Chapter 2

LAKE AND RESERVOIR WATER USES AND ABUSES

Attempting to manage anything is impossible if the usage of the object(s) to be managed, and the causes of possible management difficulties, are not clarified. Thus, it is useful to begin with the identification of lake and reservoir water uses, and the possible causes of deterioration of their water quality. Reservoirs are constructed for beneficial human water needs, sometimes for one particular purpose, but more recently for multiple simultaneous purposes (i.e., multipurpose use). In contrast, lakes are natural waterbodies, often without designated human water uses. However, the use of their water is recently becoming more intensive and multipurpose, particularly for lakes in heavily-populated countries and intensively-utilized regions. This multipurpose and extensive use can often lead to abuse and conflicts, to a reduced ability to supply water of good quality, aesthetic and safe for human consumption. This chapter distinguishes twelve types of lake and reservoir functions. The deterioration of lakes and reservoirs is more difficult to classify, and two major groups are distinguished. One is based on their improper usage—abuses of the waterbodies, classified according to sources or reasons of the deterioration. The other is based on the agents and compounds causing the deterioration—pollution. As with any classification, however, it can be more or less arbitrary, not considering the many sources and agents acting simultaneously and often with catastrophic consequences for humans and nature. This chapter concludes with some warning examples of lake and reservoir mismanagement.

2.1 LAKE AND RESERVOIR USES AND FUNCTIONS

Before considering a global overview of uses and functions of lakes and reservoirs, the items in this section are summarized in Table 2.1. Many reservoirs, from the smallest to the largest ones, have been constructed with a single purpose in mind and have later been turned into multipurpose reservoirs. As an example, Lake Kariba was originally constructed for the production of hydropower, but is now also used for irrigation, fisheries, transport and recreation. Similar things can be said of many other reservoirs around the world.

2.1.1 Drinking Water

The supply and storage of drinking water for humans and livestock is of fundamental importance in arid and semiarid regions. This reality is a causative factor for the onset of settlements and cultures along large river basins in Asia and Egypt. Generally, shallow groundwater was readily available. Thus, the establishment and use of wells (apart from

Table 2.1. Major uses and functions of lakes and reservoirs

- Drinking water
- Irrigation
- Flood control
- Fish production and production of other useful organisms
- Mining
- Fire- and ice-ponds
- Urban reservoirs
- Energy
- Industry
- Low energy purifiers
- Traffic on lakes and along lake shoreline and tributaries
- Recreation
- Conservation and biodiversity
- Training and education

rivers and springs) must have been the oldest source of water in such regions. However, in regard to irrigation and flood control, artificial lakes (such as in the Egyptian Saba Empire, in areas in the Middle East and Mediterranean regions, in Sri Lanka, etc.) have become very important. Likewise, dams in Central Europe became essential drinking water sources when the population increased during the Middle Ages (e.g., Harz, northern Germany; Pless, 1957). In the 20th Century, artificial lakes as drinking water supplies prevails in areas of low precipitation, or where low quality water from underground aquifers or rivers allows no alternative. Even in countries like Austria, which can provide high quality water for more than 160 million people, some lakes at convenient sites are sometimes used for drinking-water supply. Examples of natural lakes which represent the dominant water source in industrialized countries include Lake Constance (which has supported the city of Stuttgart, Germany, for decades), Lake Ladoga (which supplies St. Petersburg, Russia), and Lake Biwa in Japan (which provides drinking water for 13 million people). Prominent examples in the developing world include Lake Victoria and Lake Tanganyika in Africa. In addition to these examples, hundreds of reservoirs in industrial countries provide the water supply of cities (e.g., the Sosetal Reservoir, which supplies Bremen, Germany) and industrial areas, as well as in the developing world. Sophisticated technologies and careful consideration of the drainage basins of drinking water reservoirs has greatly contributed to their safe use.

2.1.2 Irrigation

Agricultural irrigation is one of the oldest water uses originally associated with river systems. The annual water volume needed for this purpose has increased by almost 300% since 1900. At present, it totals more than 2700 km^3 (approximately equal to the volume of Lake Victoria), with the irrigated areas increasing five-fold since about 1900. Irrigated crops represent 17% of the total global agricultural area (Table 2.2).

Table 2.2. Irrigated areas and agricultural water demands between 1900–2000 (from UNEP/UNESCO, 1990)

	1900	1950	1990	2000
Irrigated areas (10^3 km^2)	473	1010	2720	3470
Agricultural water demand (km^3 yr^{-1})	925	1130	2680	3250

Although dams and artificial lakes (apart from groundwater) were used to a large extent for irrigation in early culture, only much later did the exploitation of natural and artificial lakes became significant for regional irrigation. One of the most outstanding irrigation systems in Sri Lanka is presented by the "Jaya-Ganga", an 80-km long irrigation canal which connects two river systems and supplies a large number of reservoirs. The latter provide water for about 460 km^2 of paddy-fields. Another example of a natural lake with a much shorter tradition is Lake Biwa in Japan. Rice fields in the vicinity of this lake, Japan's largest, are irrigated from canals, with the assistance of water wheels (the "Jasha" and "Ryukotsusha") operated by human power. Since about 1950, large dams have contributed to the exponential increase in irrigated land. In semiarid and arid zones of Asia, India's demand of 800 km^3 of water annually for irrigation for an area of 550,000 km^2 amounts to almost 30% of the global irrigation, of which a major share is provided by dams. Similarly, in China and in the Middle East, artificial lakes and dams play an important role in expanding irrigated areas (e.g., about 460,000 km^2 in China). Many other countries (e.g., Spain) can be added to this list. In regard to cost-benefit evaluation, however, it should be mentioned that each case must be considered on its own merits.

More recently, irrigation has become a dramatic threat to large (mostly shallow) natural lakes. The diversion of their main inflows for irrigation has resulted in either total desiccation, destruction of traditional lake cultures (e.g., Lake Human-e Hilmand, Iran), or in dramatic changes in lake area, volume and salinity. Lake Aral is a globally-recognized case. In spite of repeated warnings by limnologists during the early 1980s, the main tributaries of the Aral Sea (Amu Darya, Syr Darya) became increasingly used for ambitious irrigation projects, mainly to increase cotton production in the region. Since that time, the lake's water level has dropped 15 m, causing a reduction in its surface area of more than 50%. The salinity has increased from 10‰ to almost 34‰, and continues to increase (Williams and Aladin, 1991; Ptichnikov and Nauber, 1994). Because of this salinity increase, and increased pesticide loadings to the lake, the fish harvest decreased from 44,000 tons/year to zero. About 60,000 people involved in the fishing industry lost their jobs, and the population in the vicinity of the lake has become exposed to adverse health conditions.

2.1.3 Flood Control

Along with the development of the earliest cultures and civilization in large Afro–Asia river valleys, humans learned not only to make careful hydrographic observations, but also to adapt technologies to help mitigate catastrophic flooding. Lake Möris, Egypt, provides a remarkable example of this marvelous technical adaptation. Many other retention basins in this country, Mesopotamia, Syria, and the Middle and Far East also should be mentioned.

Because of the prevalent climatic conditions in these regions, flood control was almost always combined with irrigation and drinking-water supply needs. In contrast, multiple-purpose dams from early Cretic–Mykenian and Greek periods were used exclusively for flood control. As early as the Second Millennium BC, dams in Boiotia, in combination with polders, were used to divert the rivers Kephissos and Melos and to protect the plain of Kopais, which could be claimed for settlement and agriculture. This design was remarkably similar to the current drainage of the Ijsselmeer in The Netherlands. In this regard, it is stressed that the Greek construction of dams had reached a most sophisticated stage. Careful consideration of the water pressure from one side, and possible erosion on the "air side", are among the remarkable achievements of that time.

At present, retention basins, reservoirs and polder systems, inundation plains, discharge channels and river regulation are still the main methods used for flood control. There are, however, still many unsolved problems with respect to flood control. Among these are the maintenance of valuable floodplain areas and their biodiversity in association with hydroelectric power stations, as well as the flood control of complex river sections affected by excessive regulation. The upper sections of the Rhine, with the application of retention basins, presents a paradigmatic example (Dister, 1985). From 1817 to 1880, radical regulation of the Rhine between Basle and Mannheim was carried out. Groynes were built to provide better facilities for the shipping traffic. This regulation caused greater erosion than had been foreseen, with a drop in the groundwater level and associated harm to agriculture being the inevitable consequences. Further, due to the reclamation of areas in the flood plain, the protecting dams of the flood plain were gradually moved toward the river, with the result that the final inundation space (reduced by about 130 km^2) no longer had sufficient capacity. Further detrimental measures included the construction of a Rhine canal for hydroelectric power between Basle and Breisach, exacerbating the groundwater situation, and the construction of "river loops" between Breisach and Strasbourg. In order to meet the risks of flooding, retention basins for almost 240 million m^3 of water were considered an appropriate strategy and were implemented. The final solution, however, will be the restoration of the former retention areas which, in combination with adapted dam systems and retention basins, could overcome the present problems (Dister, 1985). The disaster of the Gabčíkovo basin (Hungary, Slovakia) is similar for a large portion of the Danube floodplain.

2.1.4 Aquatic Production, Fisheries and Aquaculture

Fishing has been practiced not only throughout the *Homo sapiens* period, but also most likely by pre-hominids. During the Middle Ages (since approximately 800 AD), the establishment of fish ponds in Europe was mainly associated with cloisters. It was only at a later stage that farmers were also permitted to build and possess fish ponds. As in early China, the common carp (*Cyprinus carpio*) was the principal fish kept in numerous ponds. Perch (*Perca fluviatilis*) and pike (*Esox lucius*) also became important and, with the onset of the Tang Dynasty in China, the common carp was replaced by the Chinese carps *Ctenopharyngodon idella*, *Mylopharyngodon piceus*, *Hypophthalmichthys molitrix* and *Hypophthalmichthys nobilis*. In this regard, it is interesting that different cultures developed distinct preferences or aversions with respect to fish. In early Egypt, marine fish were considered unclean, and in the Jewish culture fish without scales (e.g., catfish, eel, lamprey) were condemned. Even in current times, carp is avoided by former British colonies, whereas it is preferred by most other nations and their former colonies.

The present global marine and freshwater fish harvest totals more than 100 million tons/year, to which rapidly-increasing aquaculture (at present about 20 million tons) contributes greatly. With Japan still leading (12 million tons), followed by China which may soon become the number one practitioner of aquaculture (10.5 million tons), and by Russia (still more than 10 million tons), a third of the global harvest is consumed. The United States, Chile, Norway, Peru, Denmark and Canada can be listed among other important fishing nations (1 million tons).

With respect to inland water fishery and aquaculture, China is clearly in the lead. Fishing harvest from natural waters totaled more than 680,000 tons/year in 1953. Because of land reclamation from lakes and increasing damming of rivers, however, this figure has dropped to about 300,000 tons. On the other hand, the production of cultivated freshwater fish in a total area of almost 30,000 km^2 has easily compensated for this loss (800,000 tons/year in the 1970s). There is no doubt that aquaculture will surpass the inland water fishery, if not the total fishing harvests, in the near future not only in China but also globally.

The adverse or even catastrophic consequences of the introduction of exotic fish to lakes also must be stressed. In Central Europe, the stocking of high alpine lakes, where fish were missing, started during the late Middle Ages and is still practiced (mainly with the alpine trout *Salvelinus alpinus*). This activity greatly affects the species diversity of invertebrates and should be prohibited. In fact, fish introductions are often carried out without any preliminary limnological surveys, which could have provided some predictions regarding the potential impacts of fish introductions. Moreover, during the late-19th and 20th Century, fish stocking increased to such a degree that evaluation studies became essentially impossible. In Saskatchewan, for example, 1.6 billion fish comprising 30 species were introduced to fresh and saline inland waters between 1900 and 1970 (Marshall and Johnson, 1971). The Neusiedlersee in Austria was not only stocked with eel (about 5–7 million fingerlings/year) for several decades after World War II, but also illegally with grass carp during the 1960s. Because of the grass carp, the submerged vegetation, which represents an important spawning site for several fish species, was almost completely destroyed. It is only slowly starting to recover. The damage done by eel to fish, amphibians, etc., in the lake was documented only at a very late stage, but nevertheless was stopped for several reasons some years ago.

In 1940, five salmoniform fish species were introduced into Lake Titicaca, although only the rainbow trout (*Oncorhynchus mykiss*) survived. Ten years later, the *Basilichthys bonariensis* from Argentina eventually entered the lake via the Rio Desaguadero. The endemic genera of Lake Titicaca (*Orestias*, *Trichomycterus*) were greatly affected by these exotic species, although the extent of the damage is still not fully understood. Similarly, the introduction of brown trout in Southern Victoria (Australia) has deleteriously affected endemic salmoniform *Galaxias* species (Jackson and Williams, 1980). The best known and paradigmatic case of catastrophic effects from exotic species is Lake Victoria. Entering it from Lake Kyogo (where *L. niloticus* was introduced in 1957), the Nile perch (*Lates niloticus*) rapidly colonized the lake, being a major predator on the plankton and detritus-feeding endemic cichlids. Moreover, four alien *Tilapia* species previously introduced to Lake Victoria in 1951–1953 also compete with the endemic *T. variabilis* for nursery grounds (Serruya and Pollingher, 1983).

Commercial fishing in the North American Great Lakes started during the 18th Century, flourishing until the 1930s with highly esteemed species as American lake trout (*Salvelinus namaycush*), white fish (*Coregonus* spp.) and lake herring (*Leucichthys artedi*). Less valuable species such as yellow perch (*Perca flavescens*), alewife (*Alosa pseudoharengus*) and common carp (*Cyprinus carpio*; introduced in 1870) predominated thereafter. This change was related to the gradual immigration of fish species through the Welland Canal, constructed in 1929 to bypass Niagara Falls (Sarhage and Lundbeck, 1992). One of the immigrating fish species, the sea lamprey (*Petromyzon marinus*), damaged the stocks of the lake trout (*Salvelinus namaycush*), white fish (*Coregonus* spp.) and other valuable species. The lamprey plague was subsequently successfully controlled by electric fences and selective chemicals. Fish stocks, however, are presently endangered by pollution.

In Brazil, rather than cultivating local, easy-to-cultivate species, *Tilapia* have been introduced into small reservoirs since the 1930s. Although the annual fish production increased, it resulted in a setback on studies in the biology, reproduction and other features of local species. An Amazonian species, tucunare (*Cichla ocellaris*) was introduced into reservoirs of South Brazil, and to Lake Gatun in Panama (Zaret, 1980). This predatory species caused complete disruption of the local food chains. An introduction of a fish species with positive effects also was noted. Corvina (*Plagioscion squamosissimus*) was successfully introduced to reservoirs of Southern Brazil (e.g., Itaipu, Barra Bonita) (Agostinho et al., 1994). The reason for its success is that the species predominantly inhabits the pelagic region, which was not previously utilized before in these reservoirs.

In contrast to the adverse effects of fish stocking, positive examples also can be mentioned. One of the most spectacular successes was achieved in Lake Kariba. In 1967–1968, the freshwater sardine (*Limnothrissa miodon*), endemic to Lake Tanganyika, was introduced into Lake Kariba. This small, planktivorous fish reaches adult size after only three months, producing a harvest of 66 tons in Zimbabwe as early as 1973. By 1980, the annual harvest had increased to a maximum yield of 8000 tons. More recently, there have been decreasing, but still considerable harvests. *Limnothrissa miodon* also was successfully introduced in Lake Volta.

Macrophytes comprise another useful product from lakes. The common reed (*Phragmites communis*), papyrus (*Cyperus papyrus*) and tatora (*Scirpus tatora*) in Lake Titicaca have played a significant role for millennia in the construction of houses (especially in the Shatt el Arab area), boats, as thatching, production of paper, baskets, mats, etc. It also partly served as cattle fodder (e.g., Lake Hamun in Iran/Afghanistan) and for human nutrition (e.g., rhizomes of *Phragmites communis* in Central Asia and *Colocasia esculenta*). Further, submerged vegetation may be used to feed cattle and pigs (e.g., Lake Titicaca area). In many tropical and subtropical countries, *Trapa* spp. is recognized for its nutritional value. In Indonesia, *Myriophyllum* spp. is used in salads, while it is considered a pest in Canada. In China and Japan, *Eichhornia crassipes* serves as small sewage treatment plants, for gas production and as pig fodder. Certain other plants (e.g., *Scirpus* spp., *Phragmites communis* and *Typha* spp.) have also generally become important as biological sewage treatment plants (Section 4.2.4).

Apart from fairy shrimps (*Artemia salina, Streptocephalus* and *Dendrocephalus*), and insects (*Dytiscus* spp., *Belostoma* spp., which are used for nourishment in North Africa and East Asia, respectively), invertebrates from lakes and reservoirs are generally only of secondary importance as food sources, compared to their marine counterparts. Among these are mussels, crabs, prawns and shrimps (*Macrobrachium*). Compared to marine aquaculture (e.g., 800,000 tons/year of the mussel *Mytilus edulis* in Norway) freshwater invertebrates only play a minor role, although promising activities have started in certain regions. The construction of Kariba Dam resulted in an increase of mussels, amounting to an estimated biomass of almost 170,000 tons. Certain species were selected and tinned. However, because of nonacceptance by the local population, this industry failed (Machena and Kautsky, 1988). In regard to mussels, the pearl industry at Lake Biwa, which still is economically feasible and flourishing, should be mentioned.

Finally, mention must be made of waterfowl, frogs and water-bound reptiles (snakes, crocodiles, etc.). The latter, however, are only locally cultivated and acceptable as food.

In Brazil, cultivation of alligators (*Caiman latirostris*) is expanding, being supported by the government. Both the meat and skin is used, the meat being sold to fashionable restaurants around the country. Cultivation is also used to re-populate regions originally inhabited by this species (e.g., the region of Pantanal). In Venezuela and Brazil, the large rodent of wetlands, capybara (*Hydrochoeris hydrochaeris*), is cultivated in great numbers (J.G. Tundisi, personal communication).

2.1.5 Mining

Mines, including abandoned mines, are nonpoint sources of pollution. An estimate of the magnitude of this type of pollution can be obtained by using a watershed-based approach (Caruso and Ward, 1998). More examples of the environmental effects of mining are given in Section 2.2.2—*Metals.*

Iron and coal. In some regions (e.g., Southern Sweden (Småland)), easily-soluble iron minerals can cause considerable formation of limonit (lake ore) in many of the lakes that contain low conductivity water. This iron ore was exploited and used for iron production until the 19th Century, when this kind of iron work became no longer economically feasible (Naumann, 1922; Montén, 1939; Thunmark, 1948). The lake ore was collected by rakes and dredging from rafts or, during the winter when the lakes were frozen, from ice. Only slight disturbances of the collecting sites occurred. On the other hand, strip mining (open-cast working) of iron or coal eventually resulted in the formation of lakes which, because of the presence of pyrites, most often became acidic, sometimes exhibiting pH values below 3. Lakes with pH values below 3.5 sometimes lack both photosynthetic production and zooplankton or benthic animals. Moderately-acidic strip-mining lakes can be managed in the same manner as lakes affected by acid rain. The use of cyanides in gold mining is an environmental time bomb, as shown by the poisoning of the Tisza River from a Romanian mine in the year 2000, reaching up to the Danube River reservoirs.

Minerals and salts. The exploitation of minerals like diatomite can result in more serious impacts than the above-noted iron collecting activity. The diatomite operation in Lake Myvatn (Iceland) increased the rate of deposition in this lake area by 32% by the end of the 1970s (Jónasson, 1979). The diatomite excavation also has increased the phosphorus load by 20% and the nitrogen load by more than 90%. Thus, phosphate precipitation from mining effluents was encouraged, and may eventually save this lake area from unwanted *Anabaena* blooms. A Conservation Act for the Myvatn area was signed by the Icelandic President in 1974.

Sand mining. Exploitation of other minerals, such as sand and gravel, mainly results in the formation of new lake basins. It extensively affects reservoirs and rivers in South America. The suspended material is highly increased, causing decreased light penetration, destroying shallow areas in reservoirs representing fish nursery grounds, and decreasing oxygen concentrations and invertebrate populations decrease.

Gold. Gold mining also represents a potential hazard to lakes. In certain regions of South America (specifically Brazil), gold mining by hydraulic removal of bottom sediments of rivers has caused considerable damage to entire river ecosystems. Rio Madeira, for example, suffered extensive loss of fisheries. Further, mercury used for amalgamation of gold has contaminated several Amazonian rivers.

Salts. The use of salt by humans for spicing and conservation has occurred since the Neolithic period. Not so long ago, caravans crossing the Sahara from the Mediterranean coast to Timbuktu sold salt for gold. Salt mining was concentrated mainly in marine coastal areas. Continental deposits, such as the outstanding ones in the Salzkammerkut (Austria), were more likely to offer high quality salt than many of the saline lakes. There are, however, a few examples of traditional use of other salts. One example is the collection of soda from lakelets east of the Neusiedlersee (Austria) during periods of desiccation. Throughout the 19th Century, this soda was used for soap production. Salt mining in saline lakes most often became important in conjunction with the modern chemical industry. Examples include the extraction of soda from Lake Magadi (Kenya) for making glass, and from the Dead Sea for chemical plants in Israel. Most recently, industrial activities near large saline lakes south of Tehran (Iran) have been developed. Obviously, salt extraction from saline lakes causes relatively little disturbance (e.g., salt gardens in the Lake Urmia basin, Iran) if such lakes are not affected in regard to their salt and water budgets.

Peat. The exploitation of peat (as fuel, for horticulture or for medicinal purposes) is mainly restricted to mires, especially peat bogs. If such excavations occur in basins, they may become ponds or small lakes. Peat collection from peat bogs within sensitive watersheds can greatly influence the water budget and water quality of the relevant waterbodies.

Gas. Gas may accumulate in considerable quantities in the monimolimnium of meromictic lakes. If reasonable amounts of methane exist, in addition to CO_2, the latter may be used as an energy source. In the Lake Kivu basin, the most remarkable site of its kind, methane is used for the energy supply of a brewery.

Mineral oil. In a few natural (e.g., Lake Maracaibo, Venezuela) and artificial (e.g., Lake Kama near Perm, Russia) lakes, oil exploitation is performed, with a high risk of water quality degradation. The most spectacular case may become like Lake Tanganyika, where sediments up to 6000 m have accumulated since the Miocene. Based on more recent investigations, they contain more mineral oil than the presently-known reserves of the United States. All efforts should be undertaken to save Lake Tanganyika with its tremendous biodiversity, which has only been partly explored. Similarly, it should be mentioned that, in spite of heavy protests, a mineral oil pipe-line along the eastern shore of Lake Constance was established during the 1960's. Because of the tectonic activities in this area, the pipeline represents a permanent danger.

The Caspian Sea, Laguna Maracaibo, Venezuela, and Lake Kama near Perm, Russia, also create high risk situations with respect to water quality. In the Caspian Sea basin, where mineral oil exploitation has occurred in the Baku area since 1871 and has spread over many areas along the western and eastern coast with large numbers of open sea oil platforms. In areas of such offshore drilling activities, oil films can cover more than 800 km^2. In addition, the sea receives annually more than 100,000 tons of oil and derivates from the Volga (Ural–Volga oilfields) (IUCN, 1980; Koptyug and Uppenbrink, 1994).

