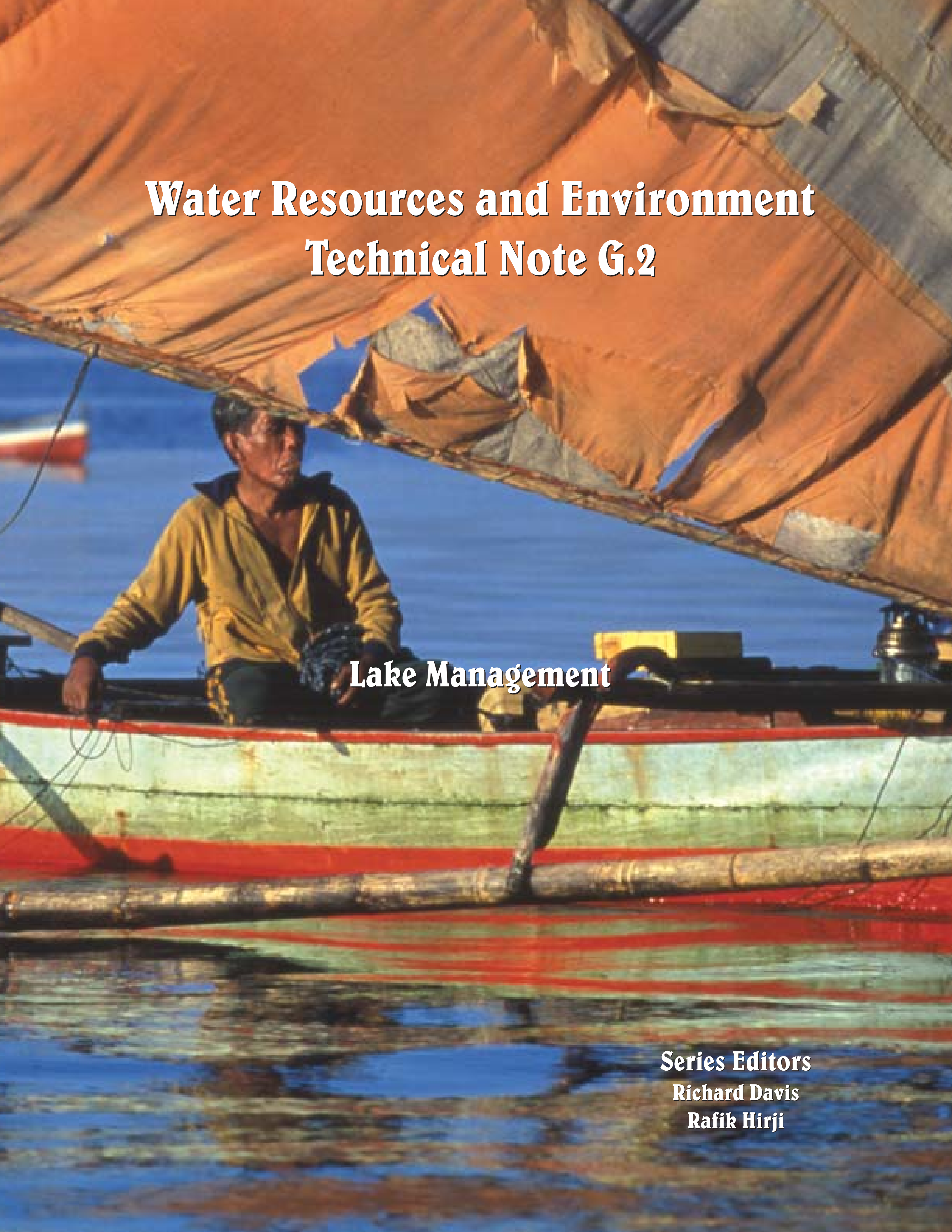
Water Resources and Environment
Technical Note G.2



Lake Management

Series Editors
Richard Davis
Rafik Hirji

Water Resources and Environment

Technical Note G.2

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Richard Davis, Rafik Hirji

The World Bank
Washington, D.C.

Water Resources and Environment Technical Notes

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Notes
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FOREWORD

The environmentally sustainable development and management of water resources is a critical and complex issue for both rich and poor countries. It is technically challenging and often entails difficult trade-offs among social, economic, and political considerations. Typically, the environment is treated as a marginal issue when it is actually key to sustainable water management.

According to the World Bank's recently approved Water Resources Sector Strategy, "the environment is a special 'water-using sector' in that most environmental concerns are a central part of overall water resources management, and not just a part of a distinct water-using sector" (World Bank 2003: 28). Being integral to overall water resources management, the environment is "voiceless" when other water using sectors have distinct voices. As a consequence, representatives of these other water using sectors need to be fully aware of the importance of environmental aspects of water resources management for the development of their sectoral interests.

For us in the World Bank, water resources management–including the development of surface and groundwater resources for urban, rural, agriculture, energy, mining, and industrial uses, as well as the protection of surface and groundwater sources, pollution control, watershed management, control of water weeds, and restoration of degraded ecosystems such as lakes and wetlands–is an important element of our lending, supporting one of the essential building blocks for sustaining livelihoods and for social and economic development in general. Prior to 1993, environmental considerations of such investments were addressed reactively and primarily through the Bank's safeguard policies. The 1993 Water Resources Management Policy Paper broadened the development focus to include the protection and management of water resources in an environmentally sustainable, socially acceptable, and economically efficient manner as an emerging priority in Bank lending. Many lessons have been learned, and these have contributed to changing attitudes and practices in World Bank operations.

Water resources management is also a critical development issue because of its many links to poverty reduction, including health, agricultural productivity, industrial and energy development, and sustainable growth in downstream communities. But strategies to reduce poverty should not lead to further degradation of water resources or ecological services. Finding a balance between these objectives is an important aspect of the Bank's interest in sustainable development. The 2001 Environment Strategy underscores the linkages among water resources management, environmental sustainability, and poverty, and shows how the 2003 Water Resources Sector Strategy's call for using water as a vehicle for increasing growth and reducing poverty can be carried out in a socially and environmentally responsible manner.

Over the past few decades, many nations have been subjected to the ravages of either droughts or floods. Unsustainable land and water use practices have contributed to the degradation of the water resources base and are undermining the primary investments in water supply, energy and irrigation infrastructure, often also contributing to loss of biodiversity. In response, new policy and institutional reforms are being developed to ensure responsible and sustainable practices are put in place, and new predictive and forecasting techniques are being developed that can help to reduce the impacts and manage the consequences of such events. The Environment and Water Resources Sector Strategies make it clear that water must be treated as a resource that spans multiple uses in a river basin, particularly to maintain sufficient flows of sufficient quality at the appropriate times to offset upstream abstraction and pollution and sustain the downstream social, ecological, and hydrological functions of watersheds and wetlands.

With the support of the Government of the Netherlands, the Environment Department has prepared an initial series of Water Resources and Environment Technical Notes to improve the knowledge base about applying environmental management principles to water resources management. The Technical Note series supports the implementation of the World Bank 1993 Water Resources Management Policy, 2001 Environment Strategy, and 2003 Water Resources Sector Strategy, as well as the implementation of the Bank's safeguard policies. The Notes are also consistent with the Millennium Development Goal objectives related to environmental sustainability of water resources.

The Notes are intended for use by those without specific training in water resources management such as technical specialists, policymakers and managers working on water sector related investments within the Bank; practitioners from bilateral, multilateral, and nongovernmental organizations; and public and private sector specialists interested in environmentally sustainable water resources management. These people may have been trained as environmental, municipal, water resources, irrigation, power, or mining engineers; or as economists, lawyers, sociologists, natural resources specialists, urban planners, environmental planners, or ecologists.

The Notes are in eight categories: environmental issues and lessons; institutional and regulatory issues; environmental flow assessment; water quality management; irrigation and drainage; water conservation (demand management); waterbody management; and selected topics. The series may be expanded in the future to include other relevant categories or topics. Not all topics will be of interest to all specialists. Some will find the review of past environmental practices in the water sector useful for learning and improving their performance; others may find their suggestions for further, more detailed information to be valuable; while still others will find them useful as a reference on emerging topics such as environmental flow assessment, environmental regulations for private water utilities, inter-basin water transfers, and climate variability and climate change. The latter topics are likely to be of increasing importance as the World Bank implements its environment and water resources sector strategies and supports the next generation of water resources and environmental policy and institutional reforms.

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INTRODUCTION

According to the World Lake Vision (2003) it is estimated that lakes, both natural and manmade, store more than 90 percent of the world's surface freshwater resources. They are heavily used for a variety of human activities, including drinking, fishing, irrigation, navigation, and recreation. As a result of this increased usage, lakes are increasingly threatened by abstractions for agriculture, pollution from discharges, and sedimentation from poor land management practices. As natural sinks with longer residence times than rivers, lakes are more fragile and susceptible to degradation from such threats. Unless these threats are reduced through better investment decisions and management practices, humans will lose access to their most readily available source of high-quality freshwater.

Lake management is an important issue for the World Bank. The Bank has described the problems of managing and restoring lakes and reservoirs in Technical Report 289 (1995) and summarized its work in supporting lake management in Technical Report 358 (1996). At present, the Bank is supporting the preparation and implementation of more than 10 major lake management projects, many with support from the Global Environment Facility. In addition, a recently launched GEF Medium Size Project–Towards a Lake Basin Management Initiative–will review experiences of about 28 GEF and non-GEF lake management projects to draw lessons for improving lake management investments

This Note is one in a series of Water Resources and Environment Technical Notes that have been prepared by the Environment Department to apply environmental management principles to water resources management. This Note presents the social and economic context of lakes within the current pattern of human development. It describes how lakes function and the threats to these functions from human activities. It also examines alternative policy approaches to lake management and remedial measures for severely damaged lakes, as well as emerging issues and future challenges for lake management. Most of the information in this Note is equally applicable to both lakes and reservoirs.

