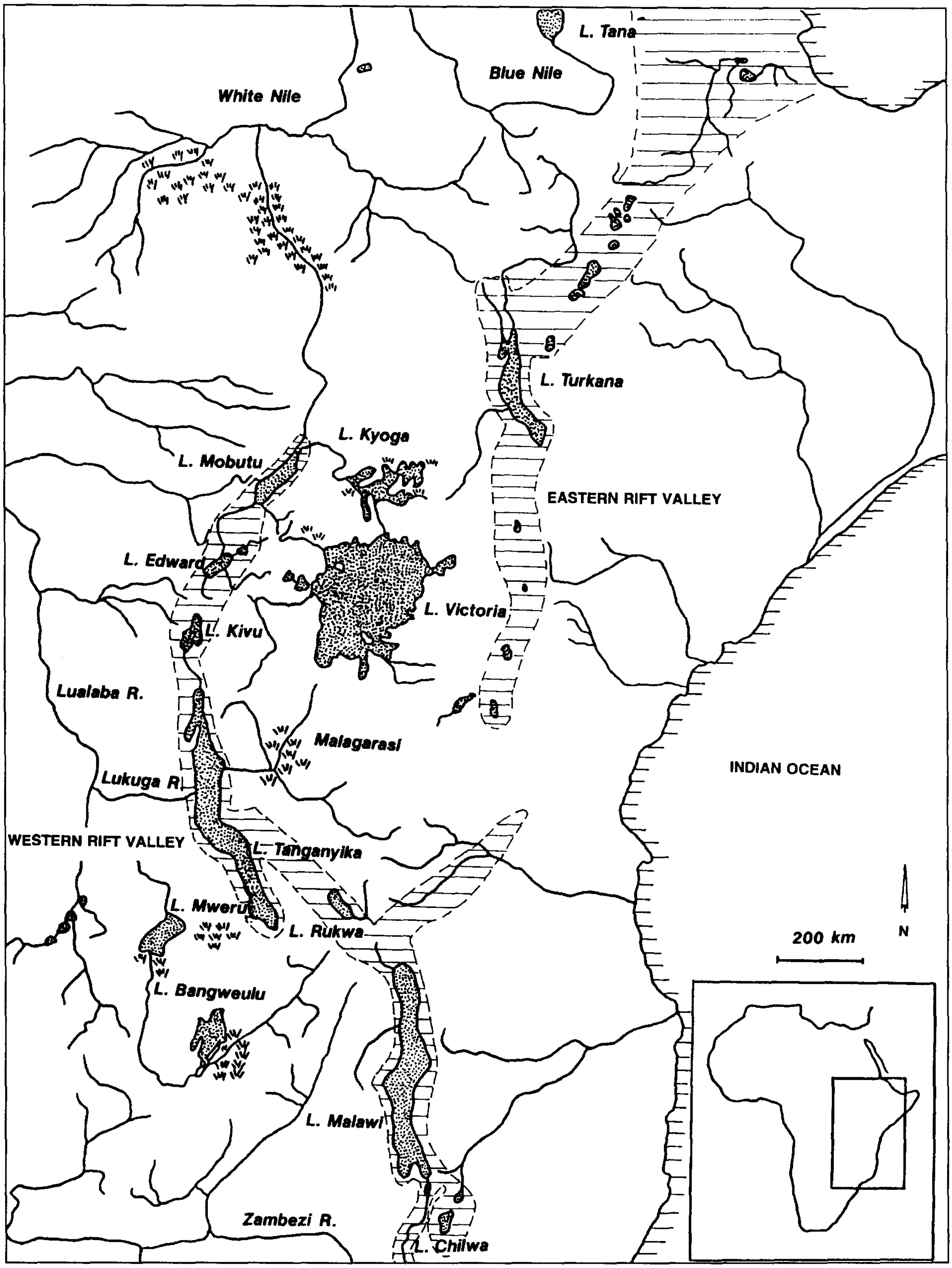

**Figure 3.1** Eastern Africa showing the Rift Valleys and their lakes. Lake Victoria lies between the two rifts.

beginning of this process occurred in the mid Pleistocene, some 500,000 years ago (Kendall, 1969). As a result of the very gradual initial uplifting, the rivers were able to maintain their westward flow. The more rapid rate of uplift causing the reversal of the rivers was a relatively recent phenomenon, as the earliest lacustrine sediments in the west appear to date from the middle or late Pleistocene.

Lake sediments were even found to the west and south of the Kagera River at a distance of about 100 kilometres from the present lake. Two fossil beaches above the west coast of the lake, which are both titled upward to the west, represent this 'western phase' of the lake's history (Kendall, 1969).

The reversed drainage of the major rivers Katonga and Kafu probably resulted in at first swampy lakes which eventually joined and formed the present Lake Victoria. Those two rivers still rise in swampy watersheds from which rivers drain in both directions. The Kagera River, now the largest (western) inflow to Lake Victoria, probably also reversed during the same period.

Large fluctuations in the water level of Lake Victoria since its formation in mid Pleistocene can be attributed to tectonic events, although climatic changes may well have played a part in the history of the lake. Climate in East Africa has not been uniform since the mid Pleistocene. Effects of climate changes cannot be distinguished separately because of the extensive and continuous earth movements during most of this period (Fryer & Iles, 1972). Although information is scarce, there is evidence for drier periods which may have caused recession of the lake levels. Reconstruction of late Pleistocene climates in the Victoria basin may come from the study of cores from the deepest part of the lake (Stager *et al.* 1986).

The history of Lake Victoria during the last 25,000 years has become available from studies of bottom sediments from the lake. The climatic history of the lake is summarized at this end of this chapter.

Three fossil beaches have been traced along the northern and southern shores of the lake (respectively 3–4 m, 12–14 m and 18–20 m above lake level) (Temple, 1964*a*, *b*). As these strand lines are horizontal, they post-date all tectonic activities and represent stages in the evolution of the modern lake and were formed during the last 12,000 years (Kendall, 1969). In the north and the south the watershed is low and water gaps are located at 18–21 metres above lake level. Therefore it is clear that the lake could not rise above its 18 m strand line. The Victoria Nile dates from this highwater stage. The three strand lines probably reflect pauses in the erosion of the Victoria Nile outlet due to resistant sills across the outlet (Temple, 1967), although the two lower beaches may have a climatic significance. The age of the lowest beach has been directly estimated, since the 3 m beach at Hippo Bay near Entebbe contained charcoal with an age of 3,720 years B.P. (Stuiver *et al.* 1960). The paleolimnology of Lake Victoria was first studied by Kendall (1969). He examined two cores from the Pilkington Bay near Jinja and one from Kome Channel near Entebbe, all in the northern part of the lake, for minerals, pollen grains and other microfossils. The longest core (P-2 Core Pilkington Bay) was 18 metres and consisted of uniform organic mud down to a level with an age of about 14,730 years. There was an unconformity around 14,000 years B.P. indicative of a period when the water level of Lake Victoria fell below the level of the P–2 coring site. The unconformity was followed by dry sediment very similar to the mud above the unconformity with remains of algae, indicating that it is a true lacustrine deposit.

Core chemistry showed that the lake was without an outlet from before 14,730 B.P. until about 12,000 B.P. when it possibly overflowed. About 14,000 years B.P. the lake level was at least 27 metres lower than the level in 1969. Later coring revealed that the level actually fell at least 75 metres (Livingstone, 1976). From 12,000 to 10,000 B.P. the lake probably had an outlet and then for a short period around 10, 000 B.P. the lake was closed again (based on a core taken in shallower water). Since that time it has drained via the Victoria Nile near Jinja. The lake's fossil record of diatoms and green algae confirm and supplement the above historical model based on the results of the core chemistry.

Information on the vegetational history of the region of the northern Victoria basin came from fossil pollen analysis. The main conclusions were that the vegetation around Pilkington Bay from at least 13,500 to 12,500 B.P was predominantly savanna. From 12,200 to 7,000 B.P. a major forest developed, changing from semi-deciduous to evergreen and interrupted by a 1,000 year period of aridity around 10,000 B.P. After 6,000 B.P the forest changed to semi-deciduous again, apparently due to a decrease of the annual rainfall in the region or its more pronounced seasonality. During the last 3,000 years the reduction of the forests was most probably caused by human activity, decrease in moisture or both (Livingstone, 1975).

New information on the period 14,000–25,000 B.P. became available from studies of bottom sediments by Stager (1984) and Stager *et al.* (1986). Fossil records of the cores from the lake bottom collected from beneath 32 metres of water in the Damba Channel (near Jinja) and beneath 66 metres of water offshore near Isamba Island (0°11'0" S, 33°16'5" E) extended the history of the lake by an additional 3,000 and 10,000 years respectively. Analyses of the first core revealed that the lake fluctuated at or below the level of its outlet between 17,500 and 14,500 B.P. The diatom record of the second core showed that from 25,000 B.P. to 15,000 B.P. Lake Victoria fluctuated at or below the Victoria Nile outlet responding to reduced precipitation : evaporation ratios. Maximum aridity in the Lake Victoria basin occurred between 15,000 and 13,000 years B.P. Water levels fell below the level of the 66 m coring site between 14,750 and 13,700 B.P. This drop in lake level would have resulted in a much smaller lake consisting of the deeper part of the actual lake (see bathymetric chart, Figure 4.6, p. 34).

This is in line with the findings of the high-resolution echo-sounding of the lake carried out under the PROBE project in April–June 1985, since a lake with a much longer lifetime than 14,000 years would have left a thicker record of acoustically transparent sediment than the maximum of 8 metres found in the offshore waters of Lake Victoria (Scholz *et al.* 1990).

The data from the Lake Victoria sediment studies revealed clear indications of large climatic changes during the past 15,000 years (Kendall, 1969). The earlier climatic history is less well known, but there is evidence for repeated change in climate in south-western Uganda since 42,000 years B.P. (Taylor, 1990). The best prospects for a reconstruction of late Pleistocene climates in the Victoria basin would be through the study of cores of the deepest part of the lake sediment.

From our present knowledge the following preliminary chronology of climatic changes in the Lake Victoria basin can be drawn up:

| | |
|---|---|
| pre *ca.* 42,000 B.P. | • similar climatic conditions to the present (Taylor, 1990) |
| 42,000 – 32,000 B.P. | • considerably colder and drier (Taylor, 1990) |
| 21,000 – 12,000 B.P. | • considerably colder and drier (Taylor, 1990, Stager *et al.* 1986) |
| 14,700 – 12,000 B.P. | • dry (Kendall, 1969) |
| 12,000 – 10,500 B.P. | • moderately wet (Kendall, 1969) |
| 10,500 – 9,500 B.P. | • moderate dry (Kendall, 1969) |
| 9,500 – 6,500 B.P. | • wet (Kendall, 1969) |
| after 6,500 B.P. | • slightly drier and/or more seasonal (Kendall, 1969) |

# 4 Present status of Lake Victoria

## INTRODUCTION

In the present Chapter background information on physical geography and climate of the catchment area of Lake Victoria will be given, together with the main characteristics of the lake and some of its gulfs where the national institutes of the three riparian countries (UFFRO, KMFRI and TAFIRI) are carrying out their main research activities.A topographic map of the lake's catchment area with the inflowing and outflowing rivers is given in Figure 4.1.

## PHYSICAL GEOGRAPHY

The catchment area of Lake Victoria, defined as its hydrological watershed, is approximately 194,200 km$^2$ (Piper *et al.* 1986). It covers parts of five countries: Tanzania, Uganda and Kenya, all three bordering Lake Victoria, plus Rwanda and Burundi.

The surface area of the lake is approximately 68,800 km$^2$. The three riparian countries of Tanzania, Uganda and Kenya control respectively 33,700 km$^2$ (49%), 31,000 km$^2$ (45%) and 4,100 km$^2$ (6%) of the area of the lake (VandenBossche & Bernacsek, 1990*a*).

The lake's geographical boundaries are 0°20′ N – 3°0′ S, 31°39′ E – 34°53′ E (Welcomme, 1972) and the altitude of the lake is 1134 m above sea level (*Times World Atlas,* 1991). The shoreline of Lake Victoria is highly irregular, especially in the north and the south, where the watershed is locally less than 25 metres above lake level. East and west of the lake the basin rises to escarpments bordering the Eastern and the Western Rift Valleys.

The inflowing rivers of the lake drain a variety of areas (Figure 4.1). The main inflowing river, Kagera, drains the mountains of Rwanda and Burundi. The rivers in the Kenyan part of the catchment area drain the forested slopes of mountain regions to the northeast. In the Ugandan part rivers drain large swamp areas, especially to the west. To the southeast the drier plains of the Serengeti are drained by rivers of the Tanzanian part of the catchment area.

The Victoria Nile is the outflowing river of the lake. In 1954 a dam – the Owen Falls Dam – was constructed across the outlet of the lake near Jinja, and is used for the production of hydro-electric power. After the construction of the dam the relationship between the outflow and the lake level is maintained according to a curve agreed upon by the interested parties after model calibration (Piper *et al.* 1986).

Since the pioneer work of Gregory (1896, 1921) on the geology of East African Rifts, geological maps have become available for most parts of Kenya, Uganda and Tanzania. Saggerson (1962) published a geological map for the whole of East Africa at a scale of 1:4 million. It showed that the Lake Victoria basin overlies Precambrian rocks and Quaternary sediments accumulated at four places along the lake: east of the Nyanza Gulf, east of Speke Gulf, south of the Mwanza Gulf and north of Kagera River (Figure 4.2).

Information on soils and vegetation of the catchment area of Lake Victoria is given by Scott (1962), Hamilton (1982) and Balarin (1985*a*, 1985*b*, 1985*c*), the latter with references of other relevant publications.

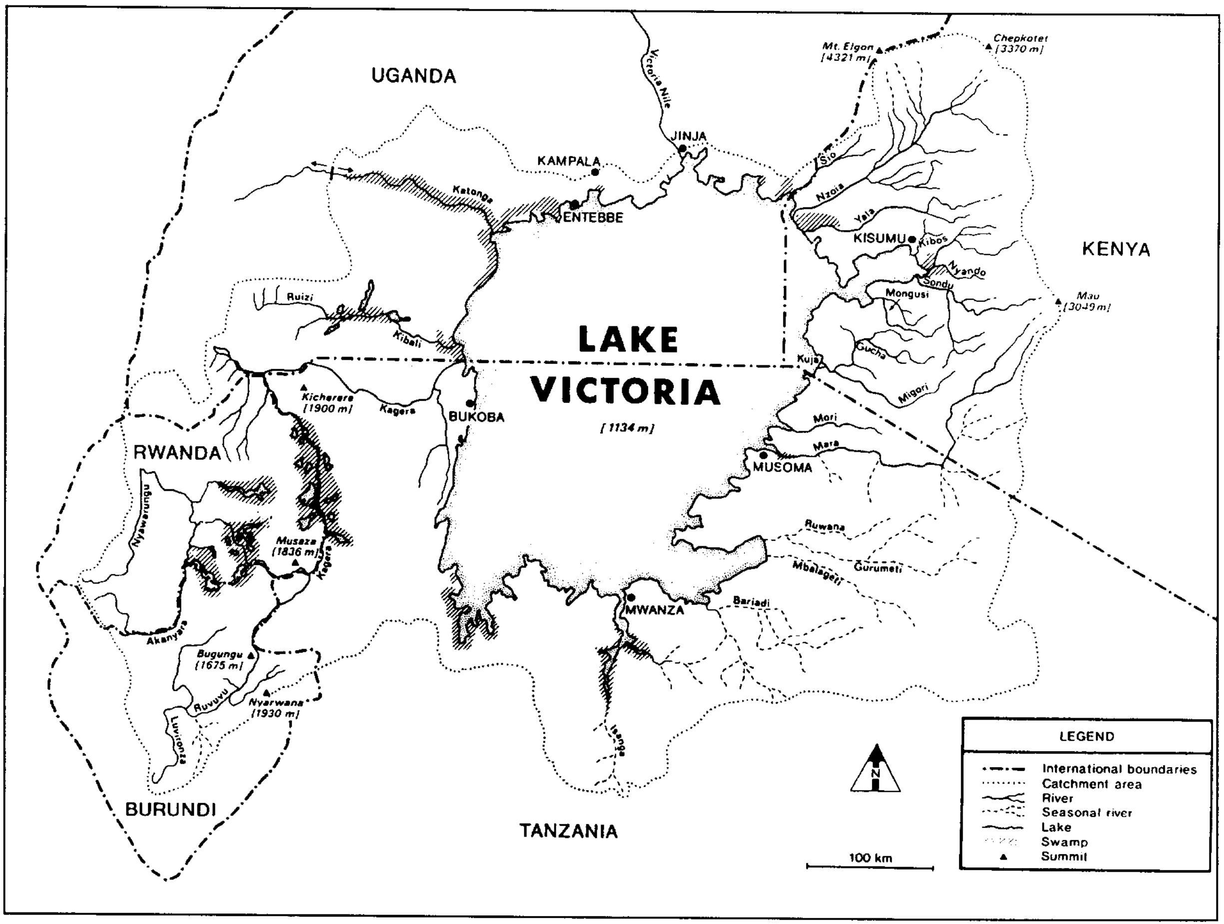

**Figure 4.1** Topographic map of the catchment area of Lake Victoria (From HEST, 1988)

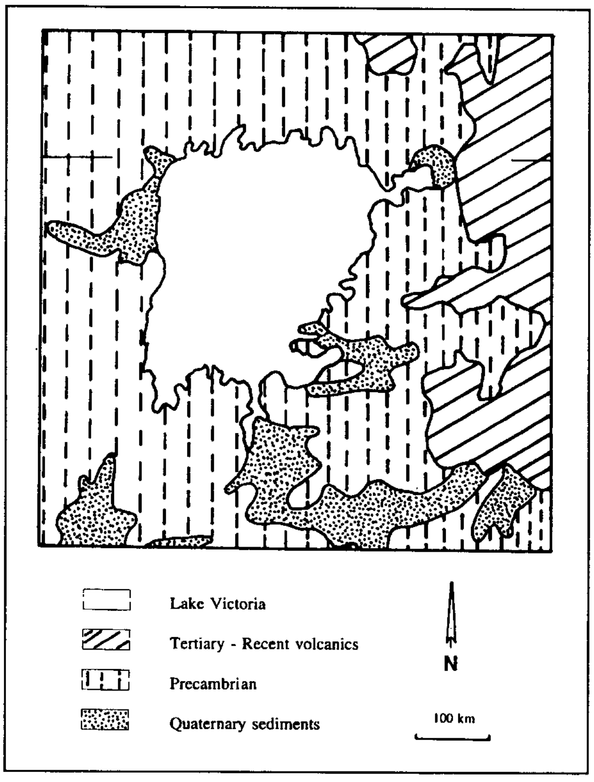

**Figure 4.2**
Geological map of the Lake Victoria region (simplified after Saggerson (1962))

## CLIMATE

General information on the climate of East Africa is provided by Griffiths (1972) and detailed information on the climatic conditions of the lake area by Balarin (1985*a*, 1985*b*, 1985*c*) as well as reports of the East African Meteorological Department at Nairobi (1975).

The catchment area of Lake Victoria lies entirely within the tropical zone and has two main climates: a wet tropical climate in the lake area and the Ugandan part of the catchment area and a tropical savanna climate in the remaining part. In the mountain regions of Rwanda, Burundi and Kenya the climate is moderated by the altitude.