Together with large quantities of other adverse substances (e.g., heavy metals) oil pollution in particular has contributed to great damage to coastal, benthic and pelagic communities. The extent of the dramatic impacts has been restricted so far mainly to the fishing industry; but even those evaluations are only of regional concern and often unrealistic. The establishment of the succession states of the former Soviet Union also has seriously affected the monitoring of the Caspian Sea.

2.1.6 Fire and Ice Ponds

Until the early 19th Century, many villages in industrial countries were dependent on wells for their water supply. If not located close to a lake or river, in case of fire they were in need of fire ponds—which otherwise provided sites for domestic ducks and geese, especially in the Pannonian Region. These ponds were usually located in the center of villages ("village greens"). Since the Second World War, most have disappeared, being replaced by settlements, small parks, or even industrial entertainment. Hundreds, if not thousands, of ponds have been lost in this manner.

Before household cooling facilities were generally available in temperate regions with frost-period and warm summers, ice was collected during the winter from special ponds, mostly located outside the villages. This ice was preserved with sawdust and used in household ice boxes. One remarkable example is presented by a still existing ice pond in Lower Austria (Zwingendorf), which was built in an area of salty soils (i.e., containing $MgSO_4$,

Na_2SO_4, NaCl). Because of its remarkable saline flora and fauna, which developed more than hundred years ago, it was recently declared a national monument.

2.1.7 Urban Lakes

Urban reservoirs are usually restricted in size, ranging from very small, pond-like waterbodies to impoundments of several million cubic meters. They are subject to very high anthropogenic pressures from surrounding communities, with the water quality in the reservoir closely tied to the hygienic and economic conditions of the surrounding populations. Even if most of the pollution is removed from the water, there often is a high level of eutrophication, due to the use of polyphosphate-containing detergents in the urban area. These nutrients eventually can reach a lake, particularly during heavy rain and storm events. Thus, the use of detergents associated with car washing, and similar activities around a lake, should be restricted. The use of chemicals in garden and lawn care also can be a source of toxins that can poison aquatic life.

The only management option specifically recommended for urban reservoirs is prevention of stormwater runoff (Novotny and Olem, 1994). Urban runoff collection is usually separated from standard effluent collection systems that are conveyed to the purification plant. This is because urban runoff consists of huge water masses with low organic matter content, but containing high turbidity and garbage. If this material was all conveyed to the purification plant, the capacity of the plant would quickly be exceeded. Increasing treatment plant capacities to meet the demands of storm events can be quite expensive. When stormwater is collected and treated separately, water quality is improved at lower costs. The response of phytoplankton to runoff consists of a phase of decreased biomass, due to decreased photosynthesis under low light conditions caused by a high input of turbidity, followed by a phytoplankton bloom stimulated by increased nutrient inputs and improved light conditions following sedimentation of the turbidity.

Most of the management options described in Chapter 4 are useful in managing urban reservoirs. Planting and protection of shore vegetation is highly recommended, since it serves as a natural pollution barrier. Fisheries that are regulated with respect to biomanipulation principles are feasible, particularly in small waterbodies primarily serving aesthetic purposes. Unregulated fisheries favoring extraction of predatory fish can result in water quality degradation. The presence of numerous aquatic birds is a sign of good water quality and proper regional management. However, if large flock of ducks or geese are fed by people, considerable pollution can result. A decision tree for urban lake management was developed by Birch and McCaskie (1999).

In larger urban reservoirs located in densely populated developing countries, the major problem is multiple-use conflicts. For example, the Xuanwu Reservoir in Nanjing, China, which has a volume of 3.32 km^2, but an average depth of only 2 m and an average theoretical water retention time of 54 days, is used as a tourist resort with swimming activities. However, it also serves as an aquatic farm, as an industrial and domestic water supply, and for agricultural irrigation. Consequently, pollution and siltation levels are very high, with dredging activities becoming necessary by 1954. Without dredging, the reservoir would become filled with sediment in just a few decades.

2.1.8 Energy

Hydropower is one of the oldest energy sources used by humans. During ancient time, it played a significant role not only with respect to water-driven engines (e.g., for irrigation), but also for cultural purposes (e.g., the remarkable water-organ).

During the Middle Age, however, and especially from the 8th and 9th Century onward, the establishment of water mills of different kinds (e.g., for cereals, oil, textiles) increased exponentially.

Due to limited engineering capacity, the damming of rivers or valleys remained an activity of limited size until the 20th Century, when the onset of the construction of large dams (e.g., Lac Loutre, Canada, with a surface area 1295 km^2, opened in 1917) began.

From observations of meromictic lakes with a high-salinity monimolimnion, which sometimes became heated to more than 60°C, the idea of establishing artificially-stratified ponds ("*solar ponds*") as an energy source originated in Israel (Tabor, 1963, 1980). To date, however, the major problem of controlling the halocline has evaded solution. Even the reduction of water mixing, by the use of nets of floating windbreaks, did not succeed. However, there is some hope that solar lakes may eventually become important energy sources, especially in arid and semiarid regions (Serruya and Pollingher, 1983).

River and lake water is used for the cooling process for power plants. In some cases, this may improve desirable production in a waterbody. It seems more advantageous, however, to use the heated water from power plants for aquaculture and greenhouses before it is returned to rivers or lakes. This kind of application also provides more predictable results than the direct return of the heated water to rivers or lakes. In contrast to the more common impacts of heating to inland waters, the drastic cooling of lakes in connection with hydroelectric activities has been reported in a few cases. Lago di Cavazzo in northern Italy originally had summer surface temperatures above 20°C. Since the 1950s, however, when flushing by a pipe was started (15–40 m^3 s^{-1}), the surface temperature has rarely exceeded 15°C. Because Lago di Cavazzo presents an important recreational site, the negative impacts on tourism has resulted in considerable economic loss for the region (Löffler, 1987).

Finally mention should be made of ponds and lakes heated by volcanic activity. Generally, however, volcanic energy from hot springs or vapor is used (e.g., Iceland, New Zealand). Lakes themselves tend to be only slightly affected. Rotamahana, New Zealand, for example, has raised temperatures by about 3°C, compared to noninfluenced lakes in the same vicinity (Hutchinson, 1957).

2.1.9 Transportation

Apart from continental channels, such as the Suez and Panama canals, which make use of intermediary lakes only for traffic convenience and economic reasons, the 3770 km shipping system of the Great Lakes in North America (started as early as 1783 and finalized in 1959) presents the most important inland waterway, with an altitude difference of 182 m. Its traffic is largely concentrated on the lakes and the economically-most important harbors. More than 130 million tons/year passed through the "Soo" sluices alone between Lake Superior and Lake Michigan during the 1960s. Along the St. Lawrence Seaway, passage of 40 million tons was exceeded during the late-1970s. Due to the increasingly-competing capacity of road and rail traffic, a significant drop in shipping transport has occurred more recently. This also is evidenced by Chicago Harbor where, instead of the previous 1000 ships/year, only about 500 are unloaded in more recent years (see also Section 2.1.4 on fish in the Great Lakes).

Commercial shipping traffic also has a long tradition on other large lakes (e.g., Lake Ladoga in Russia; Lakes Vänern and Vettern in Sweden). In many European countries, the early onset of ship traffic was mainly related to transport and recreation.

From about 1840 onward, lake traffic was increasingly carried out by steamboats. This steamboat period, in some cases carried on until now because of recreation, is evidenced by the presence of soot particles in relevant sediment core sections.

Along with a switch to motorboats, speedboats and often excessive motor-boat oil spills have become a menace to water and fish quality in many lakes. This adverse situation is not confined only to industrial countries but also has been reported for lakes in developing countries (e.g., Lake Toba in Indonesia, personal observation H. Löffler). Thus, motor boating has been restricted to commercial activities in many lakes.

Traffic along lakeshores, or even crossing lakes, is always related to such impacts as the loss of shore sections, eutrophication and pollution. Because of technical limitations, the construction of traffic ways, especially in mountain regions, was most often carried out along lakeshores. Eventually, trails and paths evolved into roads for post coaches, and finally into highways for car traffic, with much more space being occupied. In contrast to the frequently-induced lake eutrophication caused by road construction, oligotrophication of lakes may occur under certain conditions. For example, the dumping of excavated rock material in Mondsee (Austria), in connection with road and highway constructions during the late-1950s and 1960s, resulted in high turbidity and the in-lake sedimentation of nutrients and algae. Consequently, oligotrophication of the lake, with a remarkable increase in transparency, occurred for a period of several years. The pollution impact from the erosion of tires and asphalt by traffic was documented for the first time during the "Lake Constance Project" between 1960–1969 (Borneff, 1962, 1963, 1974). For a daily rate of 4000 cars, it was calculated that about 1.5–2.0 kg of cancerogenic 3,4-benzypyrene would become available from a road section of 10 km (6 m broad). Similarly tear-products used for the isolation of buildings released 3,4-benzpyrene (see also Section 2.2.2—*Persistent Organic Pollutants*). Wherever lead-containing petrol is used, serious contamination of small waterbodies or sections of lakes located close to roads have been observed. Lead is converted into toxic organic compounds by bacterial activity. It should be mentioned that train traffic also may affect lakes if steam-driven (soot) or oil-driven trains are used.

Two case studies demonstrate the importance of traffic on lake conditions. Lago di Cavazzo, one of the largest lakes of the province of Friulana (Italy), and one of the foremost recreation sites in this area, was not only heavily influenced by hydroelectric power activities, but also by the construction of the major highway from Austria to Trieste across this lake. The latter involved not only the severe destruction of the landscape, but most likely also caused water pollution impacts. Similarly, a pillar bridge project in 1972 across Neusiedlersee, 5 m above the mean water level of Austria's largest lake, and which since 1977 has become one of the countries most prominent Biosphere Reserves, threatened this site with heavy traffic and its polluting consequences. This project resulted in the first large-scale public intervention, which became a successful environmental initiative.

2.1.10 Recreation

In Europe, lake-based recreation has a long tradition, comprising a variety of sports and games (on ice), as well as bird watching. In addition, salt lakes and lakes with mineral springs (e.g., Dead Sea) have become sites used for the sake of human health.

Since the early-19th Century, tourism and recreation in lake areas has increased exponentially (especially after the Second World War). Even lakes of modest size (e.g., a few square kilometers) may experience more than a million overnight bookings annually. Lakes in developing countries also have become affected more recently (e.g., Lake Toba, Indonesia; Lake Atitlan, Guatemala). Like wetlands, lakes are particularly vulnerable to mass tourism, which generally results in lakeshore destruction for housing, camping, car parks and traffic. The types of recreational activities, and their accompanying impacts on water quality, are summarized in Table 2.3.

In order to effectively address the unwanted impacts of recreation sewer systems and other problems, technologies had to be applied that eventually improved the quality of lakes. In Austria, the costs of these kinds of sanitation systems totaled more than US $1 billion annually between 1955–1990. However, there is no doubt that most of the destroyed lake shores will never be restored. Thus, the Austrian Economic Water Association proposed a resolution as early as in 1961, stressing the danger of further reclamation of lakeshores for housing and tourist colonies, and promoting their protection against destruction by technical projects. Thus far, however, these efforts have generally been in vain. Only a few countries have succeeded in passing legislation, according to which a landside fringe (50 m in Denmark) is fully protected.

2.1.11 Conservation and Biodiversity

Conservation is understood and defined with a large variety of interpretations and perspectives, often adapted to regional conditions and need. Several authors (e.g., Williams, 1993) prefer the following definition, "Conservation is the management of human use of the biosphere so that it many yield the greatest sustainable benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations". However, this is not necessarily the case for all parts of the biosphere. For many watersheds and their lakes, located in high-mountains, polar and arid regions, where human activities are unlikely for the foreseeable future, no management efforts seem necessary. This means

Table 2.3. Types of recreational activities on and around lakes, and their potential water quality impacts

Recreation in the lake drainage basin

Pollution from recreational facilities

The use of chemicals in gardens

Erosion connected with deforestation and road building

Recreation at the lake shoreline

Housing, hotels, kiosks—As in the drainage basin

Camping—Cause of serious impacts if sanitation and waste is not carefully controlled

Walking, picnicking, sunbathing, bird watching—Depends on the numbers of people and the sanitation facilities

Fishing—Possible destruction of shoreline vegetation

Recreation on the lake surface

Sport fishery—Interference with biomanipulation procedures; pollution caused by improper disposal of fish remains and fishing supplies; excess fish feeding; introduction of nonnative fish

Commercial fisheries—Impacts cause by commercial fisheries and aquaculture vary greatly, depending on specific methods. Organic loads associated with fish farming in cages and mussel farming can be greater than the amount of organic matter removed from the lake during fish or mussel harvest

Swimming—Stirring of sediments can cause turbidity and increases in proliferation of *E. coli* bacteria, hygienic impurities, danger of infections

Scuba diving—Rarely a source of pollution

Canoeing, rowing, windsurfing—Negligible problems within the lake; potential impacts by associated shoreline activities

Sailing—Large sailboats can cause a major pollution source (see Houseboats)

Houseboats—Input from sanitary systems which can include sewage, detergents, excess organics and trash

Motor boating and water skiing—Shore erosion caused by waves, oil and fuel pollution

Cruisers and large boat traffic—Danger is minimized by hygienic arrangements (dry toilets, preservation of wastes and wastewater)

Ice skating—No known impacts

that such lakes should be left to their natural physiographic conditions which, at least for long periods, facilitate the persistence of their biological communities including migrants such as birds and mammal.

In 1959, the Societas Internationalis Limnologiae (SIL) initiated "Project Aqua", the first international attempt at lake conservation (Luther and Rzóska, 1969, 1971). The goal of the project was "to get international recognition for a list of fresh-water and brackish water areas which are of agreed international importance for research, education or training, and where therefore the countries should accept national responsibility for conservation". At the time, this was an important first step directed to the protection of lakes and at present, more than 25 years later, most of the selected 600 inland waters (including running waters, springs and wetlands) are still of relevance. More than 150 lakes and wetlands are represented among the 411 Biosphere Reserves of UNESCO (year 2002) distributed over 94 countries.

Since this list was designed for the activities of the International Biological Program, it is desirable that categories such as lakes not affected by humans and, as a high priority, old lakes originating during the Tertiary or during the early Pleistocene, be included. In fact, many of the old lakes are already listed in the Project Aqua.

Since "Project Aqua", the Ramsar Convention and the Biosphere Reserve activity of UNESCO, the World Cultural and Natural Heritage and many other international protection efforts have stimulated the selection of important lakes and their possible conservation.

Thus far, however, the protection of lakes is still far from satisfactory. In spite of the great number of lakes which, after careful assessment of their values have been proposed as relevant sites, corresponding legislation and its execution are most often not sufficient. Such legislation, which would be simple for national lakes that have not been significantly affected by human activities (e.g., Torneträsk in Sweden), becomes almost unpractical in the case of multinational lakes with conflicting interests, especially where existing traditional uses are difficult to control.

Accordingly, efficient legislation should comprise:

- The control of the hydrological regime (water retention time),
- The protection of littoral zones and their vegetation (building activities and traffic should be avoided to the maximum extent),
- The sustainable exploitation of salt and other minerals or organic matter,
- The mitigation of ongoing eutrophication or pollution which can eventually decrease diversity,
- The sustainable management of fisheries and, in most cases, avoidance of the introduction of exotic species or even exotic genetic material, and
- The sustainable management of tourism and recreation.

With regard to exotic species, it should be stressed that for a few exceptional lake cases, the biodiversity has actually increased because of the introduction of exotic species, without harm to native or even endemic fish. The introduction of tilapia (*Tilapia grahami*) into highly-alkaline Lake Nakuru (Kenya), where fish had been absent, resulted in an abundance of fish-feeding birds (e.g., pelicans, cormorants). Lake Kariba also was stocked with the freshwater sardine (*Limnothrissa*) without any disturbance to the native communities of this dammed lake, as well as a dramatic increase in fish production.

2.1.12 Training and Education

Aquatic ecosystems offer many possibilities for environmental training on all educational levels. Its comprehensible objects, watersheds, rivers and lakes, facilitate reasonable access to the understanding and functioning of ecosystems, their metabolism and energy flows.

In addition, the relatively easy construction of ponds or artificial lakes offers excellent facilities for the study of different essential properties.

The role of aquariums and small ponds in public- and high-schools has recently found a wide acceptance, although these kinds of activities in teaching basic biology in most countries are still left to the initiative of engaged and enthusiastic teachers. Moreover, wherever possible, children could be invited to protect a small lake, pond or wetland, and also should be trained for their basic management. Such small ecosystems can become "the property" of a school-class. Selected ponds, or any kind of inland waters, can be turned into sites of permanent public information, and may include facilities to measure and observe some of their basic features. At present, very few localities of this type do exist. International and nongovernmental organizations (e.g., UNESCO, IUCN, WWF, ILEC (International Lake Environment Committee), SIL (Societas Internationalis Limnologiae)) should be invited to promote these kinds of public information sites.

Consistent with the title of this book, training of students, engineers, aquaculturists, etc., for lake and reservoir management should be given high priority. Technical measures concerning sanitation, restoration, mitigation of hazards and the establishment of integrated systems for sustainable production will certainly undergo rapid development in the near future.

2.2 LAKE AND RESERVOIR MISMANAGEMENT

A difference exists among the many types of lake pollution and other types of human abuses to lakes in different regions, particularly between the Northern and Southern Hemispheres (as characterized in Chapter 1, Fig. 1.14), both in the degree of occurrence of different types and in the time sequence of their appearance. Some of these abuses are treated in Section 2.2.1 and the types of pollution in Section 2.2.2.

2.2.1 Abuse of Lakes and Reservoirs

Wastewater disposal

Since the last century, small artificial and natural ponds (e.g., backwaters of riverine areas) have increasingly become sites for waste dumping, eventually becoming completely filled. This water material often contains toxic substances likely to degrade the quality of groundwater. As a result of such (often illegal) deposits, large regions may become heavily polluted, with necessary restoration activities being not only costly, but sometimes (e.g., for large aquifers) even impossible. In spite of strict laws in many countries, this kind of dumping is still occurring, representing a large-scale environment problem (especially in regard to drinking water).

Industrial impacts

In some cases, large lakes are still used to receiving industrial wastes, an adverse tradition that became established during the 19th or early-20th Century. One of the most dramatic examples is represented by Traunsee (Austria's deepest lake) where, since the turn of this century, the alkali works at Ebensee have released up to 30 tons daily of largely insoluble substances (e.g., $CaCO_3$, $MgCO_3$, $CaSO_4$) and about 200 tons of soluble compounds (e.g., $CaCl_2$, NaCl). The latter have resulted in periods of chemical gradients in the lake and, under meromictic conditions, the insoluble material has piled up to more than 40 m close to the maximum depth area and near the mouth of the affluent. Similar accumulations of industrial or mining activities are known from several natural and artificial lakes (Kama Lake near Perm, Ural; personal communication to H. Löffler).

Industry and mining also have contributed significantly to the destruction, pollution, acidification and alkalification (Millstätter See, Austria, magnesite works) of lakes and lake shorelines. Lake Erie (USA–Canada) and Lake Orta (Italy) also can be mentioned as examples. The latter was heavily loaded with copper and ammonium sulfate by a Canadian factory producing rayon during the period 1926–1983. The maximum copper loading exceeded 50 tons/year and 2500 tons/year for nitrogen (ammonia). The consequences included a dramatic decrease in pH (to 4 and less) and the disappearance of the pelagic organisms (although a few uncommon species sometimes appeared for short periods). Because of a treatment plant established in 1981, a first recovery phase has been observed since 1983 (Calderoni et al., 1992).

Reclamation and destruction of lakes

Apart from lakes which became dry due to irrigation and eventually were used for agriculture, thousands of shallow lakes, ponds and puddles were filled or drained, and reclaimed for forestry or agriculture during the 20th Century. In China, 543 big and middle-sized natural lakes, and many more smaller ones (with areas less than 1 km^2), as well as additional reservoir area and regulating volume (totaling approximately 11,585 km^2 in area and more than 570×10^9 m^3 in volume) vanished within 30 years (1950–1980). A dramatic example of reclamation is presented by the shallow Neusiedlersee at the Austrian–Hungarian border (see Section 9.1). Cases of accelerated sedimentation in lakes often are due to activities within the lake drainage basin, including deforestation, mining, road construction, etc., followed by land erosion. The construction of a forest road close to Lunzer Untersee (Austria) caused a landslide of a forested area of more than 1 ha which, for a short period, produced a considerably increased sediment (and nutrient) load in a small effluent draining the eroded area. A greater rate of sedimentation was induced by changing the position of the entrance of the Rhine River into Lake Constance in 1900. Until that time, the Rhine River entered the lake at the so-called "Rheinspitz", when, according to a treaty between Austria and Switzerland, the mouth was shifted to flow into Fussach Bay about 10 km east of the old site. The construction of the new river bed resulted not only in a reduction of the relevant river section by 60% (from 12.4 km to 4.9 km), but also in the protection of a large area of the Rhine River valley from flooding. Because of this technical impact, the river supplies an average annual suspended load of almost 2.6 km^3, which has resulted in a decrease of the lake area (539 km^2) by approximately 1.2 km^2. A rapid increase of sedimentation caused by man's activities (less so by natural events such as volcanic ash; Edmondson, 1984) has been reported for numerous lakes, and also presents the special feature of many lakes held behind dams (e.g., Lake Nasser) and in river dams (e.g., Danube, Aschach, annually totaling up to 80 cm).

Most pre-alpine lakes lost their natural littoral zones because of rapidly-increasing tourism, becoming occupied either by sport- and other recreation centers, and by summer resorts activities which can cause eutrophication and pollution. One example of shoreline destruction in the developing world is represented by Lake Atitlan in Guatemala, where an endemic coot species incapable of flight has disappeared. Rules for the protection of lakeshores have been established in only a few countries (e.g., Denmark), restricting building activities to a minimum distance from the lake shoreline. Very recently, shore restoration has become a new strategy in other countries (e.g., Austria, Germany, Japan, Thailand). Likewise, lakes which have become dammed for hydroelectric power have lost their natural shores (i.e., loss of macrophytic vegetation) because of regular changes in their water levels. Examples of this kind of impact are common in many parts of the world, especially in mountainous regions such as the Alps. One case of extensive, and fairly recent, lake destruction is represented by the Aral Sea (see Section 2.2.2—*Salinization*).

In arid and semiarid countries, desertification (also called dryland degradation) is a cause of lake destruction. This was reported in one study as a major threat in 27% of the developing countries (Fig. 2.1). The cause is either climatic stress or human mismanagement, or both. Population growth connected with the over-exploitation of water resources, land use changes which expose soil to erosion, overgrazing and deforestation are major causes.

In conclusion, the importance of the conservation of (shallow) lakes and small bodies of water, especially the saline ones (Williams, 1993, 1996), must be stressed. Since the early-19th Century, an area of more than 50 km^2 in the natural area of lakes has disappeared in Austria. A tentative estimate of this loss on a global level would total at least 100,000 km^2. On the other hand, the fast increasing number of artificial lakes must be considered more than compensation for this loss.

2.2.2 Pollution of Reservoirs and Lakes

Water pollution—the loading of waterbodies with both inorganic and organic matter, with radioactive substances and with undesirable organisms (weeds, invertebrates and vertebrates)—is generally associated with dense, fast-increasing population levels and associated land use changes within a given watershed (e.g., deforestation, agriculture). The importance of pollution is generally related to drinking water quality, domestic use and water conditions desirable for certain recreation activities, such as bathing and swimming.