Photo by Edwin Huffman, World Bank

Philippines

VALUING LAKES AND RESERVOIRS

Freshwater constitutes only about 2.5 percent of the world's water reserves. Over 99 percent of this freshwater is locked up in groundwater, snow caps, glaciers, and permafrost. Our planet's terrestrial ecosystems, including the human population, largely depend upon the 117,490 km^3 of freshwater present in rivers, lakes, and swamps. This critical resource constitutes just 0.0085 percent of the global water reserve. Over 75 percent of this "easily accessible" water is found in lakes.

THE IMPORTANCE OF LAKES

Apart from their role in providing drinking water, irrigation water, and food supplies, lakes also provide vital service functions, such as controlling floods, assimilating plant nutrients, retaining sediments, and recharging groundwater. Yet human activities are damaging many lakes and impairing many of these functions. According to the UN's 1997 *Comprehensive Assessment of the Freshwater Resources of the World*, the water levels of many lakes are declining, and many lakes are severely contaminated by human, industrial, and agricultural wastes.

Freshwater is not only vital for human life but provides a habitat for much of the planet's biological diversity. Lakes are the main life support mechanism for many plant and animal species, as well as migratory birds. For example, freshwater fish represent 25 percent of all known vertebrate animal species.

Table 1 illustrates the functions, human uses, and major threats to some of the world's key transboundary lakes.

RESERVOIRS: NEW LAKE ENVIRONMENTS

In the last century, humans have altered the earth's hydrological cycle by damming rivers to create artificial reservoirs. There are now 45,000 dams over 15m in height that contain 20 percent of global mean runoff. These reservoirs are often deep, with steep shorelines. They act as lakes at the earliest stages of their evolution, often with unstable and poorly adapted ecosystems. Like lakes, they are filling with sediment. For example, as a result of sedimentation over a period of 25 years, the Tarbela Reservoir on the Indus River in Pakistan has lost 18 percent of live storage.[1] Shallow reservoirs also tend to suffer from eutrophication.

HOW LAKES FUNCTION

Knowing how lakes function from a biophysical perspective allows managers to understand the threats that lakes face from development, as well as possible ways to minimize those threats.

LIFE CYCLES AND WATER BUDGET

All lakes are at some point in a natural process that will eventually lead to their extinction. A few lakes are very old. Lake Baikal, for example, was formed 25 million years ago; Lake Tanganyika, 10 million years ago; and Lake Ohrid, 2 to 3 million years ago. But the ages of most lakes can be measured in thousands of years. The entire Great Lakes system, for example, was formed less than 10,000 years ago by the retreating ice sheet after the last Ice Age.

The lifetime of lakes is being shortened through water abstractions. According to the recent report of the World Commission on Dams, around 3,800 km^3

[1] World Commission on Dams (2000).

Table 1.
Transboundary lakes: Functions, uses, and threats.

Lake, countries, surface area, max depth and volume	Major ecosystem services	Major human uses	Main threats
Great Lakes (5 lakes) USA/Canada. 244,000 km^2, 406m, 23,000 km^3	■ Wetlands maintain lake biodiversity (including migratory species) and help to remove contaminants ■ Maintenance of groundwater levels ■ Local climate regulation	■ Transport ■ Water supply ■ Fishing ■ Recreation and tourism ■ Waste disposal	■ Habitat destruction (2/3 of wetlands lost) ■ Eutrophication ■ Toxic and persistent chemical pollution ■ Introduced species ■ Overfishing
Lake Baikal Russia (with Mongolia in its drainage basin). 31,500km^2, 1,620m, 23,000km^3	■ 20 percent of entire world reserve of freshwater ■ High biological diversity (2,600 plants and animals, 1,500 endemic)	■ Tourism ■ Fishing ■ Transport (summer months) ■ Waste disposal ■ Water supply	■ Untreated waste (particularly from two pulp and paper plants) ■ Toxic substances of global origin (POPs) concentrating in sediments and the food chain
Lake Ohrid Albania/Macedonia. 349 km^2, 289 m, 58.7 km^3	■ High biological diversity (60 percent of fish species endemic)	■ Tourism ■ Fishing ■ Water supply and sewage disposal	■ Dissolved phosphorus from sewage and agriculture (loading is estimated to be 150 tons per year)
Lake Chad Niger, Nigeria, Cameroon, the Central African Republic, and Chad. Dry season about 2,000km^2, 12m, 24 km^3	■ Natural barrier against desertification ■ Habitat for endemic and migratory species (including migratory bird species in wetlands)	■ Water supply for agriculture and human population ■ Fishing	■ Excessive water abstraction from tributaries ■ Climate change
Lake Victoria Kenya, Tanzania and Uganda. 69,000 km^2, 84m, 2,760 km^3	■ High biological diversity (many endemic fish species) ■ Fringing wetlands ■ Floodplain vegetation	■ Fisheries (Nile perch and tilapia) ■ Transportation ■ Hydropower ■ Water supply ■ Sewage disposal	■ Eutrophication ■ Water hyacinth ■ Introduced species (Nile perch) ■ Industrial and domestic pollution
Lake Tanganyika Burundi, Democratic Republic of Congo, Tanzania, Zambia. 33,000km^2, 1,500m, 19,000km^3	■ High biological diversity (1,500 plants and animals, 500 endemic) ■ Fringing wetlands ■ Floodplain vegetation	■ Fisheries (sardines) ■ Transport ■ Water supply ■ Sewage disposal	■ Overfishing in the littoral zone ■ Excessive extraction of ornamental fish ■ Pollution from urban, industrial, and mining sources ■ Eutrophication ■ Increased sedimentation

of freshwater is annually withdrawn from the world's lakes, rivers, and aquifers. This is twice the volume extracted 50 years ago. With such high demand, it is not surprising that the service functions and ecology of lakes are sometimes severely compromised.

The lifetimes of lakes are also being reduced by infilling with riverborne sediment, dense vegetation, or windblown desert sands. Human activity is greatly accelerating these natural processes–often shortening the life of lakes to as little as one-hundredth of their natural span–through:

- sedimentation of eroded soils, often caused by deforestation and increased tillage in the lake's drainage basin
- eutrophication (excessive nutrient enrichment)
- excessive abstraction of water from the lake or its tributaries
- climate change (altering rainfall patterns or increasing desertification).

This process will culminate in a wetland (see Note G.3) such as a bog marsh (a shallow lake filled with detritus), fen, or swamp.

Lakes exist at virtually every latitude. Their evolution is highly dependent upon the local climate and the seasonal variations of temperature. All lakes exchange latent heat with the atmosphere and affect the surrounding air temperature. Arctic lakes may form above the permafrost in the summer period and refreeze during the winter. At the other extreme, shallow lakes in arid zones may become desiccated in the summer or even for a period of several years. For example, Lake Chad can fluctuate between 25,000 km^2 and 2,000 km^2 because of natural decadal-length climate cycles.

Climate change is having a major impact on the morphology of lakes and their evolution. The recession of glaciers is leading to the formation of many new lakes, particularly in the temperate environment. Long-term climate modeling suggests that many arid areas will become even drier as a result of global warming. This may well result in the increased desiccation of lakes in these regions. The gradual drying of these lakes should be included in any development planning that requires additional abstractions of water.

Water usually enters lakes from surface runoff, direct precipitation, and sometimes from shallow aquifers (see Note G.1). Water is lost from lakes via overflow to rivers or streams, evaporation, seepage to surrounding aquifers, and abstractions for drinking water, industrial use, or irrigation. Some of these sources and sinks of water are quite difficult to measure in practice, and can usually only be estimated when planning any abstractions of water from a lake system. Thus, storm events in rivers and streams are often missed in monitoring, and interactions with aquifers can only be estimated.

The shape of a lake determines many of its properties. The surface area determines how much sunlight the lake can trap, and its shoreline length determines the amount of productive littoral vegetation. The depth (together with the local climate) determines the characteristics of the water column, particularly its propensity to stratify (below). Consequently, contoured bathymetric maps of lakes are valuable aids in lake management.

The flushing time of a lake is the time that it would take to refill the lake from its surface and subsurface inflows if it were emptied. This may vary from weeks to hundreds of years. The concept is useful to help understand the lake's vulnerability to pollution, but has practical limitations. For example, in a deep stratified lake, the surface water may flush through the lake faster than the deep water. Also, the loss of water by evaporation will leave many of the dissolved salts behind, and they will reside in the lake for much longer than its water.

Detention time is a useful engineering concept for the design of large reservoirs; for example, the Aswan High Dam can store 1.5 average years of flow of the Nile River. If the detention time of a dam is insufficient, disastrous downstream flooding may occur, as exemplified by the 2001 floods in Mozambique and Zambia when the gates of the

Kariba Dam had to be opened because of fears that the dam could burst with the high runoff from cyclone Dera. Crops were destroyed in the flooding and thousands faced starvation.

Sediment settling rates are also important for management purposes. If settling rates are rapid and threaten the longevity of a reservoir, then small primary settling ponds can be built at the point of river inflow in order to trap incoming sediments before they flow into the main reservoir. The ponds need to be dredged periodically to remove the settled material.

THE LAKE ENVIRONMENT

Whether a lake is mixed or stratified is critically important to its functioning and management. Stratified lakes are essentially two water bodies, one atop the other. The bottom layer is denser than the top layer, usually because it is significantly colder, although it can also be because of different salinities. The point of separation is called the thermocline or, for salinity stratification, the halocline. Each layer has separate physical, chemical, and ecological properties.