Records from stations around the lake are used to describe the climatic conditions in the lake area. In Table 4.1 means of climatological elements are given from three stations around the lake (Mwanza, Kisumu and Entebbe). These records show that the conditions in the lake are not uniform. Furthermore, there may be large differences between the lake and the shore where the meteorological stations are located (Goudswaard, pers. comm.). There is some evidence of greenhouse effects on the climate in East Africa resulting in higher temperatures since 1960 (Hastenrath & Kruss, 1992). Higher temperatures observed in the lake in 1990/1991 (Hecky, 1993) will have important implications for the stratification of the lake (see Chapter 6).

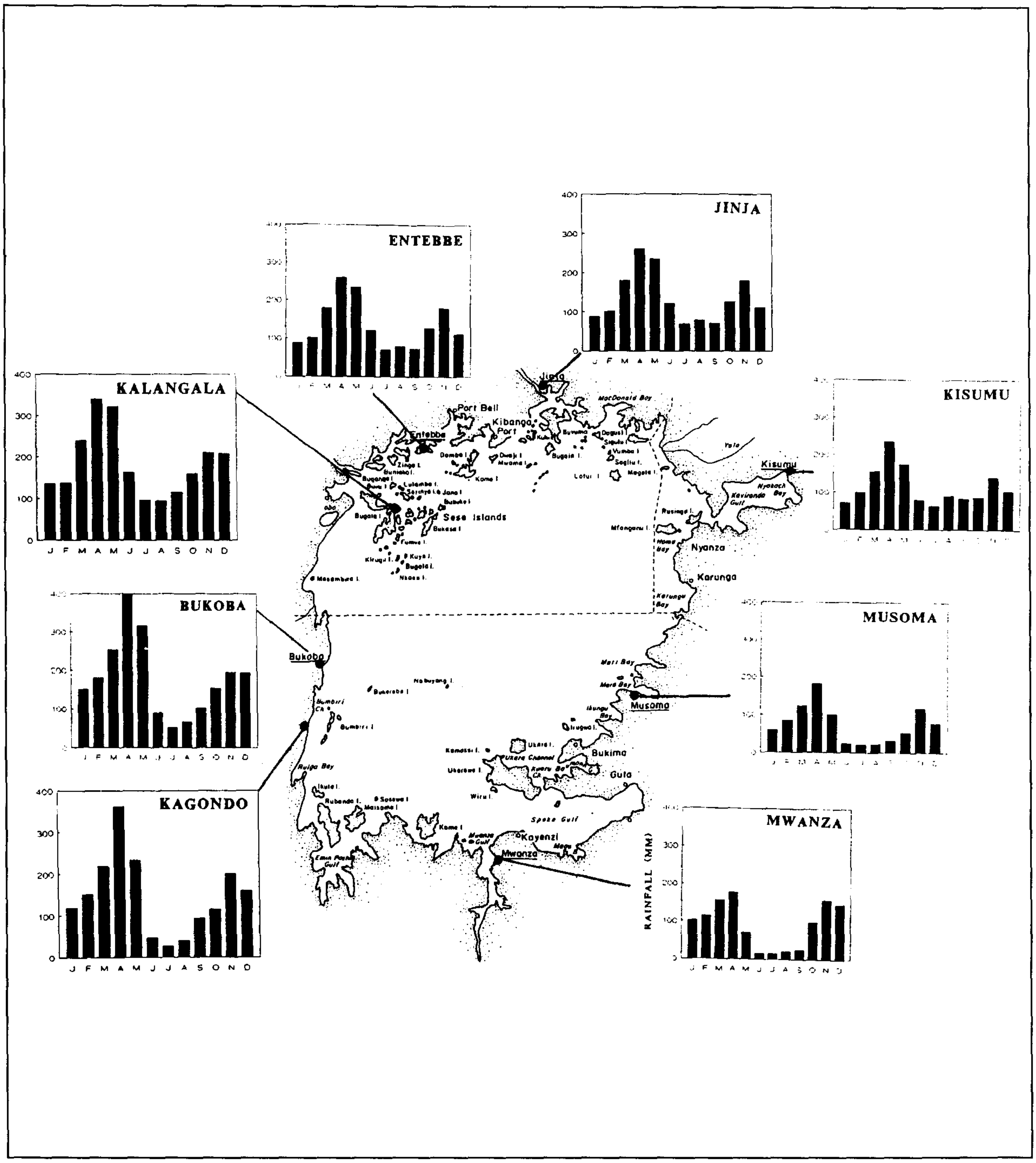

**Figure 4.3** Seasonal rainfall regimes at eight locations around the lake in the period 1956 -1978 (Data from Piper *et al.* 1986)

The main climatic elements temperature, rainfall, wind and evaporation are summarized below:

## Temperature

Air temperatures in the lake area are quite uniform. Seasonal differences between means do not exceed 3 °C. Means of maximum temperature fluctuate between 27 °C and 28.3 °C at Mwanza, between 28 °C and 31 °C at Kisumu and between 25 °C and 27 °C at Entebbe. Seasonal differences in minimum temperature are somewhat larger at Mwanza (15.3–18.5 °C) than at Kisumu and Entebbe (16–18 °C). In general July is the coolest month. The warmest month is variable and fluctuates in the period between October and February (Table 4.1). Mean daily temperature fluctuations are of the order of 8–14 °C.

## Rainfall

The major tropical rains in the area are associated with an atmospheric belt of low pressure which follows the sun twice a year across the equator. The amount of rainfall varies considerably per season, with maxima in the period March–May (Big Rains) and November–December (Small Rains) (Table 4.1). The short rainy season in November–December is not sharply delimited and may even fail, as it did in 1927

**Table 4.1** Means of various climatological elements for three stations bordering Lake Victoria: Mwanza (Tanzania), Kisumu (Kenya) and Entebbe (Uganda).

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | YEAR | Years of rec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a. **MWANZA** [Alt. 1140 m] | | | | | | | | | | | | | | |
| (Source: E.A. Met. Dep. 1975) | | | | | | | | | | | | | | |
| rainfall (mm) - means per month/year | 99 | 105 | 157 | 177 | 77 | 11 | 14 | 27 | 32 | 80 | 138 | 166 | 1083 | 20 |
| temperature (C) - means of max | 27.0 | 27.2 | 27.5 | 27.3 | 27.5 | 27.9 | 27.8 | 27.9 | 28.3 | 28 | 27.4 | 26.7 | 27.5 | 20 |
| - means of min | 18.3 | 18.3 | 18.5 | 18.4 | 17.9 | 16.3 | 15.3 | 16.4 | 17.8 | 18.4 | 18.5 | 18.2 | 17.7 | 20 |
| sunshine (hrs) | 7.6 | 7.4 | 7.2 | 7.6 | 8.2 | 9.3 | 9.6 | 9.1 | 8.5 | 7.8 | 7.2 | 7.1 | 8.1 | 13 |
| wind speed (knots) - 06h | 7 | 6 | 7 | 7 | 8 | 8 | 10 | 9 | 10 | 9 | 7 | 7 | 8 | 20 |
| - 12h | 8 | 9 | 9 | 9 | 9 | 9 | 10 | 10 | 11 | 11 | 10 | 9 | 9 | 20 |
| evaporation (mm) - pan type A | 171 | 155 | 171 | 159 | 167 | 177 | 196 | 206 | 207 | 202 | 176 | 171 | 2158 | 12 |
| b. **KISUMU** [Alt. 1145 m] | | | | | | | | | | | | | | |
| (Source: Griffiths 1972) | | | | | | | | | | | | | | |
| rainfall (mm) - means per month/year | 57 | 70 | 160 | 195 | 177 | 101 | 68 | 96 | 79 | 64 | 106 | 105 | 1278 | 32 |
| temperature (C) - means of max | 31 | 31 | 30 | 29 | 28 | 28 | 28 | 28 | 29 | 31 | 30 | 30 | 29 | 32 |
| - means of min | 17 | 17 | 18 | 18 | 17 | 17 | 17 | 16 | 16 | 17 | 17 | 17 | 17 | 32 |
| sunshine (hrs) | 8.8 | 9.0 | 8.6 | 7.7 | 8.0 | 7.6 | 7.0 | 7.0 | 7.7 | 8 | 7.3 | 8.2 | 7.8 | |
| wind speed (knots) - 09h | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 24 |
| - 15h | 12 | 13 | 11 | 10 | 8 | 8 | 8 | 9 | 10 | 10 | 10 | 10 | 10 | 24 |
| evaporation (mm) | 209 | 201 | 202 | 164 | 157 | 153 | 154 | 149 | 166 | 187 | 173 | 185 | 2100 | |
| c. **ENTEBBE** [Alt. 1146 m] | | | | | | | | | | | | | | |
| (Source: Griffiths 1972) | | | | | | | | | | | | | | |
| rainfall (mm) - means per month/year | 100 | 86 | 141 | 280 | 257 | 98 | 65 | 91 | 87 | 108 | 146 | 126 | 1585 | |
| temperature (C) - means of max | 27 | 27 | 27 | 26 | 26 | 25 | 25 | 25 | 26 | 26 | 26 | 26 | 26 | |
| - means of min | 17 | 17 | 18 | 18 | 18 | 17 | 16 | 16 | 16 | 17 | 17 | 17 | 17 | |
| sunshine (hrs) | 7.5 | 7.3 | 6.6 | 6.0 | 6.2 | 6.2 | 6.4 | 6.3 | 6.5 | 6.5 | 6.6 | 6.8 | 6.6 | 31 |
| wind speed (knots) - 09h | 4 | 4 | 5 | 6 | 6 | 6 | 6 | 5 | 6 | 5 | 4 | 4 | 5 | 7 |
| - 15h | 10 | 11 | 11 | 10 | 10 | 11 | 10 | 10 | 10 | 10 | 10 | 9 | 10 | 7 |
| evaporation (mm) | 148 | 156 | 173 | 170 | 148 | 126 | 129 | 134 | 145 | 163 | 144 | 142 | 1778 | 6 |

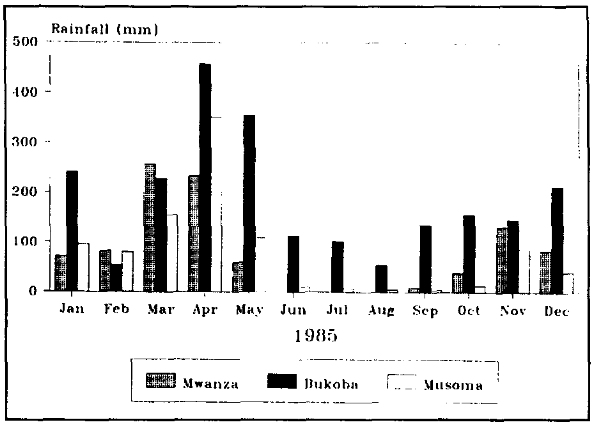

**Figure 4.4** Monthly rainfall at three locations in Tanzania: Mwanza, Bukoba and Musoma. (Data from Directory of Meteorology, Mwanza)

(Graham, 1929). There is a permanent low pressure over Lake Victoria resulting in a large amount of rain condensed from rising air masses.

In Figure 4.3 seasonal rainfall regimes at eight locations around the lake in the period 1956–1978 are given clearly showing temporal and spatial differences.

These differences in rainfall occur also within a year as shown in Figure 4.4 with the monthly rainfall at three locations in Tanzania in 1985.

Rainfall varies considerably from year to year. In Figure 4.5 the rainfall per month at Mwanza is given for the period 1982–1986. These fluctuations may even be so large that they result in marked differences of monthly means of one station when calculated over different time periods.

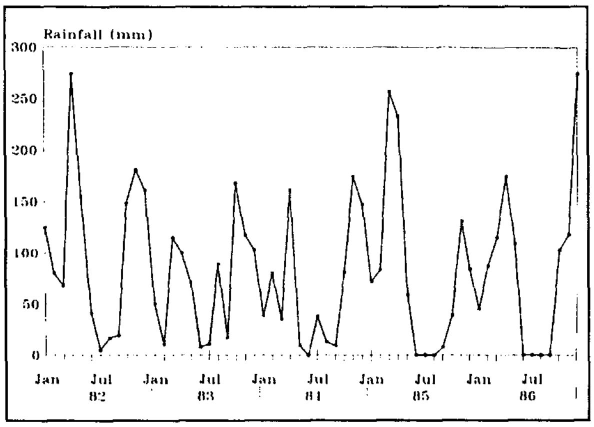

**Figure 4.5** Monthly rainfall (in mm) at Mwanza for the period 1982–1986. (from Directory of Meteorology, Mwanza)

There are large differences in the annual amount of rainfall within the lake area. Annual rainfall statistics for eight stations around the lake given by Piper *et al.* (1986) revealed these differences (Table 4.2).

**Table 4.2** Mean annual rainfall statistics (1956-1978) for eight stations around the lake (for locations see Fig. 4.3) (from Piper et al. 1986)

| | |
|---|---|
| Jinja (U.) | 1,336 mm |
| Bukoba (T.) | 2,147 mm |
| Entebbe (U.) | 1,620 mm |
| Kagondo (T.) | 1,770 mm |
| Kalangala (U.) | 2,216 mm |
| Mwanza (T.) | 1,100 mm |
| Kisumu (K.) | 1,377 mm |
| Musoma (T.) | 895 mm |

## Wind

The wind regime is dominated by the south-east trade winds blowing most strongly during May to July, but is complicated by diurnal on- and off-shore breezes (land-breeze in the morning and lake-breeze in the afternoon) (Talling, 1966). Prevailing wind directions at Mwanza, Bukoba and Musoma (Tanzania) are given in Table 4.3 (EAMD, 1975).

Seasonal variations in wind speed are small, with higher wind speeds in the period July-October at Mwanza and at Kisumu in the period January-March in the afternoon (Table 4.1). Heavy rains in the two rainy seasons may be accompanied by conventional storms. A marked diurnal variation in wind speed is noticeable around the lakeside. Wind speed normally has its minimum in the morning and its maximum in the afternoon.

## Evaporation

Evaporation rates vary and may reach much higher values on the south-eastern shore. Annual means range between 1778 and 2159 mm (Table 4.1). Variations in evaporation from year to year are likely to be relatively small. Lake evaporation was therefore estimated at a total of 1595 mm/year based on monthly averages derived by the Penman method for stations around the lake (Piper *et al.* 1986). This

**Table 4.3** Prevailing wind directions at Mwanza, Bukoba and Musoma per month at 06.00 and 12.00 (EAMD, 1975)

| *Location* | *J* | *F* | *M* | *A* | *M* | *J* | *J* | *A* | *S* | *O* | *N* | *D* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mwanza | | | | | | | | | | | | |
| 06.00 | S/SE | S/SE | S/SE | SE | SE | SE | S/SE | SE | SE/E | SE/E | SE | S/SE |
| 12.00 | N | NW | N/NW | N | N | N | N | N | NW/N | NW/N | NW/N | NW/N |
| Bukoba | | | | | | | | | | | | |
| 06.00 | W | W | W | SE | S/SE | SE | SE/S | SE | W | W | W | W |
| 12.00 | SE | SE | SE | SE | SE | SE | SE | SE | SE | E | E | E/SE |
| Musoma | | | | | | | | | | | | |
| 06.00 | E/SE | E | E | SE | SE | E/SE | E/SE | E | E | E | E | E |
| 12.00 | NW/W | NW/W | NW/W | NW | NW | NW | NW | NW/N | N | NW | N | NW |

annual total is approximately equal to the figure given by the Hydrometeorological Survey of the World Meteorological Organization.

## PRESENT FEATURES OF LAKE VICTORIA AND ITS MAIN RESEARCH AREAS

Lake Victoria is presently a huge, relatively shallow lake lying in a saucer-shaped basin with a maximum depth of about 80 metres. The lake has a long indented shoreline, much of it swampy, and a large number of islands. The indented shoreline, especially in the North and South, and the numerous islands in the lake give rise to a large number of more or less isolated and often shallow gulfs and bays and an extensive littoral zone. Much of the shoreline is fringed with papyrus (*Cyperus papyrus*), which may extend into swamps. Other shoreline habitats are sandy beaches and rocky exposures.

In Figure 4.6 the outline of the lake, the main gulfs and the location of the main islands and cities are given, as are the 20 m, 40 m and 60 m isobaths. General characteristics of the lake are given in Table 4.4 together with some hydrological and morphometric data.

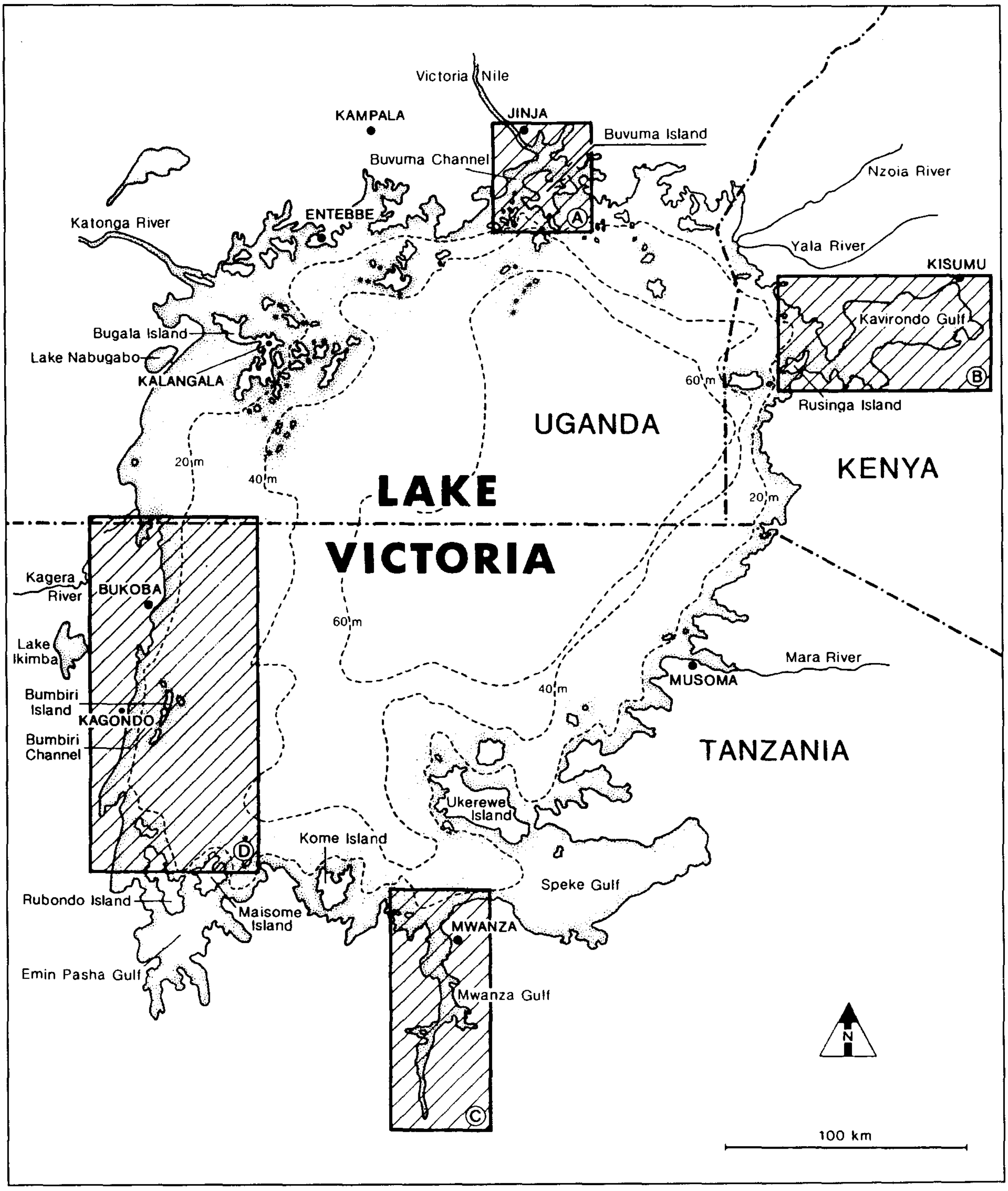

**Figure 4.6** Bathymetric map of Lake Victoria (from HEST, 1988). (Isobaths for 20, 40 and 60 m depths after Kendall (1969)

During its history the shape of the lake has changed due to fluctuations in water level caused by tectonic activities and climatic changes (see Chapter 3). Even recently, in the early 1960s, the water level rose more than two metres due to increased precipitation. This flooded large areas of adjacent land, as the lake is surrounded by a gently undulating landscape of low relief. The lake increased approximately 5% in volume due to the rise of the water level (see Chapter 5). Lake Victoria has a relatively short flushing time of 140 years compared with Lakes Tanganyika (7,000 years) and Malawi (750 years) (Hecky & Bugenyi, 1992).