This section stresses human demands for drinking water, and for high-quality water associated with recreation and biodiversity maintenance. From this perspective, lake pollution comprises a large variety of different items, including:

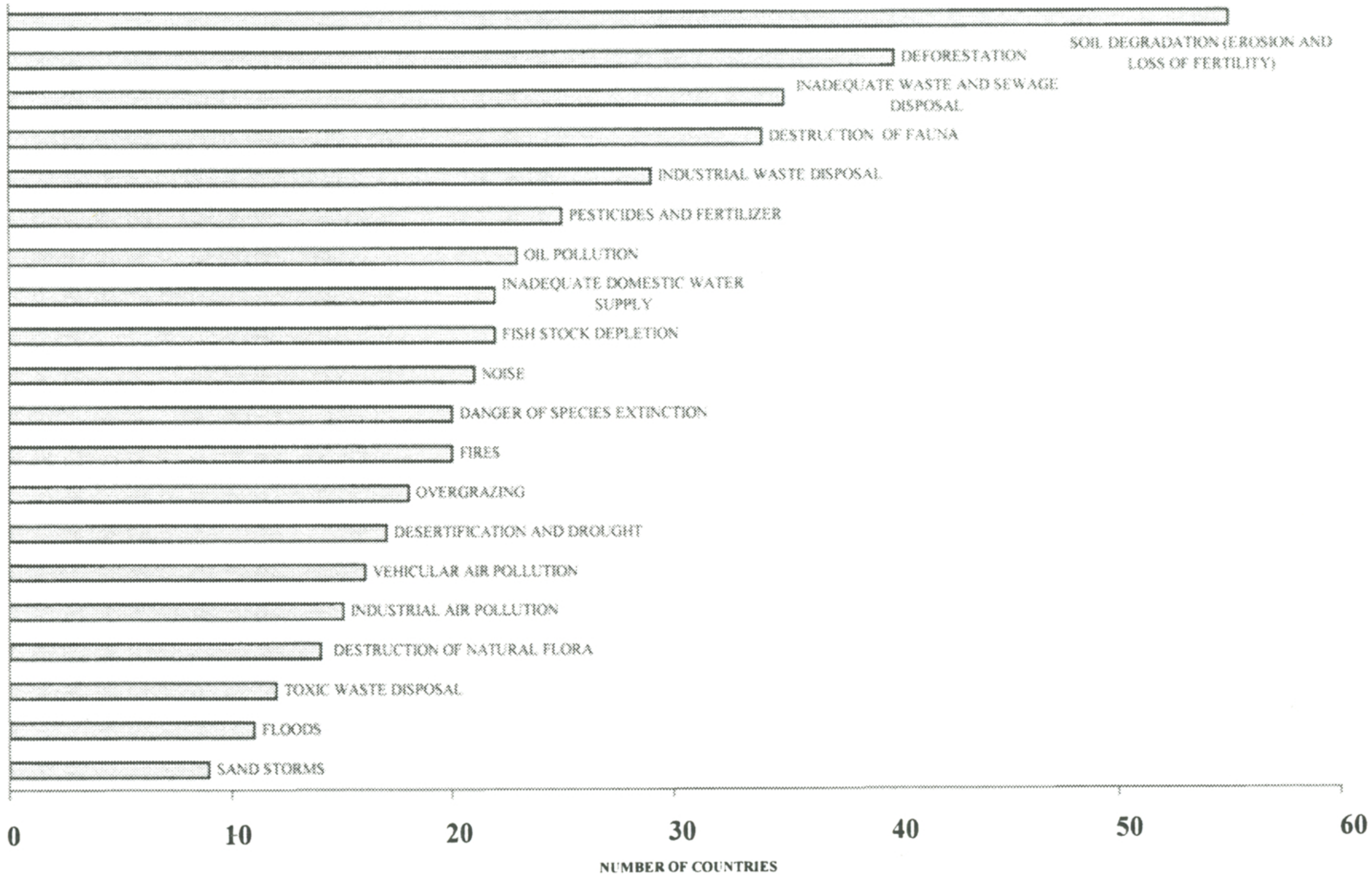

Fig. 2.1. Review of environmental problems in developing countries (modified from Nakamura).

- *Turbidity*—being of natural origin, but strongly enhanced by anthropogenic effects,
- *Sewage pollution*—general domestic pollution from population, the degree of which is lower in rural communities with no sewage service, but highly increasing with increasing urbanization and industrialization (if not decreased by purification),
- *Eutrophication*—a global phenomenon caused by excessive phosphorus and nitrogen loads to waterbodies, and closely related to rapidly-increasing watershed populations, agricultural activities and urban drainage, poor forestry management, deforestation and certain types of industrial activities,
- *Acidification*—a regional phenomenon caused by acid precipitation in areas of igneous rock and poor soil and water acid-buffering capacity (e.g., Eastern USA and Canada, Northern Europe and parts of Central Europe and Asia),
- *Siltation, radioactive matter, thermal pollution, ammonia and nitrate, salts, heavy metals, organic matter (including mineral oil) and pesticides*—local pollution with a great variety of adverse impacts, and
- *Biological pollution*—such as the sporadic immigration and introduction of exotic species and the presence of parasites.

Between the appearance of a new threat and its full impacts, as well as an apparent result of preventive and remedial measures, there is typically a degradation phase. Figure 2.2A illustrates the duration of these phases for countries with advanced sewage treatment. In less-developed countries, the transition periods are not only shifted in time, but may also be highly prolonged. Most severe is the situation in rapidly-developing countries, where many types of pollution appear nearly simultaneously, then becoming difficult to identify the individual causes and their significance in the overall pollution picture (Fig. 2.2B).

Turbidity

Soil degradation, including erosion and loss of fertility, is considered the most significant environmental problem in developing countries (Fig. 2.1). Increased erosion, particularly related to strong rains and runoff, causes turbidity with several consequences for lake and reservoir water quality, including:

- Mechanical filling of the lake basin,
- Increased organic matter input (clay particles contain organic matter subject to decay, both during suspension and after sedimentation),
- Increased bacterial production and formation of clay–organic-bacteria aggregates (Lind and Davalos-Lind, 1999),
- Increased phosphorus loads, representing the dominant part of the sum of all phosphorus sources from agriculture (on the one hand, the turbidity contributes to phosphorus concentrations in the water column; on the other hand, clay particles compete with plankton for phosphorus and can transport phosphorus to the sediments),
- Increased heavy metal concentrations, depending on their presence in the soil because of the application of fertilizers and from other sources in the drainage basin,
- Decreased light availability for phytoplankton photosynthesis, leading to water quality improvement, or at least compensating for photosynthesis resulting from increased phosphorus loads (Lind and Davalos-Lind, 1999),

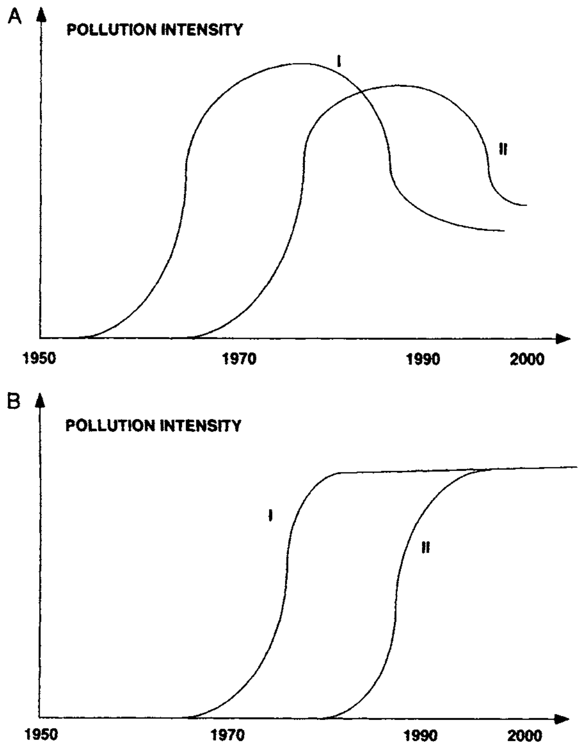

Fig. 2.2. Differences between pollution sequences in industrial countries (A) and developing countries (B). I represents an early starting country and II a later starting country.

- Interference with trophic interactions in lake plankton, particularly decreasing the visual grazers of visual grazers (Cuker, 1987).

The general nature of suspended material in the aquatic environment is described by Eisma (1992).

Summer temperature and primary production profiles of clear and turbid lakes can be quite different. The surface temperature of a turbid lake is higher than that of a clear lake because the particles causing turbidity can adsorb the incoming solar radiation in the uppermost layers. Clean water allows a deeper penetration of solar radiation into the water column, resulting in a heat gain in the deeper water strata. In a turbid lake, oxygen is produced by photosynthesis within shallower water strata than in a clear lake. Water strata exhibiting no photosynthesis, therefore, are more extensive, extending the oxygen deficit. Oxygen conditions are worse in turbid waters because of the increased nutrient load, and the production of organic matter associated with particles, as well as decreased re-oxygenation associated with photosynthesis due to light limitation of primary production. Light penetration also is important for the distribution of macrophytes in lakes (Duarte

Table 2.4. Management consequences of turbidity related to inorganic particles (modified from Hart and Allanson, 1984)

Positive effects:

- Costs of producing high quality water are low, since particles are easily flocculated
- Reduction of the potential for algal and submerged macrophyte growth
- Increased fishery potential due to associated nutrient inputs

Negative effects:

- Increased capacity to transport nutrients and toxic substances
- Reduced storage capacity of reservoirs and impoundments, as a consequence of settling out of riverborne inorganic suspended material
- Reduced fishery potential, due to high sustained levels of turbidity, which cause large zooplankton species to be grazed and restrict the littoral to a small vertical depth

and Kalff, 1987, 1990). The influence of turbidity on lake water quality is summarized in Table 2.4.

Sewage pollution

This represents the classic pollution historically created with the advent of water canalization. Before canalization, most organic matter ejected by humans was recirculated back to fields, going then straight back into receiving waters. With the development of urbanization and modernization, the organic matter became accompanied by many plastic materials that are not easily decomposable. This is creating major water quality problems, particularly in the megacities of developing countries.

The effect of sewage pollution on a waterbody is illustrated in Figure 2.3. In addition to increased concentrations of organic matter in the inflows to lakes and reservoirs, there also is a lower oxygen concentration associated with the decomposition of organic matter. The concentrations of nutrients also increase, unless the influent water receives tertiary treatment directed to the extraction of nutrients. Up to the present time, this treatment is more easily applied to phosphorus than to nitrogen. The load of pathogenic bacteria is increased. The organic matter decomposes further in the lake, particularly in the sediments where it can accumulate. Oxygen consumption by the sediments can lead to anoxia which, in reservoirs, can extend from the inflow region where most sedimentation usually occurs. Increased releases of nitrites, ammonia, iron, manganese and phosphorus are consequence of the changed chemical redox potential associated with anoxia. The presence of gases, including carbon dioxide, methane and hydrogen sulphate, increases in the hypolimnetic water. Refractory organic matter is a consequence of the partial mineralization of organic matter from sewage. The passage of the water through the lake, however, also markedly increases the quality of the water, due to self-purification processes in the lake.

The consequences of high levels of sewage pollution on water quality are extensive. Human health problems of various kinds are created. Adequate drinking water treatment is made more difficult, costly or even impossible. Fish meat can become of lower quality and even inedible, with resistant fish becoming dominant. Corrosion of structures also can occur, with a strong ebullition of gases in extreme cases.

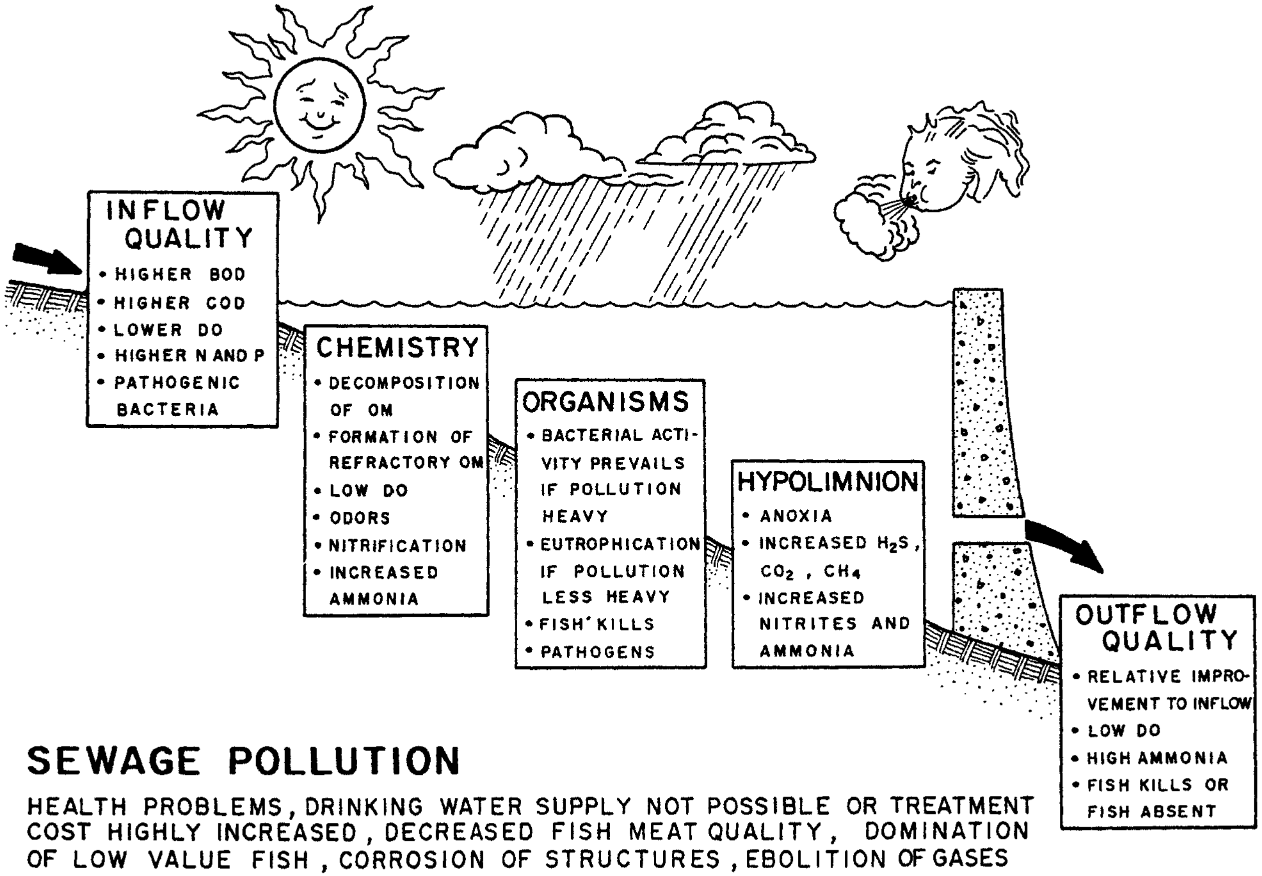

Fig. 2.3. Schematic representation of the effects of sewage pollution on lakes (modified from Straškraba and Tundisi, 1999).

Eutrophication

Trophy refers to the quantities of nutrients entering a lake (i.e., the nutrient load). Higher nutrient loads typically produce higher primary production by phytoplankton and macrophytes. Thus, *eutrophication* equates to both high nutrient loads and high aquatic production. High nutrient loads are the dominant cause, and high production the dominant consequence, creating most water quality problems associated with eutrophication. It is not the concentrations of phosphorus and carbon in a lake *per se* that cause water quality problems; rather, it is the production of phytoplankton and macrophytes resulting from the nutrients that creates the problems. The situation is different with nitrogen, in that high concentrations of nitrogen compounds in water also can have health consequences for humans, in addition to being an aquatic plant nutrient. *Oligotrophic* waterbodies (from oligo = poor) receive less nutrients from their drainage basins and, therefore, exhibit lower phytoplankton production. As a result, their water is typically very clear. Waterbodies with extremely low nutrients loads and levels of primary production are called *ultra-oligotrophic*. In contrast, *eutrophic* (from eu = rich) waterbodies are rich in nutrients, and have high levels of biological production supported by their high nutrient loads. The waterbodies lying between these two nutrient extremes are called *mesotrophic*. *Hypertrophic* refers to waterbodies extremely rich in nutrients and, therefore, also containing high phytoplankton concentrations. Higher nutrients loads are usually (though not necessarily always) associated with higher loads of organic matter from a lake's drainage basin (i.e., *allochthonous* organic matter). Phytoplankton and macrophytes can produce organic matter in a waterbody (i.e., *autochthonous* organic matter), and the consequence of the decomposition of this matter being water quality degradation. Oxygen is consumed by the microbial organisms that decompose the phytoplankton and low oxygen (anoxic) conditions can result, particularly in the hypolimnion of stratified waterbodies. There are several nutrients, or biogenic elements, necessary for phytoplankton and macrophyte growth. However, their relative quantities necessary for optimal growth are very different. The most abundant nutrients are phosphorus, nitrogen and carbon, which are typically utilized by algae and other autotrophs in a proportion corresponding to their relation in algal cells. This is the basis of the so-called Redfield ratio of carbon to nitrogen to phosphorus (i.e., $C:N:P = 106:16:1$ by atomic weight). If these nutrients are present in a waterbody in approximately this ratio, the growth of algae is not limited by any of them, but rather depends on the absolute quantities (i.e., concentrations) present in the water column. However, when the in-lake proportion differs from this ratio, the nutrient that exhibiting the most deviation is the one that limits the algal production (i.e., it is the limiting nutrient). The limiting nutrient in most waterbodies is phosphorus, with excess nitrogen typically being present. In contrast, although nitrogen does not limit algal biomass in many freshwater bodies, it is generally the limiting nutrient for the production of marine phytoplankton, and can create eutrophic conditions in closed seas (e.g., Adria, Baltic or Black Sea).

From the management perspective, therefore, reduction of the quantities of the limiting nutrient entering a waterbody, and the associated decrease in the primary production in the waterbody, usually results in a reduced production of organic matter (i.e., phytoplankton) and an associated improvement in water quality. If the load of the limiting nutrient is high, there is essentially no other logical way to significantly and reasonably improve the water quality of a lake than to reduce the nutrient input. Almost all other management methods can only be successful when the in-lake nutrient concentrations are low. However, once a waterbody becomes loaded with phosphorus over a number of years, large quantities of phosphorus may have accumulated in the lake bottom sediments. Once the external phosphorus load is reduced, therefore, it will still take several years before the phosphorus in the waterbody and its sediments is flushed out and the organic production decreased.

The nutrient load is not the only variable responsible for differing quantities of algal production in lakes and reservoirs. The same load of incoming nutrients can produce different consequences in different waterbodies, depending on their size, depth and water flushing rate. Shallow and/or smaller waterbodies generally are more eutrophic then deeper, larger ones.

Eutrophication as a process of water quality deterioration is most often due to human influences, including nutrient loads from both point and nonpoint sources. The increased nutrient loading is a result mainly of cities, settlements, recreational pressures, industry, deforestation, agriculture, erosion, damming of lakes and rivers, river diversions, poor watershed management and, last but not least, from atmospheric pollution. The latter plays a significant role in remote high-alpine lakes, which typically are not direct impacted by human activities in their drainage basins (Psenner, 1994; Löffler, 1995b). However, eutrophication (Hutchinson, 1973; Vollenweider, 1979) also can be related to natural events in exceptional cases, such as the large erosion processes associated with the retreat of glaciers during the late Pleistocene Era, or the forming of the lakes behind major landslides, which can result in excessive nutrient loads from decaying terrestrial vegetation and other natural organic matter.

The effect of eutrophication on a lake or reservoir is shown schematically in Figure 2.4. Only the qualitative picture is presented, with the quantitative aspects being dealt with in other parts of this book, including Section 3.2.3, and in Section 4.2.1 in regard to nutrient sources. Eutrophication models are discussed in Section 5.5.1. Major eutrophication processes in lakes are related to nutrient inputs from the drainage basin, and the in-lake activity of algae, Cyanobacteria, macrophytes and associated microbes and fauna. The influence of increased nutrient concentrations on algal biomass in lakes is nonlinear. With increasing concentrations of the limiting nutrient, the algal biomass first increases slowly, and then more rapidly, followed by an almost linear rise until some asymptotic value of biomass is reached at high concentrations of the limiting nutrient (Fig. 2.5). Increased algal activity associated with eutrophication increases the oxygen content of the water column, and reduces its pH due to the utilization of carbon dioxide (CO_2). However, this sequence is only valid in the upper water strata, and during thermal stratification, when water mixing oxygen concentration values can be very low, and the concentration in the hypolimnion can drop to zero. This can result in an increased release of phosphorus and heavy metals from the sediments back into the water column.

The water quality effects of eutrophication include generally-decreased water quality, increased costs of drinking water treatment, and taste and odor problems in drinking water. Filters used in water treatment can become clogged, requiring frequent cleaning. The

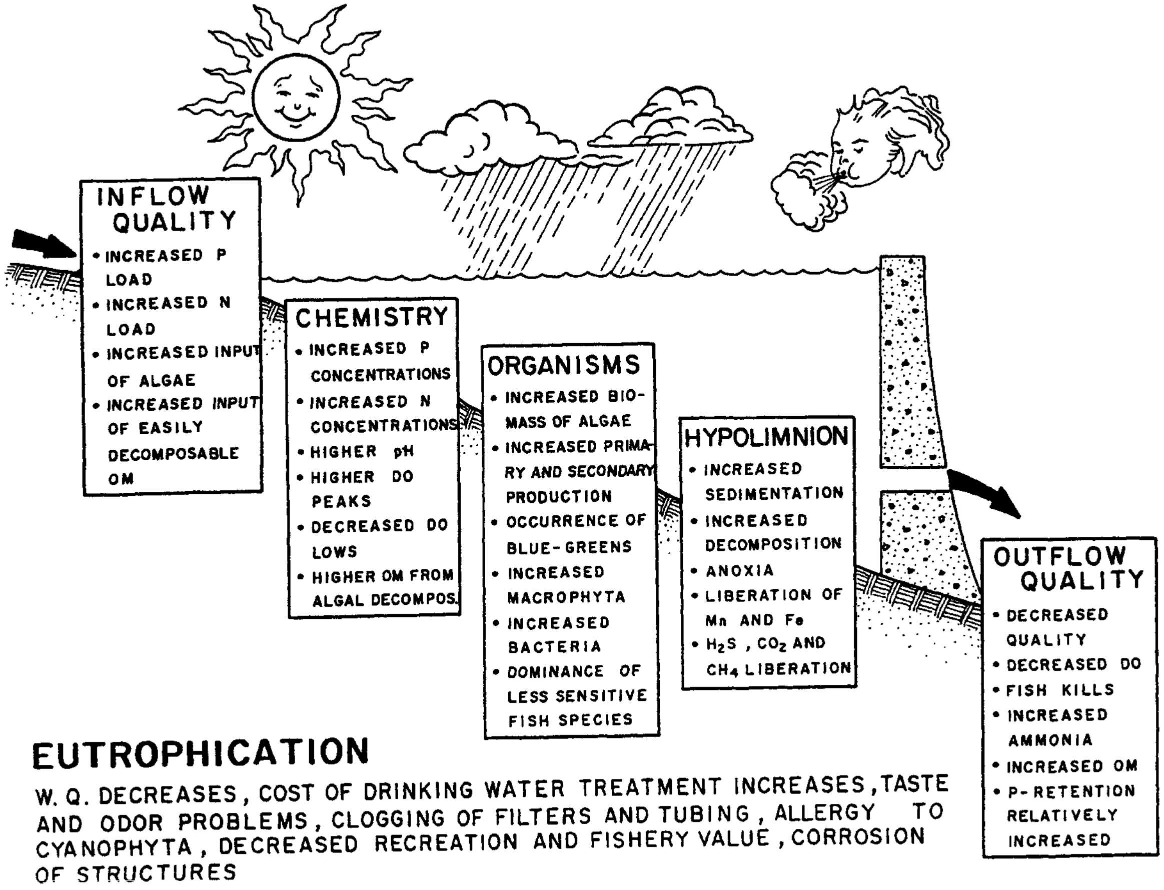

Fig. 2.4. Schematic representation of the effects of eutrophication on lakes (modified from Straškraba and Tundisi, 1999).