Sunlight and wind stress are the two primary forces providing energy in a lake. Heating from sunlight becomes absorbed within a few meters, warming the surface and subsurface water. Warm water is more buoyant than the unheated lake water, so sunlight promotes stratification of lake waters. On the other hand, wind tends to mix the waters of a lake. The wind stress acts at the lake surface, and the mixing energy it produces decreases sharply with depth. Shallow lakes are usually well mixed by the wind, and so are not stratified for long periods. In deeper lakes, the mixing energy of the wind is insufficient to mix the heated and unheated water, so stratification occurs. In temperate climates, deeper stratified lakes may mix in the Fall, when surface waters cool and there is enough wind energy to overcome the small temperature differential.

Much of our understanding of lakes comes from temperate systems. Tropical lakes are not driven by the strong seasonal temperature changes of their temperate counterparts. However, it is a popular misconception that there are no seasons in the tropics; many tropical regions experience strongly differentiated wet and dry seasons. Lake Victoria, for example, straddles the equator but stratifies during the rainy season when cool, dense water enters the lake and sinks to the bottom, forming a thermocline at a depth of about 30 meters. The strong daytime solar energy reaching tropical lakes results in temperature differences in the surface waters between day and night.

Solar radiation is essential for the growth of vascular plants and phytoplankton, the tiny free-floating photosynthetic algae that constitute the base of the open water (pelagic) food chain of aquatic environments. The euphotic zone is the layer of water that receives sufficient solar radiation for phytoplankton communities to develop. Lake waters may become turbid as a consequence of dense phytoplankton growth or the presence of large amounts of suspended sediments. Turbidity, from whatever source, reduces the depth of the euphotic zone, and hence the productivity of the lake.

Exhaustion of nutrients, particularly phosphorus and nitrogen, will limit the production of plants and algae (termed primary production) in a lake. Abundant nutrients will result in excess plant growth, or eutrophication. In lakes where nitrogen is in short supply but phosphorus is available, blue-green algae may become dominant because many of these species are capable of obtaining nitrogen directly from the atmosphere. This is generally a highly undesirable situation, because some common species of blue-green algae are extremely toxic to humans and animals (see Note G.4).

The presence or absence of stratification strongly affects a lake's chemistry and ecology. Decomposition of organic material in the lake sediments uses oxygen dissolved in the water column. If the lake is stratified for extended periods, this decomposition may remove oxygen from the bottom water—a condition known as anoxia. Oxygen-dependent biota, such as fish, are unable to survive in this anoxic zone. Nutrients are also released from the sediments in anoxic conditions. Eventually sulphate-reducing bacteria may develop, releasing toxic hydrogen sulphide gas into the bottom waters. Environmental managers are very concerned when anoxia occurs because, when the bottom and top waters eventually mix, the low oxygen and toxic hydrogen sulphide gas spread throughout the lake and may lead to the widespread death of fish—a "fish kill." Fish kills have often ruined attempts to develop aquaculture in poorly managed reservoirs.

Lakes have three inter-linked types of food web: the pelagic, benthic, and littoral webs.

- *Pelagic* food webs are based on phytoplankton and include the animals (zooplankton, fish, insects) within the water column that feed on phytoplankton.
- The *benthic* food web is based upon sediments rich in organic matter termed *detritus*. Detritus can support a variety of animals, including many species of fish. Benthic communities cannot survive under anoxic conditions.
- The *littoral* food web marks the boundary between the aquatic and terrestrial environment. It includes both pelagic and benthic communities, but is marked by the presence of plants (*emergent* plants such as reeds, or *submerged* plants such as eelgrass) and algae that grow in this sunlit zone. The littoral foodweb is the most diverse and productive system in a lake. Unfortunately, it is the one most often damaged by human activity.

The value of a lake to humans and biota is governed by the interaction of these diverse physical, chemical, and biological processes (Box 1). When natural changes—such as reductions in rainfall—or human interventions—such as increases in nutrient inputs—modify any of these processes, a complex set of events is set in train that can result in extensive, and often detrimental, changes to the lake.

BOX 1.
FACTORS DETERMINING THE STATE OF A LAKE

The natural state of a lake is determined by:

- Its morphology
- Physical mixing of its water, driven by wind stress (occasional or continuous mixing depending on depth) and temperature (annual turnover in most temperate and some tropical lakes)
- Replacement of the water by runoff and seepage into the lake and drainage out of it
- Its temperature and light conditions (plankton and vascular plants grow very slowly in temperate winters, rapidly in the tropics)
- The transparency of its waters
- The plant nutrient balance in the lake, determined by external sources (runoff, rainwater); internal sources (recycling from the lake bottom); and sinks (food chain loss, plant or animal death and sinking to the bottom, lake drainage)
- The productivity of plankton and vascular plants (depending on all of the above factors)
- The oxygen balance of its deep waters (determined by mixing, flushing, and plant production and decay)
- The trophic structure of plants and animals (largely dependent on all of the above factors, the geographical setting, and life history of the lake).

HUMAN DISTURBANCE OF LAKES

POINT AND NONPOINT-SOURCE DISCHARGES OF CHEMICAL AND MICROBIAL POLLUTANTS

The development of catchments has often included the use of rivers and lakes as receptacles of pollutants from industry, agriculture, and domestic sources (Box 2). Lakes, with their long flushing times, are particularly susceptible to pollution. Major classes of pollutants are:

- Heavy metals–from industry, mining waste, domestic sewage, and some agricultural effluents (for example, copper from fungicides). Heavy metals have direct toxic effects on lake biota and may accumulate in lake sediments and the lake's biota.
- Synthetic organic compounds–these include a vast number of compounds from industry, agriculture and domestic use, such as pesticides, polychlorinated biphenyls, surfactants (detergents), and solvents.
- Chlorinated pesticides and PCBs readily bioaccumulate and may remain in the sediments for decades. Modern pesticide formulations are more easily degraded, but are highly toxic to aquatic organisms.
- Nitrogen and phosphorus compounds that contribute to eutrophication (see Note D.3 for more information on diffuse nutrient pollution).
- Oil and oil combustion products–from spills, industry, domestic sources (including stormwater discharge), and from small craft on the lake.
- Pathogens from untreated sewage are a major problem in many countries.
- Effluents with a high oxygen demand. Most industrial and domestic waste has a high oxygen

BOX 2.
THREE LAKES ENDANGERED BY POLLUTION

Lake Mariut, Egypt

This is a 20 km^2 lake immediately to the south of the city of Alexandria, the major Egyptian seaside resort with a population of 3.5 million. From 1950 to 1985, the value of its fisheries declined from \$8 million to \$0.5 million annually, largely as a result of the decision to divert the city's sewage outfall from the sea into the lake. This diversion was to reduce pollution on Alexandria's beaches. Despite the treatment of some of the effluent, industry has continued to expand and discharge waste to the lake. At least 1 km^2 of the lake is completely anoxic, and the polluted water flows from the lake to the sea, defeating the original objective of the diversion. Without control of the pollution at its source, the situation will remain unmanageable.

Kyiv Reservoir, Ukraine

This reservoir, adjacent to the city of Kyiv (Kiev), supplies several million people with drinking water. The lake lies 50 km downstream of the Chernobyl nuclear reactor, part of which was destroyed in the catastrophic explosion of 1986. To date, there has been no evidence of contamination of Kyiv's drinking water with radionuclides. However, sediments in the reservoir contain significant loads of radioactive cesium, and flooding in the Chernobyl area could transport additional loads of contaminated sediments to the lake. Continued monitoring of the situation will be necessary for several decades.

Lake Baikal, Russia

Lake Baikal, the world's largest lake, is a fragile environment that remains almost unpolluted except for two paper and pulp mills, which are important sources of employment in the region. The mills are responsible for 76 percent of the polluted wastewater discharged to the lake. This has damaged a 20 km^2 tract of lake floor. Recent studies have suggested that high dioxin levels are associated with the larger mill. It is essential to control effluent from the pulp mills to protect the lake. The Baikal Commission was created in 1993 to coordinate the management of the basin, and the World Bank is one of the international donors assisting with the development of the lake in a sustainable manner.

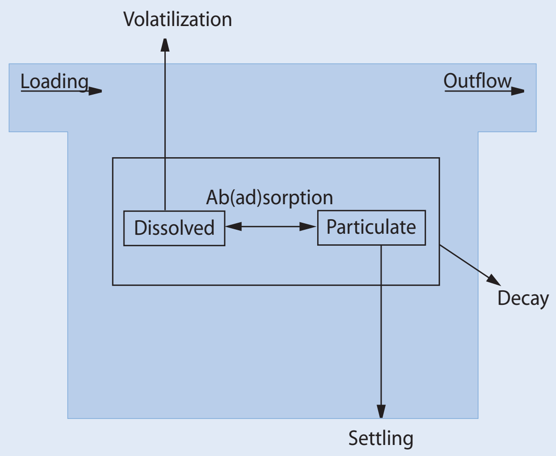
Sources: Hiley, P.D. 1996. In Richardson (Ed), *Risk Reduction: Chemicals and Energy into the 21st Century*. London: Taylor and Francis. GEF 1996. *Russian Federation Biodiversity Conservation Project*. Washington: World Bank.

demand, even after partial treatment; subsequent discharge to a lake may result in oxygen depletion in the bottom waters (see Note D.2).

Hydrodynamic and water quality models can be used to predict the impacts of these various contaminants as well as the likely success of different management interventions. However, model predictions are always uncertain, and managers should be aware of the limitations of the particular models being used.