The three research institutes around the lake attempt to carry out routine limnological studies in inshore areas close to the institutes. Detailed maps of the main research areas (hatched areas A, B, and C in Figure 4.6) are given in the Figures 4.7, 4.8 and 4.9 and main characteristics of the three areas are given in Tables 4.5, 4.6 and 4.7. Physical and chemical parameters given in the tables will be discussed in the following Chapters. Several northern inshore waters are described in EAFFRO and UFFRO reports, by Fish (1957) and Talling (1966) and in reports of the IDRC Lake Productivity Project, and Murchison Bay by Okedi (1990). Descriptions of the Nyanza Gulf can be found in Melack (1979), Rinne & Wanjala (1982) and Okemwa (1984). Information on the gulf is summarized by Burgis *et al.* (1988). Recently an ecological zonation of the Kenyan waters of Lake Victoria was used by Mavuti and Litterick (1990). Descriptions of the Mwanza Gulf and several bays are given in papers and reports of HEST/TAFIRI (e.g. van Oijen *et al.* 1981; Witte, 1981).

**Table 4.4** **General, hydrological and morphometric characteristics of Lake Victoria**
**Main sources: 4.4*a* and 4.4c – VandenBossche, J.-P. & G. M. Bernacsek, 1990*a*, 1990*b*, 1991;**
**4.4b – Krishnamurty & Ibrahim, 1973 (otherwise reference given)**

| | |
|---|---|
| *a. General characteristics* | |
| Latitude | 0°20′ N – 3°0′ S |
| Longitude | 31°39′ E – 34°53′ E |
| Altitude | 1134 m |
| Catchment area | 263,000 km$^2$ (the lake included) |
| Vegetation catchment area and savannah | Savannah woodland, savannah, high altitude forest |
| Major inflowing rivers | • in Tanzania – Kagera, Mori, Mara<br>• in Kenya – Nzoia, Sio, Yala, Kibos, Nyando, Sondu, Mongusi, Kuja (Balarin, 1985*a*)<br>• in Uganda – Kibali, Katonga, Sio |
| Seasonal inflowing rivers | • in Tanzania – Ruwana, Gurumeti, Mbalageti, Bariadi, Isanga |
| Outflowing river in Uganda | Victoria Nile |
| *b. Hydrological characteristics* | |
| Inflow from streams (I) | 18 ± 5% (× $10^9$ m$^3$) |
| Precipitation over lake (P) | 100 ± 10% (× $10^9$ m$^3$) |
| Outflow (Lake Victoria) (O) | 23.4 ± 5% (× $10^9$ m$^3$) |
| Evaporation | 100 ± 10% (× $10^9$ m$^3$) |
| Annual lake level fluctuations | 0.4 – 0.7 m (Piper *et al.* 1986) |
| Max. lake level fluctuation | 3 m (Piper *et al.* 1986) |
| Flushing time (Volume/O) | 140 yr |
| Residence time (Volume/P+I) | 23 yr |
| *c. Morphometric characteristics* | |
| Type of basin | Tectonic (epeirogenetic Type 4) (Hutchinson, 1957) |
| Surface area | 68,800 km$^2$ |
| Max. length | 400 km |
| Max. breadth | 240 km |
| Mean breadth | 172 km |
| Max. depth | 79 m (84 m, Hecky & Bugenyi, 1992) |
| Mean depth | 40 m |
| Volume | 2,760 km$^3$ (Rzóska, 1976) |
| Shore line | 3,440 km (excluding islands) |

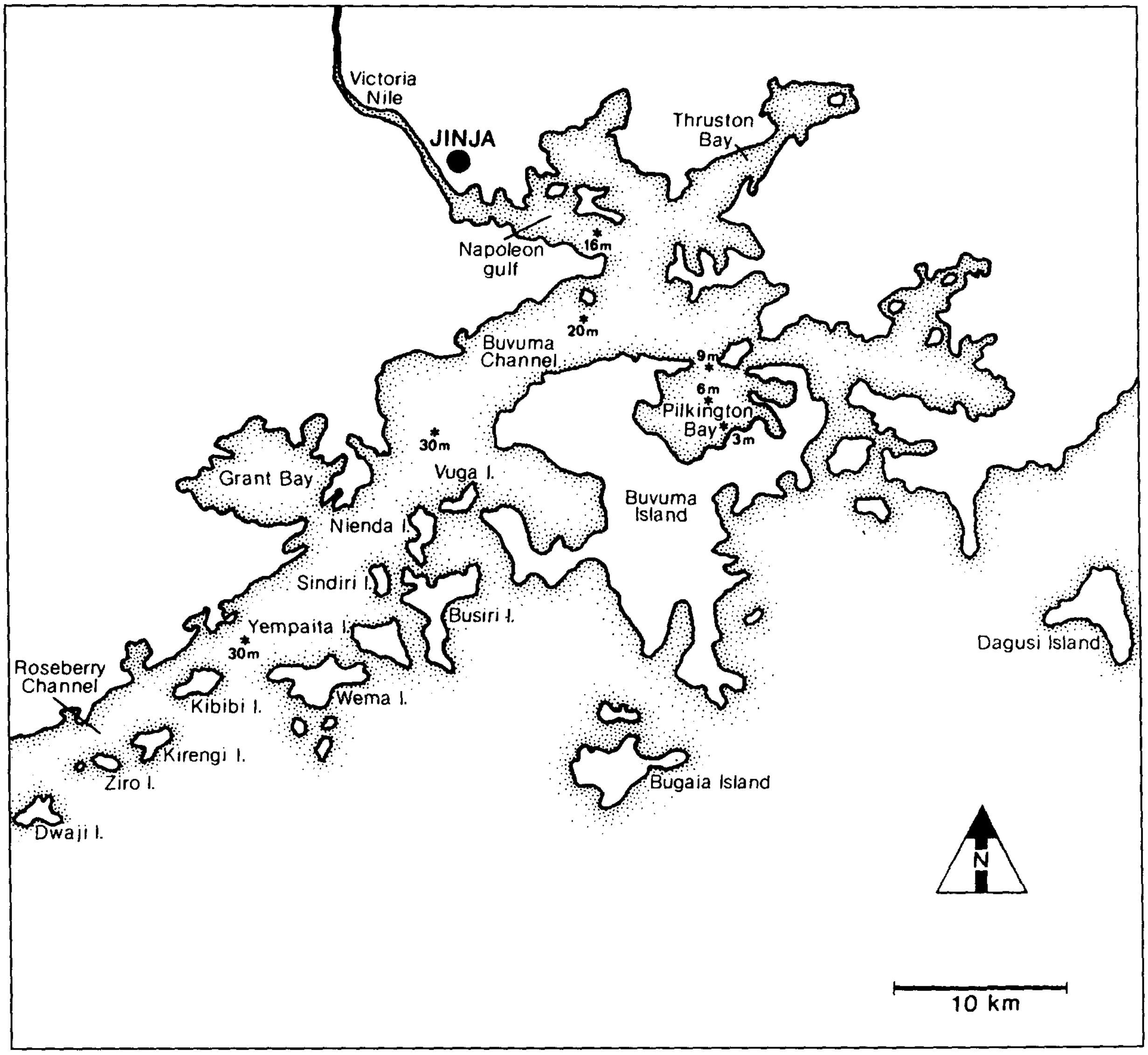

**Figure 4.7** Northwestern part of Lake Victoria near Jinja (Uganda) (from HEST, 1988)

**Table 4.5** Napoleon Gulf and bays near Jinja (UFFRO – Uganda). Main source: EAFRO/EAFFRO/UFFRO reports.

| | |
|---|---|
| *a. General and morphometric characteristics* | |
| Main gulfs and bays | Napoleon Gulf, Thruston Bay, Pilkington Bay, Grant Bay |
| Main channels | Buvuma Channel, Roseberry Channel |
| Shores | rocky with swampy shores in sheltered bays |
| Outflowing river | Victoria Nile |
| Max. depth | Napoleon Gulf, 26 m<br>Thurston Bay, 17 m (at entrance)<br>Pilkington Bay, 9 m (at entrance)<br>Grant Bay 17 m (at entrance) |
| *b. Physico-chemical data* | |
| Temperature, dissolved $O_2$ | see Figure 6.1 |
| Chemical composition | see Table 7.1 |

**Table 4.6** Nyanza Gulf (KMFRI – Kenya) Main source: Burgis *et al.* 1988 (otherwise stated)

| *a. General and morphometric characteristics* | |
|---|---|
| Synonyms | Winam Gulf; Kavirondo Gulf (colonial name) |
| Location | 0°04′ S – 0°32′ S; 34°13′ E – 34°52′ E |
| Altitude | 1134 m above sea level |
| Surface area | 1400 km$^2$ (Melack, 1979) |
| Shoreline | 500 km (Ochumba, 1983) |
| Mean depth | 12 m (offshore); 4 m (inshore) (Mavuti & Litterick, 1990) |
| Max. depth | 43 m (offshore); 6 m (inshore) (Mavuti & Litterick, 1990) |
| Max. length | 70 km |
| Max. breadth | 30 km |
| Volume | 13.1 km$^3$ (Ochumba & Kibaara, 1989) |
| Connection with lake | Rusinga Channel |
| Rusinga Channel out-flow into open lake | 0.68 km$^3$ (Ochumba & Kibaara, 1989) |
| Inflows | 3.2 km$^3$ (Ochumba & Kibaara, 1989) |
| Water retention time | 19.3 year (Ochumba & Kibaara, 1989) |
| Discharge major rivers | Nyando R. 247 × 10$^6$ m$^3$ (1969); 594 × 10$^6$ m$^3$ (1970)<br>Sondu R. 845 × 10$^6$ m$^3$ (1969); 1,961 × 10$^6$ m$^3$ (1970) |
| Shores | northern shore rocky, southern shore flat and swampy |
| Vegetation lake shore | grasses and papyrus swamps (Lind & Visser, 1963) |
| Main inflowing rivers | Nyando, Sondu, Kibos, Mongusi |
| Substratum | 44% mud and sand, 28% mud, 28% rocks |
| Catchment area | 12,300 km$^2$<br>• agriculture cotton, sugarcane, tea;<br>• livestock up to 250 head/km$^2$;<br>• industries (Kisumu) – textile, food industry, mechanical construction, soap factory |

| *b. Physico-chemical data* | |
|---|---|
| Main source | Burgis *et al.* 1988 (if not, reference given) |
| Temperature | • surface 23.8–29.0 °C (Melack, 1979*a*);<br>max. 31.5 °C 24.5–29.5 °C (Oct. 1984)<br>(Ochumba, 1990)<br>• bottom 22.9–26.7 °C (Ochieng, 1981)<br>25.1–26.0 °C (Oct. 1984) (Ochumba, 1990) |
| Dissolved oxygen | 6-7.7 mg O$_2$/l (68% – 108% sat.) (Melack, 1979*a*)<br>4.6–9.45 mg O$_2$/l (June 84)<br>3.2–4.8 mg O$_2$/l (St I, April 84) (Ochumba, 1990) |
| pH | 6.8–9.2 (June 1984)<br>6.0–7.6 (Oct. 84) (Ochumba, 1990) |
| Conductivity | 170–179 µS/cm (Melack, 1979a)<br>100-160 µS/cm (June 1984)<br>100–160 µS/cm (Oct. 84) (Ochumba, 1990) |
| Transparency | 75–150 (Aug–Dec. 1973; Melack, 1979)<br>35–155 (June 1984) |
| Alkalinity | 40–72 mg/l as CaCO$_3$ (June, 1984)<br>37–107 mg/l as CaCO$_3$ (Oct. 84) (Ochumba, 1990) |
| Turbidity | 3.3–28.5 NTU (June 1984) |
| Chemical composition | Ochumba 1990 (after Melack, 1976; Ochumba, 1984)<br>Na 0.85 meq/l, K 0.62 meq/l,<br>Ca 0.46 meq/l, Mg 0.13 meq/l,<br>HCO$_3$ 1.68 meq/l, SO$_4$ 0.17 meq/l,<br>Cl 0.20 meq/l, F 0.04 meq/l,<br>SiO$_2$ 4.0 mg/l, NO$_3$ 8.0 µg/l,<br>PO$_4$ 40 µg/l |
| Temperature (inflowing rivers) | 20–24 °C (Okedi *et al.* 1976; Mainga, 1981*b*) |

**Table 4.7** Mwanza Gulf and its bays (TAFIRI - Tanzania). Sources: 4.7*a* – HEST/TAFIRI Reports; 4.7*b* – Akiyama *et al.* 1977.

*a. General and morphometric characteristics*

| | |
|---|---|
| Location | 2°28′ S – 3°00′ S; 32°45′ E – 33°01′ E |
| Altitude | 1134 m |
| Surface area | 500 km$^2$ (Van Oijen *et al.* 1981) |
| Mean depth | 6 m |
| Max. length | 60 km (Van Oijen *et al.* 1981) |
| Mean breadth | 5 km (Van Oijen *et al.* 1981) |
| Max. depth | 25 m (near entrance of the gulf) – HEST sampling station 4 |
| Shores | • at the entrance rocky shores and some sandy beaches<br>• Juma Island rocky shores<br>• south of Mwanzarocky shores with papyrus fringes in sheltered bays<br>• south of Buzuma I<br>• shores gradually changing via swampy<br>• shores with papyrus in extensive papyrus swamps |
| Substratum | soft organic mud; decaying plant material near papyrus fringes; in wind exposed bays sandy bottom |
| Main inflowing river | Isanga (seasonal river) |
| Catchment area | • agricultural land cotton<br>• average population density 60–80 persons/km$^2$<br>• semi-intensive livestock<br>• industry around Mwanza – textile, food and soap industry. |

*b. Physico-chemical data as measured in 1973–74 at station near Nyamatala Island*

| | |
|---|---|
| Temperature | • surface 23–26 °C<br>• bottom 22–25.5 °C |
| Dissolved oxygen | • surface 6–10 mg/l<br>• bottom 3–7 mg/l |
| Transparency | 1.1–1.9 m (Secchi disk) (see also Table 8.2) |
| Alkalinity | 0.9–1.1 meq/l |
| pH | • surface 7.8–9.0<br>• bottom 6.9–8.6 |
| Major ions | $SiO_2$ 0.5–3 mg/l<br>$PO_4$-P 0–122 µg/l<br>$NO_3$-N 0–18 µg/l |
| Chlorophyll-*a* | 2–8 mg/m$^3$ (see also Table 8.1) |