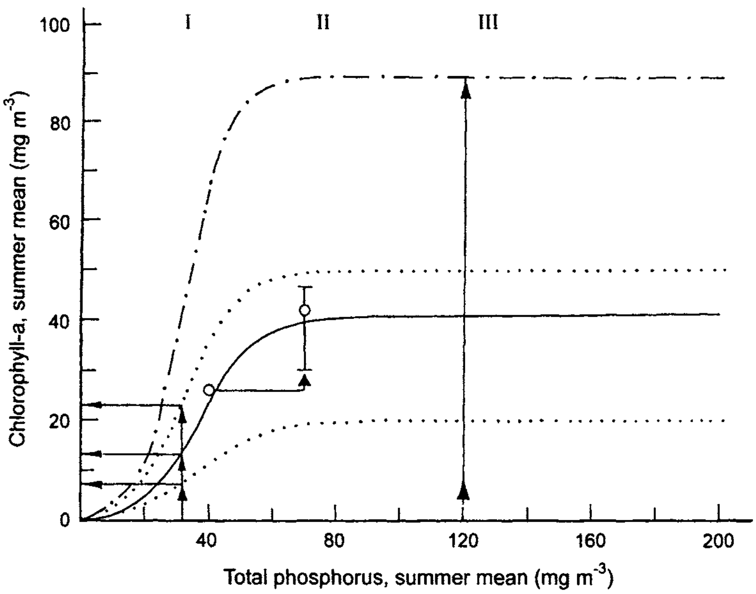

Fig. 2.5. Nonlinear reaction of lake eutrophication to phosphorus reduction (Straškraba et al., 1979).

organic matter produced by algae can create water treatment difficulties, including algal toxins and the formation of trihalomethanes in drinking water, and the presence of mucopolysacharides, causing problems for certain industrial waters. Mechanical difficulties can be created by the clogging of tubing because of organism growths, and by corrosion from high carbon dioxide and methane concentrations in extremely eutrophic waterbodies. Recreation can be threatened by high concentrations of algae, including changes in the algal species composition, and an increased presence of toxic Cyanobacteria creating health problems (including the death of humans and cattle).

Fish productivity also is increased in eutrophic lakes, which is a positive feature from the perspective of increased food production. However, the fish populations frequently change from cold-water to warm-water species that are less desirable from a recreational perspective. With further increases in eutrophication (i.e., hypertrophic waters), fish populations can collapse, due to lack of oxygen and an excess of toxic gases in the waterbody.

In addition to increased nutrient loads, organic matter also increases due to inputs from different diffuse (nonpoint) sources in the drainage basin, including the formation of organic matter in the inflowing rivers by phytoplankton and its subsequent decomposition. If point sources of nutrients are not sufficiently controlled, as is the case in many developing countries, the joint impacts of eutrophication and organic pollution must be seriously considered within the context of lake management efforts.

Most of the above-noted eutrophication symptoms and processes are related to deep lakes. Shallow lakes, however, react differently from deep lakes in some aspects. One important variable for phytoplankton development is the depth of the mixing water layer, related to the availability of light for the phytoplankton population dispersed in this layer. The narrow mixing layer of shallow lakes provides more light for phytoplankton productivity. As a result, their primary production is higher than for deep lakes receiving the same nutrient load. Thus, the phytoplankton biomass is higher in shallow lakes, and they have a tendency to be more eutrophic and more prone to Cyanobacteria blooms. In the absence of permanent thermal stratification, the oxygen concentration is fairly high at all depths, including the near bottom water layer. More details on the differences between shallow and deep lakes are presented in Section 3.2.1.

Toxic Cyanobacteria and other noxious algae. Certain toxic strains of algal species, including *Microcystis, Anabaena, Aphanizomenon, Synechococcus* and *Cylindrospermopsis*, often co-exist with nontoxic strains in the same waterbody. Some of the associated toxic substances (microcystin, anatoxin, saxitocin, cylindrospermopsin) have been analyzed over the last decade. To at least some extent, they are considered to be a means by which algae protect themselves against grazing by zooplankton. It has been observed, for example, that Cladocera unable to select nontoxic algae stop their water filtration in their presence. The occurrence of toxin-producing Cyanobacteria seems to increase with increasing eutrophication in both tropical and temperate regions. Although earlier records were dominantly from warm regions, Willen and Mattson (1997) recently reported that 47% of Cyanobacteria samples from Sweden contained toxins, compared to 44% in Finland and 48% in Norway. The occurrence in France is even higher, with Vezie et al. (1997) detecting toxins in more than 70% of their water samples. A detailed review of the health effects of Cyanobacteria was recently presented by Chorus and Bartram (1999) and Chorus and Cavalieri (2000).

Toxic, or at least allergic, effects also may be caused by some other algae, with cases of skin irritation and allergies reported for forest lakes in Sweden, because of the flagellate *Gonyostomum semen* (Cronberg et al., 1988). A recent plague resulting from intensive eutrophication in Asia is "red tide", caused by the alga *Peridinium bipes*. In Japan, red tide has been observed in reservoirs throughout the country.

Serious health events related to Cyanobacteria have been reported from many countries (Falconer, 1989, 1993). The review of Chorus and Salas (1997) on the health impacts of freshwater algae summarizes 12 case studies and reports on acute intoxication with Cyanobacteria. Human deaths have been reported from Brazil. In the town of Caracau (State of Pernambuco), 55 hemodialysis patients died of liver disease, seizures or acute hemorrhaging after receiving dialysis treatment using chlorinated water from the city reservoir. According to Chorus and Salas (1997), the cause of the deaths was Microcystin. After the closure of the Itaparica Reservoir in Brazil, 87 people died from drinking water from the new reservoir after the development of *Microcystis*. In another case, 32 deaths were reported, following 110 cases of human poisoning. Earlier in another lake (Lago del Parque), 72 cattle deaths were reported in 1973. Kontek et al. (1997) have studied the mutageneticity of toxins from Cyanobacteria.

The observed human health effects (Lawton and Codd, 1991) range from contact dermatitis, eye irritation, fever-like symptoms, gastroenteritis (resulting in diarrhoea and vomiting), basal pneumonia, hepatitis, endotoxaemia, and one observation of a suspected cause of birth defects being the drinking of water from a water supply lake with *Oscillatoria subbrevis*. Some of the signs on the skin and eyes of swimmers is assumed to be related to allergic reactions, rather then to direct toxic effects. The most extensive cases of poisoning thought to be related to Cyanobacteria involved 6000 U.S. soldiers from a base in the Philippines that used drinking water from a Cyanobacteria-infected river, and about 5000 people becoming mildly ill after drinking from an infested reservoir in Pennsylvania (see Section 4.3.5 for Cyanobacteria treatment). Falconer (1993) provides a good review of algal toxins as they appear in drinking water.

Another negative health effect related to algae and Cyanobacteria is the production of cancer-promoting trihalomethanes, which are formed as byproducts during the chlorination of drinking water. They are considered particularly to be responsible for causing bladder cancer. It appears that different types of algae exhibit similar effects in regard to trihalomethane formation, as evidenced in experimental studies with the Cyanobacteria *Anabaena flos aquae* and diatom *Asterionella formosa* by Graham et al. (1998). Toxic Cyanobacteria may occasionally cause fish kills. The decomposition of blue-green algae also may produce sufficient quantities of hydroxylamine to become lethal to fish.

Present state of eutrophication. Since the 1960s, eutrophication of many lakes and reservoirs in most industrial countries has been successfully treated. At the same time, however, eutrophication is increasing in developing countries, where the economy generally does not provide for costly sanitation facilities or lake restoration efforts. It also must be admitted that "re-oligotrophication" of lakes in industrial countries has often not resulted in the same conditions existing in the lakes before the onset of the increased nutrient loadings (e.g., organic materials and nutrient concentrations, water transparency, biodiversity). Rather, the conditions have improved only to the extent deemed desirable for human use of the lakes and reservoirs with respect to drinking water quality and recreational use.

One of the best known examples of lakes in industrial countries that have been successfully restored from eutrophication is the case of Lake Washington (Edmondson, 1991). Based on analysis of long-term data sets, the lake underwent two phases of eutrophication in the 1920s and 1950s. Based on limnological studies and careful monitoring, as well as public outcries lead by Edmondson and his co-workers, a sewage diversion scheme was set up in the late 1950s. After the diversion of the sewage was begun, the lake responded almost immediately, returning in the early-1970s to the conditions existing before 1950 (Edmondson, 1972; Edmondson and Lehman, 1981; Crul, 1995). The situation in Lake Constance (Fig. 2.6) also illustrates the degree of improvement that can be obtained.

Among the Laurentian Great Lakes of North America, only the largest ones (Superior, Huron) are still oligotrophic, exhibiting only local environmental pollution problems. This is due to the climate being too cold for intensive agriculture, and only a small number of large cities on their shorelines. In contrast, Lakes Michigan, Erie and Ontario have numerous industrial cities along their shorelines and in their drainage basins, with their more fertile soils also being subjected to intensive agriculture. In spite of its relative short water retention time, the most serious eutrophication problems have occurred in shallow Lake Erie. Domestic sewage from cities such as Cleveland and Detroit, and effluents from

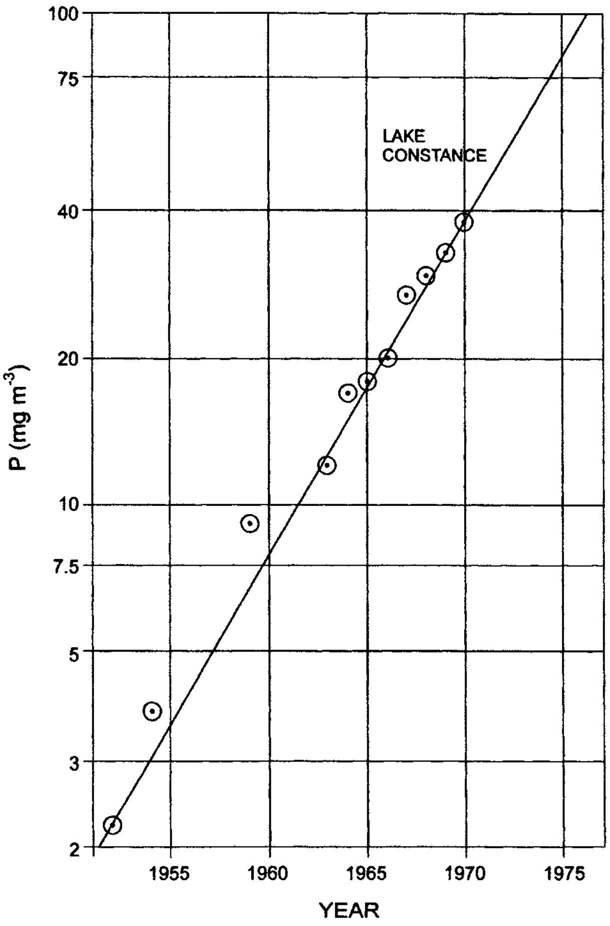

Fig. 2.6. Eutrophication of Lake Constance has shown in the period indicated an exponential trend, presented in the figure in linearized form. The trend was later stopped by the introduction of tertiary treatment, and reversed by the ban on phosphates in detergents (from Stumm and Baccini, 1978).

industries, caused severe eutrophication. A phosphorus restoration program stimulated by limnologists and Great Lakes residents, within the context of the U.S.–Canada Great Lakes Water Quality Agreements of 1972 and 1978, resulted in a sharp decrease in the phosphorus loads and concentrations in Lakes Erie, Ontario and Michigan. Chemical pollution is presently the main pollution problem in these latter lakes (Lee et al., 1978; Crul, 1995; also see Section 9.2).

Lake Tahoe in the Sierra Nevada mountains of the western United States was originally an ultra-oligotrophic lake, with Secchi readings of more than 30 m. Over the three last decades, however, the rate of eutrophication of the lake has accelerated, due to large-scale tourism and recreational activities. Inflows, groundwater seepage and atmospheric inputs of nutrients (the latter from car emissions, wood-burning stoves and possibly forest fires; Goldman, 1990) have contributed to decreasing transparency and increasing algal growths (Goldman, 1993, see also Crul, 1995). Relevant limnological studies within the lake and its drainage basin again became the basis of a legislative strategy of the Tahoe Regional Planning Agency to address the ongoing eutrophication of this unique lake.

Only little progress has been achieved in Central and Eastern Europe, where increasing recreational pressures (e.g., some Mazurian Lakes in Poland) have most often resulted in increased eutrophication. Related to rapidly-increasing tourism, the shallow Lake Balaton in Hungary is of special interest, since it not only represents a major modelling case study of the International Institute of Applied Systems Analysis (IIASA), but also a site of major restorational activity. Since one of the lake's most important nutrient loading sources is its largest tributary, the River Zala (which enters the western tip of the long-stretched lake at the lower part of its floodplain) was turned into a large wetland. As a result, the water retention time of this river section was increased and the lake's water quality improved. Further, the restoration site became an outstanding bird sanctuary (Istvanovic and Somlyódy, 1999). However, it also is obvious that, in view of the fast-growing recreational activities, this important local measure alone cannot improve the overall nutrient condition of Lake Balaton. In fact, much more effort must be expended to save Central Europe's largest lake.

Lake Baikal (Russia), with its unique plant and animal life, is threatened at least locally by industries and agriculture. Its main pollution (including eutrophication) sources include the inflowing Selenga River, which carries pollutants and nutrients from industrial plants in Ula Ude, the cellulose plant in Baikalsk (southern shore) and the area around Severobaikalsk (northern end of the lake). Since the 1970s, modest efforts have been made to reduce the pollution of the cellulose plant in Baikalsk. So far, however, only limited success has been seen.

In contrast to the ongoing efforts against eutrophication in industrial countries, virtually nothing has been achieved in most developing countries. Even more so than in Eastern Europe, economic shortcomings, as well as lack of interest on the part of decision makers and local or regional people, are among the major reasons. Generally, eutrophication began with increasing population pressures, especially so in Africa during the 1960s. Exceptions are China (e.g., Lake Dianchi) and India, where eutrophication had its onset at least several decades earlier than in Africa. A dramatic example of the first increasing population pressure on lakeshores in Africa is Kampala, the capital of Uganda.

With the exception of some 60 high mountain lakes in East Africa (Löffler, 1964) and Ethiopia, oligotrophic lakes (in terms of water transparency) are represented by some of the deep Rift Valley lakes, especially Lake Tanganyika (although local eutrophication is becoming of increasing concern). Most of the other African lakes have high nutrient loadings related to human activities or naturally-high nutrient concentrations, some examples being the East African shallow alkaline lakes (Talling, 1957; Symoens et al., 1981). Among the large African lakes, Lake Victoria is subject to lake-wide eutrophication, and a general limnological transition which occurred between 1960–1990 (Hecky, 1993). This may be due partly to higher temperatures throughout the water column in most months of a recent period of observation during 1989–1991 (compared to 1960–1961), but is more likely due to increased point and nonpoint loadings, as well as the dramatic increase of the Nile perch (*Lates niloticus*) in the 1980s, about 25 years after its introduction to the lake (Crul, 1995). This sudden increase led to a dramatic decline of the food-web structure in Lake Victoria. Lake Tai-Hu, the third largest freshwater lake in China, is faced with two conflicting requirements, including increasing the aquatic productivity and improving the water quality to meet the needs of the growing population in this lake basin. A new type of aquatic agriculture has been developed there to optimize the use of the lake's food chain with the establishment of integrated systems. These include growing selected submerged macrophytes in the area surrounding fish pens, with the macrophytes being used as fish food. The areas for plant and fish culture are changed from year to year for water quality conservation. Macrophytes also mitigate wave action and improve the water quality by absorbing nutrients. The annual fish harvest totals between 22–30 tons/ha.

Increased use of this more traditional kind of integrated systems has been made in various countries, especially in Southeast Asia. These countries are threatened by rapidly-increasing population pressures and, therefore, an increased need for more protein resources, resulting in overstocking with fish. Moreover, the use of pesticides, as well as other kinds of pollution, have had adverse impacts. These types of impacts can be observed in the numerous lateral lakes of Chang Jiang (Yangtze River). One example, among many, is the East Lake of Wuhan (Dong Hu) on the northeastern outskirts of Wuchang. This shallow lake serves as a water supply and commercial fishery. With the increased urbanization in its drainage basin over 40 years, a number of changes occurred in the lake, including an increase in the total solids (dissolved and suspended) concentration from 80 mg l^{-1} to 192 mg l^{-1}, and in the total phosphorus concentration from 9 mg l^{-1} to 150 mg l^{-1}. The previously-dominant submerged macrophytes, such as *Potamogeton maackiansis*, disappeared and others became impoverished, most likely because of overstocking with grass carp. Moreover, Cyanobacteria became increasingly dominant, while Bacillariophyta decreased rapidly. On the whole, the lake has approached "the upper limits of eutrophication" (Liu, 1984). A more general, but extensive, review of the state of a number of Chinese lakes and reservoirs is now available (Jin, 1995). The trophic level of major lakes and reservoirs in China was assessed independently by Shu and Wuang (1993). Similarly, many other lakes which were investigated in 1929 have undergone major changes, especially in regard to eutrophication and siltation.

The destruction of natural habitats by human activities in India has been far more extensive and complete than perhaps anywhere else in the world (Mani, 1974) and should be given special attention. Because of this situation, oligotrophic Indian lakes are restricted to high mountains, whereas lakes of mountainous zones below 2000 m already suffer from population pressures, tourism and, therefore, also from erosion and eutrophication. Very high nutrient loadings and corresponding algal blooms characterize the lakes and tanks (small artificial reservoirs) of most of the lowland areas in India.

In South America, Lake Amatitlan in Guatemala is negatively affected by population growth, deforestation, inadequate land use and industrial development. Although situated in a unique landscape, no significant lake management program exists. In Nicaragua, Lake Managua (Lago Xolotlán) and Lake Nicaragua suffer from untreated sewage and industrial discharges, including heavy metals. Moreover, they also contain a multitude of pesticides from agricultural and pasture lands. Unfortunately, no rational development plans have been elaborated to date for these lakes. Lake Valencia, the largest and oldest (end of Pliocene Era) lake in Venezuela, presents a disastrous eutrophication (and pollution) case, related to intensive human intervention in its drainage basin and the input of untreated wastewater from domestic, agricultural and industrial activities of about 2 million people. The use of the lake is restricted by its high salt content. Permanent algal blooms, high fish mortality, and odors prevent the use of the lake for drinking water, aquatic sports or tourism. When Gessner visited the lake in 1952 during his Venezuela Expedition, he called it one of the most beautiful lakes of South America (Gessner, 1955a, 1955b). However, sometime between Gessner's last observations in the 1960s and a later census in the 1970s (Infante, 1978), the lake obviously deteriorated completely. A project for the environmental recovery of Lake Valencia and its drainage basin was recently developed, including the proposed construction of at least three sewage plants, to be financed by the Inter-American Development Bank.

Nutrient loads from dry and wet precipitation also endanger oligotrophic lakes in the high alpine regions of Europe (Löffler, 1995b), and perhaps also Lake Victoria (Hecky, 1993). Alleviation of this problem clearly requires regional cooperation. In this connection, it should be stressed that a global monitoring program focusing on the phosphorus contents of precipitation is desirable (Section 3.4.2).

A more global picture of the state of world lakes can be obtained from the ILEC (International Lake Environment Committee Foundation) series of Data Handbooks (Kira, 1994, 1995a, 1995b).

In conclusion, in contrast to the natural nutrient loading of lakes, human-induced eutrophication is the most common and, therefore, most important problem affecting the beneficial use of lakes and reservoirs around the world (Kira, 1993). The increased biological production associated with eutrophication may only be considered desirable from the perspective of food production. However, in regard to domestic water demands, biodiversity, and recreation, eutrophication is considered an undesirable condition, and can often result in human health problems. It became a major problem in industrialized countries more than a half century ago, whereas it became a major problem in developing countries mainly after the 1960s (especially in Latin America and Africa), primarily in relation to the rapidly-increasing population pressure.

Rate of lake recovery from eutrophication. The recovery of a lake from eutrophication depends in part on the quantity of phosphorus that has accumulated over time in the lake bottom sediment, and the water volume in contact with the sediment. For most lakes subjected to reduced external phosphorus loads, the in-lake phosphorus concentrations decreased, with corresponding decreases in chlorophyll concentrations (an indicator of algal biomass) and increases in water transparency (Fig. 2.7A, B). However, in cases of high sediment phosphorus accumulation, particularly shallower lakes, the recovery of the lake proceeded at a much slower rate than the reduction in the external phosphorus load.