The development of such mathematical models is very labor-intensive. Many models have been developed by research institutions in the last 30 years; some are commercially available. Models can range from simple to very complex, depending on the problem to be managed and the data available (Figure 1). A water balance model can be relatively simple, since a limited number of equations are needed, while ecotoxicological or ecological modeling will be very complex, since many processes have to be quantified.

FIGURE 1.
WATER QUALITY MODELS



A mass balance for a toxic substance in a well-mixed lake with no sediment feedback of solids is depicted in the figure. The toxic substance is partitioned into dissolved and particulate fractions. Volatilization and settling act selectively on these components.

Source: Chapra, S. C. 1997. *Surface Water Quality Modeling*. New York: McGraw-Hill International Editions

The critical step in applying these models is the collection and quality assessment of available data for calibration. Long-term, reliable data time series are needed if the model predictions are to be believable.

RAPID SEDIMENTATION

Deforestation and the development of extensive agriculture in the catchment of a lake or reservoir often lead to a dramatic increase in soil erosion. Much of the displaced soil will be deposited as lake sediments, often smothering existing benthic communities and decreasing the depth of the lake. Fine clay particles can remain in suspension in the lake waters, reducing light input and restricting primary production.

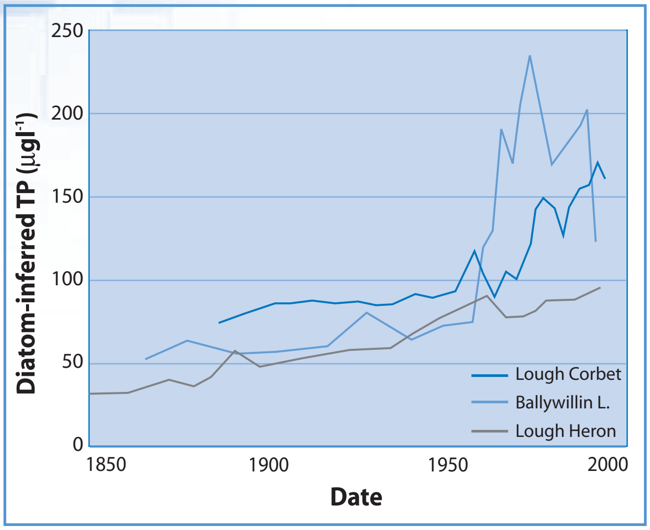
Removal of wetlands, dredging for navigation, and the isolation of river floodplains by embankments also results in an increase in the transport of sediments to a lake. Sedimentation rates can be very large. For example, about 7cm of contaminated sediments are accumulating each year in the huge Iron Gates reservoir between Romania and Yugoslavia, representing a major management problem.

Lake Baringo in Kenya provides a classic example of sedimentation. The lake depth has been reduced from over 15m in 1921 to 1.9m today from both reduced inflows and sedimentation. Only one of the eight rivers that used to enter the lake now flows continuously, as a result of settlement of the surrounding catchments and associated water use. Sediment loads have greatly increased, to 5 million m^3, from both the local catchments and the Mau Ranges. A wetland has now formed where the Molo River enters the lake, and it is likely that the whole lake will turn into a wetland in the next few decades.

EUTROPHICATION

These sediments can also transport nutrients into the lake, causing eutrophication. Phosphorus, in particular, is readily bound to sediment material. Nutrients can also enter the lake dissolved in the

FIGURE 2.
TRENDS IN PHOSPHORUS CONCENTRATIONS IN THREE LAKES IN NORTHERN IRELAND, 1850–2000.



Source: redrawn from Anderson, N. J. 1997. Historical changes in epilimnetic phosphorus concentrations in six rural lakes in Northern Ireland. *Freshwater Biology* 38(2): 427–440

water as well as in organic forms. The nutrients can originate from natural decomposition of organic matter in the catchments, from animal and human wastes, from anthropogenic sources such as fertilizers, and from natural nutrient concentrations originating from parent rock material.

For example, there are over 600 small lakes in Northern Ireland. Research on the sediments in six of these lakes has reconstructed a remarkable record of changes in total phosphorus concentration over the past 150 years that appears to be typical of lakes in most developed countries. Figure 2 presents data for three lakes that have no point sources–such as sewage–draining into them. They receive inputs from surrounding agriculture. Each of the lakes shows an increase in phosphorus, initially as a result of land clearances (plowing increases soil loss and attached natural phosphorus). Since the 1950s, there has been a more pronounced increase in phosphorus concentrations in two of the lakes. This recent large change–due to land drainage, fertilizer use, and the indirect impact of rural sanitation–is accelerating the demise of the lakes. Recent decreases during the 1990s may reflect more prudent use of fertilizers.

ACIDIFICATION

The waters of mountain and high-latitude lakes have very limited capacities to degrade acidic substances deposited from the atmosphere. Acid deposition from the burning of fossil fuels (particularly coal- and oil-fired power stations) has caused severe damage to many lakes in Canada, the United States, Scotland, Norway, and Sweden, and may be affecting alpine lakes in Central Asia. It often results in the failure of fish larval development or deformities in adults. It has been estimated that at least 20,000 lakes are affected in this manner in Sweden; as much as $27 million is spent annually in adding lime to these systems to offset the effects of acid rain.

EXCESSIVE WITHDRAWAL OF WATER

With the increased need for food production, there are increasing abstractions from lakes and the rivers feeding lakes, with consequent lowering of lake levels. Lakes downstream of hydropower plants also experience increasing fluctuations in their levels. The first communities to suffer from these changes are the ecologically rich ones in the lake's littoral zone.

An extreme case is that of the Aral Sea. Previously 67,900 km^2 in area, it has been significantly reduced in size due to the abstraction of water from its inflowing rivers, principally the Amu Darya and Syr Darya Rivers, for the purpose of upland irrigation. An extensive investigation has led to the conclusion that the original extent of the lake cannot be restored. Through the Aral Sea Basin Program, the World Bank and other donors are focusing on rehabilitating the irrigation infrastructure, conserving water, and protecting the deltaic wetlands of its rivers, which are important centers of biological diversity and provide sustenance for local populations.

DESTRUCTION OF NATURAL SHORELINES AND BEDS OF AQUATIC PLANTS

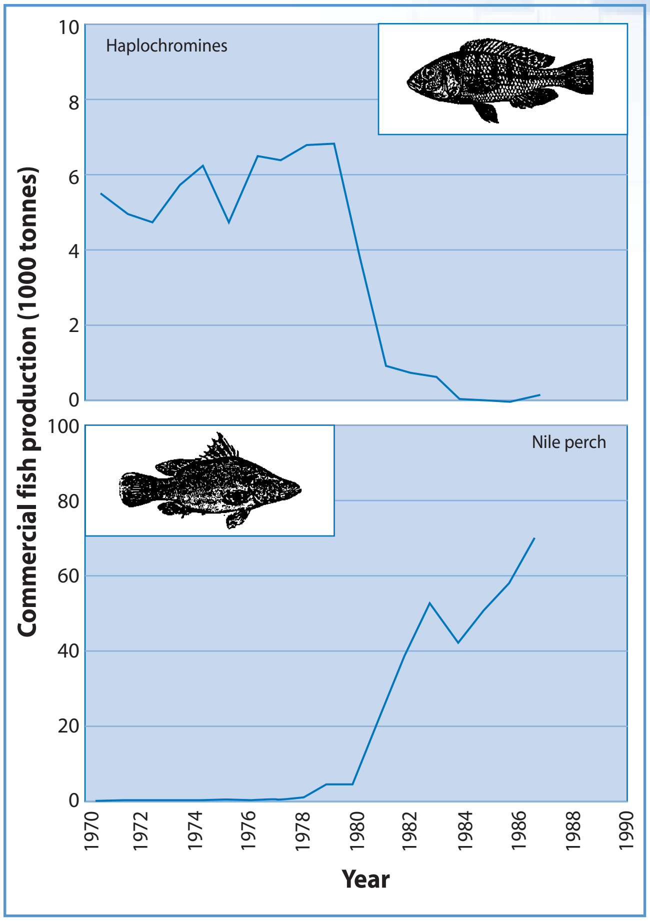
Many efforts to protect lakes focus on the waterbody itself and ignore the littoral zone. It is quite common to observe lakes in which development has replaced the natural fringing wetland transition zone. Such lakes often remain aesthetically attractive, but the loss of the biologically important littoral zone severely damages their ecological functions. These littoral areas provide important habitat for birds and aquatic fauna, intercept inflowing sediments and contaminants, and stabilize the banks of the lake.

INTRODUCTION OF EXOTIC SPECIES

Human activity has resulted in the accidental or intentional introduction of a large number of plant and animal species to lakes across the world. Species may be introduced by accident–for example, through attachment to ships and boats or by escapes from aquaria, fish farms, or as bait for anglers. Intentional introductions have been for "improvement" of fish stocks, ornamental purposes, or control of undesirable plants or animals (Box 3). Introductions are almost always detrimental to the natural ecology of a lake, although they may confer major economic advantages.

In a well-known example, some Nile perch were introduced to Lake Victoria in the late 1950s. This voracious predator gradually adapted and began to be caught in appreciable numbers by the early 1970s. By 1980 it had caused a rapid decline in native cichlid stocks (Figure 3), and has been a major fac-

FIGURE 3.
IMPACT OF NILE PERCH ON HAPLOCHROMINES IN LAKE VICTORIA



Source: Ogutu-Ohwayo, R. 2001. "Changes in life history characteristics of Nile perch, *Lates niloticus*, in Lake Victoria and the implication on the future of its fishery in the lake." LVEMP Conference, Kisumu, Kenya.