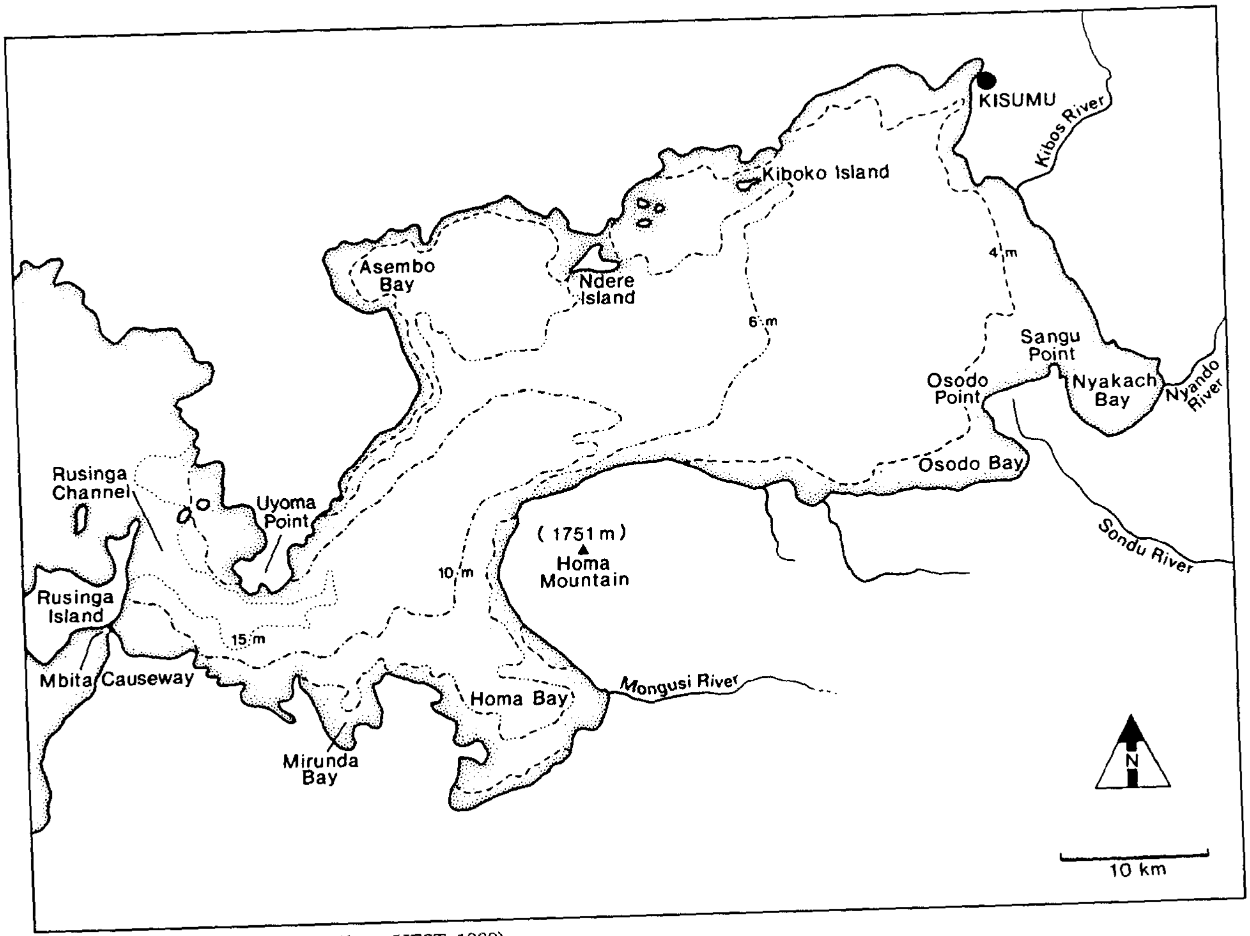

**Figure 4.8** Nyanza Gulf (Kenya) (from HEST, 1988)

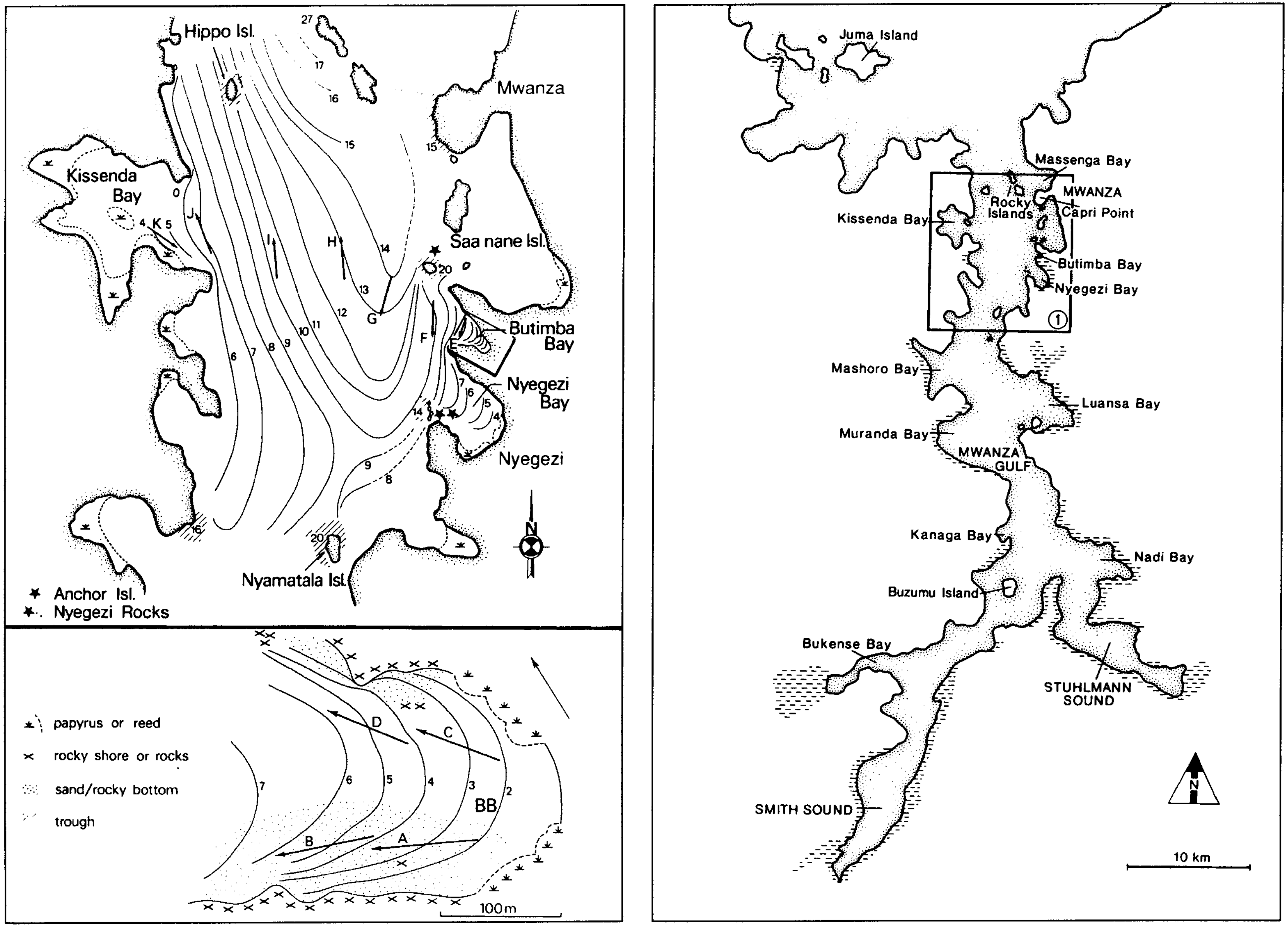

**Figure 4.9** Mwanza Gulf (Tanzania) with detailed maps of main research area HEST/TAFIRI and Butimba Bay (from HEST, 1988)

## Section III

# State of knowledge on the hydrology and limnology of Lake Victoria

# 5 Water balance

## HYDROLOGY OF LAKE VICTORIA

Prior to the construction of the Owen Falls Dam in the Victoria Nile near Jinja in 1954, the outflow from Lake Victoria was controlled by the Ripon Falls and was therefore related to lake levels. Operation of the dam controls the flow in such a way that the outflow from the lake is equal to the natural river discharge as calculated from an agreed curve relating lake levels to preconstruction discharge measurements (Kite, 1981). Kite (1981) showed that the Owen Falls Dam had only a minor effect on the Lake Victoria level over the period 1957–1980.

**Table 5.1** Annual discharge of main rivers into Lake Victoria during 1969 (Balirwa & Bugenyi, 1988)

| *Rivers* | *Discharge ($\times 10^6$ $m^3$)* |
|---|---|
| Kagera | 9474 |
| Nyando | 247 |
| Nzoia | 1777 |
| Katonga | 100 |
| Yala | 1114 |
| Kibos | 68 |
| Mara | 1038 |
| Ruizi | 61 |
| Sondu | 845 |
| Isanga | 37 |
| Sio | 287 |

There is no major inflow, but a large number of relatively small rivers and streams flow into the lake. Discharges of main inflowing rivers for 1969 are given in Table 5.1. The Kagera River is the largest of these, contributing 63% of the total river inflow in 1969 (WMO, 1974). Annual river discharges vary considerably from year to year, e.g. the discharge of the Sondu River was 845 × $10^6$ $m^3$ in 1969 and 1961 x $10^6$ $m^3$ in 1970 (WMO, 1974).

As far as is known to date groundwater flow into or out of the lake is negligible (Krishnamurthy & Ibrahim, 1973). Due to its large surface area the main input factor affecting the water balance of Lake Victoria is precipitation on the water surface and the main output factor evaporation from it.

## LAKE LEVELS

### Annual variations in lake level

Annual variations in rainfall have caused fluctuations in lake level from year to year. Regular information on lake levels has been available for Jinja since 1896. Information on high water levels in the period 1876 and 1896 was given by Lyons (1906). A historic sequence of lake levels from 1900 to 1982 can be produced using monthly means of the water level (Figure 5.1).

Long-term measurement of fluctuations revealed 10– or 11–year cycles of water level maxima prior to 1927 (Graham, 1929) and a five-year cycle since 1927 (Temple, 1964). In 1961 this five-year pattern of fluctuations changed conspicuously. In late 1961 the water level rose more than one metre in a few months and in 1964 the water level reached its maximum water level which was more than two metres above

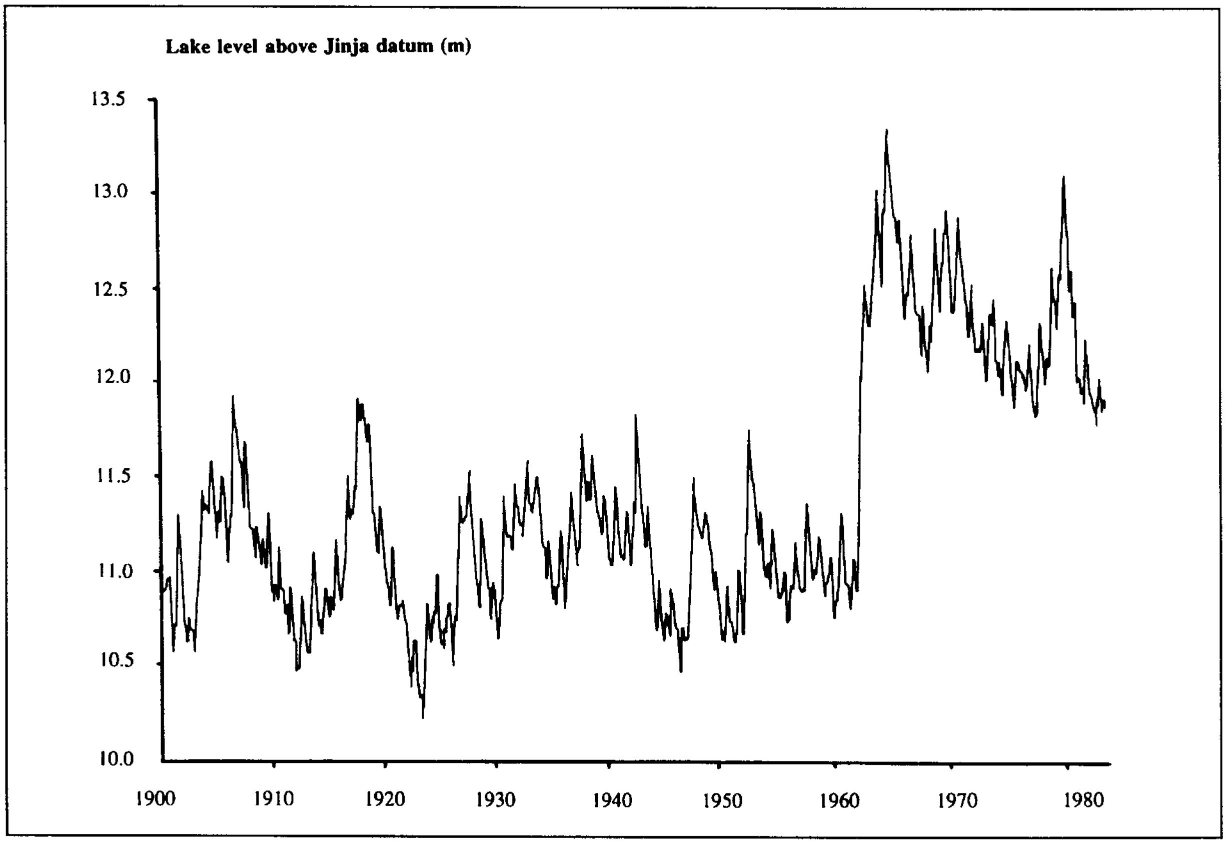

**Figure 5.1** Lake levels between 1900 and 1982 (redrawn after Piper et al. 1986)

the 1961 level and 1.4 metres above the previous highest water level of 1906. In the period from 1964 to 1983 the lake level remained at least one metre higher than the level before 1961. From historical evidence over a longer period it is clear that the 1961–1964 rise was not unique and that other similar fluctuations had occurred in the past (Nicholson, 1980).

Water level fluctuations of Lake Victoria and other East African lakes over the last century have been used together with other indicators such as atmospheric temperature, rainfall and mountain glaciers to find evidence for climatic change (Lema, 1990, 1993)

## Seasonal fluctuations in lake level

In addition to these variations from year to year there are seasonal fluctuations following the rainfall pattern within the year. The lake level rises during the main rains in April and generally reaches a maximum in May-June and a minimum in October, sometimes reaching a small secondary peak in December. The lake level declines through the rest of the year, usually between 20 and 40 cm and never more than 70 cm. The rise of the water level can be somewhat greater with a maximum of 90 cm for the period 1899–1960. During the period October–December 1960 the rise was 105 cm and by June 1961 the water level increased another 61 cm. (Krishnamurthy & Ibrahim, 1973)

Lake-level readings from gauges round the lake indicate that the west, north and north-east portions of the lake rise more rapidly in level than the southern part during the period April to July and the northern part rises about 45 cm more than the southern part (Newell, 1960; Krishnamurthy & Ibrahim, 1973).

## WATER BALANCE

The components of the lake's water balance are, in order of decreasing importance, rainfall over the lake, evaporation from the lake surface, outflow and inflows from the surrounding land areas. A rough estimation of the components of the Lake Victoria water balance is given using the results of the UNDP/WHO Hydrometeorological Survey of the catchment of Lake Victoria (Krishnamurty & Ibrahim, 1973):

| | | |
|---|---|---|
| Inflow | 18 | × $10^9$ $m^3$/year |
| Rainfall over lake | 100 | × $10^9$ $m^3$/year |
| Outflow | 23.4 | × $10^9$ $m^3$/year |
| Evaporation | 100 | × $10^9$ $m^3$/year |

Estimations of total inflow and outflow are more accurate than those of rainfall over the lake and evaporation from the lake (Kite, 1981). An error of 5% in the inflow and outflow estimates and of 10% in rainfall and evaporation already results in an error in the water balance equation of 14 billion $m^3$. This is a considerable quantity in comparison with the inflow and outflow (Krishnamurty & Ibrahim, 1973). Water balance studies under the Hydrometeorological Project described by Kite (1981) were unable to reproduce the rise in lake levels in the early 1960s. Piper *et al.* (1986) explained the water balance and lake-level fluctuations in terms of rainfall on the lake and the catchment.

# 6 Hydrodynamics

## INTRODUCTION

This Chapter will give a description of the lake's stratification cycles in offshore and inshore areas on the basis of temperature distribution, heat content, water movements, mixing and oxygen distribution.

Climatic conditions in the lake region influencing the water balance and distribution of the water temperature in the lake, are summarized in Chapter 4, together with the bathymetric features of Lake Victoria (Figure 4.6) and detailed maps of most important inshore gulfs and bays (Figures 4.7–4.9).

Data on the physical limnology of Lake Victoria are limited compared with the information available on physical phenomena in temperate lakes such as the North American Great Lakes. Most research on physical phenomena of the lake has been carried out near the three fisheries institutes in the more shallow waters of the lake due to the very large area of the lake, the lack of adequate research vessels and restricted financial budgets of the institutes.

Data from the offshore waters of the lake are therefore sparse. The first information on the temperature distribution in the offshore waters was provided by the fisheries survey of the lake in 1927–1928 by Graham (Graham, 1929; Worthington, 1930). In the 1950s and early 1960s several researchers of EAFRO/EAFFRO described the seasonal regime of stratification and overturn on the basis of the temperature and oxygen distribution in offshore waters (Fish, 1957; Newell, 1958, 1960; Talling, 1957*a*, 1962, 1964, 1966). Papers on these studies also presented information on water movements, mixing and the heat content of the lake.

Recently attention has again focused on these offshore waters and new data on temperature and other limnological parameters have been collected as part of ongoing eutrophication studies by UFFRO and KMFRI in cooperation with institutes and researchers in Canada, the USA and Israel (Ochumba & Kibaara, 1989; Bugenyi & Magumba; 1990*a,b*; Hecky & Bugenyi, 1992; Bugenyi, 1992; Anonymous, 1992*a,b*; Hecky, 1993; Gophen *et al.* 1993; Hecky *et al.* in review).

In Appendix 2 an overview is given of papers providing data on physics and related chemistry of Lake Victoria's offshore waters. Unpublished data of routine/occasional sampling at offshore stations are available at the research stations of UFFRO, KMFRI and TAFIRI. Technical and annual reports of the institutes may also provide additional information. The locations of the main sampling stations given in Appendix 2 are shown on the maps in Chapter 4.

Seasonal and diurnal temperature patterns have been described for inshore waters in the vicinity of the three research institutes: in Uganda the bays and channels between Jinja and the northern offshore station, in Kenya the Nyanza Gulf, and in Tanzania the Mwanza Gulf. The most important papers providing data on temperature and related dissolved oxygen distribution are listed in Appendix 3.

Recent observations on the offshore waters revealed limnological changes as compared to the situation in the 1950 and 1960 (Hecky, 1993). In the following summary, the situation in the 1950s and 1960s is first discussed, after which observations of recent research are provided. Data from recent observations were presented at the National Science Foundation Workshop at Jinja and the 25th SIL Congress at Barcelona in August 1992; these will be published in forthcoming papers in 1993 (Anonymous, 1992*a*; Hecky, 1993; Mugidde, 1993; Lehman & Branstrator, 1993; Hecky *et al.* in review).

## OFFSHORE WATERS

### Thermal structure

Due to the rapid change in the density of water with temperature at the temperatures prevailing in Lake Victoria (24–26 °C), as in other tropical lakes, small temperature differences may result in a stable density stratification of the water column.

On the basis of his own observations in 1956 and 1960–1961 at the open lake station (Talling, 1957*a*, 1966) and of observations of Graham (1929), Worthington (1930), Fish (1957), and Newell (1960), Talling concluded that the offshore waters of Lake Victoria are probably monomictic and he distinguished three phases in the annual stratification cycle (Figure 6.1):

#### *Phase 1 [Sept.–Dec.]*

Warming up of the surface water initially creating a small discontinuity in the upper part of the water column. In November and December, the thickness of the upper layer varies through wind action and temperature gradients are generally centred upon two small discontinuities. This phase is marked by rising water temperatures at the surface from 24 °C to 25.4 °C and at the bottom from 23.5 °C to 24 °C. The heat content of the water column rises.

#### *Phase 2 [Jan.–May]*

Stratified conditions with a single deep discontinuity between 30–60 metres create a thick mixed layer. Short temporary isothermal states of the water column (in the northern part of the lake) may alternate with stratified conditions with a superficial gradient above the deep discontinuity. The heat content of the water column rises further and in March it reaches its maximum, after which cooling begins.

#### *Phase 3 [June–Aug.]*

Surface water temperatures fall to a minimum in the coolest and most windy period of the year. The water column becomes isothermal in June and in July and in the first half of August isothermal cooling of the water column takes place. The heat content of the water column falls in this phase to its minimum.

The main determinant of the stratification cycle is the wind, since solar radiation is relatively constant throughout the year with daily averages fluctuating between 400 and 450 cal/cm/day in the northern part of the lake and between 470 and 510 cal/cm/day in the southern part. There may also be a substantial loss of heat by radiation at night, as this is a period of relatively clear skies. Breakdown of stratification in June to August caused by increased evaporative cooling as a result of the strong SE. trade winds as observed in Lake Malawi and Tanganyika is probably not occurring in Lake Victoria, as pan evaporation data did not show an increased evaporation in those months (Piper *et al.* 1986). There is some evidence that the breakdown of stratification takes place first over the shallower western areas of the lake, and then it spreads over to the north and the east in relation to uneven surface cooling. Water at temperatures below 24.6 °C were observed at the surface along the western shore near Bukoba in May 1960, while elsewhere in the lake these temperatures were only observed in deep water layers below the thermal discontinuity (Talling, 1962).

In August stratification develops with the onset of calmer weather. During the period of stratification (August–May) changes in thickness of the mixed layer are induced by variations in wind stress. This may occasionally even lead to isothermal conditions in the water column as observed in January 1957 by Fish (1957) and in January and March 1961 by Talling (1966). In view of the stratified conditions in other parts of the lake and the rapid reappearance of stratification, these isothermal situations were caused by tilting of the discontinuity across the lake (Talling, 1966). Stratification may be reinforced by nocturnal sinking of cool surface water from nearshore shallows to deeper parts in the lake (Talling, 1963).

Recent observations at the open lake station revealed higher temperatures in epilimnion waters in 1991 than in the 1960s (Hecky, 1993). Hypolimnion water temperatures as low as 23.5 °C, observed in 1952–1953 (Fish, 1957) and earlier in 1927–1928 (Graham, 1929) were not seen during recent studies in Uganda and Kenya (Hecky *et al.* in review). These data suggest a response of the lake to a possible warming trend of the climate of East Africa since 1960 (Hecky, 1993).