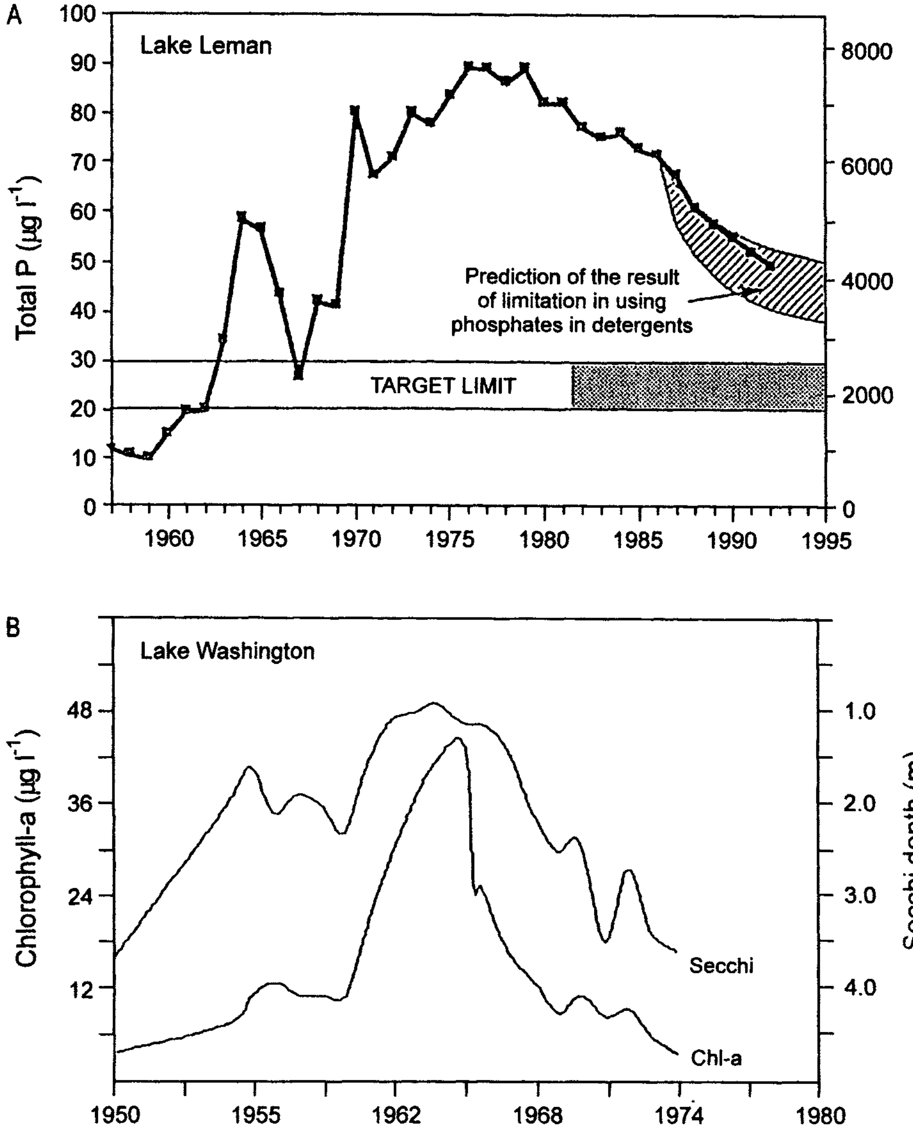

Fig. 2.7. Improvements of water quality after reduction of external phosphorus sources in the drainage basin. A—Lake Leman, Switzerland. Although rapidly approaching the target level marked by the dotted area, it was not achieved in 1995. The first arrow (1972) indicates the start of tertiary treatment, the second (1986) the ban on using phosphates in detergents (from Rapin et al., 1995); B—Lake Washington in the United States.

The accumulated phosphorus in the sediment moved by diffusion into the now more dilute phosphorus content in the hypolimnion, lengthening the phosphorus flushing process by a number of years. The lakes of the Berlin area provide an example, for which Wolf et al. (1988) reported a five-year lag period between the initiation of lake restoration efforts and full lake recovery (cf. Fig. 5.16). Another constraint to immediate lake recovery is the nonlinear, asymptotic character of the relationship between the quantity of algae and the phosphorus concentration (see Section 3.2.2). When the phosphorus concentrations in a lake are very high prior to initiation of external phosphorus load reductions, even a very significant decrease in the phosphorus concentration does not necessarily result in a significant decrease in the chlorophyll-a concentration (Fig. 2.5; also see Ryding and Rast, 1989).

Recent information and guidance on the assessment and management of eutrophication in lakes and reservoirs is summarized by Rast and Thornton (1997) and IETC (1999).

Acidification

Changes in lake acidity are generally associated with acid precipitation, which is presently confined mainly to industrial regions of the Northern Hemisphere. However, since lake acidification depends on the degree of susceptibility of a given lake and its drainage basin (i.e., its acid-buffering capacity), its distribution is limited to the northeastern United States and the adjacent parts of Canada, Scandinavia, parts of Great Britain and Ireland and small areas in Central Europe (e.g., Czech Republic, Germany, Poland, Slovakia) and Asia.

The effect of acidification on water quality is illustrated schematically in Figure 2.8. The main impacts are due to the effects of inflows, which can have high concentrations of toxic aluminum (Morris et al., 1989) associated with low pH and modified nutrient loads, compared to nonacidified lakes, because of chemical reactions in the drainage basin that can lead to decreased nitrogen concentrations and increased concentrations of phosphorus compounds. When the pH of a waterbody is low, due not only to the effect of strong acids from acid rain, but also because of humic (fulvic) acids (Hessen and Travnik, 1998), further chemical and physical–chemical reactions can modify the availability of nutrients to phytoplankton. Thus, the eutrophication of these waters is decreased (Mason, 1990; Psenner, 1994; Steinberg and Wright, 1994).

The main water quality problems of acidified lakes are that the potable water supply is endangered due to increased concentrations of heavy metals, particularly aluminium, in the water. The reduction of aquatic life is a major treat for fishery and recreational uses.

It is noted, however, that lake acidification may be a long-term natural event in some cases, if a lake's drainage basin becomes increasingly covered by peat bogs due to climatic changes. Such transitions are known, for example, from the early Holocene Era of Finnish lakes.

Among the human causes of lake acidification, various types of pollution and the treatment of lakes affected by blooms of blue green algae with copper sulfate (e.g., Lake Mendota, Wisconsin) should be mentioned. Further, lakes formed in areas with strip mines (mainly brown coal and iron ore mines) are likely to become acidic. Fonseca (1990) reported a case of stream acidification by acid mine drainage.

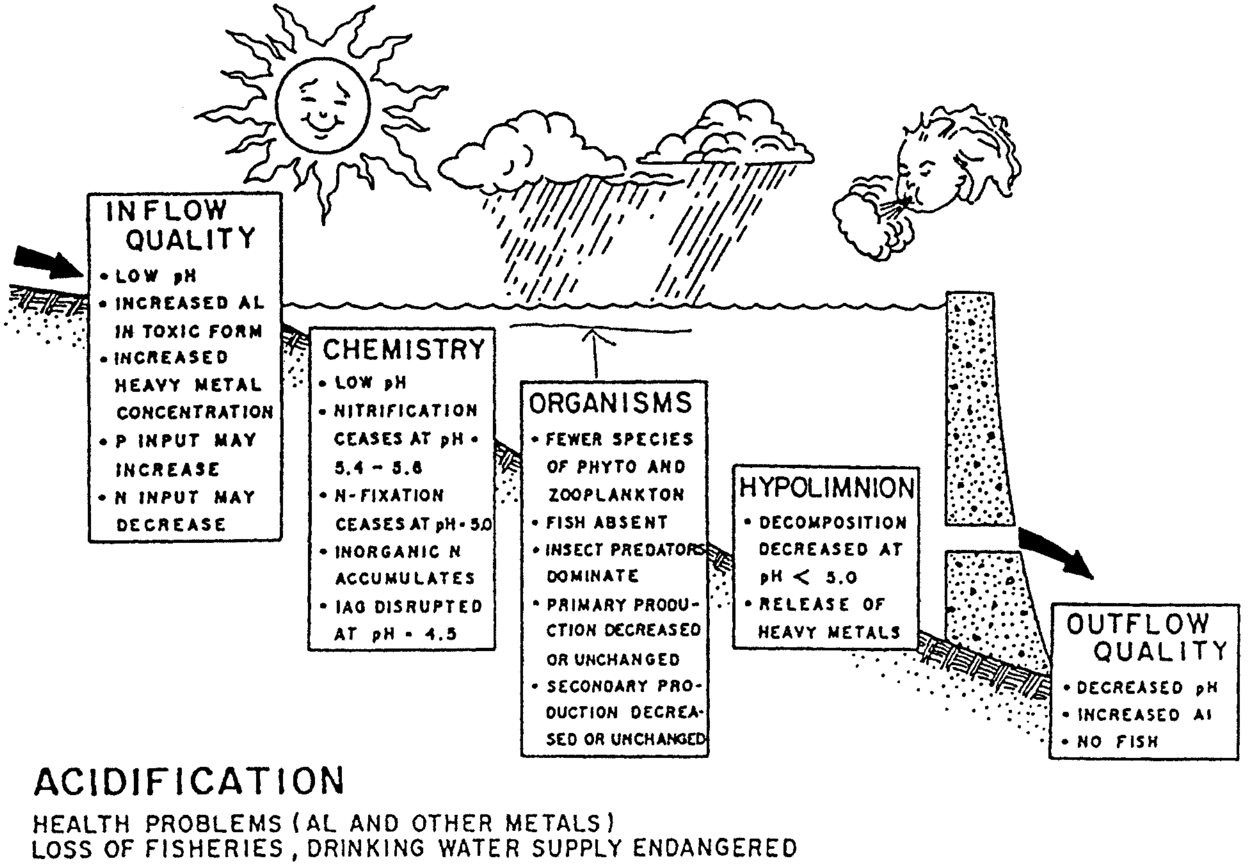

Fig. 2.8. Schematic representation of the effects of acidification on lake water quality (modified from Straškraba and Tundisi, 1999).

The starting point for increased atmospheric loadings of acidifying compounds such as sulphur oxides (SO_x), nitrous oxides (NO_x), etc., was about 1850, the time when sediment cores from acidified lakes began to exhibit high concentrations of carbonaceous particles derived from fossil combustion. It is of interest that, at some sites, conifer afforestation may contribute to acidification indirectly though, for example, the erosion of peat following land drainage (Battarbee et al., 1988). The onset of lake acidification is variable over the past 150 years. For many lakes, it occurred only after the World War II (e.g., lakes of the High Tatra in Poland and Slovakia). An example of long-term increasing acidification was presented by the lake Cerné Jezero in southern Bohemia, for which more than 120 years of data exist. This small (18 ha) lake was excavated by a glacier during the last glaciation, and presents a typical cirque (Kar) with a maximum depth of 40 m. When it was researched for the first time in 1871, it had a rich zooplankton community, high biomass level, moderate transparency (2–4 m), and a pH of about 6. About twenty years later, the brook trout (*Salvelinus fontinalis*) was introduced to the lake and may have contributed to the disappearance or large zooplankton species, as observed in the early 1890s. However, a further drastic reduction of species was observed about 40 years later, when fish in the lake finally became extinct. Cerné Jezero presently has a pH of 4.5 and a transparency of 10–15 m. The only remaining zooplankton species is the rotifer, *Microcodon clavus*, known to occur in peat bogs and obviously a recent immigrant. As usual, the acidification of this lake has resulted in high aluminium concentrations (0.185 mg l^{-1}), which may account for the disappearance of fish, and a relatively high copper concentration of 1.6 mg l^{-1} (Fott et al., 1994).

Lake acidification became dramatically apparent with large fish kills in Norway and Sweden in the early 1980s. In Sweden, about 17,000 lakes (from a total of 85,000 medium and large lakes) are presently acidified, 4000 of them seriously.

Apart from abiotic parameters of non-marine origins (e.g., SO_4 concentrations), paleolimnological analyses have become a major focus of relevant research. It is based on diatoms, chrysophytes (*Mallomonas*) and certain other groups of algae which clearly show changes in species composition caused by decreasing pH values over the last decades. In contrast to the above, zooplankton (almost exclusively Cladocera remains) and benthic animals such as mollusks and ostracods started to disappear in proportion to their tolerance to different levels of acidification. The same is true for fish, among which *Umbra pygmaea* and tench *Tinca tinca* have been identified as the most tolerant species thus far in regard to acidity ($pH < 4$). This acidity tolerance, however, depends on the aluminium concentrations (especially $Al(OH)_2^+$), and a decreased species richness and abundance possibly occurs between a pH value of 4–6. Reproductive failure at a sublethal pH appears to be the main cause for the decrease (Gahnström and Andersson, 1988a, 1988b). These and other results on the physiological, morphological and behavior features have been obtained from lab studies and field observations. Field observations also contributed to the knowledge of the effects of acidification on organisms unlikely to leave remains in the sediment, such as copepods or most of the rotifers. Apart from in-lake bag-enclosures, artificial acidification of a small lake in the Canadian Experimental Lakes Area provided the basis for a better understanding of community reactions to increased acidity. Thus far, however, only little attention has been given to the littoral fringe, which may act as a refuge for organisms otherwise missing in the rest of the lake. Terrestrial wash-in processes may provide for increased earth alkaline materials and, hence, provide a buffering capacity in this region.

Radioactive and thermal pollution

Radioactivity pollution associated with nuclear power plants has received attention in many countries, having now been monitored for thirty years (e.g., about 300 locations in France). The catastrophic Chernobyl event (ROSTE–UNESCO, 1994), which was analyzed specifically in regard to the impacts from the fallout of such radioactive elements as cesium (^{137}Cs), strontium (^{90}Sr), and phosphorus (^{239}P), has demonstrated that drinking water accounts for approximately 5% of the radioactive intake into the human body, whereas the main source of internal irradiation is food (including a not-defined quantity of fish). One of the important results arising from the Chernobyl catastrophe is that it clearly shows that the human response to radionuclide pollution is much more serious than suggested by the nuclear power industry, and that the consequences of exposure to ionizing radiation are of a long-term nature.

Thermal pollution (Langford, 1990), which was discussed recently in connection with the climatic change problem (e.g., since the 1970s Lake Victoria has been subjected to an increase of more than one degree) is otherwise restricted mainly to rivers and lakes, which provide cooling water for atomic and fossil fuel power plants. Although of local importance, and seen mainly in connection with production (e.g., sun energy deliberately used in oyster cultures), thermal pollution has been investigated more carefully than other lake pollutants. A well-studied case of a lake heated by a nuclear power plant is Stechlin Lake in Germany (Casper, 1985).

If global warming is to realistically considered, it is quite clear that one of the most serious impacts would be a switch from dimictic to warm monomictic circulation, which would provide for disastrous anoxia events. Much less harm, although often incorrectly stressed, will occur to shallow lakes, which are already subjected to large thermal changes from season to season and year to year as a result of stochastic meteorological events.

Thermal pollution also may be associated with major cooling events, if a lake is flushed artificially to some extent with cold water from a river outside its drainage basin. Such flushing actions may be desirable for improving lake water quality, but also may result in major recreational impacts. For the latter, Lago di Cavazzo in northern Italy presents a remarkable example of the misuse of an important resort. With summer temperatures well above 20°C, this lake was widely utilized for swimming and bathing, until it began to be utilized as a flushing site for an hydroelectric power plant. Since that time, its temperature has only reached 15°C during the tourist season. Improvement of its fishery (i.e., trout instead of carp) has so far not satisfied the local population, which not only has lost its recreation site, but also an economically important resource.

Ammonia and nitrate

Ammonia is produced by heterotrophic bacteria as a product of the decomposition of protein or other nitrogenous inorganic compounds. It is present in water mainly as ammonia ion (NH_4^+); under alkaline conditions, it is present as undissociated NH_4OH (NH_3). At a pH value of 9.5, the ratio of NH_4^+ to NH_4OH in a waterbody is about 1 : 1, compared to 300 : 1 at a pH value of 7. In contrast, at a pH value of 10.5, only NH_4OH is present. NH_4OH is highly toxic to many organisms, especially to fish. Many cases of sudden fish kills have been reported for eutrophic and poorly-buffered fish ponds which, due to algal assimilation, are likely to shift to high pH conditions. Cases of fish kills due to ammonia also may be observed in regard to sewage loadings or for certain alkaline lakes.

In most surface waters, nitrate is present in concentrations that do not pose human health risks, especially for small children who may suffer from lethal cyanohaemoglobinaemia if they ingest nitrate. The present upper tolerable drinking water nitrate concentration is considered by the European Union to be 25 mg l^{-1}, by the World Health Organization to be 50 mg l^{-1}, and recently by Austria to be 100 mg l^{-1}. The upper limit of 100 mg l^{-1} is only seldom reached in nature. The higher concentrations are most often found in groundwater, sometimes over extended areas, as a result of agricultural activities that facilitate nitrate (and pesticide) concentrations above those considered safe for human health. This may imply large scale drinking water problems of major economic concern.

It is noted that the construction of artificial waterbodies (e.g., fish ponds, ponds for recreation or water storage) often may dramatically influence the quality of groundwater resources. Similar to seepage lakes, artificial basins, especially in gravel areas, tend to have hydrological connections with groundwater aquifers and, therefore, may act as pollution sources. Monitoring of such loading processes often can be difficult. Thus, preventive laws concerning the establishment of artificial ponds in important groundwater areas seem to be essential.

Burt et al. (1993) provided an integrated review of the nitrate problem within a drainage basin context.

Salinization

Apart from industrial loadings (e.g., salt works) and the use of road salts for traffic security during winter snow and/or ice events, salinization is restricted mainly to semi-arid and arid zones with endorheic watersheds. In most cases, it is related to the diversion of water for irrigation, which can result in a catastrophic drop in lake levels and an intolerable salinity increase. The best known example of this phenomenon is the Aral Sea (Fig. 2.9) which, since the 1960s, has experienced a hitherto unknown degree of lake degradation. Other examples comprise medium-sized lakes (e.g., Hamun Lake (Iran and Afghanistan); possibly Niriz Lake (Iran); Ichkeul (Tunisia); see Section 9.4). Increased use of water from Lake Sevan for hydroelectric power generation and irrigation resulted in a water level drop of 18 meters, salinization and dramatic eutrophication between 1935 and 1976. Similarly, the exploitation of water from Mono Lake as a drinking water supply for the city of Los Angeles resulted in significantly increased salinity in the lake. The consequences of salinization most often involve a drastic decrease in biodiversity (e.g., almost all endemic species of the Aral Sea have disappeared), loss of natural resources for humans, which eventually forces the local people to emigrate. Most often, political decisions and a desire for profits have been the driving force for such lake-degrading actions.

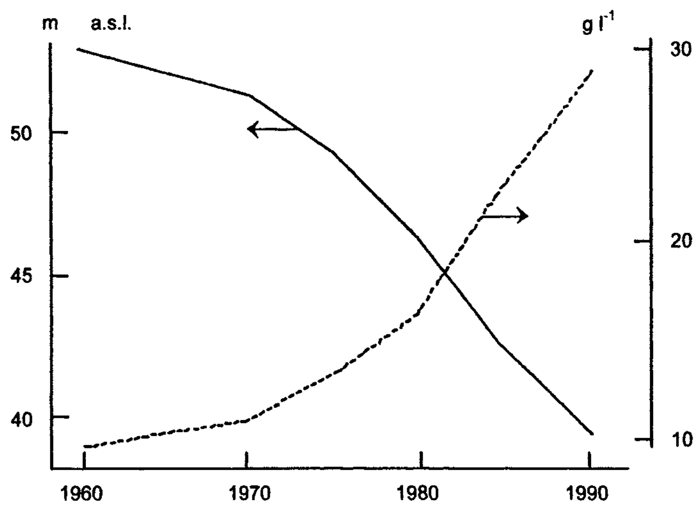

Fig. 2.9. Increases of salinity in the drying Aral Sea: Decreasing water level and increasing chloride contents (from Golubev, 1997).

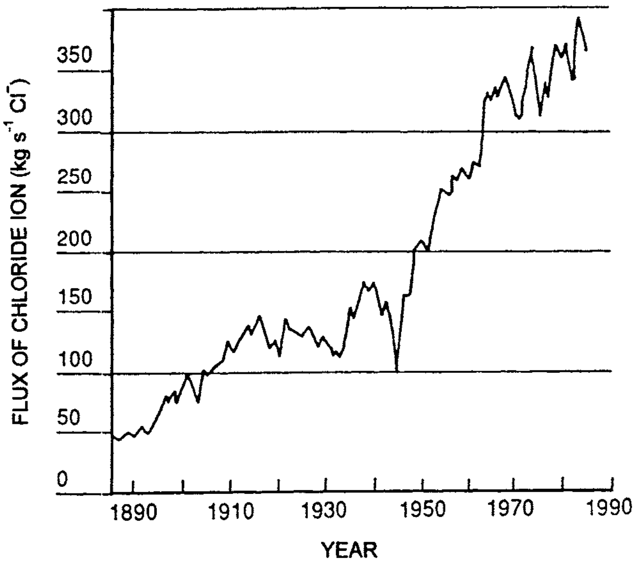

Fig. 2.10. Increase of salinity (expressed as flux of chloride ion) in the River Rhine at the border of Germany and The Netherlands (from Naiman et al., 1995).

Salt concentrations also have recently increased in industrialized areas of the temperate region (Fig. 2.10). In addition to road salting, this is due to the use of mineral fertilizers which, in addition to the nutritive salts, also contain high chloride and sulphate concentrations, and to the use of high-chloride content detergents.

Metals

Two primary groups are conveniently distinguished among the heavy metals. These include (1) those essential for organisms (e.g., iron, chromium) but which, above certain concentrations become toxic, and (2) those not essential for organisms, but which are tolerated at low concentrations and which are toxic above certain concentrations (e.g., cadmium, mercury, lead). In regard to the loading events of lakes and reservoirs, two types again may be considered, including the intentional loading of copper sulphate to lakes to reduce blue–green algal blooms, or to reduce the phosphorus concentration by precipitation with iron or aluminum salts. Although copper treatment is currently outdated for natural lakes and reservoirs, it was a routine method about 40–80 years ago (also see Section 4.3.5—*Algaecide use*). Examples of lakes receiving this potentially degrading treatment include Lakes Mendota, Monoma, Waubesa and Kegonsa in the United States, all of which are linked by one river. As a consequence, these activities have resulted in copper-rich sediment layers, representing an internal loading source for the lakes.

The second type of loading comprises direct adverse additions to lakes and reservoirs by industries and sewage from industrialized cities on the lake shoreline, or loadings from the drainage basin which may release large quantities of heavy metals to rivers and lakes if influenced by acid precipitation. An example of a lake receiving industrial loads is Lago d'Orta in Italy. The lake became heavily polluted in 1926 by a factory producing artificial silk (rayon) via the cupro-ammoniacal method. Only since the early-1980s, when a treatment plant was set up and liming strategies were used to control the pollution, has the lake started to recover from copper pollution and acidification, as demonstrated by the reestablishment of a structurally more-complex biological community. An example of an artificial lake with sufficiently high total copper concentrations to be toxic to algae, is Lake Tjeukemeer in The Netherlands. In this lake, however, the bioavailability and, therefore, the toxicity, is reduced by organic copper complexes (Verweij, 1991).

Water pollution from mining activities has been reported from several sites (also see Section 2.1.5). By far, the largest open-cast mine in China, and one of the largest in the world with an recent annual production over 60,000 tons/day, is the Dexing copper mine in the Jiang Xi province. It has affected China's largest freshwater lake (Lake Poyang) since the early-1960s. Poyang Lake (3350 km^2) and its neighboring marshes are ideal sites for white cranes, swans, wild geese and a variety of other species (Hongxiao et al., 1996). Because international investigations have only been undertaken within the past few years, the extent of the mining impacts on the lake has not yet been properly evaluated. The major loading source from the mining area is the nearly Le An River. Primary heavy metals involved in this pollution scenario are copper, zinc and lead.

Man-made lakes constructed for metal strip mining most commonly exhibit a great variety of different chemical features. As such, they can serve as valuable sites for the study of the special impacts imposed by practically all the commercially-extracted metals. Other than for iron and some other commonly-used metals, very little information exists about lake water quality impacts arising from the mining of less-common ores (e.g., platinum, gold, silver). Strip mining of tin on the Peninsular Malaysia has resulted in the formation of about 4300 bodies of freshwater, ranging in area from between less than one hectare to about 1 km^2, and with a total area of approximately 164 km^2. These man-made lakes are used as water sources (potable, domestic, irrigation, etc.), for recreation and for conservation (wildlife, native aquatic plants, gene pool for aquatic resources, etc.), and also for waste disposal and dumping (Arumugam, 1994). Thus far, these lakes have been evaluated only on the basis of common physical and chemical features (e.g., transparency, conductivity, pH, phosphate concentrations). The pH values range between 2.7–9.2, with the low values caused mainly by pyritic material. No observations, however, have been made with respect to adverse aquatic impacts by tin. Fifty-five aquatic macrophytes and 42 fish taxons were reported for about 10% of all the strip ponds.

