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Large freshwater lakes: present state, trends, and future

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SUMMARY

The large freshwater lakes of the world are an extremely valuable resource, not only because 68% of the global liquid surface fresh water is contained in them, but because of their importance to the economies, social structure, and viability of the riparian countries. This review provides decision makers with the knowledge of large lakes ($\geq$ 500 km^2) essential to establishing policies and implementing strategies compatible with sustainable development. This is achieved by considering the present state of the lakes, the extent of changes and factors causing them, long-term consequences of these changes, major threats and possible states of the lakes into the year 2025. Case studies of lakes are presented, namely the St Lawrence Great Lakes of North America as representatives of glacial scour lakes of North America, northern Europe and Asia, and the African Great Lakes as representatives of tropical tectonic lakes. Lake Baikal is also included because it is unique for its species, great age, and largest single volume of liquid surface fresh water. The Aral Sea is further included because of the ecological disaster following diversion of water away from its basin. The major impacts on large lakes are diversions, eutrophication, invasive species, land-use change, overexploitation of resources, and pollution. These impacts can or do affect all the representative lakes, but to varying degree. The St Lawrence Great Lakes have been severely impacted by eutrophication, land-use change, overfishing, invasive species and pollution. Eutrophication has been reversed for these lakes and constraints are now in place on land use change, such as shoreline alteration and destruction of wetlands. With the demise of most commercial fishing, overfishing is no longer as important. Invasive species have become a major problem as increasingly non-indigenous species gain access to the lakes. Pollution continues as a major impact. These problems are likely to continue and seriously impact use of the resources as well as bring about changes in the biota. Among the African Great Lakes, invasive species are a major problem in Lake Victoria, and eutrophication associated with land-use change and overexploitation of resources is a growing problem. Many endemic species have been lost and many are threatened, so that species associations will have changed by 2025. The Aral Sea continues to disappear and in the future, the remaining largest part of it will continue to become increasingly saline and eventually disappear. A small body of water will remain as a freshwater lake with a productive, although small, fishery. Lake Baikal shows evidence of pollution in the southern basin and is likely to be impacted by land-use changes, primarily logging. Some non-indigenous species are present, but so far, they are not a major problem. Overexploitation of resources in the watershed could lead to adverse impacts on inshore waters. Overfishing has been recognized and appears under control. The major threat to Baikal is continued and growing pollution. Climate change and pollution are global problems that will affect all lakes, large and small. At present, while some warming has occurred, climate change appears not to have impacted large lakes. Present studies on the Laurentian Great Lakes predict possible major impacts. Pollution, especially from persistent toxic substances such as PCBs, is a global problem. Diversion of water out or away from large lakes will become more of a threat as global human population growth continues and water supplies from rivers and ground water become depleted.

Keywords: large lakes, eutrophication, water diversion, land use, invasive species

INTRODUCTION

Global fresh water is the most precious human resource. Frequently Earth is called the blue planet because water covers about 75% of the globe, but most of the water is saline, less than 5% of the water is fresh (Herdendorf 1990), and much of this water is in the ice caps, glaciers and groundwater. Most of the remainder is in lakes, streams and soil moisture, and an estimated 68% of the fresh liquid surface water is in 189 large lakes with surface areas greater than 500 km^2 (Reid & Beeton 1992). Except for some remote lakes, they have been focal points for human settlement. They have been used for navigation, hydropower, irrigation, cooling water, waste disposal, leisure, and commercial and recreational fishing. Their waters have been essential for domestic and industrial consumption. Consequently, large lakes have been especially important to the economic vitality

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Table 1 Volume and area of the world's largest lakes. Adapted from Herdendorf (1990). Data for Aral area for 1994 from Glantz (1999). Aral Sea was fourth largest in area (66 900 km^2) and 13th in volume (1090 km^3) in 1960.

Volume rank	*Name*	*Volume (km^3)*	*Area rank*	*Name*	*Area (km^2)*
1	Caspian	78 200	1	Caspian	374 000
2	Baikal	22 995	2	Superior	82 100
3	Tanganyika	18 900	3	Victoria	68 460
4	Superior	12 230	4	Huron	59 500
5	Malawi	6140	5	Michigan	57 750
6	Michigan	4920	6	Tanganyika	32 900
7	Huron	3537	7	Aral	31 938
8	Victoria	2700	8	Baikal	31 500
9	Great Bear	2381	9	Great Bear	31 326
10	Great Slave	2088	10	Great Slave	28 568
11	Issykkul	1730	11	Erie	25 657
12	Ontario	1637	12	Winnipeg	24 387

and quality of life in those countries fortunate to have them (Table 1).

The purpose of the present paper is to provide decision makers with knowledge of large lakes sufficient for an objective basis for their policies and strategies, and to suggest some measures that could slow, stop and/or reverse some changes adversely affecting these lakes. Its specific objectives are:

- provide an overview of the present state of large lakes,
- provide information and evaluation of the extent and importance of changes in these lakes,
- determine why these lakes have changed and what are the key factors, whether anthropogenic and/or non-anthropogenic,
- evaluate the changes in terms of long range trends,
- determine the extent to which such information from the representative lakes can be used to predict changes in other large lakes,
- determine what are the major environmental threats to the representative lakes and lakes in general, and
- predict the possible state of large lakes within a reasonable time, i.e. by 2025.

Given the paucity of knowledge, the approach will be to use case studies of large lakes representative of various climatic, geologic, and geographic regimes and natural and anthropogenic impacts. The case studies selected are the Laurentian Great Lakes of North America, African Great Lakes, and Aral Sea and Lake Baikal of Asia. These are freshwater lakes; saline lakes, such as the Caspian Sea and Chad, are not included. The ten lakes selected are among the top 17 lakes, fresh and saline, in surface area, and among the top 18 lakes in volume (Herdendorf 1990). Some 45% of the 253 large lakes ($\geq$ 500 km^2) are less than 1000 km^2 in area. Less than 10% are greater than 10 000 km^2 (Herdendorf 1982). North America has almost half of all the large lakes. Many of the large lakes lie in glacial basins in North America and northern Europe and have very similar physicochemical features and biota (Beeton 1984); these account for 99 of the 189 freshwater lakes. Many of the glacial scour lakes are oligotrophic, although some, such as Erie, have been impacted by human activities and are considered mesotrophic or eutrophic. The flora and fauna of these lakes have populations of 'glacial relicts', which have a circumpolar distribution (Beeton 1984). Northern European lakes, such as Ladoga and Onega, have species associations closely similar to the St Lawrence Great Lakes (Beeton 1984). The invertebrate profundal fauna, nearshore zooplankton community, and the fish fauna are very similar. For example, Holmquist (1959) compared North American and Eurasian populations of *Mysis relicta* and concluded they were the same species. A strong similarity exists between some biological communities of glacial lakes that are widely separated geographically. The deepwater communities of Great Slave Lake of north-west Canada and Thirty-one Mile Lake in eastern Canada, separated by 2800 km, have a community coefficient of similarity of 80% (Dadswell 1974). The glacial lakes are generally a few thousand years old, whereas tectonic lakes may be millions of years old (e.g. Lake Baikal, Lake Tanganyika).

Lake Baikal is included among the selected large lakes because of its importance regionally and globally as the most ancient lake and of its great volume and unique biota (Kozhov 1963). The Aral Sea is included primarily because of its importance as an example of poor planning and mismanagement, and the consequences of diverting water (Glantz 1999). The African Great Lakes are included because of their tectonic origins, climate and endemic biota (Hart 1995), and their importance to regional economies and as water resources.

Among the lakes chosen for this review, the literature is most extensive for the Laurentian Great Lakes with regard to long-term trends in the biota and environment in response to environmental forcing factors. Consequently, much of the discussion is based on the Laurentian Great Lakes experience, but information on how other large lakes have responded to the same or similar forcing factors is presented. The discussion on environmental forcing factors for the Laurentian Great Lakes is presented from a historical perspective with emphasis on how settlement and development of the Great Lakes region of North America resulted in changing uses and hence changing importance of forcing factors.

ENVIRONMENTAL FORCING FACTORS

The environmental forcing factors discussed are those that have the potential to have major impact on a lake, its biota, and human uses of the lake. Some forcing factors, such as diversion of water supply, habitat alteration and visible pollution, are readily understandable; others, such as persistent toxic substances, are not easily recognized and are subtle in their effect.

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The Laurentian Great Lakes history

The consequences of human impacts and related changes are well illustrated by the history of the St Lawrence Great Lakes. The native North Americans appear to have had minimal impact on the drainage basin and the lakes (Ashworth 1987). Their uses of the lakes were largely for fishing and transportation (US Environmental Protection Agency & Government of Canada 1995). The European explorers found that the lakes provided transportation into the interior of North America, and as forts and small settlements were established, the lakes became important for commercial fishing and transportation. The forests of the region became a major source of lumber to build cities (US Environmental Protection Agency & Government of Canada 1995). The earliest witnesses to pollution are the huge quantities of sawdust that covered the bottoms of tributaries to the lakes for kilometres and resulted in their loss to the fishery as spawning and feeding sites (Milner 1874). Many harbours were built in mouths of rivers, shorelines altered, and wetlands destroyed (Ashworth 1987). The need for hydropower resulted in dams being constructed on many streams and rivers. The ecology of these flowing waters was altered and migratory fishes were seriously impacted. Early mention of domestic pollution is found in the public health records, which show increases in waterborne diseases, such as typhoid, occurring from use of lake water (Mortimer 2002). Domestic waste was a recognized problem, but little attention was given to other kinds of pollution until after the Second World War. The International Joint Commission for the Boundary Waters of the United States and Canada reported on trans-boundary pollution, which was largely bacterial. Commercial fishing became a major industry on all the Great Lakes, especially Lake Erie, before 1900, but overfishing became an issue with collapse of the lake herring or cisco (*Coregonus artedi*) fishery in Lake Erie in the 1920s.