### Heat content

Talling (1966) calculated from his data in the period 1960–1961 and from the observations by Fish (1957) in the period 1952–1953 the changes in the heat content of Lake Victoria and estimated the annual heat budget between 9,000 and 11,000 cal/cm$^2$. Heat is lost mainly between March and August due to an increased evaporation caused by an increase in wind velocity and regained between September and March.

Stability of stratification is the amount of work required to render the water column of a lake thermally uniform without addition or substraction of heat. In tropical lakes not only the maximum stability, but also changes in stability are important. A single storm can lower the temperature of the upper mixed layer by 0.5°C resulting in a heat loss of 125 cal/cm$^2$. A greater stability was observed in the stratification cycle (August 1990–June 1991) com-

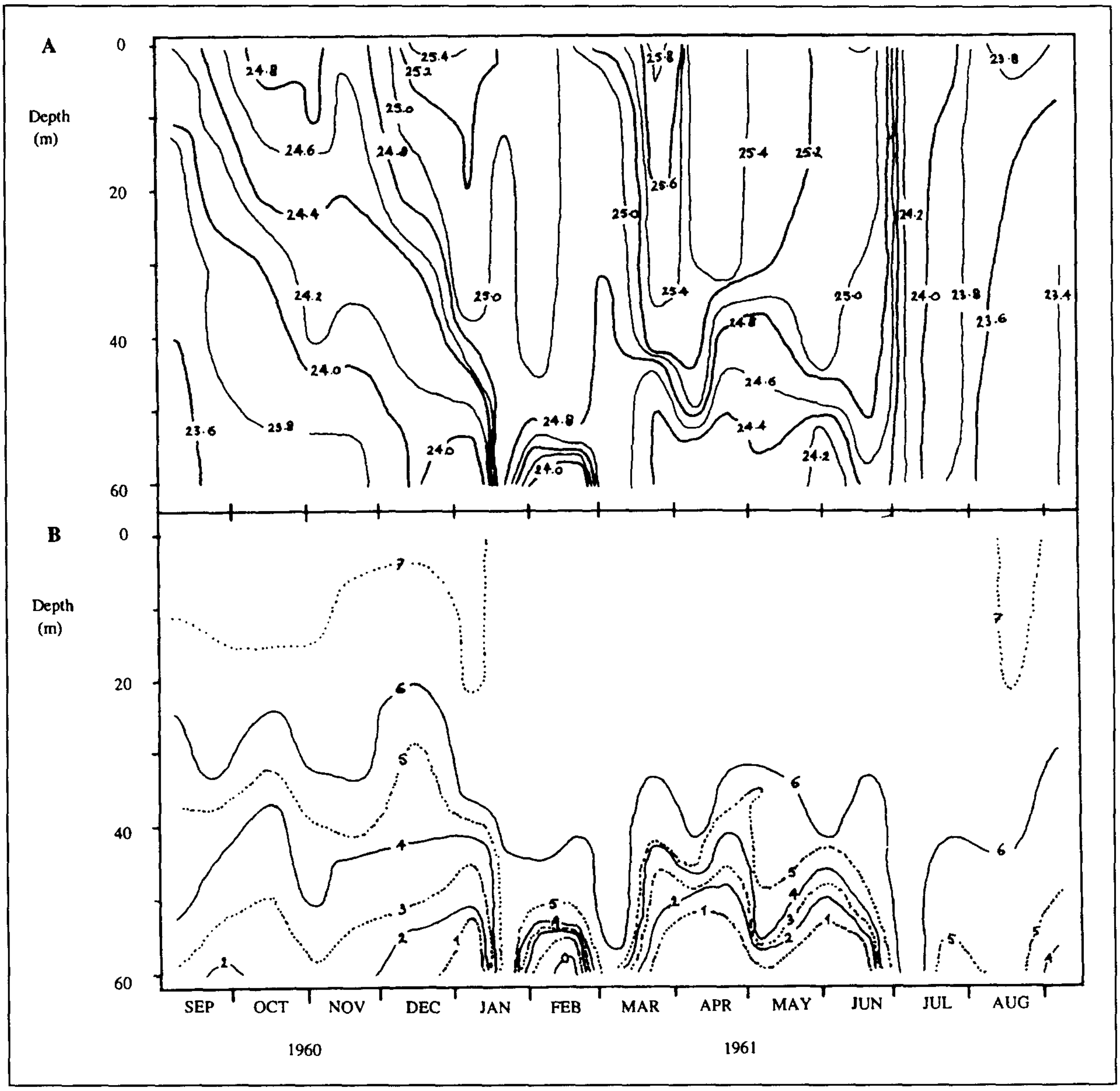

**Figure 6.1** Temperature and dissolved oxygen distribution in offshore waters (redrawn after Talling, 1966)

pared with the cycle of 1960–1961, although loss of stability occurred in April 1991, a month earlier than in 1961 (Hecky, 1993). Increased stability in the water column would have great implications for the thickness of the mixed layer during stratifications, with consequences for deep-water oxygen concentration.

## Mixing

Lakes in the tropics deep enough to stratify show a tendency to mix completely once a year, and for very deep lakes such as Lake Tanganyika and Malawi to mix deeply. Mixing in African lakes is mainly caused by a loss of stability resulting from evaporative cooling of the upper water column, although influx of cool rainwater and reduced insolation can be also significant (Livingstone & Melack, 1984).

Mixing during stratification is confined to the upper water layers. Thickness of the upper mixed layer fluctuates strongly in tropical lakes (Lewis, 1973, 1983, 1984). During storms and windy weather the upper mixed layer will thicken, and calm and sunny periods will result in a thin mixed layer superimposed on the old mixed layer. In this way multi-layer stratification may occur. Variability of the thickness of the upper mixed layer will have great implications for productivity and composition of phytoplankton.

Stratification may be broken by surface and internal waves bringing anoxic hypolimnion water to within the mixing depth at some points, or by violent storms deepening the wave-mixed layer to reach the lower anoxic layer. Kitaka (1972) gave evidence of mixing by a cyclonic storm in the offshore waters of Lake Victoria. This cyclonic upwelling may bring hypolimnion waters to the surface.

There are some indications of a decrease in thickness of the mixed layer in 1990–1991, although the frequency of sampling (monthly observations) was too low to quantify this (Hecky, 1993), taking into account the highly dynamic variations of the mixed layer in tropical lakes.

## Currents and water movements

Winds move water masses. Wind strength and direction determine the currents in the lake beside their effects on the vertical temperature distribution.

The wind regime of Lake Victoria is dominated by south-easterly trade winds, especially from May to July. The effect of the winds on the surface water would be a gradual displacement of surface water to the north. Graham (1929) already observed a west-north-west drift of water from the centre and southeastern portion of the lake using drift bottles. Current measurements by Newell (1960) indicated a general northward flow of surface water in response to the wind. This was accompanied by a compensating flow of deeper water southwards. In June 1957 a north to south section showed the presence of cooler bottom water in the south, which did not extend to the most northerly station (Talling, 1966).

In Lake Victoria surface water movements are common, as the fetch of the lake is huge, about 400 km. Fish (1957) showed that the hydrology of the lake is to a large extent controlled by the action of the wind on the surface water. Horizontal variation of the thermal structure was observed during a cruise around the lake in May 1961 which may have been caused by strong horizontal water movements coupled with tilting or local breakdown of the thermal discontinuity. Internal seiches are uncertain; the one observed by Fish (1957) was disputed by Newell (1960).

Winds conditions in inshore gulfs and bays may differ considerably from those offshore. Wind circulation in the Nyanza Gulf is controlled by the topography of the region, as hills bordering the gulf form a barrier to the free flow of the winds (Ochumba, 1983). Studies in Nyanza Gulf measured surface currents which readily followed changes in wind direction, with velocities between 0.22 and 28.67 cm/sec from the open lake into the various bays and Nyanza Gulf due to a prevailing wind from the South-west or North-west ranging from 0 to 13.4 m/sec and with a mean of 4.36 m/sec (Ochumba, 1986).

## Dissolved oxygen distribution

Stratification strongly affects the distribution of dissolved oxygen in the water column. Seasonal changes of dissolved oxygen at the offshore station reflect closely the three main phases of thermal stratification (Fig. 6.1) and the general pattern of oxygen distribution in the offshore waters is as follows (Talling, 1966):

- In the first phase of weak stratification vertical gradients extend over most of the water column.
- During the second phase of stronger stratification they are concentrated in the lower part of the column centred upon the thermal discontinuity.
- In the third phase with more or less isothermal conditions oxygen is uniformly distributed through the water column.

Oxygen concentrations in surface water during 1960–1961 were mostly close to saturation (94–103%). Only at times of isothermal mixing were lower saturation levels observed (91% in January and 90% in July). Fluctuations of the upper mixed layer may be traced by the changes of the mean oxygen content of the upper part of the water column. Low oxygen concentrations (below 10% saturation) were measured occasionally in the period between January and June in the water layer close to the bottom sediments below 55 metres.

At present, the deep offshore waters contain less oxygen than in 1960 and anoxia below 45 metres was frequently encountered during the stratified period of October–March 1990–1991, affecting up to 50% of the lake's bottom area for prolonged periods of time (Hecky *et al.* in review). On the other hand surface waters are now saturated or supersaturated with oxygen throughout the year. The higher mean oxygen concentrations now are a result of an increase in photosynthesis (Mugidde, 1993) (see also Chapter 8). Oxygen levels up to 13 mg/l were observed during blooms of blue-green algae in the Kenyan offshore waters (Ochumba & Kibaara, 1989).

# INSHORE WATERS

## Thermal structure

Lake Victoria, the largest lake in Africa, has a large number of more or less isolated bays and gulfs, with different temperature patterns for the inshore waters depending on local climatic and geographic conditions. Shallow areas of large, deep lakes can be compared with shallow lakes which undergo diurnal stratification, such as Lake George, of which the water column is heated right through and stable stratification does not occur. These lakes do not exhibit prolonged stratification except for during short periods of calm weather.

The following general remarks can be made on the temperature distribution in inshore waters:

- In channels and bays with depths of up to 30 metres stratification develops much earlier and breaks down earlier than offshore in the lake. Fish (1952, 1957) observed thermal stratification in the Buvuma channel between August and December and a breakdown of stratification in December. The onset of stratification is probably due to the greater shelter from wind action by the surrounding islands.
- In the moderate shallow part of the Mwanza Gulf (with a depth of 14 metres) temperature observations of HEST (van Oijen *et al.* 1981, Goldschmidt unpubl. data) showed that more or less isothermal conditions prevailed during most of the year. Only in the main rainy season (February-March) stratified conditions are observed during short periods of calm weather.
- Inshore areas with depths of less than 10 metres do not become stratified except on a daily basis (Worthington, 1930; Fish, 1957; Talling, 1957*b*). The water column in the Nyanza Gulf is usually isothermal in the early morning and may

become stratified from 10.00 hours onwards due to increasing air temperature and solar radiation and absence of strong winds. Daily offshore afternoon winds will break down stratification resulting in an uniform vertical temperature distribution (Ochumba, 1983). In Mwanza Gulf (at a station with a depth of eight metres) stratification did not occur during all year around sampling in 1974 (Akiyama *et al.* 1977). This is in accordance with van Oijen *et al.* (1981), who observed no stratification at a 7.5 m-depth station in the Mwanza Gulf while at the same time a 14 m-depth station was stratified.

## Dissolved oxygen distribution

Inshore areas are generally well oxygenated from surface to bottom. Low levels of oxygen were only observed in the deeper inshore waters, when a thermal discontinuity developed during a period of calm weather, e.g. in Buvuma Channel (Fish, 1957) and in the Mwanza Gulf in April 1980 and in March 1983 (Van Oijen *et al.* 1981; Goldschmidt pers. comm.). In shallow waters, as found at Pilkington and Ekunu Bay and Nyanza Gulf, fluctuations in oxygen content occur which are correlated with diurnal stratification (Fish, 1957; Ochumba, 1983).

# 7 Nutrient dynamics

## INTRODUCTION

Besides light and temperature, nutrients can limit algal productivity in aquatic ecosystems, although the high temperatures in the tropics allow rapid nutrient recycling. Lake Victoria is situated on the equator, and temperature and solar radiation which ranges between 400 and 500 cal/cm$^2$/day are sufficient for photosynthesis all year around. The elements required in largest amounts for plant production are carbon, phosphorus and nitrogen, while silicon is of importance to diatoms as a major component of the cell wall. Sulphates may also play a role in limiting phytoplankton productivity in Lake Victoria. Stratification and mixing control the annual cycle of nutrient concentrations in the mixed layer of the lake (Talling, 1966).

In this Chapter the ionic composition is summarized, followed by a description of the nutrient cycles and the main forces controlling them. As recent research in inshore and offshore waters has revealed large changes in concentrations of some nutrients (Hecky & Bugenyi, 1992; Hecky, 1993), the concentrations observed in 1960 by Talling (1966) will be compared to the present levels (Hecky, 1993).

## IONIC COMPOSITION

Lake Victoria has a 'common' water type. The ionic composition is a product of deep weathering profiles of granitic and metamorphic rocks of the African plateau and is hardly influenced by volcanic terrain (Kilham & Hecky, 1973). The chemical composition of the dilute African waters with less than 600 ppm is largely controlled by rock weathering (Kilham, 1990). The water budget of Lake Victoria is dominated by rainfall (see Chapter 5). The lake is relatively shallow (compared to the lakes Tanganyika and Malawi) and mixes completely at least once a year.

Data on ionic composition and/or nutrient concentrations have been provided by EAFRO (1952), Talling & Talling (1965); Talling (1966, 1976*a*), UFFRO (Bugenyi & Magumba, 1990; Bugenyi, 1992); Akiyama *et al.* (1977); Ochumba (1990); Ochumba & Kibaara (1989); Hecky & Bugenyi (1992); Hecky (1993).

As the lake has undergone large changes in chemistry, especially in the last 30 years, which are not yet fully understood, chemical parameters in the offshore waters in 1960 are compared to those in the present situation (Table 7.1).

The following conclusions can be drawn from the available data (Hecky, 1993). The silicon concentrations have decreased from 70 to 7 µM due to increased photosynthetic activity of diatoms and may become lower than 1.0 µM at times. Total P concentrations are similar or somewhat higher than in 1961. Due to deep water deoxygenation, denitrification may have increased in the present Lake Victoria. This resulted in lowering the ratio of Total N to Total P from 16:1 in the mixed layer to 8:1 in the hypolimnetic waters. A low N:P loading rate during mixing will favour heterocystous blue-green algae which constitute at present the dominant phytoplankton group. The 16:1 ratio of TN:TP in the mixed layer is maintained by nitrogen fixation by these cyanobacteria.

**Table 7.1** The chemistry of Lake Victoria in March 1961 (Talling & Talling, 1965) and May 1988 (Hecky, org. data, in Hecky & Bugenyi, 1992), and the chemistry of rain in 1991 (Lehman & Branstrator, 1993). (All concentrations in µM)

| | *L. Victoria 1961* | *L. Victoria 1988* | *Rain 1991* |
|---|---|---|---|
| Na | 450 | 340 | |
| K | 97 | 90 | |
| Ca | 140 | 120 | |
| Mg | 110 | 90 | |
| DIC | – | 920 | |
| Cl | 110 | 93 | 46 |
| $SO_4$ | 24 | 3 | 70.3 |
| SRSi [1] | 69.8 | 7.1 | 2.0 |
| $NO_3$–N | 0 | 0.2 | 7.07 |
| $PO_4$–P (SRP) | 0.42 | 0.23 | |
| Total P | 1.52 | 1.13 | |
| Alkalinity (me/l) | 0.92 | 0.84 | |
| Conductivity (µS/cm) | 97 | 94 | |

[1] Modern analytical treatments present silicon data in terms of 'soluble reactive silicon' concentration (SRSi) or $Si(OH)_4$ concentration. In a large number of earlier studies (e.g. Talling, 1966) equivalent silica ($SiO_2$) concentrations are cited. Conversion of units may be derived from: 1 mg $SiO_2$/l ≡ 0.47 mg Si (or SRSi)/l ≡ 17µg-at Si/l ≡ 17 µM $Si(OH)_4$.

Differences occur between offshore and inshore waters. In inshore waters denitrification occurs only in the sediments when depth is shallower than the offshore mixed layer. Total N concentrations and N:P ratios are higher inshore allowing higher photosynthetic rates and maintaining chlorophyll concentrations 2–3 times higher than offshore.

## NUTRIENT CYCLES

Distribution of the main plant nutrients nitrate ($NO_3$–N), ammonium ($NH_4$–N), phosphate ($PO_4$–P) and silicon (Si) is governed by physical factors such as changes in mixing depth during stratification and complete mixing during isothermal conditions and by biological processes such as algal photosynthesis. Cycles of main nutrients in the offshore and northern inshore areas have been determined together with the stratification cycle by Talling (1965*a*,*b*; 1966). Only for $NH_4$–N no historic data are available. During stratification the nutrients $NO_3$–N, $PO_4$–P and Si showed accumulation in the lower layers of the water column and more uniform concentrations at times of isothermal mixing. Phytoplankton and especially diatoms strongly increased in biomass after isothermal mixing, which brought nutrients back to the euphotic zone. Diatom blooms led to a lowering silica concentration decreasing to 3.0 mg $SiO_2$/l (≡ 1.4 mg SRSi/l ≡ 50 µM SRSi) in offshore waters. In inshore bays even lower concentrations were observed during diatom blooms, but concentrations lower than 1 mg $SiO_2$/l potentially limiting diatom growth, were not observed. In general, concentrations of silica remained above 4 mg/l $SiO_2$ in the 1960s (Talling, 1966). Nitrate concentrations were low throughout the year and rarely exceeded 10 µg $NO_3$–N/l in the upper 30 metres of the water column (Talling, 1966). The concentrations of $PO_4$–P remained above 7 µg/l most of the year in the upper part of the water column, which is high for fresh waters. Total phosphorus concentrations were considerably higher and fluctuated between 30 and 50 µg/l in the upper layers of the water column.

In Lake Victoria sulphates have been in short supply in the water and Fish (1956) suggested that it might be a limiting factor for growth of phytoplankton. Many rivers showed a similar shortage which led to the suggestion that soils in Africa might be deficient in sulphates (Beauchamp, 1953), which was confirmed by several Agricultural Departments (EAFRO, 1958). Large quantities of sulphur were found in bottom deposits, not in the form of sulphides but in organic combinations. Sulphur inputs via rain, surface runoff and river discharge were low (Hesse, 1956). Hecky & Bugenyi (1992) suggest a possible role of sulphate as limiting factor for algal productivity in the present situation. Lehman & Branstrator (1993) eliminate this for Lake Victoria, as the results of their nutrient bioassay experiments revealed that nitrogen is the most limiting nutrient element to the phytoplankton of Lake Victoria.

Concentrations of two other elements, iron and manganese, were also governed by stratification. Accumulation took place as a result of chemical reduction in the deeper layers near the bottom with low oxygen concentrations during the periods of strong stratification.