Among the metals present in sufficiently high concentrations in lakes and reservoirs to affect human health, mercury and lead play a more prominent role than others, such as cadmium, chromium, zinc, etc. Organic compounds of mercury and lead enriched in sediment, plankton and macrophytes may contribute to high concentrations in fish and, in this way, also can affect individuals who regularly consume fish. During the 1960s, a number of Swedish lakes were identified as hazardous with regard to mercury, with their use for commercial fishing being prohibited. Few cases of associated diseases were reported. Other than for local gold mining (Brazil, Canada) and industrial activities, the main mercury loading sources are fossil fuels (coal, with about 1 ppm mercury) and fungicides from agricultural activities. The latter was the reason that sea coatings and the use of methymercury as a pesticide were banned in Sweden during the mid-1960s (Hammond, 1971). Since then, many other countries have initiated this action. This general increased awareness of the mercury catastrophes during the 1950s has resulted in a general improvement (i.e., a drastic decrease) in the mercury contents of river and lake sediments. Figure 2.11 illustrates a dramatic decrease in cadmium, consistent with a decline in sludge of a smaller Swedish town. Addressing the long-range transport of metals associated with acid rain requires continental-scale measures. A clear sign is the decline of atmospheric mercury deposition in Sweden after the large chloralkali plants in former East Germany were closed in 1990 (OECD, 1994).

Mineral oil pollution

Only a few lakes are presently affected by oil exploitation from sediments. A major example of this phenomenon is Lake Maracaibo in Venezuela, with more than 5000 oil wells. The lake presents a large (about 14,000 km^2), shallow (maximum depth of 34 m) and oligohaline (salinity less than 2‰) bay connected to the Gulf of Venezuela (Gessner, 1953, 1955a, 1955b). Lake Maracaibo has been described as heavily eutrophied, with blooms of *Microcystis* (Gessner, 1953). However, information on practically-unavoidable mineral oil pollution is lacking. A similar situation may occur in Lakes Rukwa, Malawi and especially Tanganyika if mineral oil is exploited in these lakes in the near future (Baker, 1989). According to recent reports, Lake Tanganyika sediment (which attains a thickness of 6000 m) may contain more mineral oil resources than the presently-known reserves in the United

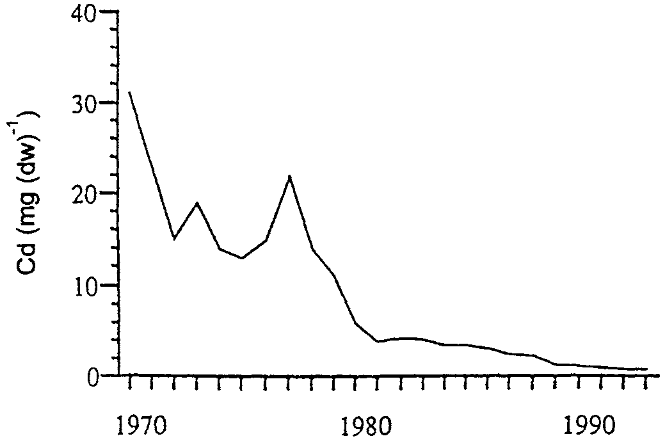

Fig. 2.11. Example of the decreasing heavy metal concentrations in the environment in Europe. Cadmium concentrations in sludge from the purification plant of a small town in Sweden (from Wilson and Jones, 1995).

States. Other problems connected with the risks of oil spills include oil storage tanks on the lake shorelines, pipelines along lakes, mineral oil transfer on lakes, and fuel barges and ships which run on fuel oil (Green and Trett, 1989). During the 1960s, and in spite of protests by prominent organizations such as the German Research Society, a pipeline was established along Lake Constance. Since that time, oil spills related to accidents of fuel barges have become frequent events. Routine boat discharges and pollution from motorboat sporting have resulted in new laws in many countries to help reduce, and even prohibit, motor boat traffic. Nevertheless, there are still many regions where such regulations do not exist. An example of ongoing excessive motorboat sporting is Lake Toba, the largest lake of Indonesia, where fishermen claim that the quality and taste of fish have decreased considerably in parts of this unique caldera lake.

Oil pollution of lakes and reservoirs can result in immediate severe impacts on water quality, since one liter of oil can contaminate one million liters of water. Loss of drinking water resources and fishery are the consequences of oil pollution, and may be irreversible for centuries in large lakes.

Persistent organic pollutants

A great variety of organic pollutants (see also mineral oil pollution) exist. Examples include PCBs (Giger, 1992) and 3,4-benzpyrene (a typical compound of tar and tar derivatives, demonstrated as a high risk chemical for Lake Constance by Borneff (1962); also see Section 2.1.9). However, there is no doubt that the most important group of pollutants in the upper layers of sediment in many lakes is pesticides. The first alarm about the serious impacts of pesticides began to surface when DDT was recognized as being harmful to humans and animals. For example, pesticides locally comprise more than 20 ppb. Further, an import of 100 tons DDT was reported for Nepal for 1994 (Shrestha, 1996).

Polychlorinated biphenyls (PCBs) also are recognized as persistent environmental pollutants of high potential danger (Waid, 1986). The most dramatic accidents concerning humans were related to rice oil in Japan ("Yusho" accident) and Taiwan ("Yu-Cheng" accident). PCBs also have frequently been detected in fish (Giger, 1992).

Pesticides affecting lakes and reservoirs arise mainly from:

- Agriculture and forestry,
- Campaigns against aquatic weeds (such as the water fern *Salvinia molesta*, *Eichhornia crassipes*, etc.),
- Campaigns against parasites and waterborne diseases, such as malaria, and schistosomiasis,
- Control of fish populations with rotenone (an active ingredient of derris, known as a fish poison for centuries).

Among the great variety of pesticides used in agriculture, atrazine (used to protect corn from weeds) has been recognized as harmful to humans and, therefore, has recently been banned in several European countries and in Austria since 1995. However, it is still applied in other countries of the European Union. It mainly affects groundwater, but may also be expected to be present in harmful concentrations in lakes and reservoirs within highly-productive agricultural areas. Similarly, bentazone has been identified as a problem, mainly in groundwater. Lindane, an organochlorine insecticide, is poisonous to fish in concentrations as low as one part per million. Moreover, it is a long-lived pesticide.

A rather large variety of pesticides also is applied in forestry activities. In addition to those used in agriculture, they include rodenticides such as zinc phosphide. Only local adverse effects on lakes and reservoirs have been reported for these pesticides.

The application of pesticides to control unwanted (and often introduced) weeds, such as the water fern *Salvinia* spp., water hyacinth *Eichhornia crassipes*, water fern *Azolla* sp. and water lettuce *Pistia stratiotes*, should only be considered if mechanical or biological strategies fail. This is most likely to happen only in very large lakes, or in cases of immediate emergency connected with the blocking of essential harbors or other important sites by weeds. The use of such pesticides should always be considered problematic. Even if their adverse biological consequences are regarded as minor (which generally is unrealistic), the decay of the dead plant material also can influence the water quality.

Since the invasion of Lake Victoria by water hyacinth *Eichhornia crassipes* in 1989, the plant has not only rapidly increased, but also (based on wind-induced currents) choked and blocked areas of important water intakes, as well as becoming a major problem to fisheries. At present, mechanical methods (which imply labor for the poor), biological treatment with South American curculionid beetles (weevils), and chemical strategies are being considered to address this serious problem. The infested area currently (1996) comprises about 4000–6000 ha. Based on first evaluations, it appears that mechanical removal of the weed should be given priority, under the assumption that only the most efficient equipment (e.g., harvesting boats and harvesting from certain shoreline sites) will be made available (also see Section 4.3.4).

Very often, if not always, the use of harvested weeds becomes a problem in countries without relevant tradition. The lack of information on their alternative uses (e.g., as fodder, fuel, biogas, mulch) does not contribute to the ongoing harvesting activities, and education and training in this field should, therefore, be immediately initiated.

In Lake Kariba (see Section 9.7), the weed problem has a quite different aspect (Ramberg et al., 1987). When finally filled in 1963, the reservoir became affected by a large bloom of the water fern *Salvinia molesta,* which finally covered 22% of the reservoir's surface. Instead of considering this unexpected outburst as the consequence of nutrients from the decaying processes of the flooded terrestrial vegetation and organic matter in general, its management involved control strategies that were both costly and useless. In this case, an assessment of available nutrients within the flooded valley, in relation to the lake's water retention time, would have resulted in much more economic planning. In fact, only two years after the *Salvinia* water fern bloom had its climax, it disappeared because of exhausted nutrient supplies.

Biological pollution

Lakes and reservoirs are becoming increasingly affected by biological pollution, comprising four major items:

- Excess growths and spreading of local species,
- Excess growths of exotic species,
- Parasites,
- Waterborne diseases (also see Section 2.2.3—*Health Risks*).

The excessive growth of local species comprises a wide range of Cyanobacteria and algae as well as submerged, floating and emergent macrophytes. Among the latter, only a few species have gained the character of a "weed". An example is the water fern, *Salvinia molesta,* which is the only nuisance species of the genus *Salvinia.* The water hyacinth, *Eichhornia crassipes,* has spread throughout the tropics. Since 1989, it has been a serious problem in Lake Victoria. Both species are of South American origin and belong to item two above (i.e., exotic species). Likewise, the common water lettuce, *Pistia stratiotes,* is most likely a neotropical native. During the late-19th Century, the genus *Elodea* invaded Europe, probably in connection with the introduction of several North American fish species.

Local animal species that have become a nuisance include the European coot, *Fulica atra,* and the mallard, *Anas platyrhynchos,* both of which can affect local water quality. Among exotic birds and mammals, the mute swan in Europe, the Canadian geese in Norway and the musk rat *Ondatra zibethicus* introduced from North America into Europe in 1905 (Czech Republic) can be mentioned. The latter spread throughout Central Europe within decades of their introduction, being introduced deliberately much later in Finland.

Bioinvasions can often result in the extinction of one or more species. Along with eutrophication, new invertebrates may immigrate into a lake and compete with, or even eliminate, other invertebrate species. A large number of intentionally-introduced exotic species in Europe (e.g., the crayfish genera *Pacifastacus, Orconectes, Cambarus,* the amphipod *Gammarus tigrinus*) have not been reported to have caused the extinction of local species, although they may have influenced the biological community structure. The crayfish (*Pacifastacus leniusculus*) was thought to have replaced the indigenous species, which almost became extinct due to the introduction of the fungi *Aphanomyces astaci* (introduced first to northern Italy in 1869 from North America and, within three decades, spread throughout Europe). The freshwater crab, *Eriocheir sinensis*, introduced unintentionally from East Asia to Europe, does considerable damage to dams. Most recently, the zebra mussel (*Dreissena polymorpha*), a mussel from the Caspian, Black Sea and Baltic watersheds rapidly expanded throughout Europe during the 1960s, reaching North America during the 1980s. The zebra mussel attaches to all types of solid substrates, becoming widely dispersed by boating and yachting sports. Whenever this species has been detected in a new lake, its population has increased dramatically over several years before it starts to decrease to a level characteristic of its original habitat.

Most recently (Dumont, private communicate), the Caspian Sea was invaded by the comb jelly, a voracious plankton feeder, known already from the Black Sea since the late 1980s. Its presence caused a catastrophic decrease of the mainly endemic zooplankton (*Cladocera*). Fortunately, a melon jelly (*Beroe* sp.) immigrated shortly afterwards which preys mainly on the dangerous comb jelly. Hopefully this event will work to the benefit of the Caspian endemic zooplankton.

With respect to stocking with exotic fish, the two classical examples of catastrophic failures are Lake Victoria and Lake Titicaca. Apart from cichlids introduced to Lake Victoria, which are known to compete with endemic species, the Nile perch (*Lates niloticus*) is a prominent example. During the 1950s, Nile perch "got into the lake". However, from 1987 on, they increased to such an extent that it caused major changes to the biological communities in this largest African lake. One of its major impacts concerns the still unknown degree of extinction of the haplochromine cichlid species. There is no doubt, however, that the Nile perch has since become the most important food and economic resource of the lake. Its present annual harvest amounts to about 500,000 tons. Introduced fish invasions are now dominating in many places of the world, including Europe, with the largest European lake, Lake Balaton in Hungary, being a prominent example (Fig. 2.12). In conclusion, it should be stressed that intended use of exotic species requires not only economic consideration, but also ecological precaution.

Most often, such an evaluation can only be achieved by careful preliminary examination, which should be ordered by law. Such a need is clearly demonstrated by high-alpine lakes where, due to hydrographic features of the watershed, fish are absent. Introduction of char conceded by local authorities (as still going on in the Tyrolian high mountain lakes) can result in the immediate extinction of fairy shrimps or (and) rare daphnids (e.g., *Daphnia middendorffiana*). Therefore, the minimum requirement before any stocking with exotic species is the compilation of an inventory (species diversity at least throughout a period of years) of the relevant lake or reservoir.

2.2.3 Risks from Lakes and Reservoirs

Health risks

Between 1870–1900, 450 epidemic events of typhoid fever occurred in Central Europe. Between 1920–1960, the United States and Canada experienced 540 epidemics. In addition to

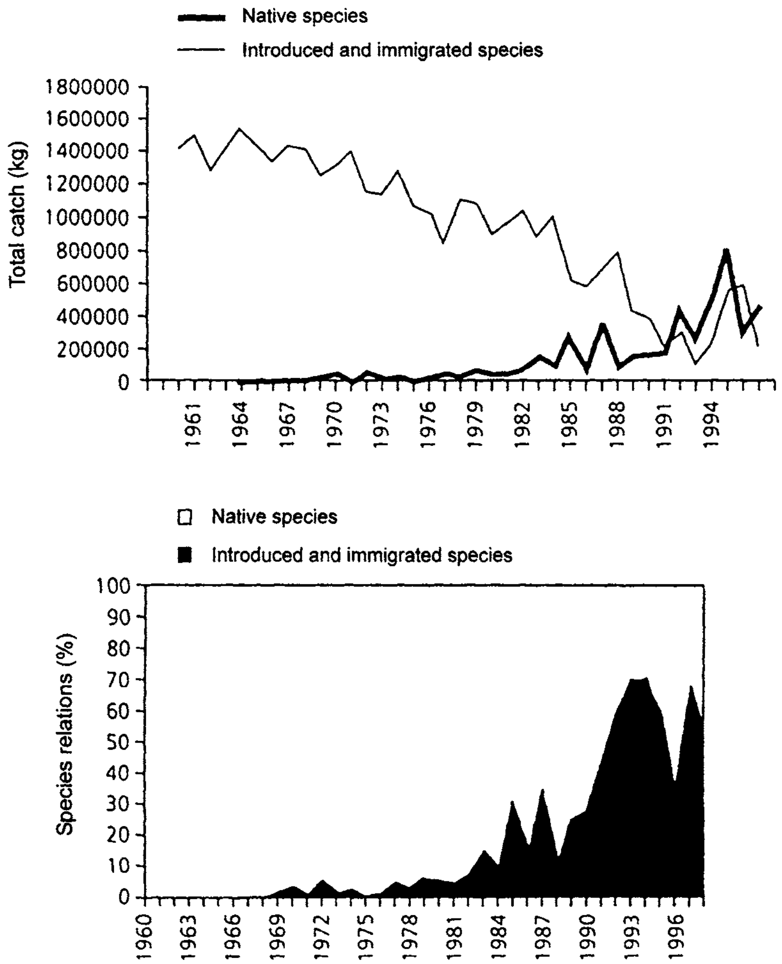

Fig. 2.12. Occurrence of native and introduced species in commercial capture in Lake Balaton, Hungary (from Biró, 1993).

typhoid, paratyphoid fever, dysentery and cholera remained a major catastrophic event during the late-19th Century (e.g., 17,000 causalities in Hamburg in 1892). These epidemics have been greatly reduced in number and extent in industrial countries. In contrast, however, large parts of the developing world and the former Soviet Union are still experiencing not only these waterborne diseases, but also diseases resulting from poor sanitation. Within the topical and subtropical zones, water-based and aquatic insect-related diseases also are major problems (GEMS, 1987).

More than 80% of all the disease in the world is attributed to inadequate water treatment or sanitation facilities. This includes the effects of contaminated drinking water, water acting as a breeding ground for disease carriers, and diseases caused by the lack of washing water. There are 9.1 million lethal causalities annually caused by waterborne diseases. The 6 million children less than five years old that die each year because of diarrhea (about 100 million people are infected by diarrhea at any given time) demonstrates the serious nature of this continuing situation (UNESCO and UNEP, 1992). Hygienic diseases also are a major problem (e.g., 500 million people suffer from trachoma). This includes diseases resulting from poor sanitation, such as hookworm infections (ancylostomiasis, affecting 800 million people), other parasitic nematodes (1000 million people) and whipworm (trichuriasis, affecting 500 million people), water-based diseases such as schistosomiasis (affecting 60–200 million people), dracunculiasis (affecting about 80 million people), and water insect-related diseases such as malaria (affecting about 160 million people) and yellow fever (onchocerciasis). Unfortunately, there is little hope that the number of infected people from water-related diseases will decrease in the near future, although new research in developed countries is providing guidance for managing these diseases (e.g., Smith and Loyd, 1997, for protozoan parasites).

With respect to lakes, reservoirs and ponds, it should be mentioned that, except for onchocerciasis and hygienic diseases such as trachoma, most water-related infections can be serious problems. This is especially so with dracunculiasis (the small crustacean *Cyclops* is a vector) and schistosomiasis. The crustacean may by swallowed with drinking water from ponds or the littoral zone of lakes (Steib, 1985). Schistomiasis has especially become a problem related to large dams (e.g., Aswan, Kariba, Volta) and is a continuing human risk in large and small tropical lakes and rivers, mainly in Africa.

Waterborne diseases spread by aquatic invertebrates and vertebrate organisms acting as carriers are produced mainly by platyhelminth and nematode worms (Löffler and Malkhazowa, 1990). Estimates of schistosomiasis infections total up to 200 million, a figure reported more than two decades ago and, therefore, not realistic at the present time. This figure implies 200,000 casualties annually. Diseases such as different types of filariasis and dracunculiasis and cestode infections also can be mentioned. In conclusion, it is stressed that, among these listed diseases, aquatic insect related and water-based infections (primarily schistosomiasis) are related to the use of pesticides.

Pollution of medical concern represents a global problem. According to the World Health Organization, about 80% of all diseases are related to inadequate water quality or sanitation, comprising waterborne diseases such as typhoid fever, cholera, dysentery, diarrhoea (gastroenteritis), infectious hepatitis, amoebic meningo-encephalitis, allergic reactions caused by viruses, bacteria, Cyanobacteria, protozoa (*Entamoeba histolytica*, *Naegleria* spp., *Trichomonas* spp., *Giardia* sp., *Cryptosporidium* sp., etc.). About 1.8 billion infected people, and about 3 million casualties (mainly children of less than 5 years age) were reported in 1993 (Brown, 1997). In the coastal waters off the coast of Lima, Peru, a viable form of *Vibrio cholerae* causing "Asiatic cholera" was found associated with several phytoplankton, zooplankton and freshwater macrophyte species (water hyacinths, duckweed) (Epstein, 1993). Similar presence of a viable form of *Vibrio* has not yet been reported from freshwater. However, it is probably possible under favorable conditions, as evidenced by its presence in freshwater macrophytes off the coast of Lima.

Among the aquatic insect-related diseases, malaria has recently increased, restricted mainly to developing nations. Annual estimates for 1993 and 1994 are between 300–500 million, which resulted in an estimated 2 million casualties. In addition, yellow fever and dengue fever, carried primarily by the mosquito *Aedes aegypti*, presently infects about 700,000 people annually. During the mid-1980s, the tiger mosquito (*Aedes albopictus*) from East Asia immigrated into the United States. In addition to being a carrier of encephalitis, it may contribute to the spreading of dengue fever. Onchocerciasis, carried by blackflies, affects an estimated 20 million people in tropical Africa and Latin America. Blackflies also exert heavy impacts on livestock.

Drinking water supplies also are subjected to further risks from pollution by pesticides, mineral oil, allochthonous organic loading, heavy metals, etc. These risks also may be related to lake eutrophication and acidification. Moreover, eutrophication can result in blooms of Cyanobacteria (e.g., *Microcystis*, *Anabaena*, *Aphanizomenon*, *Oscillatoria*, *Nodularia*, *Nostoc*) that are likely to produce neurotoxins and hepatotoxins. Human ingestion can result in illness or even death (see Section 2.2.2—*Eutrophication*). The effects of human ingestion can be gastrointestinal, respiratory and dermatological in nature. The latter are recognizable by initial symptoms which appear after a few hours, comprising erythema and burning pain, followed by the formation of blisters and desquamation which can last for days. Critical toxicity may be caused by hepatotoxins in drinking water, which can affect the liver and even produce liver tumors. It is also stressed that the toxins produced by certain Cyanobacteria may also penetrate into groundwater.

The most common waterborne bacterial pathogens detected in contaminated drinking water supplies in the United States during 1961–1983 were *Shigella*, *Salmonella*, *Campylobacter*, toxigenic *Escherichia coli*, *Vibrio* and *Yersinia* (Craun, 1985). Other waterborne bacterial pathogens were *Mycobacterium*, *Pasteurella*, *Leptospira* and *Legionella*, which also were often detected in swimming waters (Meybeck et al., 1989). The sources of bacterial pathogens for reservoirs are not fully eradicated when human-caused pollution is stopped. Many outbreaks appear to be caused by wildlife living in the drainage basin. Birds and waterfowl can contribute *Salmonella* in their fecal droppings (Anonymous, 1954). Several outbreaks of *Campylobacter* enteritis from drinking water reservoirs had their origin in wildlife, farm animals and animal pets living in the drainage basin. Swimmer illnesses associated with gastrointestinal infections are caused through dispersion of pathogenic agents by fecal wastes discharged in domestic sewage. These pathogenic agents appear to have a better correlation with *Staphylococcus* occurrences in water than with fecal indicators (Seyfried et al., 1985a, 1985b).

Among human viral agents, hepatitis A, Norwalk and *Rotavirus* are reported to have been responsible for 68 outbreaks over 22 years in the United States alone (Lippy and Waltrip, 1984). Other viral agents capable of waterborne transmission include enteroviruses (*Coxsackievirus*, *Echovirus*, *Adenovirus*), *Parovirus* and "gastroenteritis type A". New viral agents capable of waterborne transmission are continuously being found as better methods of detection are developed.

The most significant pathogens debilitating or dangerous to human health from protozoa belong to *Giardia*, *Entamoeba*, *Cryptosporidium* and *Naegleria*. They can produce dysentery in the human intestinal tracts, dehydration and weight loss. Infection by *Naegleria gruberi* invading the brain and causing meningoencephalitis is almost always fatal. A total of 84 outbreaks of *Giardia* was noted in the United States during 1961–1983, with almost 23,000 people infected. The source of the pathogen was generally found to be the wildlife population, particularly beavers, but also coyotes, muskrats, voles, cattle and animal pests (Meybeck et al., 1989). The density of *Giardia* cysts in reservoirs is often found to be present in the order of magnitude of 1–10 cysts/100 liters of water, thereby being undetectable with common detection methods.