The establishment of a large population of the predatory sea lamprey (*Petromyzon marinus*) in the lakes above Niagara Falls by the 1940s resulted in decimation of the multi-million dollar lake trout fishery (Applegate & Moffett 1955). The sea lamprey invasion was mostly viewed as a unique problem, and not as part of a larger problem that was to become of major concern in the 1990s.

By the 1960s, eutrophication, because of excessive nutrients from agriculture, poor waste management, and use of phosphate detergents, became a major concern (Beeton 1965). Populations of fish and invertebrates changed in size, polluted beaches were closed, large blooms of blue-green algae occurred, and dissolved oxygen became depleted in some bottom waters (Beeton 1969). Citizens became concerned and demanded action by local, state and provincial governments, and especially from the federal agencies of Canada and the USA. Concern subsequently turned to the adverse effects of persistent toxic substances, which affected all aquatic life, birds and humans (Colborn *et al*. 1990). All this occurred during the period when the 'environmental movement' was rapidly evolving.

Toxic substances, especially in larger predatory fish, remain of concern, and fishing and public health agencies issue advisory notices about the danger of eating larger fish from the Great Lakes. The focus has been on persistent toxic substances (PTSs) in fish because this has been the major route of exposure (Johnson *et al*. 1998). PCBs and dioxin-like compounds can cause neurobehavioural problems in humans (Johnson *et al*. 1998). Some of the PTSs continue to enter the lakes from local sources. In Green Bay, Lake Michigan, the dominant contributor of mercury is the Fox River; only 14% of the total mercury load to the Bay can be attributed to atmospheric deposition (Rossmann & Edgington 2000). Concentrations of chlorinated organic compounds have declined in some Great Lakes fish, but remain high for all species in Lakes Michigan and Ontario (Rowan & Rasmussen 1992). Data on fish contaminated with PTSs show between-basin and between-species variation. This between-lake variability of PTSs in fish can be explained by basin specific ecological attributes, namely fish lipid content, trophic position and trophic structure of the food chain, which vary appreciably between lakes (Rowan & Rasmussen 1992). Therefore, while concentrations of PTSs in water and sediment appear to be indicators of local pollution loading, they do not necessarily indicate resulting fish contamination.

The newer issues are invasive species, lake levels and climate change (Leach *et al*. 1999; Quinn 1999; Lofgren *et al*. 2000). The establishment of large populations of the zebra mussel (*Dreissena polymorpha*) in the 1980s turned attention to invasive species. These invaders are thought to have gained access to the lakes largely through oceangoing ships that discharged ballast water into the lakes (Leach *et al*. 1999). Over 139 non-indigenous species are in the lakes; the fish community now has a large non-indigenous component. Many fishes have been purposely introduced (e.g. several kinds of salmon), while others have been unintentional introductions.

Lake levels dropped rapidly between 1998 and 2000 because of decreased precipitation, above average water temperatures and reduced ice cover, which permits increased evaporation (Great Lakes Environmental Research Laboratory, unpublished data). Only the outflow of Lake Superior and the St Lawrence Seaway can be controlled. Low lake levels affect shipping, leisure use and wetlands.

Climate change will affect precipitation and evaporation, and consequently lake levels (Lofgren *et al.* 2000). Climate and lake warming could affect thermal structure of the lakes and, in a worst-case scenario, reduce mixing and result in possible deficits in dissolved oxygen in bottom waters (Quinn & Lofgren 2000); this could change sediment chemistry and increase release of toxic materials (Mortimer 2002).

Increases in annual average temperatures have been 1.3ºC for Canada and 0.7ºC for the Laurentian Great Lakes. Discharge of the St Lawrence River (1970–1990) is above the long-term mean of 7000 $m^3 s^{-1}$ (Mortsch *et al*. 2000). There

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is at present no evidence of adverse or positive impacts of global climate change on the biota or uses of the lakes.

Diversion of water into or out of the Great Lakes has been of concern for many years and there has been agreement among the Great Lakes states and Ontario against water leaving the basin (Ashworth 1987). Some water was diverted from Lake Michigan into the Illinois River in 1900 when the Chicago Sanitary and Barge Canal was opened (Quinn 1999). The quantity is regulated by court order. Water has been diverted from the Hudson Bay watershed into Lake Superior (Quinn 1999), but suggestions of further diversions, in or out, have been severely criticized (US Environmental Protection Agency & Government of Canada 1995).

Aral Sea

The diversion of the two major tributaries to irrigate cotton mean that the Aral Sea, which was once the fourth largest in surface area and thirteenth in volume in the world, is now reduced to two small lakes with only one-quarter of the former volume (Stone 1999). The entire Aral Sea basin of 2 million km^2 has been adversely affected by the decision to irrigate the arid and semi-arid soils of the region, which includes all of Uzbekistan and Tadzbrikistan, and portions of Kazakstan, Kirghistan and Turkmenistan, northern Afghanistan and north-east Iran. Irrigation probably began in this region more than 2000 years ago, however the recent extensive poorly-planned and ill-managed irrigation resulted in water logging, salinization and desertification (Glazovsky 1995); the Aral Sea was sacrificed to satisfy the needs of regional economic development planning (Bornik 1999). The USSR Plan for Nature Transformation in Central Asia (Glazovsky 1995) called for taking water from a major tributary, the Amu Darya, via the Main Turkmen Canal. Some of the consequences for the Aral Sea were recognized, but it appears the anticipated impacts on the Aral Sea were accepted in favour of economic development of the region (Golubev 1996). Anthropogenic and climatic factors caused the changes that took place after 1961 (Bornik 1999).

The signs of change were appearing during the 1960s–1980s (Glantz 1999). These included wind erosion, salt-laden dust storms, loss of spawning area for fish as the lake level dropped and fishery collapsed, and increased salinity, which eventually affected all aquatic life. Disruption of navigation as the lake level dropped, loss of wildlife in the deltas, climate change, and reduction in streamflow occurred (Bornik 1999).

African lakes

Lakes Victoria, Tanganyika and Malawi are experiencing somewhat different forms of environmental impact (Turner 1994; Alin *et al*. 1999). Victoria appears to be subject to some dramatic changes, while Tanganyika appears more resilient, perhaps because of a greater water volume and lower human population density in its watershed (Bootsma & Hecky 1993). Eutrophication, pesticides and alteration of the biological communities are of concern for the three lakes, plus possible consequences of petroleum extraction in Lakes Malawi and Tanganyika (Hecky & Bugenyi 1992).

The riparian human population of these lakes is largely dependent on the lakes for nutrition and general welfare (Hecky & Bugenyi 1992). Mean population growth in the region is at a mean of 2.4% annually and most densely populated areas are on the lake shores. Deforestation, soil erosion, desertification and atmospheric pollution are seriously degrading the lakes (Hecky & Bugenyi 1992).

These Great Lakes have nearly closed basins, water input is mainly precipitation, they have very long water-residence time, and biological processes modify water quality (Hecky & Bugenyi 1992). These characteristics make the lakes very sensitive to atmospheric sources of pollution. Outflows are low compared to the volumes of the lakes; flushing times are 750 years for Malawi, 7000 years for Tanganyika, and 140 years for Victoria. Consequently, pollutants are retained and accumulate in sediments (Hecky & Bugenyi 1992). Only Victoria mixes completely, while Malawi and Tanganyika are meromictic; as a result, anoxia persists in their deep waters.

Lake Victoria has been impacted by invasive species, especially the Nile perch *Lates niloticus,* overfishing, and land-use changes. About two-thirds of the endemic haplochromine cichlid fishes have disappeared along with explosion of the Nile perch, which was introduced some 30 years ago (Lowe-McConnell 1994). Other changes occurred in the fish community with introductions between 1953 and 1962 of non-native tilapias, which replaced endemic tilapias. Overfishing increased five-fold during 1970–1990 in a fishery dominated by Nile perch, Nile tilapia (*Oreochromis niloticus*) and the endemic cyprinid (*Rastrineobola argentea*).

The increasing human population in the Lake Victoria basin has accelerated changes in land use, resulting in increased run-off of sediments and nutrients. Clearing of riparian vegetation has led to erosion and loss of vegetation that acted as filters (Lowe-McConnell 1994). Changes in sedimentation rates and plankton have been taking place for 90 years (Lowe-McConnell 1994), while eutrophication started in the 1920s and accelerated in the 1960s with land clearance (Hecky 1993).

The Lake Malawi fish community has been adversely impacted by increased exploitation of inshore fishes resulting in declining catches and loss of biodiversity (Turner 1994).