## NUTRIENT LOADING

Nutrient sources include atmospheric deposition, riverine input, nitrogen fixation, and the upward flux of nutrients from the water layers below the epilimnion (Bootsma & Hecky, 1993). Rain falling direct onto the lake may contribute significant quantities of minerals and nutrients. The main source of nitrogen in rainwater is atmospheric dust and possibly the oxidation of nitrogen gas to nitrate by photochemical action or even by lighting discharges (Visser, 1964, 1974).

The P concentration in rain on the north shore of Lake Victoria appears to have increased dramatically over the last three decades, possibly associated with increased burning and soil erosion, while both nitrogen and sulphur appear to have changed little since 1961 (Bootsma & Hecky, 1993).

An important supply of nitrogen is the fixation of the elemental nitrogen in the air by both blue-green algae (e.g. *Anabaena*) and bacteria. Phytoplankton composition in Lake Victoria has changed towards a dominance of nitrogen-fixing blue-green algae (see Chapter 8) (Hecky, 1993). Current nitrogen-fixation rates in Lake Victoria are high, of the order of 0.02 mmol/m$^3$/h in inshore and offshore waters (Hecky, 1993).

Recent paleolimnological studies of a sediment core in 55 metres of water off western Kenya revealed increased deposition rates of N and P which are likely the result of watershed and airshed disturbance. This eutrophication of Lake Victoria may already have started in the 1920s. The rise in Si and P deposition pre-dated the outburst in Nile perch populations in the early 1980s (Hecky, 1993).

# 8

# The biotic environment

## THE PHYTOPLANKTON COMMUNITY

### Phytoplankton studies

The phytoplankton of Lake Victoria has been studied floristically since 1888 and by quantitative ecological methods since 1950 (see Appendix 1). Primary productivity has been studied by Talling (1957*b*, 1965*a,b,c*), Richardson (1964) and Melack (1979). Recent and ongoing research includes studies on massive fish kills by Ochumba (1987, 1990) and on blue-green algal blooms in the Kenyan waters of the lake by Ochumba & Kibaara (1989), primary productivity studies by Mugidde (1993), diatom species composition in Murchinson Bay by Byarujali (1992) and a study on the effects of grazing and nutrient enrichment on net growth rates of phytoplankton by Lehman & Branstrator (1993) in the northern Ugandan waters, and phytoplankton studies in the Mwanza Gulf and Luansa Bay (Tanzania) by Kashindye (1992). Several new blue-green algae were identified by Komarek & Kling (1991). The phytoplankton composition, distribution and productivity in the 1960s as described by Talling (1966, 1976*b*, 1987) will be compared with recent data (Ochumba & Kibaara, 1989; Hecky, 1993; Mugidde, 1993; Gophen *et al.* 1993).

### Species composition

Species composition was thought to have been more or less stable since 1888, an idea not surprising in view of the large size of the lake and the minimal industrial development around it. However, recently a shift towards blue-green algae dominance has been observed, probably caused by changes in the ecosystem of the lake due to eutrophication, the introduction of Nile perch and possibly climate changes in the last decades (Hecky, 1993).

Phytoplankton in the 1960s was largely made up of blue-green algae, diatoms and green algae (Talling, 1987). Generally an abundant and often dominant component of the phytoplankton were the small coccoid blue-green algae of the genus *Aphanocapsa*. Other blue-greens in the offshore waters were *Microcystis* spp., *Anabaena* spp., *Anabaenopsis tanganyikae* and *Lyngbya circumcreta*. The latter was most abundant in inshore waters. *Melosira nyassensis* var. *victoriae* was the most abundant diatom of the offshore region. This species and other diatoms followed vertical mixing in the offshore waters. Another diatom, *Nitzschia acicularis*, may seasonally predominate in inshore bays and gulfs. *Stephanodiscus astrea* and smaller *Cyclotella* spp. are seasonally common offshore. *Surirella* and *Cymatopleura*, both very variable in form, were widespread in the plankton. Green algae are exceptionally diverse, although quantitatively they are not so important as the species mentioned above. Species of the genera *Staurastrum* and *Coelastrum* are the most abundant species of the desmids and the Chlorococcales respectively. There was a pronounced differentiation between the plankton communities of inshore and offshore regions. Species useful as indicators of inshore water are *Merismopedia* spp. and *Melosira ambigua*. Larger desmids are characteristic of the open lake.

A group of phytoplankton so far overlooked has been the picoplankton. A recent sample revealed moderate numbers ($3.70 \times 10^4$ cells/ml) in the Nyanza Gulf (Kenya) in 1987 (Hawley & Whitton, 1992).

Recent research has revealed changes in species composition. Species of the genus *Melosira* which often dominated the inshore and offshore waters in the 1960s, have been replaced throughout the year by dominant N-fixing cyanobacteria (Hecky, 1993). This shift may be explained by declining Si concentrations and the low N/P loading ratio. The so-called N/P hypothesis which states that low N/P ratios benefit blue-green algae, both nitrogen-fixing and non-fixing, is one out of six hypotheses to explain blue-green dominance (Shapiro, 1990). *Melosira* is now even absent from the lake, except for some marginal bays and areas near river inflows, where Si remains available (Hecky, 1993), as observed by Ochumba & Kibaara (1989) near the inflows of Nzoia and Migori rivers in 1986 and by Kashindye (1992) in the Mwanza Gulf (Tanzania).

Observations on the phytoplankton in the Kenyan waters of Lake Victoria in 1988–1990 (Gophen *et al.* 1993) revealed that it was characterized by a high diversity and high abundance of Cyanophyta, a high diversity and low abundance of Chlorophyta and a relatively low diversity and relatively high abundance of diatoms. The Dinophyta, Cryptophyta and Euglenophyta were represented by a low number of species.

## Seasonal fluctuations

Seasonal fluctuations of the dominant diatoms and blue-green algae were described by Fish (1952, 1957), Talling (1957, 1965*a*) and Akiyama *et al.* (1977).

In the 1950s and 1960s the lake was characterized by a well-developed, seasonal variable diatom flora with species of the genus *Melosira* and *Nitzschia* dominating the annual maximum of phytoplankton biomass in August, after the period of complete mixing (Fish, 1957; Talling, 1966). A second maximum developed in the upper layers during November-December when blue-green algae were predominant in the phytoplankton (Talling, 1966).

Vertical mixing is probably the most important source of seasonal change. The response of algae to increased mixing varied from strongly positive (diatoms, *Coelastrum* spp. ) through weak or indifferent (desmids) to negative or delayed (blue-green algae) (Talling, 1987). Contrasts in vertical seasonality are clearly shown in depth-time profiles of *Melosira nyassensis* and *Anabaena flos-aquae* in 1960–1961 in offshore waters (Talling, 1966).

## Vertical and horizontal distribution

Vertical distribution patterns of the phytoplankton are of importance in relation to the depth of the euphotic zone. Differences in vertical distribution of the various species during stratification may be explained by different rates of sinking and differing degrees of resistance to the condition of the nearly deoxygenated lower layer. The types of distribution observed in the 1960s were summarized in four classes (Talling, 1963):

I. Maxima in the upper layers (0–30 m): *Aphanocapsa elachista*, *Botryococcus braunii* and *Ceratium brachyceros*.
II. Nearly uniform distribution: *Staurastrum* spp.
III. Weak maxima in the lower layers (30–60 m): *Cyclotella kutzingiana*, *Nitzschia acicularis*.
IV. Strong maxima in the lower layers (30–60 m): *Melosira nyassensis* var. *victoriae*, *Pediastrum clathratum*.

Total phytoplankton biomass can be obtained from chlorophyll-*a* measurements. Chlorophyll-*a* concentrations in offshore and inshore waters measured since 1960 are summarized in Table 8.1.

Inshore bays typically supported much higher phytoplankton densities. In the 1960s, chlorophyll-*a*

**Table 8.1** Chlorophyll-*a* concentrations in offshore and inshore waters

| *Date* | *Location* | *Depth (m)* | *Chlorophyll-a* | | *Source* | *Remarks* |
|---|---|---|---|---|---|---|
| | | | *Range (mg/m³)* | *mean (mg/m³)* | | |
| *Offshore* | | | | | | |
| 1960–61 | Open water station | 60 | 1.2–5.5 | – | Talling, 1965 | 14 observ. in 10 months |
| 1990–91 | Bugaia | 60 | 8.4–40 | 24.5 | Mugidde, 1993 | 15 observ. in 15 months |
| *Inshore* | | | | | | |
| Feb.-Apr. 61 | Pilkington Bay | <9 | 10–15 | 12.5 | Talling, 1965 | 2 observ. |
| Dec. 60 | Nyanza Gulf | | 21 | | Talling, 1965 | |
| Dec. 73 | Nyanza G. (Homa Bay) | | 17 | | Melack, 1979 | 1 observ. |
| 1973–74 | Mwanza Gulf | | 2–8.5 | | Akiyama *et al.* 1977 | 20 observ. in 22 months |
| – | Nyanza Gulf | | | 17.8 | Ochumba & Kibaara, 1989 | Data from Winam Gulf Baseline Study Report 1985 |
| 1990–91 | Pilkington Bay | <9 | 22.2–67.1 | 46.7 | Mugidde, 1993 | 15 observ. in 15 months |
| 1985–86 | Open lake stations, Kenyan waters | 10–40 | 8.0 -77.6 | – | Ochumba & Kibaara, 1989 | |

concentrations in the Nyanza Gulf ranged between 17–21 mg/m$^3$ as compared with 1.2–5.5 mg/m$^3$ in the offshore region (Talling, 1965*a*, 1966; Melack, 1979).

Presently, inshore waters have two–three times higher chlorophyll-*a* concentrations than offshore waters and the chlorophyll-*a* concentrations in both the offshore and inshore waters have increased markedly as compared to the concentrations in the 1960s (Mugidde, 1993).

## Light penetration

Photosynthesis is restricted to the euphotic zone ($z_{eu}$). The lower limit of the euphotic zone is defined as the depth at which light is reduced to 1% of its value at the surface. Underwater irradiance measurements have only been carried out in Lake Victoria on a limited number of occasions. The euphotic zone in Lake Victoria in the 1960s ranged between 15 and 20 m offshore and between 2 and 5 m in inshore waters (Talling, 1965). Recent measurements have shown a decreasing euphotic depth in offshore waters (Bugaia Station) ranging between 7.8 and 29.2 m (with a mean of 14 m). Inshore, in Pilkington Bay, the euphotic zone ranged between 3.7 and 6 m (mean 5 m) (Mugidde, 1993). Other light measurements were carried out in Kenyan open lake waters near the inflow of the Nzoia River (St. 53) by Ochumba & Kibaara (1989) (euphotic zone 4 m) and in the Mwanza Gulf (Tanzania) by de Beer (1990).

An approximate evaluation of water transparency can be made with a Secchi disk, a 20-30 cm full white disk (or with black and white quadrants). Secchi disc transparencies correlate well with percentage transparency. In comparison to measurements with underwater photometers, The depths of Secchi disc transparency most commonly vary between 10% and 15% transmission (Wetzel & Likens, 1991). Ranges of Secchi disk readings are given for several locations in Lake Victoria in Table 8.2. The reduction of the euphotic zone due to the increased phytoplankton biomass was also observed in the Secchi disk readings which decreased from 7–8 m in 1928 (Worthington, 1930) to 1.3–3 m in 1990s (Mugidde, 1993).

Transparency in Lake Victoria may fluctuate temporally and spatially due to differences in plankton density and may be significantly reduced during algal blooms (Ochumba & Kibaara, 1989).

**Table 8.2** Secchi disk readings in inshore and offshore waters since 1927

| *Date* | *Location* | *Depth (m)* | *Secchi disk readings* | | *Source* | *Remarks* |
|---|---|---|---|---|---|---|
| | | | *Range (m)* | *(No. observ.)* | | *(measurement technique)* |
| *Inshore* | | | | | | |
| Oct.–Nov.1927 | Nyanza Gulf | 9–11.8 | 1.3–1.45 | 2 | Worthington, 1930 | white disk, 20 cm |
| Aug.–Sept. 1973 | Nyanza Gulf | n.a. | 0.75–1.4 | | Melack, 1979 | white disk, 20 cm |
| Jun. 1984 | Nyanza Gulf | n.a. | 0.35–1.55 | | Burgis *et al.* 1988 | n.a. |
| Nov. 1986 | Nyanza Gulf | 7–14 | 0.7–0.95 | | HEST 4th Quart.Rep.86 | n.a. |
| Sept.–Oct. 86 | near river inflows | 5–15 | 0.5–1.2 | 6 | Ochumba & Kibaara, 89 | disk 20cm; sts 51,53,105 |
| Feb.–May | near river inflows | 5–15 | 0.3–0.8 | 5 | Ochumba & Kibaara, 89 | disk 20cm; sts idem; algal blooms |
| Jan. 1928 | Speke Gulf | 5–7 | 0.6–0.95 | 3 | Worthington, 1930 | white disk, 20 cm |
| Feb .1928 | E.Pasha Gulf | 10 | 1.8 | 1 | Worthington, 1930 | white disk, 20 cm |
| Apr.–Dec. 73 | Mwanza Gulf | 8 | 1.4–1.8 | | Akiyama *et al.* 1977 | white disk, 20 cm |
| Jan.–Dec. 74 | Mwanza Gulf | 8 | 1.1–1.9 | | Akiyama *et al.* 1977 | white disk, 20 cm |
| Feb.–Apr. 1980 | Mwanza Gulf | 7–14 | 1.8–2.5 | | Van Oijen *et al.* 1981 | white disk, 30 cm |
| Nov. 1986 | Mwanza Gulf | 7–14 | 0.7–0.9 | 6 | HEST 4th Q.Rep. 1986 | white disk, 30 cm |
| Mar.–May 1987 | Mwanza Gulf | 7–14 | 0.85–1.25 | | de Beer, 1990 | Bl.& wh.disk, 30 cm |
| 1989–91 | Pilkington Bay | <9 | 0.8–1.7 | 15 | Mugidde, 1993 | white disk, 20 cm |
| 1990–91 | Nyanza Gulf | 3–15 | 1.4 (mean) | | Gophen *et al.* 1993 | Bl.& wh.disk, 20 cm |
| 1990–91 | Rusinga Ch.(deep) | 30–56 | 2.0 (mean) | | Gophen *et al.* 1993 | Bl.& wh.disk, 20 cm |
| 1990–91 | Rusinga Ch. (shallow) | 4–11 | 1.5 (mean) | | Gophen *et al.*1993 | Bl.& wh.disk, 20 cm |
| *Offshore* | | | | | | |
| Jan. 1928 | off Sango Bay | 17 | 5.5 | 1 | Worthington, 1930 | white disk, 20 cm; sandy bottom |
| Sept. 1927 | open waters | 60–69.5 | 7.3–7.9 | 5 | Worthington, 1930 | white disk, 20 cm |
| Jan. 1928 | open waters | 37.5–61 | 6.4–8.2 | 4 | Worthington, 1930 | white disk, 20 cm |
| Sept.–Nov. 85 | open waters Kenya | 25–40 | 1.3–2.5 | 6 | Ochumba & Kibaara, 89 | disk 20 cm; sts 32,35,103 |
| Feb.–May 86 | open waters Kenya | 25–40 | 0.2–1.7 | 5 | Ochumba & Kibaara, 89 | disk 20 cm, sts idem; blooms |
| 1989–91 | Bugaia | 60 | 1.3–3 | 15 | Mugidde, 1993 | white disk, 20 cm |
| 1990–91 | offshore Kenya | 28–66 | 2.1 (mean) | | Gophen *et al.* 1993 | Bl.& wh.disk, 20 cm |

Bottom type and depth also influence transparency (de Beer, 1990), as well as the stirring-up of sediments during periods of mixing and the silt load of inflowing rivers during the rainy season.

### Phytoplankton photosynthesis

Primary productivity measurements are summarized in Table 8.3. Recent research (Mugidde, 1993) suggests a higher primary productivity throughout the year than in the 1960s. The daily productivity per unit area in offshore waters increased from an average of 7.4 $gO_2/m^2/day$ in the 1960s (Talling, 1965*a*) to 13.9 $gO_2/m^2/day$ in 1990 (Mugidde, 1993). In Pilkington Bay, inshore productivity increased from an average 10.6 in the 1960s to 22.3 $gO_2/m^2/day$ nowadays, which is about 62% higher than offshore.

The study also revealed that productivity has not increased in proportion to chlorophyll-*a* concentration and that the lower rates of photosynthesis per unit chlorophyll-*a* now indicate a less efficient photosynthetic system than in the 1960s. The results of the study also suggest that photosynthesis in Lake Victoria is now light-limited.

## MACROPHYTES

### Swamps

Papyrus (*Cyperus papyrus*) is the most widespread swamp plant of central and eastern tropical Africa. For permanent establishment, papyrus requires an almost continuously waterlogged soil. It disperses primarily by the branching growth of rhizomes. When it spreads out from the shore, the rhizome mat actually floats on an entrapped mass of decomposing organic matter and silt, forming a gas-rich floating layer of soil. An important feature of these floating mats is that there is no limit to the depth of water above which they can flourish.

Along the coasts and island shores of Lake Victoria dense papyrus often merges into the open water. These lakeside papyrus beds are influenced by winds and currents which frequently tear off parts of these mats. Floating papyrus islands are a familiar feature of the inshore waters of Lake Victoria after stormy weather.

Like most other African swamps, swamps on the shores or in the vicinity of Lake Victoria are characterized by the presence of tall vegetation dominated by papyrus. The swamps are common in the flat areas in the northern and southern part of the lake. Of all African wetlands (swamps, marshes, bogs, floodplains) swamps have been studied in most detail. Work on papyrus swamps in Uganda was carried out by Beadle (1932), Carter (1955), Beadle & Lind (1960), Visser (1964), Gaudet (1975, 1976, 1977) and Thompson (1976). An extremely important feature of swamps is their buffering capacity. Beadle (1932) already observed that a papyrus swamp blocking a small river in Western Uganda removed phosphate from the water passing though it. The swamps bordering the lake provide a natural filtering of inflows, and are very important as fish breeding sites and refuges. Reclamation of the remaining swamps around the shores of Lake Victoria may have serious implications for the lake as the reduced natural buffering capacity would lead to a further eutrophication of the lake.

### The water hyacinth

The water hyacinth *Eichhornia crassipes* was introduced to the African continent in the early part of this century, first in Egypt followed by South Africa. It consequently spread to other countries in southern Africa and appeared in the Zaire River and the upper Nile swamps in Sudan in the 1950s. At present about 15 African countries have problems with this plant (Thompson, 1991*a*). In 1989 the water hyacinth was formally noted in Ugandan waters of Lake Victoria. It has been in the lake for probably no longer than 10 years. The source is undoubtedly the Kagera River, as large quantities of weed pass out of the mouth and the plant is well established along the fringes of the river throughout its meandering lowland section (Thompson, 1991*a*). The species is now widespread in Lake Victoria: in Uganda among the Sese Islands, along the western shoreline and in parts of the northern portion of the lake near Jinja (Twongo, 1992); it has also been observed in Kenya as well as the Mwanza Gulf in Tanzania (Witte *et al.* 1992*a*). The weed impedes navigation and fisheries, as it invades and covers breeding and nursery sites for fish species like Nile tilapia and Nile perch, it depletes

**Table 8.3** Primary productivity measurements in offshore and inshore waters

| *Date* | *Location* | *Depth (m)* | *Primary productivity ($gO_2/m^2/day$)* *Range* | *Mean* | *No. exp.* | *Source* |
|---|---|---|---|---|---|---|
| *Inshore* | | | | | | |
| Feb–Apr 1961 | Pilkington bay | <9 | 10.2–11.0 | 10.6 | 2 | Talling, 1965*a* |
| Aug–Sept 1973 | Nyanza Gulf | n. a. | 4.3–9.8 | 7.4 | 9 | Melack, 1979 |
| 1989–91 | Pilkington Bay | <9 | 8.9–36.2 | 22.3 | 14 | Mugidde, 1993 |
| *Offshore* | | | | | | |
| 1960–61 | Open water station | 60 | 4.9–11.4 | 7.4 | 14 | Talling, 1965*a* |
| 1989–91 | Bugaia | 60 | 8.2–20.4 | 13.9 | 14 | Mugidde, 1993 |

dissolved oxygen in the areas under the mats and makes fishing grounds and landing places inaccessible (Thompson, 1991*b*).