BOX 3.
SOME DAMAGING INTRODUCTIONS

Water hyacinth (*Eichhornia crassipes*), a native of South America, is now found in most tropical countries. It can spread over tens of km^2 within a year of introduction. It prevents light from penetrating the lake surface and depletes oxygen in the water, resulting in anoxia and the elimination of many species. It can also greatly increase transpiration losses of water from the lake surface. Examples of lakes with serious hyacinth problems are Lake Victoria, Africa; Lake Chapala, Mexico; and Chilika Lake in Orissa, India.

Zebra mussels were accidentally introduced from Central Europe to the Great Lakes in the late 1980s. They have now spread through many internal waterways in the United States. They attain large populations, displacing local bivalves and clogging cooling pipes. Attempts at control have been unsuccessful so far.

Sea lampreys, a parasitic fish native to the North Atlantic, invaded the upper Great Lakes after the construction of the Welland Canal in 1929. This parasite, together with overfishing, led to the collapse of the lake trout fishery by the late 1950s. Currently, the sea lamprey is partly controlled by a selective toxicant applied to streams to prevent spawning.

Ruddy ducks, a native of North America, were introduced to Western European lakes for ornamental purposes but now threaten endangered native species by crossbreeding. Plans are being made to eliminate the species through hunting.

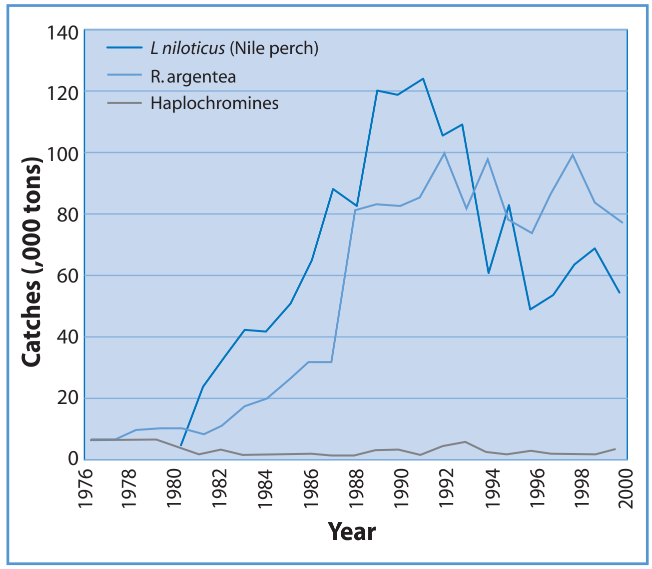
tor in the extinction of 200 to 400 species of the lake's endemic fish.

However, the Nile perch, together with the Nile tilapia, became the basis of a new and sophisticated trawl fishery. This fishery is now a significant contributor to the export earnings of all three riparian countries. Kenya earned $34 million in 2000 from exports of Nile perch. While this new industry was beneficial to the national economies, it was detrimental to local communities that had been previously dependent on catches of native fish. Consequently, these groups have decreased access to a cheap source of protein. Thus, the effects of this introduction were not simple: some groups in society benefited financially and others have suffered, while there has been a major decrease in biodiversity.

OVEREXPLOITATION OF FISHERIES

Overfishing is a major problem in some lakes, not only because of its economic consequences, but also because of the ecological implications. Thus, there is now good evidence that Nile perch in Lake Victoria are being overfished, with significant decreases in landings in recent years(Figure 4). One of the major causes has been the reduction in net mesh size, resulting in the capture of many juvenile fish below reproductive age. The problem is being tackled by encouraging fishing communities to take more responsibility for the regulation of their industry.

FIGURE 4.
ANNUAL FISH CATCH FROM KENYAN PART OF LAKE VICTORIA



Source: Njiru, M., A. Othina A. & E. Wakwabi. 2001. "Impact of water hyacinth on the fishery of Lake Victoria, Kenya." LVEMP Conference, Kisumu, Kenya.

Removal of the top fish predators through overfishing may result in effects throughout the foodchain. For example, grazing pressure may be reduced on free floating or attached algae, thus promoting algal blooms (See Note G.4). However, the ecological interactions in lakes are so complex that it is very difficult to predict whether overfishing will result in the promotion of nuisance species or not.

POLICY APPROACHES FOR IMPROVING LAKE MANAGEMENT

Many of the current threats to lakes and reservoirs–such as sedimentation and eutrophication–originate well beyond the margins of the lakes themselves; corrective or preventive actions are often necessary across the entire watershed. This section will discuss a policy approach that requires integrated catchment management, as well as some of the constraints to implementing this approach. This approach is designed to incorporate the management of lakes and reservoirs into the process of sustainable development. The approach includes sectoral cooperation and joint planning, stakeholder participation, and the linkage of economic causes and effects (transfer of benefits and responsibilities) by applying economic instruments.

INTEGRATED CATCHMENT MANAGEMENT IN THE CONTEXT OF LAKES

Integrated Water Resources Management (IWRM) is embedded in the Bank's 1993 Water Resources Management Policy and is the framework adopted in the World Bank's new Water Resources Sector Strategy.

One of the underlying reasons for the deterioration of many lakes is the poor understanding among managers and the general public of the boundaries of the hydrological system, in both spatial and temporal terms. Activities that may provide short-term benefits in the upper catchment of a river often lead to longer-term detrimental consequences downstream, including in lakes. Unfortunately, the strongly sectoral organization of governments does not usually lead to policies that integrate all of the costs and benefits of a proposed action into a common decisionmaking process.

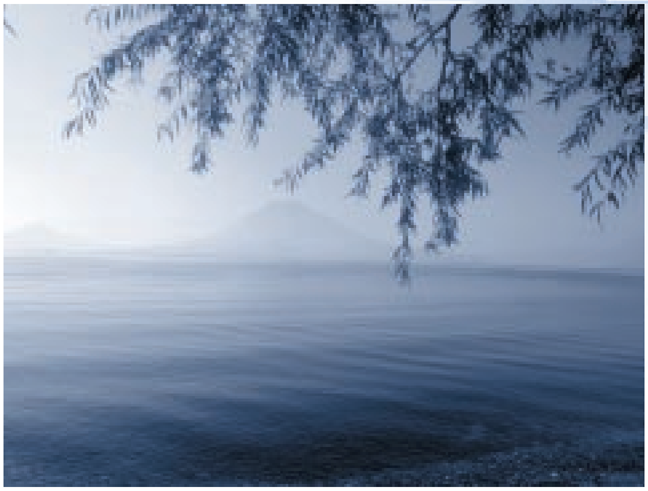


Photo by Curt Carnemark, World Bank

Guatemala

Integrated catchment management (ICM) promotes the management of water resources on a whole-catchment basis rather than by conventional administrative boundaries. The costs and benefits of development need to be assessed across the full catchment. This may require re-aggregation of existing economic data to fit the catchment boundaries. In this manner, true project costs for a variety of alternatives can be compared with the potential benefits. For example, the discharge of nutrients from agriculture may have little impact within a particular tributary, and so there will be little local incentive to control it. But it may have major downstream consequences for a lake. Thus, upland farmers are unknowingly subsidizing their production through consumption of environmental capital downstream. The policy framework, including regulatory or market mechanisms, for the overall catchment must be strong enough to internalize such externalities or pay the cost of remedial action. In practice, this is quite difficult to achieve.

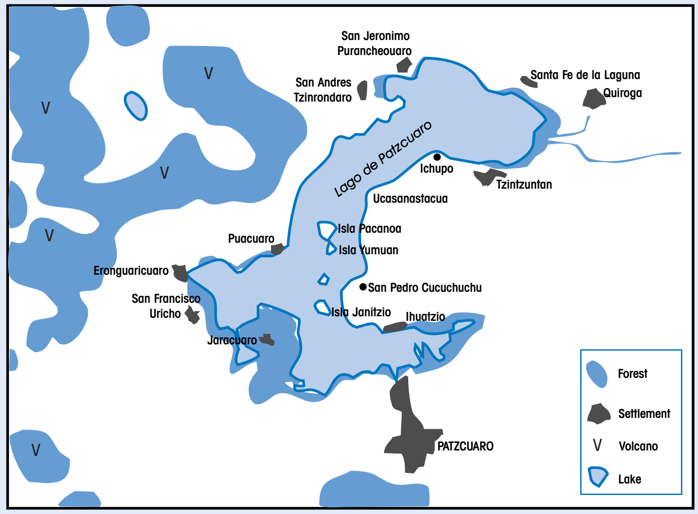
Poor catchment land-use practices have contributed to many of the problems affecting lakes and reservoirs (Box 4). The increasing sediment loads in many rivers during flood times arises from a combination of erosion and the removal of sediment deposition zones, such as floodplains, through development. Sediments and attached contaminants are best controlled at the source–after all, erosion represents a loss to farmers as well as a cost to downstream water users. Numerous studies have demonstrated that natural wetlands and floodplains are the most effective means of controlling floods and reducing sediment transport.

A particularly difficult problem exists with projects that include new dams or reservoirs. Where a reservoir is likely to suffer gradual siltation, it is necessary to assess the cost of remedial action or decommissioning across its projected lifetime. There is little experience on how to do this because conventional economic techniques heavily discount even large costs in future years. The World Commission on Dams has conducted an integrated economic analysis of a number of case studies across the world, but cautions that "applying a 'balance-sheet' approach to assess the costs and benefits of large dams, where large inequities exist in the distribution of these costs and benefits, is seen as unacceptable given existing commitments to human rights and sustainable development."