The impacts of pollution do not appear to be as critical as in the Laurentian Great Lakes. For example, a study of the River Ntahangwa, considered the most polluted tributary of Lake Tanganyika, concluded that organic pollution to the lake was negligible and direct signs of pollution were not readily apparent (Vandelannoote *et al*. 1996). There are relatively high concentrations of phosphorus (Vandelannoote *et al*. 1996), although nitrogen is considered the likely macronutrient (Hecky & Bugenyi 1992).

Compared to the Laurentian Great Lakes, concentrations of chlorinated pesticides at Senga Bay, Lake Malawi, were

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similar in the air, but lower in the water, and food web and fish samples had low concentrations of a range of chlorinated organic compounds (Karlsson *et al.* 2000). This situation may be due to rapid transformation of chemicals in Lake Malawi, and removal processes might be faster generally in the tropics than in temperate and arctic regions (Karlsson *et al.* 2000). Long-range transport of chlorinated organic compounds was not found and local and/or regional sources appeared to dominate.

Lake Baikal

The limnology and biota of Lake Baikal have changed very little from the historical record (Kozhov 1963; Grachev 1991; Flower 1994). The threats to the lake are the increased pollution from industrial and domestic discharge, from trans-boundary-transport of pollutants into the region, and from logging in the watershed (Rose *et al.* 1998). Partially treated sewage enters the lake in the far north at Severobaikalsk. Most pollution enters the southern basin, directly and via the Selenga River. Major pollution arises from the pulp and cellulose mills at Baikalsk and Selinginsk, which are on the Selenga River (Rose *et al.* 1998). Atmospheric contamination, due to increases in industrial emissions, is a growing problem. Significant amounts of heavy metals enter the lake via atmospheric transport from outside the basin (Kozhova & Silow 1998).

Organochlorine compounds have been of special concern since analyses have shown that Lake Baikal water, fish and seals all have measurable levels (Kucklick *et al.* 1994). Furthermore, the concentrations in Lake Baikal water and fish in 1991 were similar to those observed in the upper St Lawrence Great Lakes, except chlordanes, which were about a half those in Lake Baikal (Kucklick *et al.* 1994). There was more unconverted 4,4'-DDT and 2,4'-DDT in Lake Baikal than in the Great Lakes, which suggests inputs from continued use of DDT in Asia (Kucklick *et al.* 1994). Lake Baikal appears to be receiving new inputs of PCBs either locally or through regional, probably atmospheric, transport (Iwata *et al.* 1995; Kucklick *et al.* 1996). The mortality of several thousand seals in 1988–1989, while attributed to viral infection, may have been in part a consequence of persistent organochlorines, which affect their immune system (Iwata *et al.* 1995).

It appears that Baikal has not been adversely impacted by non-indigenous species, and no extinction of any of the 1500 to 2000 endemic species is known to have occurred (Grachev 1991). Deforestation and land cultivation, leading to increased mineralization of tributaries, are considered the greatest long-term influences on the lake (Kozhova & Silow 1998).

IDENTIFIED LONG-TERM TRENDS

Probably the most valuable sources of long-term data are fisheries catch records, which are available for all the large lakes discussed here. In addition, some trend data are available on toxic substances in Lake Baikal and the Laurentian Great Lakes, and for invasive species and eutrophication in the African and Laurentian Great Lakes.

Trends in the fishery of the Laurentian Great Lakes

Commercial fish production data for the Laurentian Great Lakes appeared in reports starting in 1867 in Canada and in 1879 in the USA (Baldwin *et al.* 1979). The Canadian data are continuous for many species since 1867. The USA data are incomplete for many years during 1879–1914, largely because not all the states were collecting the information. Commercial landings are reasonably complete for the USA starting in 1914, although the licensed Michigan commercial fishers did not submit daily reports prior to 1929.

The commercial fishing data for highly prized fishes in the Laurentian Great Lakes, such as lake trout (*Salvelinus namaycush*), whitefish (*Coregonus clupeaformis*), and lake herring (*C. artedi*), probably represent the status of the fish populations, whereas data for carp (*Cyprinus carpio*), goldfish (*Carassius auratus*), sheepshead/drum (*Aplodinatus grunniens*) and other less desirable species probably reflect market conditions. Reports before 1900 indicate that yields of some species declined before data on commercial landings were being routinely collected (Brown *et al.* 1999*b*).

The commercial fishery of Lake Michigan probably started in the 1820s (Brown *et al.* 1999*b*). The early fishery was for whitefish, which were abundant near shore, but by 1860 stocks were depleted in some areas. By the 1870s, concern over scarcity of whitefish was common, although production was 5.4 million kg in 1879. The whitefish fishery remains important and has recovered in recent years after being impacted by sea lamprey predation in the 1950s and environmental changes over many years (Brown *et al.* 1999*b*).

The deepwater ciscoes of Lake Michigan were part of the commercial fishery since at least 1869 (Wells & McLain 1973). Unfortunately, catch records for these species were often combined with other coregonid species or not recorded. Usually the catch records were not separated by species and were just recorded as chubs. Records of the kinds of fishing gear used suggest changes in the abundances of the several species. *Coregonus nigripinnis* and *C. johannae* are the largest ciscoes. The early fishery used gill nets with mesh size as large as 11.5 cm, but mesh size decreased several times to 6.4 cm by 1950. These decreases in mesh sizes are likely to have reflected declining stocks of the larger ciscoes. Fortunately, fishery surveys were conducted in 1930–1932, 1954–1955 and 1960–1961. The largest-sized species were already depleted by 1930–1932 and made up a small portion of the population. It appears that the largest species were depleted by the early 1900s (Smith 1972). The bloater (*C. hoyi*), the smallest species, increased and continues to provide a fishery (Brown *et al.* 1999*a*).

According to Smith (1972), none of the deepwater ciscoes ever made a recovery in any lake after severe decline. This

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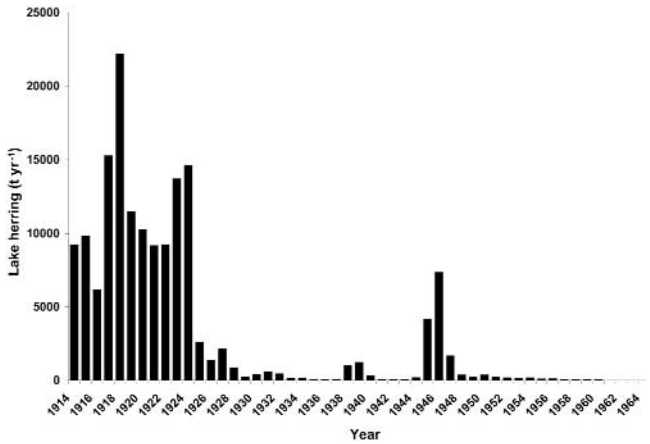


Figure 1 Lake herring (cisco) production in Lake Erie 1914–1964. Data from Baldwin *et al*. (1979).

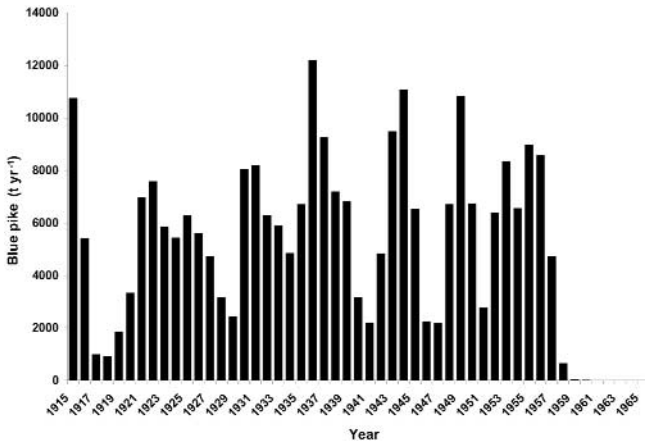


Figure 2 Blue pike production in Lake Erie 1915–1965. Data from Baldwin *et al.* (1979).

could be due to competition with the smallest ciscoes occupying the niches and the continued fishery, which selected the largest fish. In addition, changes in water quality and the presence of marine invasive species probably contributed to collapse and lack of recovery of deepwater ciscoes.

The lake herring (*C. artedi*) is evidently not resilient and populations collapsed in each of the lakes except Lake Superior. Lake herring and deepwater ciscoe populations collapsed in Lake Ontario by the mid-1950s. Most of the Lake Huron fishery was in the eutrophic waters of Saginaw Bay, where production peaked in the 1930s, sharply declined in the 1940s, and collapsed in the 1950s (Brown *et al*. 1999*b*). Lake herring comprised the major share of the fishery in the 1800s and early 1900s in Lake Michigan (Wells & McLain 1973). Subsequently, production declined into the 1940s, increased briefly in 1952 and then declined drastically in the 1960s. Much of the catch was from Green Bay, which was seriously polluted in some areas and showed early signs of eutrophication (Beeton 1969).