## ZOOPLANKTON

### Zooplankton research

Rzóska (1956, 1957, 1976) reviewed research on zooplankton of Lake Victoria, which started in 1888 when Emin Pasha and Franz Stuhlman took the first plankton sample. Mavuti (1983) reviewed the results of the expeditions and studies of individuals in the 1920s and 1930s collecting and describing zooplankton from the African Great Lakes. Information on distribution, seasonal changes and production of zooplankton is limited to Worthington (1931), Rzóska (1957), EAFFRO (1969), Green (1971), Okedi (1970), Akiyama *et al.* (1977), Ochieng (1981), Hoogenboezem (1985), Mavuti & Litterick (1991), Mwebaza-Ndawula (1990*a*,*b*; 1993) and Gophen *et al.* (1993).

### Zooplankton composition

The zooplankton of Lake Victoria belongs mainly to the common groups of Rotifera, Cladocera and Copepoda. Other planktonic organisms found amongst the zooplankton in the Kenyan waters of Lake Victoria were Microturbellaria, Hydracarina, Ostracoda, and larval stages of insects, especially Chaoboridae (Mavuti & Litterick, 1991). Rzóska's list (1976) of the zooplankton species of Lake Victoria included 20 species. Recent research yielded a checklist of 49 zooplankton species (of which 26 were Rotifera, 12 Cladocera and 19 Copepoda) recorded in the Winam Gulf between 1984 and 1987 (Mavuti & Litterick, 1991). The Copepoda are the dominant zooplankton in Lake Victoria (Rzóska, 1976; Akiyama *et al.* 1977; Hoogenboezem, 1985; Burgis *et al.* 1988; Mavuti & Litterick, 1991; Gophen *et al.* 1993). They contributed about 85% to the total zooplankton in all ecological zones in the Kenyan waters of the lake and the two most dominant species found at all stations were *Thermocyclops neglectus* and *T. emini* (Mavuti & Litterick, 1991). Dominant species of Cladocera in the Nyanza Gulf were *Bosmina longirostris, Diaphanosoma excisum* and *Moina macrourus* (Mavuti & Litterick, 1991). These species were also dominant in the Mwanza Gulf (Akiyama *et al.* 1977). Rotifers were widely distributed and dominated by brachioniids in both the Nyanza and Mwanza gulfs. Total zooplankton densities appear to decrease progressively from Kisumu Bay through the open waters of the Nyanza Gulf, Rusinga Channel to the main lake stations.

### Zooplankton distribution

The first observations on the vertical distribution of zooplankton were carried out by Worthington during the Fishing Survey in 1927, the first zooplankton investigation ever made on a tropical lake. The observations clearly showed well-marked diurnal migrations of all species, with animals rising to the surface by or soon after sunset and descending at dawn (Worthington, 1931). Observations on the vertical distribution of zooplankton in the Mwanza Gulf in September-October 1983 were given by Goldschmidt *et al.* (1989).

In the Mwanza Gulf seasonal fluctuations of zooplankton were observed in 1973/74 by Akiyama *et al.* (1977) and in 1984 by Hoogenboezem (1985). Copepods increased from May to August 1973 and decreased rapidly in September 1973. In 1974, fluctuations were less clear and in 1984 were similar to those observed in 1973. Cladocera were more abundant in the rainy season than in the dry season in 1973/1974.

## BENTHOS

The benthos of Lake Victoria has not been examined in a systematic way. In the 1950s and 1960s insect larvae were the main objects of study, since they constituted the main food of certain species of fish and particularly of young fish. Research focused on stomach contents of fishes in conjunction with studies of the biology, emergence and flight activity of aquatic insects. The first studies of benthic invertebrates were conducted by MacDonald who joined EAFRO in 1949 and worked in particular on the lake fly larvae (Chironomidae and Chaoboridae) (EAFRO, 1950; MacDonald, 1953). Quantitative studies on the distribution of insect larvae seem to have been carried out only once (MacDonald, 1956). *Chaoborus* larvae showed densities up to 2,500/m$^2$ and Chironomid larvae up to 1,000/m$^2$.

A few years later, in 1955, Corbet and Tjønneland initiated their research on aquatic insects at the EAFRO station at Jinja. They described the results of their extensive research carried out from 1955 to 1966 on emergence, daily and lunar rhythms and food relations in some 30 papers (for references Corbet and Tjønneland see *A Bibliography of Lake Victoria (East Africa)*, UNESCO Technical Documents in Hydrology, 1995. Observations dealt with insects whose larvae formed a large part of the benthos and included species of Ephemeroptera, Odonata, Trichoptera, and Diptera (Culicidae, Chironomidae).

Other researchers in the 1950s carried out studies on benthos in relation to the emergence and biology of Ephemeroptera (Hartland-Rowe, 1955, 1958) and the biology of Chaoborids and Chironomids (MacDonald, 1956). Knowledge on taxonomy of the benthos is far from complete and identification of a number of less common benthic groups of Insecta is still inadequate (Davies & Hart, 1981).

In 1950 EAFRO started studies on molluscs. Mandahl-Barth (1954) made lists of 126 species of molluscs, 86 gastropods and 40 bivalves in Uganda and adjacent territories, of which 65 species and subspecies occurred in Lake Victoria, which showed a remarkable speciation. Species and subspecies of *Bulinus* and *Biomphalaria* are the respective vectors for *Schistosoma haematobium* and *S. mansoni* which cause bilharziasis; the mollusc fauna was therefore mainly investigated with respect to this disease (Cridland, 1954, 1955, 1957). In the pre-Lates period molluscs contributed greatly to the food web, as they constituted an important element in the food of many fishes. They converted plant material into animal protein, digested cellulose and secreted sulphuric acid (Fish, 1955). In Lake Victoria, which has sulphate in very low concentrations, this was of great importance, since it kept this nutrient in circulation.

In the 1970s research was carried out on benthic invertebrates in northwestern Lake Victoria by Mothersill *et al.* (1980), providing information on species composition, abundance and substrate preference. Biomass, standing crop and spatial distribution of the benthos (Insecta, Mollusca and Annelida) in Murchinson Bay (Uganda) were recently studied by Okedi (1990). Mbahinzireki (1992) studied the distribution and abundance of benthic organisms in inshore and offshore Ugandan waters.

### Crustacea

*Caridina nilotica* is the only species of prawn occurring in Lake Victoria. Observations in the 1950s revealed that they were often extremely abundant in littoral and sub-littoral regions over hard bottom. There were indications that they occurred in dense aggregations at certain times of the year, since they occasionally formed the entire content of fish stomachs (EAFRO, 1955). It has been a common food item for several non-cichlid fish species (Corbet, 1961) and for prawn-eating haplochromines of the *Haplochromis tridens* group (Witte & van Oijen, 1990). Information on the diet of *Caridina* has been given by Fryer (1960), who described the prawn as a detritus feeder, feeding on material accumulating on the bottom and on submerged vegetation.

Information on *Caridina nilotica* has been compiled by Goldschmidt *et al.* (1993) in order to investigate the hypothesis that it replaced the demersal detritivorous haplochromines. Over the last decade, *Caridina* increased its biomass and became the nearly exclusive prey of juvenile Nile perch (Witte *et al.* 1992*a,b*). Catches on the HEST transect in the Mwanza Gulf have contained prawns in large quantities since 1986. And increased densities of the prawn have also been reported in the littoral areas along vegetated margins and rocky shores (Goldschmidt *et al.* 1993). ROV observations revealed that *Caridina* was abundant and active near and below the point where oxygen levels declined toward zero (Kaufman, 1992). Observations of diurnal and nocturnal vertical distributions of the prawn at a sampling station in the Mwanza Gulf revealed that during daytime the complete prawn population was concentrated in the lower part of the water column and that at night the prawn migrated into the middle and upper part (Goldschmidt *et al.* 1993).

## TROPHIC DYNAMICS

An understanding of trophic relationships is necessary to predict the impact of eutrophication and of changes in fish species composition and abundance presently occurring in Lake Victoria. Trophic relationships are often very complex in tropical waters, and this is particularly so in the African Great Lakes Victoria, Malawi and Tanganyika which have the richest fish faunas in the world, dominated by endemic cichlid species flocks, and which are unique examples of fish speciation and evolution. Numerous references to studies on fish in Lake Victoria are given in Fryer & Iles (1972), Greenwood (1974, 1981), Beadle (1981), Coulter *et al.* (1986), Lowe-McConnell (1987) as well as in the *Bibliography on Lake Victoria (East Africa)* (Crul *et al.* ) published by UNESCO in its Technical Documents in Hydrology series (1995).

Fish are a very important biotic component in the lake. The lake's fish fauna was dominated by a large flock of endemic haplochromines extensively studied by Greenwood (1974, 1981), Fryer & Iles (1972), and researchers of HEST (for references see van Oijen *et al.* 1981; Witte, 1987; Goldschmidt, 1989; Witte *et al.* 1992*a,b*). The ecological adaptation of the haplochromines was demonstrated by the existence of many trophic groups: detritus feeders, phytoplankton feeders, algae grazers, zooplankton feeders, insectivores, piscivores including egg eaters and scale scrapers, mollusc feeders, crustacean eaters and parasite feeders (Witte & van Oijen, 1990). Some 50 fish species other than haplochromines are mentioned in the *Check-list of the freshwater fishes of Africa* (CLOFFA) (Daget *et al.* 1984, 1986) as occuring in Lake Victoria. The food of 26 species of these fishes has been described by Corbet (1961). Recently information on taxonomy, ecology and fishery of the seventeen most abundant non-haplochromine fishes has been collected by van Oijen *et al.* (1988).

An estimated two-thirds of the *circa* 300 haplochromine cichlids species have become extinct as a result of the introduction of the large piscivore Nile perch in the early 1950s. The lake also shows signs of advancing eutrophication, such as an increase in chlorophyll concentration and primary productivity, blue-green algal blooms and a decrease in water transparency (Hecky, 1993; Ochumba & Kibaara, 1989; Hecky & Bugenyi, 1992; Mugidde, 1993; Gophen *et al.* 1993). Coincident with the Nile perch explosion and the reduction of the haplochromine cichlids and the contemporaneous eutrophication, a vital change occurred in the physical conditions of Lake Victoria. Recent observations in the Kenyan offshore waters revealed that the lake was stratified for the entire year and that extensive areas of the lake remained anoxic at the bottom (Gophen *et al.* 1993). There are indications that the intensity of vertical mixing has diminished over the last 30 years (Lehman & Branstrator, 1993). This may have been caused by an increased stability of the lake due to recent changes in climate (Hecky, 1993).

Both 'top-down' and 'bottom-up' processes are probably of importance in affecting trophic dynamics of Lake Victoria and are both responsible for the large changes which have taken place in the ecosystem of the lake.

Major changes occurred at the lower trophic levels: a shift in phytoplankton towards blue-green algae and a decrease of the formerly dominant diatoms. Algal blooms have occurred regularly (Ochumba & Kibaara, 1989; Mugidde ,1993; Gophen *et al.* 1993). The zooplankton community is presently dominated by small-bodied species of copepoda (Gophen *et al.* 1993). An increase in densities of *Caridina nilotica* and oligochaetes has been observed, although quantitative data are not available (Witte *et al.* 1992*a,b*; Goldschmidt *et al.* 1993). The decline of the haplochromines disrupted the food chains in the lake ecosystem, since these fishes played a major role as phytoplankton and detritus feeders (Witte *et al.* 1992; Goldschmidt *et al.* 1993). Algal material gradually increased and accumulated in the deeper layers and increased microbial processing, resulted in oxygen depletion in the deeper layers. During stratification the water column between 20 m and 50 m depth is subjected to severe deoxygenation, while during the mixing period (June–August) water below 50 m remains anoxic (Gophen *et al.* 1993).

The food web of Lake Victoria prior to the Nile perch explosion was dominated by the haplochromines (Ligtvoet & Witte, 1991). The major trophic groups were respectively the detritivores/planktivores and the zooplanktivores making up 60% and 20% of the total haplochromine biomass (Witte *et al.* 1992). The major food chains starting from detritus and phytoplankton were via the various trophic groups of haplochromines (Witte & van Oijen, 1990) to the piscivores. A direct food chain existed from phytoplankton to several tilapiine species (Ligtvoet & Witte, 1991). After its introduction in the early 1950s the Nile perch increased explosively in the 1980s, causing a dramatic decline of the haplochromines, as they were initially the major prey of the Nile perch. Only after the densities of the haplochromines had declined to near zero, did the Nile perch switch to other prey such as the prawn *Caridina nilotica* (Goldschmidt *et al.* 1993), the cyprinid *Rastrineobola argentea* and its own juveniles (Witte *et al.* 1992*a,b*).

In the present food web following the introduction of the Nile perch and Nile tilapia *Lates* is the top predator in the food web, replacing all original piscivores. The detritivorous/phytoplanktivorous haplochromines have been replaced by the atyid prawn *Caridina nilotica* and the zooplanktivorous haplochromines by the cyprinid *Rastrineobola argentea*. The indigenous tilapiine species have been replaced by the introduced *Oreochromis niloticus*. An important feature of the present system is the extensive cannibalism within the *Lates* population, which already starts at very young stages (Ligtvoet & Mkumbo, 1990). The bulk of the biomass within the fish community shifted from primary consumers to the top predator *Lates*. The tilapia species in Lake Victoria which were phytoplanktivores before the introduction of Nile perch, are presently mostly benthic feeders. They are pushed from the open water by the perch to shallow water, where they are obliged to utilize the food available there which is mostly bottom fauna and flora (Gophen *et al.* 1993).

# 9 Sediments

## BOTTOM STRUCTURE AND GENERAL COMPOSITION OF SEDIMENTS

The first observations on the nature of the bottom of Lake Victoria were made by Graham and Worthington during their survey in 1927–1928 (Graham, 1929). They stated that nearly the whole bottom of the lake was covered with a fine greenish-black mud which was almost entirely composed of the dead shells of diatoms. In the western part of the lake in the shallower waters north and east of Bukoba they discovered two areas with sand. From the northerly area of sand to the deeper part of the lake near Godsiba Island they found two areas of blue or green clay.

From 1949 onwards a large number of studies were carried out by EAFRO/EAFFRO on benthos and fish and these linked distribution patterns and species composition with bottom substratum. For references on benthos see Chapter 8 and for references on fishes see reviews by Fryer & Iles (1972), Greenwood (1974, 1981), Witte (1981) and Lowe-McConnell (1987). These publications on benthos and fishes provided additional information on the nature of the bottom in several inshore gulfs and bays.

Echo-sounding in experimental trawling operations by EAFFRO and LVFRP in the late 1960s provided information on the nature of the bottom of inshore waters near Jinja and Entebbe (Gee, 1966; Gee & Gilbert, 1967, 1968; Gee, 1969). A map of the bottom types and bathymetry of the inshore waters near Entebbe was provided by Gee (1968, p.60, Fig. G1). Gee & Gilbert (1968) mentioned a 2–3 m semi-flocculent layer of soft mud over a harder substrate, which contained much plant debris and supported a large population of molluscs. SCUBA-diving observations revealed a 1-m layer of flocculent plant material covering the bottom in water of the Ingira bay (Buvuma Channel area) (Cordone & Kudhongania, 1971).

New data on sediments have become available through recent and ongoing research on sediments, benthos and other organisms conducted by the three research institutes and university departments. Information on sediments and bottom types in Murchinson Bay near Kampala (Uganda) is given by Okedi (1990) and on inshore and offshore waters in Uganda by Mbahinzireki (1992). Information on the bottoms and sediments in the Nyanza Gulf is provided by Mothersill (1976) and Mothersill *et al.* (1980). The bottom of the Mwanza Gulf and of several bays near Nyegezi has been described by Witte (1981) and other researchers of HEST/TAFIRI.

As part of the Duke University's Project PROBE, a high-resolution echo-sounding system collected about 1800 km of multichannel seismic reflection data. As this system was especially effective for examining recent lacustrine deposits and lake-floor structures, the study provided new information on bathymetry, sediment distribution and lake floor structures (Scholz *et al.* 1991). The study revealed that fine-grained late Pleistocene and Holocene sediments, having a maximum observed open-basin thickness of about eight metres, overlie older desiccated lake sediments, alluvial materials, Precambrian crystalline and tertiary volcanic rocks, depending on the position in the lake. The distribution of these sediments mimics bathymetry. Thicker sediment layers may be found near bathymetric depressions and in inshore waters. In the echograms curious features and structures were observed. The western part of the lake floor was mostly barren of sediments and sediment waves were observed probably due to currents created by the S-SE prevailing winds scouring the relatively shallow lake floor. In the eastern part of the lake spiky diffractions may represent boulders which also dot the landscape around the lake, lying beneath the sediments, although the diffractions could also be related to biogenic gas production in the sediments.

As part of the Lake Victoria Research Project a Remotely Operated Vehicle (ROV) was used for controlling the coring of the lake bottom surface sediments (Station 103 – Kenya (Ochumba)). Some results of this coring are reported in Hecky (1993). The ROV was also used to make videotape recordings of the water column at and below the thermocline and the bottom surface (National Underwater Research Center, Avery Point, Videotapes 1987/1990, Unpubl. material).

## CHEMICAL COMPOSITION

In the 1950s, studies on sediments were carried out by EAFRO in relation to nutrient availability and productivity of the lake. The rate of decomposition of the bottom deposits of Lake Victoria proved to be extremely slow and was therefore considered to be the most important single factor limiting productivity (EAFRO, 1955).

Analyses of the composition of oven dried samples of mud revealed 24–64% silica, 4–25% carbon, 1.5–4.8% iron, 0.6–2.2% nitrogen, 0.5–2.0% sulphur, 0.04% phosphate, 0.3% Ca, 0.07% Mg, 0.05 K and 0.03 Na. Inshore samples contained more sand than samples from deeper waters, where the silica content was mainly in the form of diatom frustules (EAFRO, 1955). An additional spectographical analysis of bottom deposits from Pilkington Bay revealed a somewhat higher value for Na (0.45%) and 13.1% Al (Chamberlain, 1956). Microbiological analysis of a bottom sample from Pilkington Bay revealed that the greater part of the deposits consisted of blue-green algae and bacteria in almost equal proportions and only a small proportion consisted of detritus, i.e. diatom frustules and plant fragments (Newell, 1958). The chemical composition of dried Pilkington Bay mud was analysed by Watts (1968).