The development and implementation of environmental policies for the use, protection, and restoration of lakes requires a strong information base. This in turn requires a long-term commitment to research, monitoring, and evaluation (see Note D.1). Environmental monitoring of two types is usually required: (1) compliance monitoring, to ensure that regulations are enforced and milestones met; and (2) status and trends monitoring, to evaluate changes in environmental health and to help set new objectives and policies.

Box 4.
Lake Patzcuaro, México

Lake Patzcuaro is 130 km^2 in area and has a mean depth of 5 to 8 meters. The catchment has no rivers, only small streams that feed the lake during rainy periods. With its eight islands and mountainous landscape, it is a place of outstanding natural beauty and remarkable biological diversity. The basin includes 120 villages and two major towns, which are experiencing accelerated growth. The region has a large indigenous population, many of whom inhabit the islands in the lake, which has traditionally relied on subsistence farming and fishing. The lake is a national and international tourist attraction and there has been a recent shift to service industries.



Lake Patzcuaro showing settlements and forested areas

The major problem affecting this lake is the dramatic deforestation of the catchment and conversion of land to cattle ranching with increased settlement density. This has resulted in massive soil erosion (64-140 million m^3 of sediment annually deposited in the lake) and reduced inflows. As a result, water levels in the lake are receding, rapidly threatening the major asset of the region and its biological diversity. Furthermore, the lack of sewage treatment and the use of fertilizers has led to the eutrophication of the lake. Over 28,000 m^3 of untreated waste are now discharged to the lake every day.

More than 20 Mexican federal institutions are engaged in development and environmental protection in the area. However, this has not resulted in measurable improvements in the lake or in the social welfare of local people. There is no long-term management strategy, and little or no integration of effort across the various agencies. The situation is exacerbated by frequent changes in local officials and disregard of the traditional knowledge of indigenous people. More recently, the federal and state governments have agreed on priority programs for reforestation and protection of forests, regulation of fisheries, erosion control, and the control of siltation. A major program is also being developed in environmental education and strengthening of civil society. It remains to be seen whether these actions will result in the integrated approach necessary for managing the catchment and protecting the lake.

INSTRUMENTS FOR IMPROVING LAKE MANAGEMENT

Note B.2 provides a general introduction to instruments available for water resources management. This section will describe the use of specific instruments in the context of lake–and associated catchment–management.

Regulatory instruments. These typically include laws (statutory and customary) and regulations as well as the administrative procedures for enforcing them, such as prohibitions, permits, or licenses.

Most countries require environmental impact assessments (EIAs) for proposed developments. EIAs are designed to provide information to help decisionmakers properly weigh the benefits of a project against its impacts on stakeholders and on the integrity of the environment. For lakes and reservoirs, it is necessary to examine impacts in the entire watershed and, if there are migratory species, beyond it. Environmental assessments, incorporating the views of persons affected by the project–including indigenous people, the poor, and disadvantaged groups–are also a requirement of the World Bank for the projects that will have environmental impacts. However, there is room to improve many of these assessments with early and better stakeholder participation and an evaluation of a wider range of alternatives.

Economic Instruments. Note B.2 provides details of several economic instruments–such as tariffs, user fees, and pollution penalties–that may be applied to the management of lakes and reservoirs. However, it is particularly difficult to find viable mechanisms to cover long-run costs such as reservoir decommissioning or eventual lake rehabilitation. Some instruments useful for lake management are:

- ***Pollution charges.*** This involves paying a fee that reflects the environmental damage for every unit of wastewater discharged. This encourages factory managers to adopt measures for water conservation, recycling, and treatment prior to discharge.
- ***Tradable discharge permits.*** If a total acceptable level of discharge to a lake can be established (particularly for nutrients and biodegradable organic material), permits can be issued up to this level. These permits can then be traded on a market. This approach will only work if the number of sources within the lake catchment area is large enough to sustain a reasonable level of trading without any one source having a disproportionate influence on the market. A similar approach may be employed for trading permits to fish or extract any other renewable resource from the system.
- ***Subsidies to environmentally sound management practices.*** Subsidies are inefficient instruments but may be justified for practices such as integrated pest management and organic farming if they reduce the cost of environmental damage that society would otherwise have to bear.
- ***Fishing Licenses.*** It is common in the developed world for goverments to partly finance the management of lakes through fishing licenses. These recognize the cost of managing the fishing resource. A fishing levy has been proposed for Lake Victoria in East Africa as a means of having the fishing community recognize the cost of exploiting this natural resource.

Participatory Instruments. The involvement of stakeholders is a fundamental part of ICM. This inevitably requires community-level participation. Stakeholders in the case of lake or reservoir management may include users of the lake itself such as local authorities, fisherfolk, recreational users, power generation company staff, water distribution and sewage authorities, as well as catchment groups such as farmers, urban community groups, and industrialists. Other interested parties include scientists, conservationists, and the public in general. Local or international NGOs are often important actors in lake conservation programs. Involving these stakeholders promotes choice and enables transparency and accountability (Box 5). It reduces conflicts and fosters commitment to the management options selected, although there are considerable costs arising from the time and effort needed to engage these groups.

Environmental education is essential in order to ensure long-term sustainability of a participatory process. It should be conducted at two levels: (1) public awareness of the problems of environmental degradation, especially the linkages between

Box 5.
Integrated catchment management and the Great Lakes

The Great Lakes, shared between the United States and Canada, measure more than 15,800 km^2 in area. They account for 20 percent of the world's surface freshwater supply, and 95 percent of the surface water in the United States. Joint management of the lakes began in 1909 with the establishment of the International Joint Commission. The lakes have suffered serious environmental decline due to chemical pollution, introduced species (Box 3), and overfishing. Conventional approaches to pollution control proved inadequate, and in the 1970s scientists and resource managers called for an integrated ecosystem-based approach, including the participation of the main stakeholder groups interested in the lakes. Following a comprehensive assessment, 42 areas of concern were identified for urgent action using the integrated approach. For each of these areas, a remedial action plan (RAP) was created. The RAPs helped to set priorities and coordinate remedial activities, but they have not fundamentally changed the predominant sectoral nature of resource management in the catchment.

Source: Mackenzie, S.H. 1987. *Environmental Management*. 21(2): 173-183.

catchment activities and consequences on downstream waterbodies such as lakes and reservoirs, and (2) formal education of young people, in order for them to understand the central role of the natural environment in their future welfare.

INSTITUTIONAL ARRANGEMENTS FOR NATIONAL AND TRANSBOUNDARY LAKES

At the national level, the major challenge for lake management is to achieve the political support necessary to achieve a coordinated policy approach among the various sectors whose activities affect lakes. The agreed approach can be enshrined in a Lake Management Plan following the principle of ICM. The plan should clearly define objectives; legal prerogatives; the responsibilities of the actors involved; actions to be taken, with milestones and economic costs; provisions for monitoring and evaluation; and the institutional arrangements for coordination. Without a clearly identifiable local coordinating and implementing mechanism, the plan is almost certain to fail. Box 6 provides a good example of a coordinating mechanism that takes the form of a permanent lake commission. This mechanism is proving relatively successful, but has still failed to curb illegal use of the lake for shrimp farming.

At the international level, nearly half of the world's largest lakes are shared among two or more countries. Although this does not change any of the principles involved, it adds considerably to the

BOX 6.
DEVELOPMENT OF A COORDINATION MECHANISM: CHILIKA LAKE, ORISSA, INDIA

Chilika is India's largest lake. It is a coastal lake connected to the Bay of Bengal and supports a number of economic activities, including fishing (100,000 fisherfolk) and tourism. The brackish lake is suffering from a number of serious problems, including siltation, shrinkage of area, choking of the inlet as well as the outer channel to the sea, decrease in salinity, weed infestation, decrease in fish productivity, and an overall loss of biodiversity. There is a serious ongoing social conflict between traditional fisherfolk and operators of illegal shrimp aquaculture units.

In response to the declining environmental situation, the Government of Orissa created the Chilika Development Authority (CDA) in 1992. It is part of India's National Lakes Management Programme and has the following principal objectives:

- To protect the lake ecosystem and biodiversity
- To execute multidisciplinary developmental activities, either by itself or through other agencies
- To collaborate with other institutions—state, national, or international—for integrated development of the lake
- To establish a management information system and database of the lake
- To promote long-term multidisciplinary research, prepare environmental status reports, and establish a research center for the lake.

CDA has partnered with a number of local, state, national, and international institutions and nongovernmental organizations to carry out scientific investigations. These include understanding the biophysical and ecological nature of the complex lagoon and how it functions; determining the threats faced by the lake; monitoring the in-lake hydrology and ecology, and the catchment water quantity and quality; modeling the biophysical processes of the lake; and predicting the changes in sediment dynamics in response to changes in flow within the lake and between the lake and the sea.

As a result of these studies together with monitoring information and modeling, CDA has carried out a major restoration effort to improve the lake's hydraulics. In September 2000, with the support of the Government of India, they dredged large sections of sediment deposition within the lake and cut a new opening to the sea.

The restoration efforts have resulted in impressive changes in water quality (salinity levels are much higher), in freshwater flow patterns, and increases in zooplankton densities. The endangered Irrawady Dolphin *(Orcaella brevirostris)* has returned to Chilika Lake; many species thought to have been locally extinct are now found; and fish, crab, and shrimp production has dramatically increased. The income of the fisherfolk has more than doubled in the last 3 years.

This work has been recognized by the Ramsar Secretariat, which recommended the removal of Chilika Lake from the Montrex List as a threatened wetland and granted CDA a Ramsar award. CDA is now working on developing a long-term plan to manage the lake sustainably.

complexity of management. For example, it is difficult to set uniform water quality and effluent discharge standards among riparian countries with different industrial bases and traditions.