The collapse of the lake herring or cisco fishery in Lake Erie (Fig. 1) caused great concern resulting in a limnological survey of the western basin to determine the causes (Wright 1955). The fishery was subject to wide fluctuations in catch (Baldwin *et al*. 1979); a catch of more than 14 million kg yr^{-1} in 1924 abruptly dropped to *c*. 3 million kg yr^{-1} in 1925, and the fishery continued to decline. A brief recovery occurred in 1946–1947, with production over 7.3 million kg yr^{-1}, but this recovery was short. Decline continued into the 1960s and production has not exceeded 227 kg yr^{-1} since that time (Brown *et al.* 1999*b*). The catch records show the fishery declined first in the far west end of the lake in water receiving the inflows of the Detroit and Maumee Rivers, both affected by pollution and excessive nutrients. The fishery declined next in the Ohio waters and subsequently in Pennsylvania and New York, i.e. progressively from west to east from shallow polluted areas to the deeper, cleaner eastern waters (Beeton & Edmondson 1972).

The bluepike (*Stizostedion vitreum glaucum*) fishery collapsed during the same general period (Fig. 2) as the collapse of the cisco fishery in Lake Erie (Baldwin *et al*. 1979). The commercial catch fluctuated widely during the period of record 1915–1957. The catch dropped abruptly from over 4 million kg yr^{-1} in 1957 to *c*. 635 000 kg yr^{-1} and continued to decline, until by 1962 only 454 kg yr^{-1} were taken. During this period, all the fish were older and it appears recruitment of young fish had ceased and negligible reproduction occurred after the mid-1950s (Brown *et al.* 1999*b*). The bluepike fishery had never been significant in Lake Ontario; production never attained 450 000 kg yr^{-1}, and collapsed during the same period as the collapse of the fishery in Lake Erie. This species is now considered extinct in both lakes (Brown *et al*. 1999*b*).

Over-exploitation of especially desirable fish stocks was a major factor in the decline and, in several cases, extirpation of species in the Laurentian Great Lakes. Undoubtedly, other factors, such as changes in the drainage basins, played a major role. Early records indicate that most species now considered open-lake and/or deepwater species were abundant, at least sometimes, in bays, marshes and tributaries (Smith 1972). The earliest fisheries used gear appropriate to shallow waters. River-run coregonids, lake trout, walleye (*S vitreum*), and yellow perch (*Perca flavescens*) were common in the 1800s (Smith 1972). The construction of many mill dams for hydropower changed the hydrology of tributaries and affected migration of fishes (Smith 1972). The Atlantic salmon (*Salmo salar*) was especially vulnerable to the mill dams since these salmon spawned in streams that were no longer accessible. The fishery for this latter species collapsed by 1890 (Baldwin *et al*. 1979).

Eutrophication and pollution of the Laurentian Great Lakes

Changes in the biota and environment of the Laurentian Great Lakes, especially Lake Erie (Beeton 1969), were of increasing concern in the 1960s. Low dissolved oxygen levels occurred in Lake Erie and Green Bay. Increases in abun-

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dance and changes in the species composition of algae occurred in Lakes Erie, Michigan and Ontario (Beeton 1969). Phosphorus concentrations increased along with phosphorus loadings, and some of the changes in fish populations were closely similar to those observed in small lakes affected by eutrophication (Beeton & Edmondson 1972).

Long-term anthropogenic effects are shown by analysis of siliceous microfossils, largely diatoms, in cores from Lake Erie (Stoermer *et al.* 1987). Oligo-stenothermal species were dominant and microfossil deposition rates were low before European settlement in the watershed. Following settlement, deposition rates increased and subsequently a species shift occurred during 1920–1930 when eutrophic species became dominant. Species tolerant of hypereutrophic conditions dominated the flora after the 1940s (Stoermer *et al.* 1987). Sediments deposited in the 1980s show a qualitative shift in the diatom community, possibly reflecting reduction in phosphorus loadings.

Compared to small lakes, large lakes are of such size and diversity of habitats as not to show an overall response early in nutrient enrichment. Inputs of nutrients and other pollutants occur into nearshore areas and bays, and early surveys of Lake Erie (Wright 1955; Fish 1960) showed pollution along the shore, but this was dismissed as a shore effect that did not get very far into the lake in a harmful form. However, continued and accelerated loading of nutrients eventually affected both nearshore and offshore waters (Beeton & Edmondson 1972).

The early view, as expressed by the International Board of Inquiry for the Great Lakes Fisheries (1943), was that decline in fish populations was directly attributable to man's activities, including pollution, and not a natural change in environment (Beeton 1969). Consequently, pollution was considered a manageable problem that when controlled would allow return to pre-pollution status. The long-term trends in total dissolved solids coincided with the growth in human population for each drainage basin except Lake Superior (where population increase was minimal). Large increases in major ions in Lakes Erie and Ontario started around 1900 (Beeton 1969). The trends over time were very similar, as would be expected, because the major inflow to Lake Ontario is from Lake Erie via the Niagara River. The fact that the concentrations continued to increase into the 1960s indicates increased loading of the several ions, as the flushing rate is low, namely about 2.7 years in Lake Erie and about 7.5 years in Lake Ontario (Quinn 1992).

Efforts to reduce and/or reverse eutrophication have been successful. Loading of phosphorus (Table 2) has decreased to targeted levels (International Joint Commission 1989). Upgraded sewage treatment and efforts to control non-point as well as point sources have resulted in decreases in chlorides in Lake Ontario (Beeton *et al.* 1999) and presumably elsewhere. Algal blooms have declined in severity, the benthos has benefited and *Hexagenia* populations are back in Western Lake Erie, Green and Saginaw Bays (T. Nalepa, unpublished data 2001). The recovery of walleye fisheries in these environments cannot be attributed entirely to improvement in the environment, however; control of overfishing must also be a factor. Discovery of mercury in walleye flesh in 1970 in Lake Erie resulted in a two-year ban on commercial and recreational fishing, which later became a five-year moratorium (Hatch *et al.* 1987). This moratorium provided opportunity for walleye stocks to grow and allowed implementation of the international interagency management plan. As mercury declined after 1972, after reduction in discharge of mercury, the fishery was reopened gradually and quota management implemented by 1976 (Hatch *et al.* 1987). Commercial fishing as well as sport fishing continued in Ontario waters, but only recreational fishing was allowed in Michigan and Ohio waters. Walleye populations have recovered in both Green and Saginaw Bays and support successful recreational fisheries (Bence & Smith 1999).

Table 2 Estimated phosphorus loadings (tonnes yr^{-1}) to the Great Lakes 1976 to 1990 and target loads of phosphorus (tonnes yr^{-1}) from Great Lakes Water Quality Agreement (International Joint Commission 1989).

Year	*Lake Superior*	*Lake Michigan*	*Lake Huron*	*Lake Erie*	*Lake Ontario*
1976	3550	6656	4802	18 480	12 695
1977	3661	4666	3763	14 576	8935
1978	5990	6245	5255	19 431	9547
1979	6619	7659	4881	11 941	8988
1980	6412	6574	5307	14 855	8579
1981	3412	4091	4481	10 452	7437
1982	3160	4084	4689	12 349	8891
1983	3407	4515	3978	9880	6779
1984	3642	3611	3452	12 874	7948
1985	2684	3956	5758	11 216	7083
1986	3059	4981	4210	11 118	9561
1987	2000	3500	3000	8100	3000
1988	2100	2800	3200	8000	2900
1989	2300	4400	3400	8100	2900
1990	1800	3000	2600	13 000	5000
Target loads	3400	5600	4360	11 000	5000

Water quality has continued to improve at the mouth of the Detroit River where it enters Lake Erie, and at 16 major tributaries (Michigan Department of Environmental Quality 2000). Concentrations and loading rates of chlorine, lead, copper and zinc have decreased. Removal of contaminated sediments in Areas of Concern increased during 1991–1998 (Fig. 3). Beach closures continue largely due to stormwater run-off and combined sewer overflows. The Toxic Release Inventory shows a significant decrease in releases of hazardous chemicals by industry in the eight Great Lakes states (Michigan Department of Environmental Quality 2000).

The persistence of chemicals such as chlorinated organic compounds in fish remains a major cause of impaired use of the Great Lakes fishery resource (DeVault *et al.* 1996). Since the 1970s, most contaminants, such as PCB, DDT, dieldrin, and oxychlordane, have shown declines (Fig. 4). The trends

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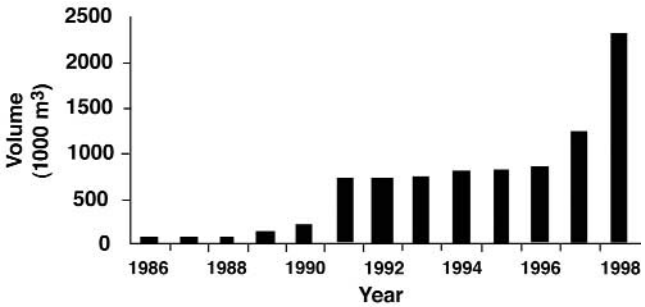


Figure 3 Volume of contaminated sediments removed from the Laurentian Great Lakes 1986–1998. (Adapted from Michigan Department of Environmental Quality 2000.)