Large quantities of sulphur were found in the bottom deposits. Sulphur was not present in the form of sulphides but in organic combination as sulphate esters with organic molecules. Sulphur inputs via rain, surface runoff and river discharge were low (Hesse, 1956). Fish (1956) suggested that sulphur may be a limiting factor for growth of phytoplankton. Molluscs appeared to secret sulphuric acid, which is of great importance as it keeps this nutrient in circulation (Fish, 1955). Recently, Hecky & Bugenyi (1992) suggested a possible role of sulphate as a limiting factor for algal productivity, although this is contested by Lehman & Branstrator (1993).

## PALAEOLIMNOLOGY

Sediments accumulated in lake basins consist of various organic and inorganic substances, which contain records of the history of the lake, e.g. pollen, diatoms, and inorganic compounds. Palaeolimnology is a multidisciplinary science using information preserved in sediments to reconstruct past environmental conditions in aquatic systems. Over the last decade tremendous progress has been made in the development of palaeolimnological techniques and approaches. Advances include increased knowledge of indicator organisms, and better use and combination of indicators and refinements in sampling techniques (Smol, 1992). Palaeolimnological data may therefore prove to be crucial in providing information on the changes in the ecosystem in Lake Victoria during the last decades, as long-term observations are not available.

Studies of the sediments of Lake Victoria were undertaken to interpret changes in climate and describe the history of the lake. The first palaeolimnological study of the bottom deposits of Lake Victoria was that of Kendall (1969). It provided information on the history of the lake covering the last 15,000 years and on the climatic history of East Africa as summarized in Chapter 3. Later additional cores were examined by Livingstone (1975), Stager (1984) and Stager *et al.* (1986) provided additional information and confirmed the findings of Kendall (1969).

Recently studies of the surface sediments were used to evaluate and assess limnological changes in the lake during the last century and especially during the last three decades. The analyses of the sediment core taken in 55 m water off western Kenya in 1990 represented over 200 years of sedimentation and provided evidence on the eutrophication of the lake through deposition rates of N and P, changes in diatom composition and changes in sedimentation rates since 1960 (Hecky, 1993).

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# Appendices

**APPENDIX 1.** **Overview of limnological research on Lake Victoria.**
**(Sources: EAFRO/EAFFRO Annual Reports, Rzóska 1976, UFFRO Reports, KMFRI Reports, TAFIRI Reports, Beadle 1981, Worthington 1983, Fryer & Talling 1986, Talling 1986, HEST Reports). For references, see *A Bibliography of Lake Victoria (East Africa)*, 1995, Technical Documents in Hydrology, UNESCO.**

| RESEARCH/INSTITUTE | RESEARCHER(S) | LOCALITY | PERIOD | REFERENCES | SCOPE/SUBJECT(S) |
|---|---|---|---|---|---|
| EXPEDITION | | | | | |
| Emin Pasha | Stuhlmann | Bukoba, Mwanza | 1888-1889 | Stuhlmann, 1888<br>Stuhlmann 1889<br>Stuhlmann 1891 | reports on plankton collections |
| SURVEYS | | | | | |
| | Whitehouse/Hunter | lake-wide | 1898-1902 | Whitehouse, 1907<br>Hunter, 1912 | Admiralty Charts 3252, 3665<br>Admiralty Plan 1120 |
| EXPEDITIONS/STUDIES | | | | | |
| | Kollmann | | | Kollmann, 1899 | meteorological observations |
| | Knox | Mwanza | | Knox, 1911 | meteorological observations |
| | Carpenter | whole lake | | Carpenter, 1920 | meteorological observations |
| | Hurst | lake | | Hurst, 1925 | meteorol. observ., chemical and physical studies of the lake |
| | Graham & Worthington | whole lake (235 stations) | 22/8/1927 – 19/2/1928 | Graham, 1929 | limmnological observations physiography, ecology |
| | Worthington | *idem* | *idem* | Worthington, 1930 | physical limnology |
| | Worthington | offsh. stat. 66 | 22-24/9/1927 | Worthington, 1931 | zooplankton observations |
| | Hurst & Philips | whole lake | | Hurst & Philips, 1931, 1938 | meteorological observations, water budget |
| TAXONOMIC/STUDIES/SURVEYS | | | | | |
| Taxonomic Studies of Algae and Zooplankton | Schmiddle/Stuhlmann | Bukoba & others | 1892 | Schmidle, 1898 | phytoplankton (desmids) |
| | Schmiddle/Stuhlmann | Bukoba & others | 1892 | Schmidle, 1902 | algae (general) |
| | Weltner/Stuhlmann | Bukoba, Mwanza | 1888/89 | Weltner, 1891 | Cladocera |
| | Weltner/Stuhlmann | Bukoba, Mwanza | 1888/89 | Weltner, 1898 | Cladocera |
| | Mrazek/Stuhlmann | Bukoba, Mwanza | 1888/89 | Mrazek, 1897/8 | Copepoda |
| | West/Cunnington | Bukoba, Entebbe | 1905 | West, 1907 | algae (general) |
| | von Daday/Bogert | Kisumu, Entebbe | 1904 | von Daday, 1907 | flagellates/zooplankton |
| | von Daday | | | von Daday, 1910 | list of all invertebrate groups |
| | Sars/Cunnington | | 1902 | Sars, 1909 | copepods and ostracods |
| | Verestchagin/Dogiel | | | Verestchagin, 1915 | plankton |
| | Ostenfeld/Bogert | Kisumu, Entebbe | 1904 | Ostenfeld, 1908 | algae (general) |
| | Ostenfeld/Agassiz | Mwanza, Shirati | 1908 | Ostenfeld, 1909 | algae (general) |

| | | | | |
|---|---|---|---|---|
| Schröder/Talling | Winam Gulf | 1910 | Schröder, 1912 | diatoms (one species) |
| Virieux *et al.* | Entebbe, Kisumu | 1911 | Virieux ,1913 | algae (general) |
| Woloszynska/Schröder | whole lakeshore | 1910 | Woloszynska, 1914 | algae (general) |
| Hustedt/Schröder | Shirati, Mwanza, Winam, Smith Sound | 1910 | Hustedt, 1922 | phytoplankton (diatoms) |
| Borge/Schröder | Shirati, Mwanza | 1910 | Borge, 1928 | algae (general) |
| Delachaux | Bukoba | | Delachaux ,1917 | Cladocera |
| Bachmann/Worthington | offshore, gulf | 1927/28 | Bachmann, 1933 | algae (general) |
| EAFRO (1948-1960), EAFFRO (1960-1970) | | | | |
| Beauchamp | Jinja | 1947-1959 | Beauchamp (sev. refs) | hydrology, nutrients |
| Fish | Jinja | 1947-1954 | EAFRO, 1950-1955 | hydrology and algology |
| | | | Fish (several refs) | hydrology, algology, food of *Tilapia* |
| Teiling | Jinja | 1950 | Teiling, 1951 | algal taxonomy |
| Macdonald | Jinja | 1949-52 | Macdonald, 1956 | aquatic insects |
| Carter | Jinja | 1952 | Carter, 1955 | swamps |
| Ross | Jinja | 1952 | Ross, 1953,1955 | diatoms, algae |
| Cridland | Jinja | 1954-1959 | Cridland, 1954, 1955, 1957 | bilharzia |
| Mandahl-Barth | Jinja | 1950-1954 | Mandahl-Barth, 1954 | molluscs and bilharzia |
| Corbet | Jinja | 1954-1957 | Corbet and Tjønneland, 1955*a,b* | aquatic insects |
| | | | Corbet (sev. refs) | aquatic insects |
| Hesse | Jinja | 1955 | Hesse, 1956/57/58 | sediments |
| Chamberlain | Jinja | 1955 | Chamberlain, 1956 | sediments |
| Thomasson | Entebbe | 1953 | Thomasson, 1955 | algae |
| Rzóska | Jinja | 1956 | Rzóska, 1956 | Cladocera |
| Newell | Jinja | 1956 | Newell, 1956*a,b* | microbiology, sediments |
| | lake | 1956-1958 | Newell, 1956*b*, 1960 | hydrological observations |
| Fryer | Jinja | 1957-1959 | Fryer (several refs) | invertebrates, fishes |
| Evans | Jinja | 1960 | Evans, 1960, 1961*a,b* 1962*a,b* | phytoplankton, nutrient bioassay, inshore distribution, phytoplankton |
| Mölder | Entebbe | 1952 | Mölder, 1961 | diatoms |
| Hurst | Lake | | Hurst, 1952 | hydrology |
| Talling | Jinja | 1957-61 | Talling (sev. refs) | hydrology, phytoplankton, algal productivity, |
| Grönblad | Murch. Bay | 1950-1952 | Grönblad *et al.* 1964 | desmids |
| Kitaka | Jinja | 1965-1971 | Kitaka (several refs.) | plankton, limnological observ. |
| | | | EAFFRO, 1966-1969 | hydrological observations |
| Kendall | Pilkington Bay | 1960-1964 | Kendall, 1969 | paleolimnological studies; diatoms in sediment cores |
| Richardson | Pilkington Bay | 1960-1961 | Richardson, 1964, 1968 | plankton, diatoms, |

Appendix 1 (contd)

| RESEARCH/INSTITUTE | RESEARCHER(S) | LOCALITY | PERIOD | REFERENCES | SCOPE/SUBJECT(S) |
|---|---|---|---|---|---|
| | | Napoleon Gulf | | | lake typology |
| | Livingstone | offshore stns | | Livingstone, 1972 | sediment cores |
| | Visser | Kampala | | Visser, 1961, 1964 | chemical analysis of rainwater |
| | Lind | Uganda, Kenya | | Lind (several refs.) | swamps, phytoplankton studies |
| | Green | inshore | | Green, 1971 | zooplankton |
| EAFFRO (1970-1977) | | | | | |
| | Kitaka | Jinja | 1970-1973 | Kitaka (sev. refs.) | hydrology, limnology |
| | Bugenyi | Jinja | 1975-1977 | Bugenyi, 1977 | limnological studies |
| | Gaudet | Kampala | 1972-75 | Gaudet, 1975,1976,1977 | swamps, nutrient exchange |
| UFFRO (1977-1987) | | | | | |
| | Bugenyi | Jinja | 1977-present | Bugenyi (sev. refs) | limnological studies, pollution, eutrophication |
| KMFRI (1977-1987) | | | | | |
| | Ochumba | Nyanza Gulf | 1983-present | Ochumba (sev. refs.) | limnological studies, fish kills, |
| | Offshore waters | 1988-present | | | algal blooms, prim. productivity, eutrophication |
| | Ochieng | Nyanza Gulf | 1982 | Ochieng, 1983 | water quality studies |
| University of Nairobi | | | | | |
| | Mavuti & Litterick | Nyanza Gulf open waters | 1984-1987 | Mavuti & Litterick, 1991 | zooplankton |
| | Melack | Nyanza Gulf | 1970-1975 | Melack, 1976, 1979 | primary productivity, phytoplankton |
| | Kilham, P. | Nyanza Gulf | 1970-1989 | Kilham, P. (sev. refs.) | diatoms, nutrient cycles |
| | Kilham, S. | Nyanza Gulf | 1989-present | Kilham, S. (sev. refs.) | diatoms, nutrient cycles |
| | Mothersill | Nyanza Gulf | 1975-1977 | Mothersill, 1976 | sediments |
| | | | | Mothersill *et al.* 1980 | benthic invertebrates |
| FFTI | Akiyama | Mwanza Gulf | 1973 | Akiyama *et al.* 1977 | limnological observations, phyto/zooplankton |
| TAFIRI/HEST (1978-1987) | Kajumola & Olsen | Mwanza Gulf | 1978-1987 | van Oijen *et al.* 1981 | limnological observations |
| | | | | Several HEST reports | (temperature, D.O., Secchi) |
| | Hoogenboezem | | 1983 | HEST reports | zooplankton |
| | Goldschmidt | | 1986-1988 | Goldschmidt (sev. refs.) | zooplankton, limnological observ. |
| | | | | HEST Reports | *Caridina* |
| | de Beer | | 1987 | de Beer, 1990 | light measurements |
| | Wanink | | 1988-1989 | Wanink (sev. refs) | zooplankton, limnological observ. |

RECENT AND ONGOING LIMNOLOGICAL RESEARCH (1987–PRESENT)

| | | | | |
|---|---|---|---|---|
| UFFRO | Bugenyi | Ugandan waters | Balirwa & Bugenyi ,1988 | hydrology |
| | Balirwa | | Bugenyi & Balirwa, 1989 | pollution |
| UFFRO/(FWI Canada)<br>Lake Product.<br>Project (IDRC Funded) | Bugenyi | inshore/offshore | Bugenyi ,1992 | limnology, pollution |
| | Magumba | | Bugenyi & Magumba, 1990*a*,*b*, 1993 | physico-chemistry |
| | Mugidde | | Mugidde, 1993 | primary productivity |
| | Mwebaza-Ndawula | | Mwebaza-Ndawula, 1990*a*,*b*, 1993 | invertebrates, *Caridina* |
| | Mbahinzireki | | Mbahinzireki ,1990 | benthos |
| | Ogutu-Ohwayo | | Ogutu-Ohwayo& Hecky, 1992 | fish introductions |
| | Hecky | | Hecky, 1993<br>Hecky *et al.* in review | eutrophication |
| UFFRO | Lehman | | Lehman & Branstrator, 1993 | phytoplankton |
| | Kling | Buvuma Ch.<br>Pilkington Bay | Komarek & Kling, 1991 | phytoplankton (Cyanophyta) |
| Makerere University | | | | |
| Botany Dept. | Byarujali | Murchison Bay | Byarujali (Anon.1992*a*) | diatom composition |
| Inst. of Envir. and | Kateyo Chapman | Murchison Bay | Kateyo (Anon.1992*a*) | Crustacea |
| Nat. Res. Biol.Stat.<br>New Engl. Aq./Harvard Un. | Chapman, Kaufman & Liem | Western Uganda | Chapman et al. (Anon. 1992*a*) | papyrus swamps |

RECENT AND ONGOING LIMNOLOGICAL RESEARCH (1987 - PRESENT)

| | | | | |
|---|---|---|---|---|
| KMFRI/LVRCP | Ochumba | open waters, | Ochumba *et al.* (Anon., 1992*a*) | DO/ROV observations |
| | Kaufman | Nyanza G. | Kaufman, 1992 | DO/ROV observations |
| LBDA/Un. of Milan/KMFRI | Aketch, Calamari<br>Ochumba | catchment area | Aketch *et al.* (Anon., 1992*a*) | pollution catchment area |
| KMFRI | Ochieng | inflowing rivers | Ochieng (Anon., 1992*a*) | pollution inflowing rivers |
| KMFRI/University of Oklahoma<br>Israel Oc. and Limn. Res. Inst<br>(USAID funded) | Ochumba, Gophen<br>Pollingher | offshore, Nyanza G. | Gophen *et al.* (1993) | Hydrolab observations phytoplankton, zooplankton, tilapia food composition |
| TAFIRI/HEST | Kashindye | Mwanza Gulf | Kashindye (Anon. 1992*a*) | phytoplankton, physical observations |

**APPENDIX 2.** **Data on physical limnology of Lake Victoria's offshore waters (based on published papers)**

| RESEARCHER | DATA | LOCATION | TIME SPAN | FREQUENCY | PERIOD MONTH/YEAR | REFERENCE(S) |
|---|---|---|---|---|---|---|
| Graham & Worthington | Temp./D.O., currents | Lakewide 235 stations of which several offshore (for locations see Table X Graham 1929) | 4 months | - | 8/27–2/28 | Graham, 1929<br>Worthington, 1930 |
| Fish | Temp./D.O., currents | Open lake station northern waters (EAFRO) | 20 months | monthly | 6/52–2/54 | Fish, 1957 |
| Newell | Temp., currents | Open lake station (EAFRO) several transects | 2 years | monthly | 1956–1958 | Newell, 1960 |
| Talling | Temp., D.O. | Offshore (=open lake) station several other offshore sampling points | 1 year | every two weeks | 9/60–9/61 | Talling, (1966 and several other refs) |
| Kitaka | Temp., D.O., conductivity | 14 stations in two cruises | - | - | cruise A: 2/69<br>cruise B: 3/69 | Kitaka, 1972 |
| KMFRI. Principal investigator : Ochumba | Temp., D.O., currents | Offshore Kenyan waters (several sampling points) | 2 years<br>3 years | monthly<br>monthly | 1985–1986<br>1989–1991 | Ochumba & Kibaara, 1989<br>Ochumba *et al.* 1992, Gophen *et al.* 1993 |
| UFFRO. Principal investigator: Bugenyi | Temp., D.O. | Open lake station (= open lake station EAFRO) | 3 years | monthly? | 1989–1991<br>Hecky 1993, | Bugenyi, 1990;<br>Hecky *et al.* in review |

**APPENDIX 3. Overview of information on temperature and oxygen distribution in inshore waters of Lake Victoria**

| RESEARCHER | DATA | LOCATION | TIME SPAN | FREQUENCY | PERIOD MONTH/YEAR | REFERENCE(S) |
|---|---|---|---|---|---|---|
| *Lakewide:* | | | | | | |
| Graham & Worthington | T, D.O. | lakewide 235 stations of which several in inshore waters (for locations see Table X Graham 1929) | 4 months | – | 8/27–2/28 | Graham, 1929<br>Worthington, 1930 |
| *Ugandan inshore waters* | | | | | | |
| Fish | T, D.O. | inshore waters between Jinja and open water station (EAFRO) | 20 months | monthly | 6/52–2/54 | Fish, 1957 |
| Newell | T, D.O. | inshore waters between Jinja and open water station (EAFRO) | 2 years | monthly | 1956–1958 | Newell, 1960 |
| Talling | T, D.O. | inshore waters between Jinja and open water station (EAFRO) | 3 months | | 9/60–11/60 | Talling (1957, 1966 and several other refs) |
| UFFRO | T, D.O. | inshore waters between Jinja and Bugaia (near open water station) | regular | monthly | 1975–1991 | UFFRO Reports; Bugenyi, 1990; |
| *Kenyan inshore waters* | | | | | | |
| Melack | T, D.O. | Nyanza Gulf | – | occasional | 1974 | Melack, 1976, 1979 |
| KMFRI | T, D.O. | Nyanza Gulf, inshore bays | | monthly | 1984–1986 | Ochumba, 1987,1990;<br>Ochumba, & Kibaara, 1991 |
| | | Nyanza Gulf | regular | monthly programme | 1989–1991 | Ochumba et al., 1992;<br>Gophen et al., 1993. |
| *Tanzanian inshore waters* | | | | | | |
| Freshw. Fish. Inst. Nyegezi/ Freshw. Fish. Res. Laboratory Japan | T, D.O. | Mwanza Gulf | 1 year | monthly | 1974 | Akiyama et al., 1977 |
| TAFIRI/FFTI | T, D.O. | Mwanza Gulf | | occasional | 1975–1991 | TAFIRI/FFTI Reports |
| HEST/TAFIRI | T, D.O. | Mwanza Gulf, Butimba Bay | regular | | 1979–1989 | Van Oijen et al., 1981<br>HEST/TAFIRI Reports |
| TAFIRI | | Mwanza Gulf | | occasional | – | Kashindye, 1992 |

IMPRIMERIE DARANTIERE DIJON-QUETIGNY