Management of these systems requires cooperative institutional structures, empowered through appropriate policy, legal, and financial instruments, and staffed with personnel trained in lake management and conflict resolution. International commissions for transboundary lakes have existed for over 100 years, but these have traditionally focused on exploitation and territorial issues rather than environmental protection. However, these require a high-level of agreement and cooperation between the relevant countries and are not the only option for lake management. In the past two decades, there has been increasing awareness of the fragility of lake environments and the need for integrated management practices across countries.

Box 7.
Transboundary Lakes in East Africa: Management approaches and the involvement of the GEF

Lake Victoria Environmental Management Project. Lake Victoria is shared by Kenya, Tanzania, and Uganda. Following an integrated approach, 14 pilot zone activities are intended to develop groundwater resources; conserve and develop wetlands; reduce sediment and nutrient flow, especially of phosphorus; reduce fecal coliform and municipal nutrient output; regulate industrial effluent; identify contaminants in fish and prevent any increase; stabilize the catch of Nile perch; increase the catch of indigenous species; increase incomes of local fisherfolk; and reduce water hyacinths to manageable levels. Lake-wide actions have assessed and measured sources of nutrients causing eutrophication; measured fisheries-trophic state interactions; modeled and monitored lake circulation; defined and measured the contaminant threat; harmonized regulation and legislation; monitored recovery and impact; and built institutional capacity. The project has been extended to 2004; a second phase, focused on implementing management actions using the knowledge base developed in the first phase, is being prepared.

Lake Tanganyika Biodiversity Project. Burundi, DR Congo, Tanzania, and Zambia all border Lake Tanganyika. The accelerating rate of environmental change caused by overfishing and eutrophication is now much faster than the fauna's adaptive capabilities. The lake's problems start on the land. Ownership and responsibility for land maintenance is uncertain and information on better techniques has not reached the practitioners.

The conflict in Burundi and DR Congo has made the implementation of this project very complex. The initial 5-year phase of the project was completed in July 2000, with the principal outputs being a body of technical studies on the biodiversity of the lake and the threats to it; a regionally agreed Strategic Action Program (SAP); and a draft legal convention. The SAP involved local communities in its development, embracing the dual needs of development and conservation. A follow-on project is now being prepared to implement the SAP.

Lake Malawi/Nyasa Biodiversity Conservation Project. Lake Malawi/Nyasa, the third largest lake in Africa, is shared by Malawi, Tanzania, and Mozambique. The lake is reputed to have the highest biological diversity of fish species in the world. Over 90 percent of the fish species are endemic to this lake. The lake provides abundant water for domestic uses in a water-scarce region; supplies essential and cheap protein through its fisheries; facilitates transportation and irrigation, especially downstream in the Shire River; contributes to hydroelectric energy production; attracts tourists; and provides recreational and aesthetic opportunities. A recent massive fish kill (1999) exemplifies the danger of increasing human pressure on the system, and there is growing evidence of eutrophication, habitat destruction, and overfishing. The three biggest challenges to the project and to conserving the biodiversity of the lake while allowing sustainable utilization are 1) to increase awareness among riparian peoples of the natural wealth the lake represents; 2) to understand how the lake has come to express and maintain such great biodiversity; and 3) to increase the resident expertise of the three countries to implement the management plan.

The GEF project in this lake was a relatively small "enabling" project with diverse activities, including reviews of environmental law and regulations, strategic park planning, environmental education, water quality assessment (WQA), zoogeography, fish taxonomy, and fish ecology. Under the WQA, the quantification of all the major nutrient inputs and outputs has been achieved for the first time on an African Great Lake. Perhaps the biggest challenge has been to engage local stakeholders using innovative activities such as the "Theatre for Africa," which has been highly successful. Postgraduate work for students, field training for environmental education extension officers, and on-the-job training for national research officers and technicians is ongoing. There are no plans at present to fund a follow-up GEF project.

The World Bank is currently implementing a number of transboundary, GEF-funded projects. These include Lake Victoria (3 countries), the Aral Sea (5 countries), Lake Ohrid (2 countries), Lake Malawi (3 countries), and Lake Chad (5 countries). UNDP–another of the GEF implementing agencies– is implementing similar projects for Lake Tanganyika, Lake Titicaca, and Lake Peipsi. A summary of the GEF interventions in East African lakes is provided in Box 7.

TOOLS FOR REMEDIAL ACTION

Remedial actions for seriously damaged lakes and reservoirs tend to be expensive and may either provide a temporary respite, involving high recurrent costs, or transfer the problem downstream. As a general rule, it is more cost-effective to control problems at their source than to undertake remedial action. Nevertheless, remedial approaches are sometimes unavoidable. For example, Lake Washington, situated near Seattle, Washington in the United States, has received discharges from industry, domestic sources, agriculture, and logging since early in the 20th Century. It was seriously eutrophied by the early 1950s. In 1958, a project began to divert effluent from 11 sewage treatment plants to discharge directly to the sea following primary treatment. The engineering works were completed by 1967, and by 1975 the lake had recovered to a near-pristine state. The capital cost of this work was high, $366 million ($650 per capita) at 1990 costs, with an annual operating cost of $2.1 million. The intensive recreational use of the lake alone provides benefits that exceed this cost.

Water quantity problems–either periodic or permanent reductions in lake levels–inevitably require action at the source of the problem.

Photo by Curt Carnemark, World Bank

Indonesia

The most common water quality problems encountered in lakes are excessive growth of either algae or nuisance aquatic weeds, although other quality issues such as accumulation of pesticides or heavy metals, acidification, and salinization can also seriously affect lake biota. Algal blooms and aquatic weeds can be tackled using a variety of techniques. The choice of technique will depend on the causes of the problem and the expertise and funding available. Techniques are briefly described below; Note G.4 provides detailed information.

ALGAL BIOMASS CONTROL

The main techniques for controlling the biomass of algae in eutrophic lakes are summarized in Table 2.

MACROPHYTE BIOMASS CONTROL

Excessive growth of aquatic plants may severely reduce the useful lifespan of the lake. In tropical systems, the presence of floating water hyacinths may result in the complete breakdown of the natural lake ecosystem.

For example, water hyacinths started to spread in Lake Victoria at the end of the 1980s. By 1996, the floating mats had become so dense that ports were becoming blocked. Mechanical means were incapable of harvesting such a large biomass. Later the same year, trials began of introductions of a weevil, *Neochetina sp.*, originally from South America. Initial results of the introduction were discouraging, but in December 1999, local scientists reported that 60 percent of the hyacinths had been eliminated from the lake. The reasons for the sudden reduc-

Table 2.
Techniques for controlling algae in eutrophic lakes

Technique	Example	Costs[1]
Advanced wastewater treatment. This usually involves removal of phosphorus from effluents discharging to the lake, since algal communities in lakes are often phosphorus-limited. Phosphorus can be removed with aluminium sulphate (alum), calcium carbonate (lime), or ferric chloride (iron). This is worthwhile only when significant proportions of nutrients come from point sources. Effluents can also be diverted entirely away from the lake, such as to land disposal on tree lots.	Diversion: Lake Washington (USA), Lake Norrviken (Sweden); AWT: Shagawa Lake (USA), Lake Zurich (Switzerland)	Typical per capita costs of diversion (1990 prices) are $350 to $1,350, with annual O & M costs from $4 to $16. Per capita costs for AWT are typically $600 to $1,100, with annual O & M costs between $77 and $115.
Dilution and flushing. This depends upon the availability of a large volume of clean freshwater to flush the lake at regular intervals and physically replace eutrophic water. Use of this freshwater may impose costs on upstream water users.	Moses Lake (USA), Lake Veluwe (Netherlands)	Highly variable
Hypolimnetic withdrawal. The removal of high nutrient, low oxygen, bottom waters of smaller lakes (usually less than 4 km^2). This is achieved by constructing a siphon tube from the lake bottom to replace the surface outflow from the lake. It may lead to further problems downstream.	Lake Bled (Slovenia), Lake Kortowo (Poland)	Typically under $1 million; very low O & M.
Phosphorus inactivation. Phosphorus bound in lake sediments may continue to be released for long periods of time if the bottom waters remain anoxic. It is possible to reduce phosphorus concentrations in the water column by chemical precipitation or to retard phosphorus release from sediments. Chemicals used are aluminium salts, which form a colloid that settles on the lakebed and takes up phosphorus. An alternative involves less environmentally damaging calcium nitrate application to oxidize surface sediments (Riplox process)	Alum application – L. Langsjon (Sweden); 3 Mile Pond (USA); Riplox – L. Trekanten (Sweden)	$640/ha (3 Mile Pond); $3,900/ha (L. Trekanten) (1990 prices)
Biomanipulation. Management of the food web to enhance the grazing of algae. The technique is not always successful because of the complexity of aquatic foodwebs. It requires a comprehensive understanding of the ecosystem.	Lake Michigan (USA) – control of lamprey, restocking of salmon. Bautzen Reservoir, Germany – unsuccessful example of long-term restoration	Typically $300 to $600/ha capital cost.
Algicides. Algicides, such as copper sulphate, can be sprayed on the lake surface to kill algal blooms. Although temporarily effective, they have major negative impacts on the ecosystem and should only be used for crisis situations.	Casitas Res. (California, USA)	$30 to $700/ha for a single application depending on dosage

[1] Estimates are taken from Cooke, G.D, E.B. Welch, S.A. Peterson. and P.R. Newroth. 1993. These refer to a limited number of case studies and are presented for indicative purposes only.

tion are not properly understood, although the weevils undoubtedly contributed. Water hyacinths had ceased to be a major problem by 2001 although, given favorable conditions, the problem could reoccur. (See Note G.4.)