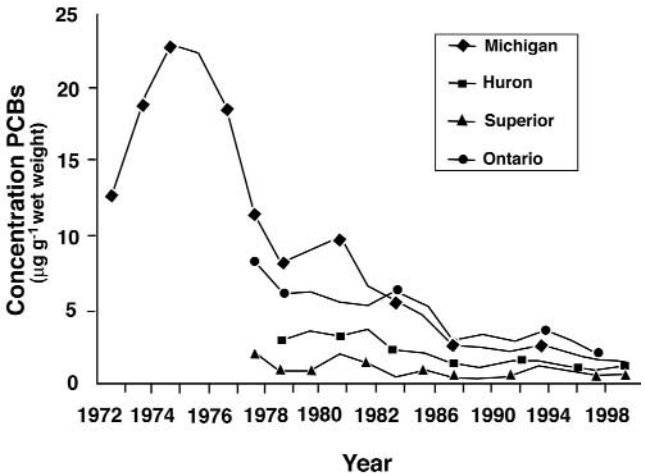


Figure 4 Concentration of PCBs in lake trout in Laurentian Great Lakes 1972–1998. (Adapted from Michigan Department of Environmental Quality 2000.)

for Lake Michigan DDT have been similar to those of the PCBs, as were the trends for PCB and DDT in Lakes Huron, Ontario and Superior (Michigan Department of Environmental Quality 2000).

PCB concentrations decreased in Great Lakes fish through the early 1980s, but reduction of PCBs in fish has apparently not occurred since 1986 (Jeremiason *et al.* 1994). PCBs decreased in Lake Superior water from 2.4 ng l^{-1} in 1980 to 0.18 ng l^{-1} in 1992, which represents a loss of 26 500 kg to the lake, whereas sediment cores show 4900 kg of PCBs have been deposited since 1930 (Jeremiason *et al.* 1994). Consequently, it appears the dominant loss process for PCBs is volatilization, not sedimentation, as shown by an estimated volatilization of 1900 kg and a loss to sediments of 110 kg of PCBs in 1986. Large oligotrophic lakes in mid-latitudes do not always act as sinks, but act as sources increasing the residence time of PCBs in the atmosphere (Jeremiason *et al.* 1994). Under these conditions, concentrations of PCBs in fish will decrease very slowly and remain a problem for years.

Decline in persistent toxic substances in various fishes has not been uniform. For example, whole-body concentrations of DDE and PCBs in smelt (*Osmerus mordax*) and of PCBs in the slimy sculpin (*Cottus cognatus*) from Lake Ontario showed no significant time trend, whereas mercury concentrations in these fish decreased from 1977 to 1988 (Borgmann & Whittle 1992). During this period, concentrations of DDE in lake trout declined; it seems that contaminant trends in a lake cannot be accurately assessed by monitoring a single species (Borgmann & Whittle 1992).

Polychlorinated dibenzodioxin (PCDD) and polychlorinated dibenzofurans (PCDFs) in herring gull eggs declined in a number of colonies from 1981 to 1984, following controls and bans for such compounds in the early 1970s (Hebert *et al.* 1994). Concentrations of PCDDs and PCDFs remained relatively constant indicating inputs and outputs to the biota of the Great Lakes are at or near equilibria (Hebert *et al.* 1994). Data on PCDDs in lake trout and walleye showed bioaccumulation patterns closely similar to those observed for herring gull eggs, suggesting that these animals are regional indicators of ecosystem contamination (Hebert *et al.* 1994).

Modern sedimentation rates are much the same as those for the last 7000 years (Robbins & Edgington 1975). ^{210}Pb techniques showed that stable lead profiles in cores from Lake Michigan reflect the history of lead input from burning of coal and use of leaded gasoline (Edgington & Robbins 1976). Sediment cores from Saginaw Bay, Lake Huron, show large input of petroleum compounds; aliphatic hydrocarbon concentrations were 30 μg g^{-1} in pre-1876 sediments and average 385 μg g^{-1} in modern sediments (Meyers *et al.* 1980).

Lake Superior has been impacted by mining, which discharged more than a billion tonnes of tailings; high copper and mercury contents of cores can be traced to mill and smelting sources (Kerfoot *et al.* 1999).

Climate change and the Laurentian Great Lakes

Several studies have already developed scenarios and determined if climate changes have affected the Laurentian Great Lakes. Changes in precipitation, basin run-off and evaporation have affected lake levels over periods lasting months to years (Chagnon 1987). Water temperature records from the Erie Pennsylvania water treatment plant for 1918–1958 show a warming of Lake Erie by 0.8 to 1.1 ºC, which is consistent with the increase in annual air temperatures for southwestern Ontario (Beeton 1961). There have been changes in the freeze and break-up dates of ice on Northern Hemisphere lakes, including Grand Traverse Bay of Lake Michigan, Toronto Harbour of Lake Ontario, and Lake Baikal, during 1846–1995. Freeze dates were on average later by 11.4, 36.9 and 11.0 days/100yr, and break-up dates were earlier by 11.8, 7.4 and 2.1 days/100yr, respectively for these lake, both trends attributable to global warming (Magnuson *et al.* 2000).

Non-indigenous species, Laurentian Great Lakes

Changes in the drainage basin, pollution, eutrophication, and overfishing have all adversely impacted the Laurentian Great Lakes, but probably the greatest long-term impact has been,

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and will continue to be, the intentional and unintentional introduction of non-indigenous species. Many plants and animals have invaded the Great Lakes and, of these, 139 species have become successfully established since the early 1800s (Leach *et al.* 1999). Not all these species have caused major problems. Some, for example several kinds of salmon, are considered to have been beneficial, but several have caused major changes in the biota and the very nature of the lakes. The alewife (*Alosa psuedoharengus*), sea lamprey (*Petromyzon marinus*), carp (*Cyprinus carpio*), ruffe (*Gymnocephalus cernuus*), and round goby (*Neogobius melanostomus*) are fish that have been especially troublesome (Leach *et al.* 1999). Other fishes such as the smelt (*Osmerus mordax*), several species of salmon (*Oncorhynchus*), brown trout (*Salmo trutta*), and white perch (*Morone americana*) may have impacted native species, but they have been accepted as they have provided useful fisheries. Among the invertebrates, the most troublesome have been the zebra and quagga mussels (*Dreissena* spp.). *Dreissena polymorpha* populations have clogged water intakes of power plants (Kovalak *et al.* 1993) and a city, Munroe (Michigan), where several water outages occurred in 1989 and 1990 (LePage 1993).

Uncertainty surrounds the relative importance of exploitation, habitat degradation and lamprey predation (Hansen 1999), but sea lamprey predation probably caused the complete collapse of the lake trout fishery in all the Great Lakes except Lake Superior (Brown *et al.* 1999*b*) and this caused major socio-economic problems in the fishing communities. The fishery had been intense as populations of lake trout collapsed, but it is likely the additional stress of lamprey predation led to demise of the lake trout (Smith 1972). The lamprey probably entered Lake Ontario in the early 1800s and gained access to Lake Erie via the Welland Canal in the 1920s (Applegate & Moffett 1955), but few streams favoured its reproduction (Hansen 1999). The major problem began when the lamprey entered Lake Huron in the 1930s; the catch of lake trout started to decline in 1939; in 15 years less than 45 000 kg yr^{-1} were taken (Baldwin *et al.* 1979) and the fishery collapsed. The same scenario occurred in Lake Michigan; the fishery began to decline in 1945, and had collapsed by 1950 (Fig. 5). Other large fish such as the whitefish, deepwater ciscoes, and the burbot (*Lota lota lacustris*) were also attacked. The lamprey gained access to Lake Superior, and although not all the lake trout stocks were depleted, they were seriously impacted.

The alewife gained access to Lake Erie above Niagara Falls in the 1930s via the Erie and Welland Canals (Smith 1970), and subsequently entered Lakes Huron and Michigan in the 1930s and 1940s, where collapse of the coregonid populations and demise of the top predator provided very favourable conditions. Alewife populations exploded and they quickly became the dominant species. Decreases in the large planktonic Crustacea of Lake Michigan, as well as in average size of *Daphnia*, are attributable to alewife predation (Wells 1970).

It is likely that the additional competition of the alewife led to demise of the lake herring in Lake Michigan. The lake herring population increased when smelt populations were low and decreased when smelt populations were high in the mid 1950s (Beeton 1997). After the establishment of the alewife in the 1950s, the lake herring fishery collapsed and did not recover.

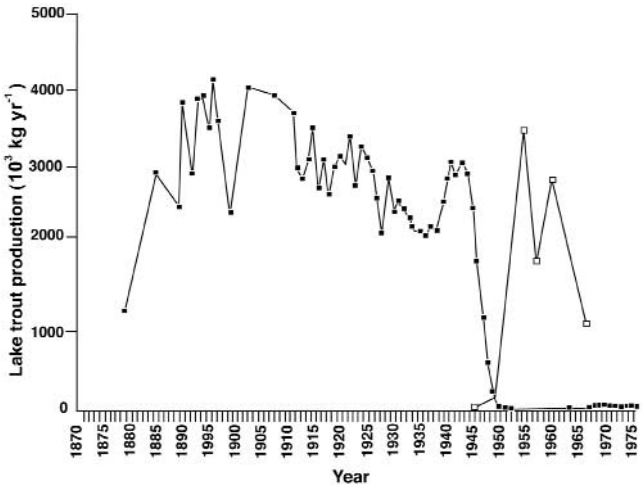


Figure 5 Lake trout production in Lake Michigan (black squares) and estimates of sea lamprey abundances (white squares). Lake trout data from Baldwin *et al.* (1979), sea lamprey abundances from Hansen (1999).