Of the parasitic worms found in heavily-polluted reservoir inflows, *Taenia saginata* (beef tapeworm), *Ascaris lumbricoides* (large intestinal round worm), various species of *Schistosoma* (blood flukes) and *Ancylostoma duodenale* (hookworm) are common.

A recently-detected human health problem is endocrine disruptors, which can cause sexual malfunctions of vertebrate (including human) males. An investigation in the United Kingdom detected estrogenic activity in five rivers by measurement of vitelogenesis in male trout (Harries et al., 1997). Matsui et al. used different chemical methods to detect estrogenic activity in treated sewage effluents in Japan, observing that human estrogens from urine are the major causative substances for their appearance in sewage.

As previously noted by the World Health Organization, about 80% of the diseases in the world are attributable to inadequate water quantity and quality as well as sanitation, including the effects of polluted or contaminated drinking water, water acting as a breeding ground for disease carriers, and diseases caused by inadeguate or no washing.

Apart from lack of water even for drinking, and even less for hygienic activities (see Chapter 1 and this chapter), pollution, such as allochthonous organic loading, mineral oil, heavy metals, and also the effects of eutrophication mainly from Cyanobacteria (producing neuro- and hepatotoxins by certain strains), as described in this chapter is a great risk to stored water.

Waterborne diseases, such as infectious hepatitis, typhoid fever, cholera, dysentery, diarrhoea caused by viruses, bacteria and protozoa (genera *Cryptosporidium, Entamoeba, Giardia, Naegleria, Trichomonas*, etc.) contribute greatly (almost two billion infected and annually 3 million casualties have been reported by Brown) to the present worldwide poor health conditions. About 400–500 million people suffer from trachoma (*Chlamydia trachomatis*), about 2 billion are infected by different nematodes (*Ascaris, Ancylostoma, Trichuris*, etc.) not necessarily related to water themselves. Many other examples of parasites related to poor hygienic could be mentioned.

In addition water-based diseases are a permanent threat to the health of more than 250 to 300 million people in mainly tropical and subtropical regions. These are caused mainly by trematode (schistosomiasis and other diseases such as fasciolasis) and nematode worms (dracunculiasis) and other infections such as angiostrongylosis). The most widespread among these diseases is presented by schistosomiasis or bilharzia (intestinal and urinary). The first larval stage is highly specialized on certain snails, which also are carriers of schistosomiasis of domestic stock, wild mammals and birds. Seventy–Eighty percent of the afflicted persons are African residents. In contrast to *Schistosomiasis, Dracunculiasis*

(*Dracunculus medinensis*) is confined to Africa, India and Southwest Asia. The larvae of this nematode are carried by cyclopoid copepodes and swallowed with infected water.

As previously noted, among the aquatic insect related diseases, malaria (spread by the *Anopheles* mosquito) is the most important one, annually affecting 150–200 million people and resulting in more than a million casualties. Yellow and dengue fever carried by the mosquito *Aedes aegypti* also infect approximately 700,000 people each year. Many mosquitos are also vectors of arboviruses (species of *Aedes, Anopheles, Culex, Mansonia*), causing different kinds of diseases, several of which are locally restricted, such as different types of encephalitis, epidemic polyarthritis, etc. In additional to malaria, *Anopheles* species also can carry larval stages of the nematode *Brugia* (*Wocheria*), which may be disseminated by the mosquitoes of the genera *Aedes* and *Mansonia* too.

Another important midge family with respect to diseases is the blackflies (*Simuliidae*), which transmit Onchocerciasis ("Driver blindness") in Africa and Central America, being caused by the nematode *Onchocerca volvulus* (Africa) and *O. caecutiens* (Central America). *Onchocerciasis* affects human skin, eyes and the lymphatic system. The disease is particularly widespread in western and central Africa, where 80–100% of the adult population is infected. Two other Simulium species that are pests to man and livestock are *S. chufferi* and *S. bovis* in central and southern Africa. In the Senar and Roseires Reservoirs in Sudan, *S. damnusum* has spread. Blackflies viciously attack humans and livestock, with severe loss of the latter being reported in various parts of the world. In Rumania, for example, more than 17,000 animals were killed during one season (Rietschel, 1975).

Catastrophic events from reservoirs and lakes

Catastrophic degassing. Meromictic lakes (recognized by a persistent vertical gradient; see Chapter 1) and volcanic lakes may accumulate considerable amounts of gases (CO_2, CH_4, H_2S) in their monimolimnium or hypolimnium. Among the meromictic lakes, Lake Kivu in East Africa (2370 km^2, $z_{\max} = 480$ m) is well known for its high methane content which is exploited commercially. The largest meromictic body of water with high, even critical, concentrations of gases, especially hydrogen sulfide (H_2S) is represented by the Black Sea, whereas the largest meromictic lake (Lake Tanganyika) is characterized by only a moderate CO_2 concentration. More recently, however, sudden degassing from two rather small volcanic lakes in Cameroon resulted in human casualties and loss of animal stock. Both lakes are rather deep (96–208 m) and occupy small explosion craters located within a volcano-tectonic feature that extends about 1400 km from central Africa into the South Atlantic basin.

The first CO_2 burst from Lake Monoun in August 1984, although causing 37 human casualties, received only little attention (Sigurdsson, 1987) and was thought to have been released by a landslide. In contrast, a much more catastrophic event occurred in Lake Nyos in August 1986, resulting in 1746 casualties and a loss of more than 8000 livestock, and receiving immediate worldwide attention, was the impetus of an international conference organized by UNESCO in early 1987. The very speculative explanations given (volcanic explosion, etc.) were finally replaced by realistic interpretations of both cases, recognized for the first time by scientists (Sigurdsson, 1987). The gradual influx of volcanic CO_2

in the bottom region of the relevant lakes obviously increases the gas concentration in the hypolimnic water continuously to an extent controlled by the pressure of the upper stratified epilimnetic water-mass. Cooling or (and) cold precipitation, which happen during August and September in this part of Cameroon, most likely resulted in a collapse of the high density stratification, allowing a sudden degassing of the lake. As recognized by eroded areas of elevated shore sections, the burst of Lake Nyos caused a giant water fountain more than 80 m in height. The gas cloud then flowed down the Nyos Valley, about 190 m lower than the lake, affecting more than 60 km^2. Among preventive measures discussed, the Olszewski syphon tube technique seems to be most appropriate, since it will provide for the continuous draining of bottom water subjected to continuous CO_2 influx (see Chapter 1).

Impacts by hydrologic alterations

In the valley of Bagnes (Valais, Switzerland), a lake (200 m long; 60 m deep) became dammed behind an avalanche in 1818. Efforts to drain the lake gradually failed, resulting in a disastrous flood (Hutchinson, 1957). In Tyrol, the headwaters of the Ötztal were often blocked by ice barriers during periods of glacier advance (1599–1601, 1677–1682, 1770–1774 and 1845–1848). In association with a sudden increase in temperature and heavy rainfall, a dam formed by the Vernagt Glacier in 1678 and 1680 burst, resulting in the worst disaster observed in the area. Whole villages were destroyed to such an extent they could not be rebuilt (Patzelt, 1994).

The eruption of lakes held behind the terminal moraine of a glacier has been reported for several areas in the Alps, and more especially in the Andes (Löffler, 1988). The most disastrous event happened in 1970 in Peru, when the city of Yungay was completely destroyed, with 18,000 people losing their lives. In this case, however a rock- and glacier-fall from Mt. Huascarán, released by an earthquake, was involved. Part of it fell between two morainic mountain lakes, which contributed to the final dimension of the catastrophe. More recently, Watanabe et al. (1994) reported the prospect for a catastrophic flood in Khumbu Himal, Himalayas.

Catastrophic floods in the Mississippi Basin in 1993, along the Rhine in 1995 and most recently (August 2002) in northern Austria, Bohemia and eastern Germany (along the Elbe River) associated with casualties and tremendous economic losses, have clearly demonstrated that even rich industrial countries, in spite of their relevant knowledge, are not willing to invest in the provision (most often for the return) of adequate retention areas, and for dams and dykes capable of resisting unusual by large floods. Moreover, dam systems along rivers were not prepared (regular removal of sediment mud) for floods of this magnitude, therefore contributing greatly to mud problems during the inundation (see also Section 2.3).

2.3 BAD MANAGEMENT

Lack of ecological understanding and inadequate knowledge has contributed greatly to the mismanagement of lakes and reservoirs and their drainage basins around the world. A list of selected cases of lake mismanagement is given in Table 2.5.

Table 2.5. Selected cases of lake mismanagement

Drainage basin:
- Regulation of rivers
- Destruction of wetlands
- Uncontrolled deforestation or adverse afforestation
- Adverse agricultural activities resulting in erosion and pollution with nutrients and pesticides
- Excessive livestock
- The use of inadequate sewage plants for polluting settlements and industries
- Polluting mining activities
- Traffic in sensitive parts of the drainage basin

Lake/reservoir shores:
- Destruction and reclamation for industry, traffic, agriculture and recreation (tourist centers, sport boating, yachting harbors, etc.)
- Destruction (including drainage) of littoral wetlands
- Improper introduction of macrophyte-feeding fish (e.g., grass carp) to lakes
- Chemical treatment of macrophytes
- Rooting of submerged vegetation
- Heavy eutrophication as an impact on macrophytes

Lake/reservoir:
- Point sources of pollution without adequate treatment
- Neglect of nonpoint pollutant sources
- Erradication of algal blooms by pesticides
- Flushing of meromictic lakes, which may result in a massive release of nutrients from the monimolimnion
- Aeration at the wrong time and/or wrong depth
- Stocking with fish species with adverse influences, including increased internal loading, removal of large zooplankton, and general decrease of biodiversity
- Excess use of sport boating, yachting, etc.

Reservoir:
- Point sources of pollution
- Stocking with exotic species, unless careful investigations on possible harm are made prior to introduction

Since the 1950s and 1960s, rapidly-increasing limnological knowledge has significantly aided our ability to provide solutions for sustainable management of lakes and reservoirs, and to address most of the major problems regarding inland waters, provided that public awareness exists, that decision makers are willing to act, and that the economic requirements are not prohibitive. That the mismanagement of lakes and reservoirs still occurs in many regions of the world is due mainly to such factors as:

- Rapidly growing population in the drainage basin,
- Rapidly growing tourism and recreational activities along the shorelines,
- Political pressures and quests for profits (which are often related),
- Poor financial capacity,

- Lack of education and training, resulting in a lack of awareness of the consequences of serious problems, and
- Complex, multinational problems requiring regional cooperation (pollution in multinational drainage basins, acidification, climatic change, etc.).

The most obvious failures, which comprise all of the items mentioned above, are the lack of a holistic perspective of the problem and its solutions, and of long-term planning.

Lakes and reservoirs in developing countries are the most-cited examples of the lack of a holistic perspective. Lake Victoria serves as a prominent example. The rapidly growing population in its drainage basin is evidenced by the capital of Uganda. In the early-1960s, it had a population of only about 90,000 inhabitants, which increased to nearly one million people by 1996. The consequences of this magnitude of population increase (e.g., pollution, deforestation, reclamation of shoreline areas and wetlands within the drainage basin, traffic and rapidly growing agriculture) have resulted in significant eutrophication problems, particularly in the embayments of the lake. Moreover, the introduction of the Nile perch in the 1950s, and the immigration of the water hyacinth in 1989, have caused additional serious problems.

Lack of long-term planning, most prominent in industrial countries during the 1960s and 1970s, has recently received attention and, therefore, this problem seems to have be mitigated to some degree. However, tourist pressure is still increasing in the Lake Tahoe drainage basin in the United States. It also is a major problem in the developing world, with Lake Atitlan in Guatemala, and Dal Lake in India being good examples (Gopal, 1996). In addition to the increasing population (lacking sewerage), industrialization and overgrazing, tourism development also is a significant causative factor in this problem.

Political pressure is clearly recognized as a significant causative factor in the case of the Aral Sea. An international meeting in 1980 included an address by a limnologist of the former Soviet Union, praising the irrigation activities in the Aral Sea drainage basin. However, other participants raised their voices in earnest warnings. Their warnings were, at that time, met with rather harsh criticism from some Soviet participants. Within a relatively few years, however, the magnitude of the Aral Sea catastrophe became obvious to everyone (Glantz, 1998).

Inadequate financial capacity is probably the most important hindrance to sound management of lakes and reservoirs in many countries today, with developing countries forced to give priority to the survival and well-being of its inhabitants. Donor organizations and other agencies, such as the World Bank, United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP) continue to try to improve or mitigate ecological conditions, even after they have become catastrophic in nature. An example of this "fire brigade" type of activity is the recent Lake Victoria Environment Management Project. The project is estimated to be able to stabilize, or slightly improve, the present serious problems of this multinational lake involving the five countries of its drainage basin. A total of US $300–600 million is proposed to address the deteriorated fishery, whereas a sum of only US $3.5 million has been provided for the stabilization of its present water quality. The latter sum is less than the amount deemed necessary to attempt to address the water hyacinth problem (US $6–10 million).

Lack of public (and decision maker) awareness of serious problems is a consequence of inadequate or nonexistent education and training. Until the 1960s, limnological knowledge on the part of the public and decision makers was generally poor. As a result, early warnings from limnologists regarding pollution, and the consequences of inadequate lake management, did not find any response. Even less concern was given to those aspects of drainage basin management related to lake and reservoir water quantity and quality. In fact, increasing the awareness of the importance of considering the entire drainage basin of a lake or reservoir remains an ongoing process around the world even today, in both developed and developing countries. In many mountainous areas, for example, a clear-cutting forest strategy is still followed, sometimes contributing to a large nutrient load to waterbodies. Other adverse ongoing activities, such as tourism and holiday village construction on lake shorelines, an example being Lake Tahoe (Goldman et al., 1970; Goldman, 1990, 1993), also must be considered in regard to economic pressures.

The most sensitive, and most frequently affected, habitat of lakes and reservoirs is their littoral zone, which is most often subjected to damage and degradation. At the same time, the littoral zone (with its micro- and macrozonation) represents the most sensitive zone in a lake or reservoir and can react to even moderate eutrophication pressures and other changes within the drainage basin. Apart from tourism pressures, and less so for agriculture and hydrological changes, activities directed to increasing awareness on the part of the public of its importance for the entire ecosystem, with regard to water quality and biodiversity, has only begun in earnest during the last two decades, and still requires considerable additional effort.

Thousands of examples of the lack of awareness and/or inadequate management of the littoral zones of lakes around the world exist. Zürichsee (Switzerland; Thomas, 1972; Schanz, 1993) is a typical case among the pre-alpine lakes in Eastern Europe. Due mainly to land reclamation (e.g., for parking space), a major area of its Phragmites stands disappeared by 1931, when the first census by airplane was conducted. A further reduction of about 70% of the remaining stands took place during the 1950s and 1960s, when eutrophication of the lake contributed greatly to the vanishing of reed stands (Thomas, 1960). Only after 1970, when the nutrient loading of Zürichsee became successfully controlled, coupled with a rapidly growing awareness of the importance of the *Phragmites* remnants, did efforts to facilitate their preservation occur. The total reed area totals 5.14 ha at present, which is probably less than 10% of that existing prior to 1931.

The littoral zones of the artificial Nette lakes (peat mining and mill-ponds, established between the 16th and 19th Century) in northwest Germany were once important breeding sites for birds, such as the little bittern (*Ixobrychus minutus*), the marsh harrier (*Circus aeruginosus*), the bluethroat (*Cyanosilvia suecica*), etc. They subsequently were largely destroyed as a result of using reed stands as dumping sites, by road construction activities, and by other more complex impacts on the macrophytic vegetation (especially reeds), and by increasing eutrophication. Unfortunately, sanitation and restoration measures applied thus far to the lakes have met with little success.

The loss of littoral habitats, demonstrated by the above examples, belongs among worldwide lake impacts, which often do not contain any attempts at restoration, and which often results in a complex combination of lack of awareness, mismanagement, profit motivation at the expense of environmental protection and conservation, inadequate financial capacity, and rapidly growing populations, especially in cities. Chicago, Detroit, Buffalo, Toronto and other cities on the shores of the Great Lakes in North America, and near Kampala, Uganda near Lake Victoria, serve as examples for large lakes. Few attempts have been made so far to conserve or revitalize the still-existing littoral zones, similar to that mentioned for Lake Zürich.

Mismanagement is even more apparent in regard to the thousands of reservoirs, artificial ponds and lakes created mainly for recreational purposes. Recommendations and standards so far proposed (e.g., in Austria) to ensure desirable water quality and self purification have been largely ignored. These recommendations and standards comprise:

- Topographical requirements (e.g., construction only outside of risk zones),
- Protection of at least 30% of their area for self purification,
- A 50–100 m protected littoral zone,
- Avoidance of conflicting activities (e.g., fishing, which implies feeding of fish), and
- The proper management of submerged vegetation, and avoidance of adverse control methods (stocking with grass carp, etc.).

In Central Europe (and elsewhere), it is likely that less than 1% of recreation ponds currently meet these standards.

An even greater lack of limnological understanding can be observed in regard to ecosystem-drainage basin management (see Chapter 7). The ecosystem-drainage basin concept appears to have originated with the Hubbard Brook Watershed–Ecosystem, described in a series of publications by Bormann and Likens and others (Likens et al., 1977; Bormann and Likens, 1979), and even earlier by Mackereth (1966) as stressed by O'Sullivan (1979).

As an important outcome of this concept is the construction of models (see Chapter 5), in which the basic indivisibility of ecological and hydrological processes in any ecosystem-watershed, and the particular role of water in linking the various parts of the system, have been stressed (e.g., O'Sullivan, 1979).

REFERENCES

Agostinho, A.A.H.F. and Petrere, J.M., Jr., 1994. Itaipu reservoir (Brazil). In: I.G. Cowx (Ed.), Impacts of the Impoundment on the Fish Fauna and Fisheries. Fishing News Books, Oxford, pp. 171–184.

Anonymous, 1954. Ketchikan laboratory studies disclose gulls are implicated in disease spread. Alaska's Health, 11: 1–2.

Arumugan, P.T., 1994. Present utilization and recommendations for management of tin-mine lakes in Malaysia. Mitt. Int. Verein. Limnol., 24: 265–272.

Baker, J.M., 1989. Oil and African great lakes. In: R.M. Lowe-McConnell, R.O.M. Crul and F.C. Roest (Eds), Symposium on Resource Use and Conservation of the African Great Lakes Mitheil. IVL, 23: 71–78.

Battarbee, R.W. (Ed.), 1988. Lake Acidification in the United Kingdom 1800–1986. Evidence from Analysis of Lake Sediments. ENSIS Publ., London, 68 pp.

Bergstrom, S.K.D., 1991. In: International Conference on an Agenda of Science for Environment and Development into 21st Century. Section I, Theme 5. Vienna.

Birch, S. and McCaskie, J., 1999. Shallow urban lakes: A challenge for lake management. In: D.M. Harper, B. Brierley, A.J.D. Ferguson and G. Phillips (Eds), The Ecological Bases for Lake and Reservoir Management. Kluwer Academic Publishers, The Netherlands, pp. 365–377.

Biró, P., 1993. Management initiatives of fish stocks. In: Limnological Bases for Lake Management. Proceedings, ILEC UNEP Int. Training Course. Tihany, Hungary.

Bormann, F.H. and Likens, G.E., 1979. Pattern and Process in a Forested Ecosystem. Springer-Verlag, Berlin, 253 pp.

Borneff, J., 1962. Untersuchungen von Phytoplankton eines Binnensees auf polycyklische, aromatische Kohlenwasserstoffe. Arch. Hyg., 146 (5): 334.

Borneff, J., 1963. Kanzerogene Substanzen im Wasser. Münchner Med. Wschr., 105(24): 1237-1242.

Borneff, J., 1965. Vorkommen und Herkunft krebseeregender Substanzen im Wasser. Umschau, 65: 593–596.

Borneff, J., 1974. Hygiene, ein Leitfaden für Studenten und Ärzte 2. Aufl. G. Thieme, Stuttgart.

Brown, L.R. (Ed.), 1997. State of the World 1996. Fischer-Verlag, Stuttgart.

Burt, T., Heathwaite, A.L. and Trudgill, S.T., 1993. Nitrate: Processes, Patterns and Management. Wiley, 444 pp.

Calderoni, A., Mosello, R. and Ruggio, D., 1992. Sixty years of limnology on Lago d'Orta: A case history of recovery from heavy pollution. Mem. Ist. Ital. Idrobiol., 50: 201–223.

Caruso, B.S. and Ward, R.C., 1998. Assessment of nonpoint source pollution from inactive mines using a watershed-based approach. Environ. Manage., 22(2): 225–244.

Casper, S.J. (Ed.), 1985. Lake Stechlin—A Temperate Oligotrophic Lake. Monographiae Biologicae, 58. Junk, The Hague, The Netherlands.

Chen, G. and Huang, J.Ch. (Eds), 1999. Proceedings of the International Symposium on Development of Innovative Water and Wastewater Treatment Technologies for the 21st Century. Hon Kong, 8–10 October, 1999.

Chorus, I. and Bartram, J. (Eds), 1999. Toxic Cyanobacteria in Water: A Guide to Public Health Significance, Monitoring and Management. E&FN Spon, London.

Chorus, I. and Cavalieri, M., 2000. Cyanobacteria and algae. In: J. Bartram and G. Rees (Eds), Monitoring Bathing Waters. E&FN Spon, London, pp. 219–271.

Chorus, I. and Salas, H.J., 1997. Health impacts of freshwater algae. In: III regional AIDIS Congress for North America and the Caribbean. San Juan, Puerto Rico, 7–12 June, 1997.

Collet, L.W., 1925. Les lacs: leur mode de dormation, leurs eaux, leur destin—éléments d'hydrogéologie. Paris, 320 pp.

Craun, G., 1985. An overview of statistics on acute and chronic water contamination problems. In: Fourth Domestic Water Quality Symposium: Point-of-Use Treatment and Its Implications. Water Quality Assoc., Lisle, IL, pp. 5–15.

Cronberg, G., Lindmark, G. and Björk, S., 1988. Mass development of the flagellate *Gonyostomum semen* (*Raphidophyta*) in Swedish forest lakes—An effect of acidification? Hydrobiol., 161: 217–236.

Crul, C.M., 1995. Limnology and Hydrology of Lake Victoria. The UNESCO Press, Paris, 80 pp.

Cuker, B., 1987. Field experiment on the influences of suspended clay and P on the plankton of a small lake. Limnol. Oceanogr., 32: 840–847.

Dister, E., 1985. Taschenpolder als Hochwasserschtzmassnahmen am Oberrhein. Geowissenschaften unserer Zeit, 4(6): 194–203.

Dokulil, M.T., 1993. Anthropogenic impacts on lakes. Are shallow lakes more vulnerable than deep lakes? In: H. Sund, Yu Xiaogan et al. (Eds), Environmental Protection and Lake Ecosystems. Proceedings of an International Symposium Held in Wuxi from March 27 to April 1, 1993. China Science and Technology Press, Nanjing, pp. 81–97.

Duarte, C.M. and Kalff, J., 1987. Latitudinal influences on the depth of maximum colonization and maximum biomass of submerged angiosperms in lakes. Can. J. Fish. Aquat. Sci., 44: 1759–1764.