The various techniques to control nuisance macrophytes are summarized in Table 3. Chemical methods are not discussed, as they are considered environmentally unacceptable

TABLE 3.
TECHNIQUES TO CONTROL NUISANCE MACROPHYTES

Technique	Example	Costs
Water-level drawdown. This is a relatively simple technique employed in smaller reservoirs. The water level is lowered in order to expose the lakebed in the littoral zone. Exposure of roots for sufficient time during freezing or dry, hot conditions will kill the plants. Negative consequences include possible algal blooms after reflooding and damage inflicted on wetland communities. Not always effective if the nuisance plants produce persistent seed stock.	Commonly employed technique in temperate reservoirs in the United States.	Typically $5 per ha. in the United States.
Preventative and manual methods. Prevention involves regulatory and public awareness measures to avoid the introduction of nuisance exotic species. Manual methods for removal include (1) diver-operated dredges; (2) harvesting of plant biomass (using single or multiple stage harvesters); and (3) derooting by barge-mounted rototillers or similar equipment. Environmental effects are minimal (mostly because of the small areas treated) but regrowth is almost inevitable.	Eurasian watermilfoil removal in the United States and Canada (species introduced in the 1940s); restoration of Lake Hornborga, Sweden	Diver dredging typically $4,000 to $16,000/ha (Canada). Harvesting, indicative cost $400 to $1,400/ha. Derooting (indicative) $900 to $1,200/ha. Capital costs of the equipment used is highly variable (typically $30,000 to $100,000 for a medium-sized harvester).
Sediment covers. By physically covering sediments with an impenetrable material, plants are prevented from rooting or growing. Typical materials employed are polyethylene, polypropylene, fibreglass/PVC (Aquascreen), or burlap. The method is symptomatic; removal of the cover soon results in regrowth unless preventive measures are taken. It may also "balloon" when gases are naturally released from the sediments.	The techniques have been employed in British Colombia, Canada to control Eurasian watermilfoil	Approximately $6,200 to $17,000/ha
Biological controls. Exotic macrophytes proliferate partly because of eutrophication, but partly because of the absence of natural controls. By studying the plants in their native habitat, it is sometimes possible to identify the control agent and transfer it to the site of the invasion. This carries its own risks, as the control agent may attack native species in the new habitat and worsen the environmental damage. The control agent should be specific to the invasive species, or easily removed following the successful intervention.	Aligatorweed, introduced to the US in 1884, choked many ponds and lakes until the stem-borer, *Agasicles,* was released in 1964, eliminating 98 percent of the weed in 17 years; Grass carp were used to clean Lake Parkinson in New Zealand of an exotic plant.	$70 to $200 (for Grass Carp)

MULTIPLE BENEFIT TREATMENTS

Table 4 illustrates techniques that can have multiple benefits, including algal control, control over release of toxicants, and habitat renewal. However, all are based on engineering approaches, which can be costly and require significant technical expertise.

Water quality monitoring is a central element of management whose costs are not incorporated into the above estimates. These lake interventions, by themselves, may overcome an immediate problem. However, they will almost always need to be augmented by longer-term measures through the application of policies and practices for ICM.

Table 4.
Multiple benefit treatments

Technique	Example	Costs
Hypolimnetic aeration. A characteristic of eutrophication is the depletion of O_2 in bottom waters (the hypolimnion). In small lakes and reservoirs where preventive measures have failed, aeration of the hypolimnion may alleviate the problem.	420 ha Tegeler See, Germany, 12 m³ air/min. from 15 airlifts; Kolbotnvatn, Norway, 5.5 m³ air/min;	Highly variable, Tegeler See installation cost was $2.7 million, $6,500/ha/yr operation.
Artificial destratification. The objective is to promote circulation between bottom and top layers of a stratified lake to enlarge the habitat for animals, maintain oxygenation, and reduce internal P cycling. Mixing is promoted by injecting air into a horizontal pipe perforated with a series of holes, lying at the bottom of a lake. A curtain of bubbles will rise from the pipe to the surface, entraining water with it. Typically very energy intensive unless designed to maximize natural mixing from wind forces.	Commonly employed in small eutrophied systems in the United States, Germany, Poland, Sweden, Canada, Australia, and the United Kingdom	Typical installation costs are $720/ha; corresponding operating costs would be $320/ha/yr. Financially impractical for large lakes.
Sediment removal. A technique for effectively creating a new benthic system. It removes the sediment nutrient pool, eliminates rooted macrophytes, and restores effective circulation. Mechanical, hydraulic, and pneumatic dredges may be employed. There are serious environmental considerations and the technique is only justified in chronic cases. Species may be lost and benthic habitats destroyed. Furthermore, disposal of contaminated dredged material is a major problem.	Lake Trummen, Sweden, 100 ha, received effluent from 1895-1970. 1m of accumulated sediments removed in 1970-71, 90 percent reduction in dissolved total P achieved, lake now used for wildlife and recreation.	Lake Trummen restoration cost about $5,700/ha (should be amortized over a 25-year period)

Care should also be taken to incorporate procedures for encouraging habitat restoration in any lake rehabilitation project. For example, migratory waterfowl cannot wait for two or three years for habitats to recover after a major intervention, but may need to be provided with artificial islands or rafts for nesting.

FUTURE CHALLENGES

The 1997 UN *Comprehensive Freshwater Assessment of the World* concluded that all economically accessible water in the world would need to be utilized in order to grow enough food for everyone to receive a healthy diet and for industrial, household, and environmental needs to be met. There will inevitably be increasing competition in meeting these needs. ICM offers the framework for reconciling these competing demands, but actual implementation will require increasing support from donors such as the World Bank, UNDP, UNEP, and the Global Environment Facility in the specific case of transboundary waterbodies.

At a local or regional level, there will be more challenges such as that faced in the restoration of Lake Sudoche, which is part of the Amu Darya river delta that used to be contiguous with the Aral Sea. Engineering solutions can reshape the hydrology of Lake Sudoche, providing that the countries in the Amu Darya catchment are willing to release water to maintain its level. Restoration is now under way as part of the World Bank/GEF Aral Sea Basin Programme, and the prospects for the lake are positive.

The kind of trade-off confronted in the case of Lake Sudoche is likely to become increasingly common in arid regions of the world. This is why it is important to understand lakes, not as isolated water bodies, but as a functional component of the larger catchment area. Strategic impact assessments and the application of ICM, together with the judicious use of engineering techniques for restoration, will help to maintain the vital role of these waterbodies and that of the ecosystems and social amenities they support.

FURTHER INFORMATION

The following references provide general information on lake and reservoir planning and management.

Ayres, W., A. Busia, A. Dinar, R. Hirji, S. Lintner, A. McCalla, and R. Robelus. 1996. *Integrated Lake and Reservoir Management*. World Bank Technical Paper No. 358. Washington, D.C.: The World Bank.

ILEC/UNEP. 1988-98. *Guidelines in Lake Management*, Vols.1-8. Nairobi, Kenya: UNEP. (also available at EarthPrint.com).

UNEP GEMS. 1994. Environment Library No. 12: *The Pollution of Lakes & Reservoirs*. Nairobi, Kenya: UNEP. (also available at EarthPrint.com).

World Lake Vision Committee. 2003. World Lake Vision: A Call to Action. Shiga, Japan: ILEC/UNEP/Shiga Prefecture.

The World Commission on Dams contains a thorough description of reservoir planning and development. The Bank has endorsed its core values and strategic priorities for its own lending.

World Commission on Dams, 2000. *Dams and Development*. London: Earthscan Publications.

The following document provides guidance on lake monitoring:

UN/ECE. 1996. *Current practices in monitoring and assessment of rivers and lakes*. Vol. 2. Geneva: UN/ECE Task Force on Monitoring and Assessment.

Restoration of lakes is described in the following publications:

Cook, C.D., E.B. Welch, S.A. Peterson, and P.R. Newroth. 1993. *Restoration and Management of Lakes and Reservoirs, Second Edition*. Boca Raton: Lewis Publishers.

Dinar, A., P. Seidl, H. Olem, V. Jorden, A. Duda, and R. Johnson. (1995). *Restoring and Protecting the World's Lakes and Reservoirs*. World Bank Technical Paper No. 289. Washington, D.C.: The World Bank.

Eiseltová, M., ed. 1994. *Restoration of Lake Ecosystems: A Holistic Approach*. London: International Waterfowl and Wetlands Research Bureau Publication 32, Slimbridge, UK.

United States Environmental Protection Agency (USEPA). 1988. *The Lake and Reservoir Restoration Guidance Manual*. Washington, D.C.: USEPA.

Some useful websites with information on lake and reservoir management are:

The Global Environment Facility
http://www.gefweb.org

The Global International Waters Assessment (a GEF project to examine the root causes of degradation in international waters)
http://www.giwa.net

The World Commission on Dams
http://www.dams.org

International Commission on Large Dams
http://icold-cigb.net

Lake Ohrid cooperative project
http://www.allcoop-macedonia.homestead.com/locp.html

Update on the Lake Chad Basin Commission
http://www.oieau.fr/ciedd/contributions/atriob/resume/rcblt.htm

Lake Tanganyika Biodiversity Programme
http://www.ltbp.org

Great Lakes Environmental Atlas and Resource Book
http://www.epa.gov/glnpo/atlas/intro.html

International Lake Environment Committee
http://www.ilec.or.jp

LakeNet
http://www.worldlakes.org

Wetlands International
http://www.wetlands.agro.nl