Except for a massive die-off in 1967, the alewife has continued as a dominant species, and supported a large commercial fishery (Baldwin *et al.* 1979). However, with consumption of alewife by salmonines surpassing commercial landings every year after 1969 (Brown *et al.* 1999*a*), a fish that had originally been considered undesirable became desired as forage for the salmon. The State of Michigan banned trawling for alewives in 1991 because of concern expressed by the sports fishers.

Dreissena polymorpha was first found in Lake St Clair in 1988 and probably entered in ballast water from an ocean vessel (Hebert *et al.* 1989). The mussel is an efficient suspension-feeding bivalve, and an early sign of its effect on the environment was an increase in water clarity in Lake Erie along with dramatic changes in abundance and species composition of phytoplankton (Holland 1993). Increased water clarity favoured increased abundance and wider distribution of aquatic macrophytes. Changes also occurred in water quality of Western Lake Erie. Ammonium, nitrate, soluble reactive phosphorus and silica concentrations were greater shortly after the zebra mussel became established (Holland *et al.* 1995). The zooplankton community was also affected; rotifers and copepods were much less abundant in the 1980s and 1990s in Lake Erie after the zebra mussel was found than in the 1970s (Beeton & Hageman 1994).

Similar changes to those observed in Lake Erie were reported for Saginaw Bay, Lake Huron (Nalepa *et al.* 1999). Water clarity and vascular macrophytes and benthic algae increased, whereas chorophyll and particulate nutrients decreased.

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It appears the zebra mussel may be affecting the dynamics of the nutrients, which influence blooms of blue-green algae. Such blooms ended after steps were taken in the 1970s and 1980s to reduce phosphorus loading to Lake Erie, but in 1995 *Microcystis* blooms reappeared in western Lake Erie after establishment of the zebra mussel. The mussel can be selective in its feeding and can reject *Microcystis* (Vanderploeg *et al*. 2001). Consequently, fewer algae other than the blue-greens are there to remove nutrients, and the rejected *Microcystis* has adequate nutrients for blooms.

Initially it appeared that the shallow waters of the Laurentian Great Lakes would be affected by the zebra mussel, but deeper waters below the thermocline would be inhospitable to the mussels (Dermott & Kerec 1997). However, *D. bugensis*, which inhabits soft sediment, and in 1993 made up 91% of the benthic biomass in water deeper than 30m in eastern Lake Erie, may now be adversely affecting populations of an amphipod, *Diporeia hoyi*, which is a major food for deepwater fishes (Dermott & Kerec 1997). The amphipod declined from 38% to only 1.8% of the benthic biomass in Lake Erie between 1979 and 1993, and has now also disappeared from large areas of the southern basin of Lake Michigan (T. Nalepa, personal communication 2000).

Aral Sea

The degradation of the Aral Sea is an alarming example of the consequences of diverting water away from a lake (Golubev 1996). The decision in the late 1950s to develop 3 million ha of new irrigated land meant that all available water would be used and the Aral Sea received little water except when natural flow was above average (Glazovsky 1995; Golubev 1996). Water levels dropped from 53.3 m above sea level in 1960 to 39.0 m in 1990 (Fig. 6). The salinity of the waters increased from 10 g l^{-1} to 29.0 g l^{-1} over the same period, and subsequently further to 40 g l^{-1} (Bornik 1999). The lake now exists as a small sea, Maloe More, in the north-east and a larger shallow lake, the Bol'shore. The Aral Sea was 68 300 km^2 before 1960 and the surface area had decreased to 34 800 km^2 by 1990. The Aral Sea did not have a large biodiversity before 1960, with some 20 fishes and 195 species of invertebrates (Aladin & Williams 1993), but some species disappeared and others were introduced as salinity increased. By the 1970s, most freshwater and moderately halophilic species were gone. The phytoplankton biomass had decreased three- to five-fold (Aladin & Williams 1993).

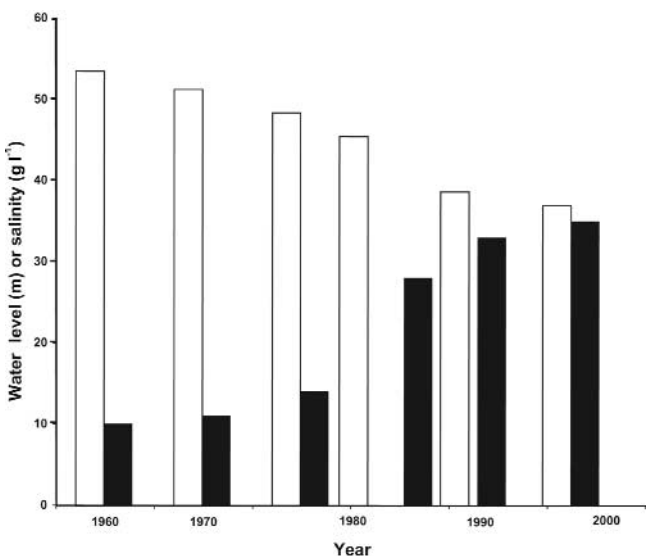


Figure 6 Changes in Aral Sea water level above mean sea level (white bars; m) and salinity (black bars; g l^{-1}). Data from Glantz (1999).

African Great Lakes

Relatively little information is available on trends in conditions affecting the African Great Lakes. Of the three major lakes, Victoria has shown signs of being severely impacted by human activities, the introduction of the Nile perch being associated with the demise of endemic haplochromine cichlid fishes, and changes in the fish community being accelerated by overfishing (Lowe-McConnell 1994). Eutrophication started as early as the 1920s and accelerated in the 1960s; there were decreases in water clarity, changes in phytoplankton, and increases in cyanobacteria linked to anthropogenic impacts. Algal biomass increased three- to five-fold and productivity doubled (Lowe-McConnell 1994). Algal blooms have been associated with fish kills. Dissolved oxygen in the hypolimnion has decreased to less than 1 mg l^{-1}. Water-column transparency decreased from 7–8 m in 1960–1961 to 1.3–3 m in 1990–1991 (Mugidde 1993). Chlorophyll concentrations were three- to five-fold greater than those observed in the 1960s (Hecky 1993). The loading of nitrogen and phosphorus increased. In the diatom community, *Melosira* spp. nearly disappeared and were replaced by *Nitzschia,* changes linked with eutrophication (Marshall 1997).

Lake Baikal

The water quality of Lake Baikal is excellent and no long-term changes have been reported. The major ions and nutrients have not changed in 30 years (Granina 1997). Apparently, concentrations of sulphate (SO_4^{2-}) (G. Galazy, unpublished data) did not change over 53 years (Grachev 1991), as in Lake Superior (Beeton 1969). Some decrease in dissolved oxygen has occurred inshore near the paper mill and some benthic species have been replaced by more pollution-tolerant species (G. Galazy, unpublished data). An endemic Baikal chironomid has been replaced by a Palearctic species (G. Galazy, unpublished data).

Sediments show that significant shifts have recently occurred in species composition of endemic planktonic diatom assemblages (Flower 1998). Such shifts precede low-level widespread industrial contamination, especially particles from fossil fuel combustion post-1930s (Flower 1998).

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There has been some increase in sediment Pb from 10.9 μg g^{-1} to 14.8 μg g^{-1} (Boyle *et al.* 1998), largely representing natural variation rather than pollution. The impact of the burning of fossil fuels by industry is seen in the sediment record for the southern basin, where anthropogenic sources dominate. Lack of detectable anthropogenic Pb enrichment of sediments in the northern lake indicates long-distance Pb transport is small (Boyle *et al.* 1998).

The effective settling rates of ^{137}Cs and ^{210}Pb in sediments are the same as reported for the St Lawrence Great Lakes and indicate similar sedimentation rates; a longer residence time in Lake Baikal is a consequence of its greater depth (Edgington *et al.* 1991).

Over-exploitation of the sculpin (*Comephorus dybowskii*), a major food of omul (the whitefish, *Coregonus autumnalis migratorius*), resulted in decrease in abundance of the predator (Grachev 1991). Subsequently, the omul increased predation on the copepod *Epischura baicalensis*. The average body mass of omul decreased, although total biomass of the stock has remained essentially the same (Grachev 1991). Too many omul were feeding on a reduced population of sculpins and the copepod and, as a result, omul growth decreased (Grachev 1991). Consequently, it appears overfishing has had an impact on this lake.

Oil products, phenols and metals are pollutants of concern (Kozhova & Silow 1998). Concentrations of oil products do not appear to follow a consistent trend over time and have fluctuated from year to year in amounts less than 1 mg l^{-1}. Significant amounts of heavy metals enter the lake via atmospheric transport from outside the basin, ranging from 0.03 kg km^{-2} yr^{-1} for uranium to 68 kg km^{-2} yr^{-1} for aluminium.

Some non-indigenous species have become established in Lake Baikal. *Elodea canadensis* was found in the lake in the 1970s and now occurs widely (Kozhova & Silow 1998). Several non-native fishes, namely *Percottus glehni, Coregonus peled* and *Cyprinus carpio,* have become established. These species may compete with the omul and/or affect the nearshore biota.

POTENTIAL STATES IN 2025

Laurentian Great Lakes

Anthropogenic changes have been, and continue to be, rapid, resulting in instability of the lake ecosystems. Consequently, biota that do not readily adapt to changing conditions may not survive. Furthermore, management programmes will now have to be flexible to continue to be useful.

There is a long history of efforts to deal with the many problems including efforts to develop fisheries management in the 1940s, the 1920s limnological surveys of western (Wright 1955), central and eastern Lake Erie (Fish 1960), a major effort to control the sea lamprey in Michigan and Huron in the 1950s, a continuing chemical control programme, and major efforts to control ballast water discharge from oceangoing vessels. There are 22 federal laws in the USA that are important to fish management in the Great Lakes (Dochoda 1999).

Not all the various institutional arrangements and programmes to deal with the many problems have been successful, but several stand out. A programme to control the lamprey became successful when a means of selective chemical control was discovered and lamprey abundance declined to about 10%. The Great Lakes Fishery Commission was created in 1954 by Canada and the USA through a Convention on Great Lakes Fisheries (Dochoda 1999) to control sea lamprey and advise the countries on fishery issues.

The sea lamprey is considered controlled at the reduced level and efforts have been made for more than 30 years to restore the lake trout populations, but with limited success (Hansen 1999). Lake trout restoration has had some success in Lake Superior, but sea lamprey predation and fishing are still limiting factors. Given increased control measures for lamprey and further restrictions on fishing, the lake trout fisheries in Lakes Huron, Michigan and Superior may recover by 2025. Other large fish should also benefit.

The establishment of invasive species has brought about significant changes in the biota and physicochemical conditions in shallow areas of the lakes, such as in western Lake Erie, Saginaw and Green Bays. It is now evident that the quagga mussel is adversely impacting the deepwater fauna of Lake Ontario and with time will probably add to the impact of *Dreissena polymorpha* in Lake Michigan. A restructuring of these ecosystems and those in deep waters of Lake Huron are certain to be seen by 2025. The full impact of *Dreissena* spp. is yet to be realized as these mussels move into new habitats, but the decrease in phytoplankton and increases in water clarity will continue into the future. The changes in the abundance of deepwater benthos are likely to be coupled to the decrease in phytoplankton in the pelagic due to mussel filtration, but the long-term consequences remain uncertain. The trend in the nature and abundance of the fish community may be toward a greater benthic production, which would resemble the historical condition (Hansen 1999). Indices of this trend are the decline in alewife and smelt and increase in burbot, bloater, whitefish, and deepwater sculpins (*Myoxochephalus thompsoni*). This trend could be disrupted by the rapidly declining abundance of the amphipod *Diporeia,* the major deepwater fish food (Beeton *et al.* 1999). Especially troubling to the sport fishery would be the impact on Pacific salmonines, which depend on pelagic production. These fishes will undoubtedly continue to be important, but will not dominate the fish community to the extent that they do today (Kocik & Jones 1999).

Helpful trans-boundary agreements

Perhaps it has been beneficial that the Laurentian Great Lakes are shared by two countries, Canada and the USA, because issues affecting the lakes need to be agreed upon at

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the national level, which also usually means access to federal, as well as state and provincial, funds. Various early disputes arose in use of the lakes leading to a purely advisory International Waterways Commission in 1905 (National Research Council & Royal Society of Canada 1985). The need for a body with authority to make binding decisions led to the Boundary Waters Treaty of 1909 and the International Joint Commission. It was significant that the Treaty addressed the quality of the boundary waters. 'It is further agreed, that the water herein defined as boundary waters and waters flowing across the boundary shall not be polluted on either side to the injury of health or property of the other' (Article IV, National Research Council & Royal Society of Canada 1985). The early pollution studies were concerned with bacterial pollution (1912) and then industrial contaminants (1946–1948) and resulted in recommendations for water quality objectives.

The sentinel activities of the International Joint Commission were those that resulted in the Great Lakes Water Quality Agreement of 1972, which included common water quality objectives, standards, and commitments on implementing programmes to achieve objectives and monitoring the progress (International Joint Commission 1989). The 1978 Agreement includes the basic 1972 conditions, but revised the water quality objectives and stringent standards for radioactivity and contaminants. Abatement for industrial pollution was included. Stringent overall reduction in phosphorus loadings was set, and discharge of toxic chemicals was to be eliminated. Three hundred and fifty hazardous polluting substances would be banned from the Great Lakes (International Joint Commission 1989). For the first time the Great Lakes basin ecosystem was defined as 'the interacting components of air, land, water, and living organisms including man, within the drainage basin of the St Lawrence River at or upstream from the Point at which this river becomes the international boundary between Canada and the United States' (International Joint Commission 1989, p. 5). This revised Agreement covered all five of the lakes and their tributaries. The purpose of the Agreement was 'to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes Basin Ecosystem' (International Joint Commission 1989, p. 7).

The 1978 Agreement has a lot to do with determining what the St Lawrence Great Lakes will be in 2025. Eutrophication was a major issue in the 1970s and 1980s and the emphasis was on controlling phosphorus loadings by reducing phosphorus in discharge from sewage treatment facilities, reducing phosphorus in detergents, and control of non-point sources. The emphasis was on the sewage treatment plants and detergents. Target phosphorus loadings have been achieved and actually surpassed to the extent that some fisheries managers suggested phosphorus levels are now too low (Gaden 1998). The Lake Erie Committee decided to continue with present control (Gaden 1998), and thus it appears that, even with increased human population growth, eutrophication may be controlled into the year 2025.

Persistent toxic substances are addressed in Annex 12, contaminated sediments in Annex 14, and airborne substances in Annex 15 of the 1978 Agreement (International Joint Commission 1989). Annex 12 includes the philosophy of zero discharge and the goal of virtual elimination (International Joint Commission 1989). Significant progress has been made to control point-source discharge of toxic substances (International Joint Commission 2000). The challenges are the contaminated sediments and airborne pollutants. Contaminated sediments are major problems in Areas of Concern. However, some progress has been made in the implementation of Remedial Action Plans, and remediation efforts have recently reduced potential inputs of 18 priority toxic chemicals to the Niagara River by 90% (Wooster 2000). Airborne pollutants will continue to be a problem (International Joint Commission 2000) and toxic sediments and airborne chemicals are likely to be a problem into 2025.

Concern has increased over possible diversion or transport of water outside of the Great Lakes Basin. Consequently, Governors of the Great Lakes states have reached agreement on how the region manages basin waters. The Annex 2001 agreement will improve the region's ability to reject environmentally-harmful proposals to use the Great Lakes water (Gilbert 2000). The Agreement will include a standard so that no state or province will allow new or increased withdrawal unless it is established that a proposal includes implementation of all reasonable conservation measures, does not cause significant impact to the quantity or quality of the waters or water-dependent natural resources, and results in an improvement to the waters and water-dependent natural resources of the Basin (Gilbert 2000). This Agreement is an improvement over the present, but it appears not to prevent damaging export and diversion projects (Gilbert 2000). The latter issue is likely to remain a problem into the future, especially as demand grows in water-deficient regions.

Climate, preservation, overfishing, land use and pollution

Climate scenarios defining possible climatic conditions at some unspecified time have been developed for the St Lawrence Great Lakes region (Quinn & Croley 1999; Lofgren *et al.* 2000). The results depend on which general circulation model is used. Modelling using the Canadian Centre for Climate Modelling and Analysis (Lofgren *et al.* 2000) predicts decreases in lake levels of up to 1.38 m for Lake Michigan by 2090. The drop in lake level would be the result of decreased precipitation, increase in air temperature, and related increase in evaporation. Use of the UK Meteorological Office's Hadley Centre model (Lofgren *et al.* 2000) predicts a maximum rise in level of 0.35m for Lakes Michigan and Huron by 2090 due to increased precipitation and reduced air temperatures. Ice cover would be reduced greatly using the Canadian model (Lofgren *et al.* 2000). Lake Erie would be ice-free for 96% of the winters by 2090. The

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change would be important because ice cover impedes evaporation.

Under a doubled CO_2 climate, thermal habitat for fishes would potentially increase in deep lakes, less dissolved oxygen would occur below the thermocline, and fish growth and production would increase (Magnuson *et al.* 1997). Ranges of fishes would move northward, and extirpations of colder water fishes would increase. The overall effects would largely depend on other stresses, including pollutants, eutrophication and invasive species. It is likely that some climate warming effects will be experienced by 2025. The duration of ice cover is already decreasing (Magnuson *et al.* 2000).

African Great Lakes

The major concerns for the African Great Lakes, namely the Nile perch fishery (Hart 1995), preservation of endemic species (Pitcher 1995; Witte *et al.* 1995), pollution (Coulter 1991; Vandelannoote *et al.* 1996; Karlsson *et al.* 2000), changes in land use (Katonda 1997; Alin *et al.* 1999) and eutrophication (Hecky 1993; Mugidde 1993; Marshall 1997), are interconnected. As demonstrated by some success in dealing with similar problems in the Laurentian Great Lakes, an integrated ecosystem approach is needed to coherently address these major problems in Africa.

The Nile perch stocks appear to be greatly overfished (Lowe-McConnell 1994), and their collapse would be disastrous because the fishery has employed some 350 000 people directly and many more people peripherally (Hart 1995). The consequences could also be long-term, so that a major effort might be made to re-establish the Nile perch and recognition of the consequences of overfishing might result in regional fisheries management plans and agreements (Lowe-McConnell 1994), but negative impact could arise from public, industrial and political pressure to introduce other non-indigenous species, which would place additional stress on the remaining endemic species in Lake Victoria.

The changes in land use are closely coupled with growth of human population in the region, especially in the lake basins (Alin *et al.* 1999). The increased erosion of the disturbed land contributes sediments and associated nutrients, heavy metals, and other pollutants to the Lakes (Lowe-McConnell 1994). Burial of substrate, reduced light, and release of nutrients and toxins will affect the rocky benthic habitats (Alin *et al.* 1999). Consequently, in the future, fewer species will occur in the littoral zone.

The land use changes will contribute to pollution and eutrophication. Pollution is perhaps the greatest long-term threat to Lake Malawi (Tweddle 1992). Chemical pollution from urban domestic and industrial sources and from fertilizers, herbicides and pesticides used in agriculture has been increasing (Ntakimazi 1992; Coulter & Mubamba 1993), and will continue to increase as the human population grows and natural landscapes are converted for agriculture, habitation and transportation. Lake Tanganyika might be more resilient to human environmental impact than Lake Victoria because of its greater volume and lower human population density (Alin *et al.* 1999). However, in view of the development in the region, it is very likely that Lake Tanganyika will be subjected to more and more changes in land use and increased pollution.

A study of chlorinated pesticides in the Lake Malawi area indicates that the dynamics of these pesticides may be different from those observed in temperate lakes (Karlsson *et al.* 2000). Lake Malawi did not have the levels of these substances found in temperate lakes, and it appears that considerable transformation of these pesticides occurs in the water column (Karlsson *et al.* 2000). It also appears that regional and local sources of pesticides dominate in the Lake Malawi area, since no long-range transport source was identified. These findings are encouraging because the opportunity exists to control local sources. Global concerns over chlorinated pesticides will be likely to help reduce use of pesticides such as aldrin and endosulfan, but others including DDT will continue to be used because of health concerns over malaria.

Possible pollution from oil is of concern. Exploration for oil started in the 1980s in lakes Tanganyika and Victoria (Ntakimazi 1992; Coulter & Mubamba 1993). Discovery of oil will benefit the economies of several countries, but the downside will be oil spills and impact on water quality, biota, and tourism over the period to 2025.

Existing data indicate eutrophication in Lake Victoria (Hecky 1993; Lowe-McConnell 1994) is fostered by changes in land use, increased human population and pollution (Schneider & Van Dijk 1997). Eutrophication may not be readily apparent lake-wide, and although Lake Tanganyika is still thought of as unexploited and unpolluted (Coulter & Mubamba 1993), the fact that water pollution is seen near population centres is a cause for concern. Early surveys of Lake Erie also detected nearshore pollution, which was initially dismissed, but later recognized as the early sign of eutrophication, which subsequently progressed from shore waters to the whole lake (Beeton & Edmondson 1972).

Pollution and eutrophication can be controlled, or at least mitigated, but controls require an ecosystem approach and commitment and cooperation of relevant citizens, industries and politicians. The needed implementation of adequate wastewater treatment, changes in land use, research, and institutional infrastructure are costly. It is unlikely that the resources and commitment will be available, and accelerated eutrophication in the African Great Lakes will be seen. A Global Environment Facility (GEF) initiative offers some optimism for regional cooperation (Schneider & Van Dijk 1997) among Kenya, Uganda, and Tanzania, and the World Bank and the United Nations Environment Programme. Eventually such a programme will lead to regional cooperation, whether it is this GEF or some other.

Steps have been proposed and can be implemented to conserve endemic fishes. The conservation aims are to avoid gross changes in natural communities and to retain fauna in

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an unexploited state in some areas of Lake Tanganyika (Coulter & Mubamba 1993), for example through underwater parks or other sanctuaries (Pitcher 1995).

Obviously, the critical need is for regional cooperation among the riparian countries to deal with the many environmental problems. Hopefully, some institutional arrangements, such as the Great Lakes Water Quality Agreement for the Laurentian Great Lakes (International Joint Commission 1989) will occur. However, given that they are unlikely, further disappearance of endemic fishes, continued overfishing and possible collapse of the Nile perch fishery, increasing pollution from atmospheric and land sources, and increased deforestation and increased agriculture leading to soil erosion contributing to eutrophication are anticipated. Some endemic fishes will have disappeared, additional non-indigenous fishes will have been introduced, shifts will occur in algal populations due to eutrophication, and severe contamination of the environment and biota from pollution will occur by 2025.

Aral Sea

The gradual disappearance of the Aral Sea is a major ecological disaster (Glazovsky 1995; Golubev 1996; Glantz 1999) and some 35 million people living in the basin have suffered (Stone 1999).

The Aral Sea has continued to dry up, but it appears that the small lake of *c*. 3000 km^2 will continue to exist and a fishery will be present as the water quality improves. The Aralsk local government has built a 19.3 km long, 26m wide dike to separate the remaining small and large lakes (Matloff 1999), the latter continuing to shrink and being likely to disappear. The consensus is that it will not be possible to restore the Aral Sea; it is of secondary importance to the need to deal with the social, ecological and economic problems of the region (Glazovsky 1995).

The World Bank and the UNDP are providing leadership to improve the supply of drinking water, revamp agricultural practices and sustain biodiversity in the basin (Stone 1999). It is the hope that these steps will deal with some of the human health and socioeconomic problems (Stone 1999).

Lake Baikal

The greatest long-term influence on Lake Baikal will be changes in land use, especially mineralization of the tributaries because of deforestation and land cultivation (Kozhava & Silow 1998). Existing nearshore pollution will undoubtedly spread as land-use changes, mining, industrialization and population growth continue, but the open lake waters do not appear to have been impacted to date (Grachev 1991; Granina 1997). Considering the similarities of lakes Baikal and Superior, as well as the great volume of Lake Baikal (Table 1), significant changes may not appear in Lake Baikal by 2025, other than in some nearshore areas. The nearshore waters in the southern basin will continue to be degraded and zones of pollution will gradually spread lakeward. The endemic fauna and flora are vulnerable to invasions of non-indigenous species as well as overexploitation (Grachev 1991). The combination of these two stresses could seriously impact the endemic species, especially fishes, and result in major changes similar to those observed in the Laurentian Great Lakes. The organochlorine compounds found in water, fish and seals of Baikal are a major long-term threat to the biota and humans of the region.

CONCLUSIONS

Literature on lakes representative of different geologic, geographic, and climatic regimes has been reviewed here to determine the present state of these lakes, the extent and importance of changes affecting them, the factors causing change, the consequences of their changes, and the major threats.

The Laurentian Great Lakes showed early changes in fish abundance and distribution as consequences of overfishing, habitat alteration and sawdust pollution. Invasive species were becoming a problem in the 1940s and 1950s with establishment above Niagara Falls of large populations of the sea lamprey, which decimated populations of lake trout and other large fishes. Eutrophication and pollution were major problems in the 1960s. Toxic substances, especially persistent toxic substances, seriously impacted the air, water, sediments and biota of the lakes. In the 1980s, the impacts of invasive species caused great concern. The major concerns at the turn of the century are low lake levels and possible impacts of climate change.

Diversion of water is the overwhelming forcing factor for the Aral Sea. For other lakes, eutrophication, pollution, overexploitation of resources and invasive species are major concerns. Eutrophication and pollution are threats to the African Great Lakes and Lake Baikal, fishery overexploitation and invasive species to Lake Victoria, but invasions are of concern for all lakes.

The impacts are all likely to persist into the future and greatly influence the nature and usefulness of the lake resources. Fisheries catch records and long-term water quality and paleolimnological data have been useful for determining long-term trends. Persistent toxic substance data show alarming long-term trends in all the lakes.

The Laurentian Great Lakes show that given a concerned community of stakeholders and governments, appropriate institutional arrangements, infrastructures, technology, and funds, the impacts can be dealt with and even reversed to some degree. Changes impacting the Aral Sea are so severe that there is scarcely hope of recovery. Lakes Malawi and Tanganyika are beginning to be impacted, but these impacts can be mitigated by taking reasonable, cost-effective preventive measures. Lake Victoria has been impacted by invasive species and recovery to an earlier state is no longer possible, but the ecosystem should eventually stabilize if additional invasive species are not introduced. Lake Baikal can be

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preserved if measures are taken to control local pollution, manage adverse land-use changes, and prevent introductions of invasive species.

Research has been underway on the African Great Lakes to meet the need for hydrologic data in water cycles and water quality, and limnologic data needed for ecosystem modelling. Institutional arrangements are critically needed among the riparian countries to effectively deal with future and present impacts.

For the Aral Sea basin, there is need to recognize and institute a basin-wide ecosystem approach to management of land use, water resources, wildlife, and public health. This approach requires cooperation and institutional arrangements among the basin countries, possibly by creation of a basin-scale commission.

It is likely other large freshwater lakes are responding similarly to the same major forcing factors and trends discussed in this review, especially the glacial scour lakes of North America, Europe and Asia. The relative importance of the major impacts and trends will vary among lakes and regions. Likewise, the future of the African Great Lakes likely predicts the future of other African rift lakes. Regardless, shared concern and cooperation among all stakeholders, leading to appropriate institutional arrangements to deal with deteriorating ecosystems, are essential. The Great Lakes Water Quality Agreement provides an example for such cooperation and institutional arrangement.

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