Duarte, C.M. and Kalff, J., 1990. Patterns in the submerged macrophyte biomass of lakes and the importance of the scale of analysis in the interpretations. Can. J. Fish. Aquat. Sci., 47: 357–363.

Edmondson, W.T., 1972. The present condition of Lake Washington. Verh. Int. Verein. Limnol., 18: 284–291.

Edmondson, W.T., 1984. Volcanic ash in lakes. Northwest Environ. J., 1(1): 139–150.

Edmondson, W.T., 1991. The Use of Ecology: Lake Washington and Beyond. Univ. Washington Press, Seattle, 329 pp.

Edmondson, W.T. and Lehmann, J.T., 1981. The effects of changes in nutrient income on the condition of Lake Washington. Limnol. Oceanogr., 26: 1–29.

Edmondson, W.T. and Litt, A.H., 1981. Mt. St. Helens ash in the lower Grand Coulee, Washington State. Verh. Int. Verein. Limnol., 22: 510–512.

Eisma, D., 1992. Suspended Matter in the Aquatic Environment. Springer-Verlag, Berlin, 315 pp.

Epstein, P.R., 1993. Algal blooms in the spread and persistence of cholera. BioSystems, 32: 209–221.

Falconer, I.R., 1989. Effects of human health of some toxic cyanobacteria (blue-green algae) in reservoirs, lakes and rivers. Toxicity Assessment, 4: 175–184.

Falconer, I.R. (Ed.), 1993. Algal Toxins in Seafood and Drinking Water. Academic Press, San Diego, CA, 240 pp.

Filho, W.L., 1993. Environmental education: The key to sustainable living. Network 28. Centre for Our Common Future, 3.

Fonseca, O.J.M., 1990. Acidification of streams by acid mine drainage in the state Rio Grande do Sul. Acta Limnologica Brazileira, III(2): 979–992 (in Portuguese).

Fott, J., Pražáková, M., Stuchlík, E. and Stuchlíková, Z., 1994. Acidification of lakes in Šumava (Bohemia) and in the High Tatra Mountains (Slovakia). Hydrobiol., 274: 37–47.

Gahnström, G. and Andersson, G., 1988a. Effects of acidification on aquatic organisms. In: H.M. Seip (Ed.), Acid Precipitation, Literature Review. Nordic Council of Ministers.

Gahnström, G. and Andersson, G., 1988b. Countermeasures: Ecological effects on aquatic ecosystems. In: H.M. Seip (Ed.), Acid Precipitation, Literature Review. Nordic Council of Ministers.

Gaston, K.J. (Ed.), 1996. Biodiversity, a Biology of Numbers and Difference. Blackwell Scientific Publications, Oxford, 396 pp.

Geldenreich, E.E., 1997. Pathogenic agents in freshwater resources. In: N.E. Peters, O.P. Bricker and M.M. Kennedy (Eds), Water Quality Trends and Geochemical Mass Balance. Wiley, Chichester, pp. 191–210.

GEMS (Global Environmental Monitoring System), 1987. Global Pollution and Health. WHO and UNEP, Yale Univ. Press, New Haven, CT.

Gessner, F., 1953. Investigaciones hidrographicas en el Lago Maracaibo. Acta Scientifica Venezolana, 4 (5): 173–177.

Gessner, F., 1955a. Das Plankton des Maracaibo. Ergebnisse der deutschen limnologischen Venezuela-Expedition. VEB deutscher Verlag der Wissenschaften, Berlin, pp. 67–92.

Gessner, F., 1955b. Die limnologischen Verhältnisse in den Seen und Flüssen von Venezuela. Verh. Int. Verein. Limnol., 12: 284–295.

Giger, W., 1984. Das Verhalten organischer Waschmittelchemikalien in der Abwasser-reinigung und in den Gewässern. Mitt. EAWAG, 18: 1–7.

Giger, W., 1992. Polychlorierte Biphenyle. 25 Jahre "klassische" Umwelchemikalien. GAIA, 1: 50–53.

Glantz, M.M., 1998. Creeping environmental problems in the Aral Sea Basin. In: I. Kobori and M. Glantz (Eds), Central Eurasian Water Crisis. Caspian, Aral and Dead Seas. United Nations University Press, Tokyo, pp. 25–52.

Goldman, Ch.R., 1988. Primary productivity, nutrients and transparency during the early onset of eutrophisation in ultra-oligotrophic Lake Tahoe, California—Nevada. Limnol. Oceanogr., 33: 1321–1333.

Goldman, Ch.R., 1990. The importance of long-term limnological research with emphasis on Lake Tahoe and Castle Lake. In: R. de Bernardi, G. de Giussani and L. Barbanti (Eds), Scientific Perspectives in Theoretical and Applied Limnology. Mem. Ist. Ital. Idrobiol., 47, pp. 221–231.

Goldman, Ch.R., 1993. Lake Tahoe: A microcosm for the study of the impact of suburbanization on fragile ecosystems. In: R.H. Platt (Ed.), The Ecological City: Preserving and Restoring Urban Biodiversity. Univ. Massachusetts Press, MA, pp. 247–260.

Goldman, Ch.R., Jassby, A.D. and de Amazaga, E., 1990. Forest fires, atmospheric deposition and primary productivity at Lake Tahoe, California—Nevada. Verh. Int. Verein. Limnol., 24: 499–503.

Goldman, Ch.R., Moshiri, H. and de Amezaga, E., 1970. Synoptic study of accelerated eutrophication in Lake Tahoe—A sub-alpine lake. In: International Symposium Water Pollution in Cold Climate. Univ. Alaska, Alaska, pp. 125–132.

Golubev, G.M., 1997. Environmental problems of large Central Asian lakes. In: S.E. Jørgensen and S. Matsui (Eds), The World's Lakes in Crisis. Guidelines of Lake Management, Vol. 8. International Lake Environment Committee and UNEP, Kusatsu, Japan, pp. 67–78.

Golubev, G.M. and Biswas, A.K. (Eds), 1985. Large Scale Water Transfers. Water Resources Ser. Vol. 7. UNEP and Tycooly Publ., Oxford.

Gopal, B., 1996. Overview of Lakes and Wetlands in India. In: M. Ando (Ed.), Conservation and Management of Lakes/Reservoirs in India. ILEC, Kusatsu, Japan, pp. 1–17.

Graham, N.J.D., Wardlaw, V.E., Perry, R. and Jiang, J.-Q., 1998. The significance of algae as trihalomethane precursors. Water. Sci. Technol., 37(2): 83–89.

Green, J. and Trett, M.W. (Eds), 1989. The Fate and Effects of Oil in Freshwater. Elsevier, Amsterdam, 338 pp.

Hammond, A.L., 1971. Mercury in the environment: Natural and human factors. Science, 171: 788–789.

Harries, J.E., Sheahan, D.A., Jobling, S., Matthiessen, P., Naell, P., Sumpter, P.J., Tylor, T. and Zaman, N., 1997. Estrogenic activity in five United Kingdom rivers detected by measurement of vitellogenesis in caged male trout. Environmental Toxicology and Chemistry, 16: 534–542.

Harris, J.R.W., Bale, A.J., Bayne, B.L., Mantoura, R.C.F., Morris, A.W., Nelson, L.A., Radford, P.J., Uncles, R.J., Weston, S.A. and Widdows, J., 1984. A preliminary model of the dispersal and biological effect of toxins in teh Tamar estuary, England. Ecol. Model., 22: 253–285.

Hecky, R.E., 1993. The eutrophication of Lake Victoria. Verh. Int. Verein. Limnol., 25: 39–48.

Henderson-Sellers, B., 1979. Reservoirs. MacMillan Press Ltd., London, 128 pp.

Hessen, D.O. and Tranvik, L.J. (Eds), 1998. Aquatic Humic Substances. Ecology and Biogeochemistry. Springer-Verlag, Berlin, 352 pp.

Hongxiao, T., Zijian, W. and Jingyi, L., 1996. Ecological impacts of heavy metal pollution from Dexing copper mine on Poyang Lake, China. Ecological effects of heavy-metal pollution in the Dexing copper mine region, Jiang Xi Province, China. Final report. The UNESCO Press, Paris, pp. 13–16.

Hunter, P.R., 1991. Human illness associated with freshwater cyanobacteria (blue-green algae). PHLS Microbiology Digest, 8(3): 96–100.

Hutchinson, G.E., 1957. A Treatise on Limnology 1. Wiley, New York, NY, 1015 pp.

Hutchinson, G.E., 1973. Eutrophication. The scientific background of a contemporary problem. American Scientist, 61(3): 269–279.

IETC, 1999. PAMOLARE (Planning and Management of Lakes and Reservoirs). UNEP–IETC, Osaka/Shiga, 375 pp.

Infante, A., 1978. Natural food of herbivorous zooplankton of Lake Valencia (Venezuela). Arch. Hydrobiol., 82: 347–358.

Istvanovics, V. and Somlyódy, L., 1999. Limnological differences between a shallow pre-reservoir and a shallow lake—A case study of the upper Kis–Balaton reservoir and Lake Balaton. In: J.G. Tundisi and M. Straškraba (Eds), Theoretical Reservoir Ecology and Its Applications. Brazilian Academy of Sciences, International Institute of Ecology, Backuys Publishers, Brazil, pp. 347–383.

IUCN (supported by UNEP and WWF), 1980. World Conservation Strategy; Living Resource Conservation for Sustainable Development, Gland, Switzerland, 21 pp.

Jackson, P.D. and Williams, W.D., 1980. Effects of brown trout, *Salmo trutta L.*, on the distribution of some native fishes in three areas of Southern Victoria. Aust. J. Mar. Freshwater Res., 31: 61–67.

Jin, X., 1995. Lakes in China—Research and Their Environment, Vols I–II. China Ocean Press.

Jonasson, P.M., 1979. Lake Myvatn. Oikos, 32(1/2): 1–308.

Kajak, Z., 1980. The impact of land use on eutrophication of lakes reservoirs and possible protective measures. In: A. Duncan and J. Rzóska (Eds), Land Use Impacts on Lake and Reservoir Ecosystems. Proceed. MaB 5 Workshop. Poland 1978. Facultas-Verlag, Wien, pp. 135–378.

Kira, T., 1993. Major environmental problems in world lakes. Mem. Ist. Ital. Idrobiol., 52: 1–7.

Kira, T. (Ed.), 1994. Data Book of World Lake Environments-2. Africa and Europe. ILEC UNEP, Kusatsu, 368 pp.

Kira, T. (Ed.), 1995a. Data Book of World Lake Environments-3. The Americas. ILEC UNEP, Kusatsu, 496 pp.

Kira, T. (Ed.), 1995b. Data Book of World Lake Environments-1. Asia and Oceania. ILEC UNEP, Kusatsu, 428 pp.

Kling, G.W., 1987. Seasonal mixing and catastrophic degassing in tropical lakes, Cameroon, West Africa. Science, 237: 1022–1024.

Kontek, R., Osiecka, R., Blaszczyk, A., Tarczynska, M., Zelewski, M. and Luchniak, P., 1997. Toxins produced by freshwater cyanobacteria as potential environment mutagens. In: Proceedings of Spring Symposium on Plant Cytogenetics, 19–22 May, 1997, Cieszyn, Poland.

Koptyug, A.K. and Uppenbrink, M., 1994. Sustainable development of the Lake Baikal Region. Springer-Verlag, Berlin (in coop. NATO ASI.) 2. Environment 6, (347–353) 372 pp.

Korzoin, V.I., Sokalov, A.A., Budyko, M.I., Voskresensky, K.P., Kalinin, G.P., Konaplyontsev, A.A., Koratkevich, E.S. and Lvovich, M.I., 1979. Atlas of World Water Balance. The UNESCO Press, Paris.

Langford, T.E.L., 1990. Ecological Effects of Thermal Discharges. Elsevier, London, 468 pp.

Lawton, L.A. and Codd, G.A., 1991. Cyanobacterial (blue-green algal) toxins and their significance in UK and European waters. J. Inst. Water Environ. Manag., 5(4): 460–465.

Lee, G.F., Rast, W. and Jones, R.A., 1978. Eutrophication of water bodies: Insight for an age old problem. Environm. Sci. Technol., 12: 900–908.

Likens, G.E. (Ed.), 1985. An Ecosystem Approach to Aquatic Ecology: Mirror Lake and Its Environment. Springer-Verlag, New York, NY, 516 pp.

Likens, G.E., Bormann, F.H., Pierce, R.S., Eaton, J.S. and Johnson, N.M., 1977. Biogeochemistry of a Forested Ecosystem. Springer-Verlag, New York, NY, 176 pp.

Lind, O.T. and Davalos-Lind, L., 1999. Suspended Clay: Its Role in Reservoir Productivity. In: J.G. Tundis and M. Straškraba (Eds), Theoretical Reservoir Ecology and Its Applications. Brazilian Academy of Sciences, International Institute of Ecology, Backuys Publishers, Brazil, pp. 85–97.

Lippy, E. and Waltrip, S., 1984. Waterborne disease outbreaks, 1946–1980: A thirty-five-year perspective. J. AWWA, 76: 60–67.

Liu, J.K., 1984. Lakes of the middle and lower basins of the Chang Jiang (China). In: F. Taub (Ed.), Lakes and Reservoirs. Ecosystems of the World., Vol. 23. Elsevier, Amsterdam, pp. 331–355.

Löffler, H., 1964. The limnology of tropical high-mountain lakes. Verh. Int. Verein. Limnol., 15: 176–216.

Löffler, H., 1987. Il recupero dei laghi in relazione alle condizioni termiche, obiettivo lago; in Lago die Cavazzo o dei tre vomuni, un patrimonio da salvare e valorizzare. Comuni di Bordano Cavazzo Carnico, Trasaghis montana del Germonese, pp. 199–202.

Löffler, H., 1988. Natural hazards and health risks from lakes. In: Water Resources Development, 4. Butterworth Publishers, Stoneham, MA, pp. 276–283.

Löffler, H., 1995a. Bioreserve Fertö—Neusiedlersee. Evolution and man made changes. In: Poster, UNESCO, International Conference on Biosphere Reserves, Sevilla, Spain.

Löffler, H., 1995b. The impact on alpine high-mountain lakes by atmospheric nutrient loading and stocking with fish. In: EURO-MAB IV. Conf. Papers 21, IGiPZ Warszawa, pp. 107–110.

Löffler, H. and Malkhazova, S., 1990. Impacts of wetlands on man. In: B.C. Patten (Ed.), Wetlands and Shallow Continental Water Bodies, Vol. 1. Academic Publ., The Hague, The Netherlands, pp. 347–362.

Los, I.P., 1994. Main directions of the Ukrainian population radiation protection at ostacciden reconstruction period. In: Proc. Intern. Round Table "Chernobyl: Never again". UNESCO, ROSTE, Technical Rep., pp. 48–56.

Luther, J. and Rzóska, J., 1969. Project Aqua. IPB Central Office, London.

Luther, J. and Rzóska, J., 1971. Project Aqua, a Source Book of Inland Waters Proposed for Conservation. IPB Handbook, Vol. 21. Blackwell Scientific Publications, Oxford.

Machena, C. and Kautsky, N., 1988. A quantitative diving survey of benthic vegetation and fauna in Lake Kariba, a tropical man-made lake. Freshw. Biol., 19: 1–14.

Mackereth, F.J.H., 1966. Some chemical observations on postglacial lake sediments. Phil. Trans. Roy. Soc., 765(250): 165–176.

Mani, M.B., 1974. Fundamentals of High Altitude Biology IX, Oxford and LBH Publ. Co., New Delhi, Bombay, Calcuta.

Marshall, T.L. and Johnson, R.P., 1971. History and Results of Fish Introductions in Saskatchewan 1900–1969. Fisheries Rep. 8. Saskatchewan.

Mason, B.J. (Ed.), 1990. The Surface Water Acidification Programme. Cambridge University Press, Cambridge, 522 pp.

Matsumura, T., and Yoshiuki, S., 1981. An optimization problem related to the regulation of influent nutrient in aquatic ecosystems. Int. J. Syst. Sci., 12: 565–585.

Meybeck, M., Chapman, D. and Helmer, R. (Eds), 1989. Global Freshwater Quality. World Health Organization and United Nations Environment Programme, Blackwell Ltd, Oxford.

Montén, E., 1939. Bodentopographie und Strandmorphologie des Sees Algunnen bei Aneboda. Medd. Lunds Univ. Limnol. Inst., Vol. 3.

Morris, R., Taylor, E.W., Brown, D.J.A. and Brown, J.A. (Eds), 1989. Acid Toxicity and Aquatic Animals. Cambridge University Press, Cambridge, 282 pp.

Müller-Wegener, U., Kleine, W., Kaschanian, B., Ehrig, Ch., Schmidt, R., Poll, K. and Milde, G., 1994. Pflanzenauswirkingen auf Trinkwassertalsperren. Fischer-Verlag, Jena.

Myers, N., 1993. Questions of Mass Extinction. Chapman and Hall, London.

Naiman, R.J., Magnuson, J.J. and McKnight, D.M., 1995. The Freshwater Imperative. Island Press, Washington, DC, 200 pp.

Naumann, E., 1922. Södra och mellersta Sveriges sjö–och myrmalmer. Deras bildningshistoria, utbredning och praktiska betydelse. Sver. Geol. Unders. Ser C, 297, Stockholm.

Novotny, V. and Olem, H., 1994. Water Quality—Prevention, Identification, and Management of Diffuse Pollution. Van Nostrand, New York, NY, 1054 pp.

OECD (Organization for Economic Cooperation and Development), 1994. Mercury Risk Reduction. OECD Monograph, Vol. 4, pp. 37–38.

O'Sullivan, P.E., 1979. The ecosystem–watershed concept in the environmental sciences—A review. Internat. J. Environmental Studies, 13: 273–281.

Patzelt, G., 1994. Former lakes dammed by glaciers and resulting floods in the Otztal. Tyrol. Mountain Res. Develop., 14(4): 298–301.

Pless, H., 1957. Die Talsperren in der Bundesrepublik. Umschau, 57(4): 112–113.

Procházková, L., 1980. Agricultural impact on the nitrogen and phosphorus concentration in water. In N. Duncan and J. Rzoska (Eds), Proceedings MaB 5 Workshop. Facultas-Verlag, Wien, pp. 78–100.

Psenner, R., 1984. Prime esperienze con l'analisi delle prezipitazioni nel Tirolo (Austria). Inquinamento Atmospherico, pp. 249–273.

Psenner, R., 1994. Environmental impacts on freshwaters: Acidification as a global problem. Sci. Total Environ., 143: 53–61.

Ptichnikov, A. and Nauber, J., 1994. Ökologische Forschung und Monitoring am Aralsee. UNESCO Heute II, pp. 183–189.

Ramberg, L., Björk-Ramberg, S., Kautsky, N. and Machena, C., 1987. Development and biological status of Lake Kariba—a man-made tropical lake. Ambio, 16(6): 314–321.

Rapin, F., Blanc, O., Pelletier, J.-P., Balvay, G., Gerdeaux, D., Corvi, C., Perfetta, J. and Lang, C., 1995. Impact humains sur les systemes lacustres: Example du Leman. In: R. Poutrriot and M. Meybeck (Eds), Limnologie Generale. Masson, Paris.

Rast, W. and Thornton, J.A., 1997. Trends of eutrophication research and control. In: N.E. Peters, O.P. Bricker and M.M. Kennedy (Eds), Water Quality Trends and Geochemical Mass Balance. Wiley, Chichester, pp. 171–190.

Rietschel, P., 1975. Die Zweiflugler: Mucken. In Grzimeks Tierieben 2, Kindler-Verlag, pp. 371–395.

ROSTE–UNESCO, 1994. Report 19. Proc. Internat. Round Table "Chernobyl–Never Again".

Ryding, S.-O. and Rast, W., 1989. Control of the Eutrophication of Lakes and Reservoirs. Man and the Biosphere Programme, Vol. 1, United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, 354 pp.

Sarhage, D. and Lundbeck, J., 1992. A History of Fishing. Springer-Verlag, Berlin, 348 pp.

Schanz, F., 1993. Zwölf Jahre Schilfbeobachtungen am unteren Zürichsee von 1979–1991. In: Seeuferzerstörung und Seeuferrenaturierung in Mitteleuropa. Limnologie aktuell. Fischer-Verlag, Jena, Vol. 5, pp. 123–129.

Scheffer, M., 1998. Ecology of Shallow Lake. Chapman and Hall, Chichester, 357 pp.

Serruya, C. and Pollingher, U., 1983. Lakes of the Warm Belt. Cambridge Univ. Press, Cambridge, 569 pp.

Seyfried, P.L., Tobin, R.S., Brown, N.E. and Ness, P.F., 1985a. A prospective study of swimming-related illness. I. Swimming-associated health risk. Amer. J. Pub. Health, 75: 1068–1070.

Seyfried, P.L., Tobin, R.S., Brown, N.E. and Ness, P.F., 1985b. A prospective study of swimming-related illness. II. Morbidity and the microbiological quality of water. Amer. J. Pub. Health, 75: 1071–1075.

Shrestha, U.K., 1996. Pesticide use and its effect on the environment in Nepal. In: ICIMOD, UNESCO, International Conference on Ecohydrology of High Mountain Areas, Kathmandu. Abstracts, pp. 89–90.

Shu, J. and Wuang, W., 1993. Assessment of trophic level of main lakes and reservoirs in China. In: H. Sund, Yu Xiaogan et al. (Eds), Environmental Protection and Lake Ecosystems. Proceedings of an International Symposium Held in Wuxi from March 27 to April 1, 1993. China Science and Technology Press, Nanjing, pp. 99–107.

Sigurdsson, H., 1987. Lethal gas bursts from Cameroon crater lakes. Eos, The VGP News, pp. 1–5.

Smith, H.V. and Lloyd, A., 1997. Protozoan parasites in drinking water: The UK perspective. New World Water, 2: 109–116.

Steib, K., 1985. Epidemiologie und Vektorökologie der Dracunculose in Obervolta (Burkina Faso), Westafrika. Diss. Fak. II, Univ. Stuttgart-Hohenheim.

Steinberg, C.W.E. and Wright, R.F. (Eds), 1994. Acidification of Freshwater Ecosystems: Implications for the Future. Wiley, Chichester, 420 pp.

Straškraba, M., Desortová, B. and Fott, J., 1979. Zur Methodik der Bestimmung und Bewertung des Chlorophyll-a in Oberflächengewässern. Acta Hydrochim. Hydrobiol., 7(6): 569–590.

Straškraba, M. and Tundisi, J.G., 1999. Reservoir Water Quality Management. Guidelines of Lake Management, Vol. 9. International Lake Environment Committee, Kusatsu, Japan, 229 pp.

Stumm, W. and Baccini, P., 1978. Man-made chemical perturbation of lakes. In: A. Lerman (Ed.), Lakes. Chemistry, Geology, Physics. Springer-Verlag, New York, pp. 91–126.

Symoens, J., Burgis, M. and Gaudet, J.S., 1981. The Ecology and Utilization of African Inland Waters. UNEP Rep. and Proc. Ser. 1.

Tabor, H., 1963. Large area solar collectors for power production. Solar Energy, 7(4): 189–194.

Tabor, H., 1980. The promise of solar ponds. Kidma, 19: 8–11.

Talling, J.F., 1957. Diurnal changes of stratification and photosynthesis in some tropical African waters. Proc. Roy. Soc. B, 147: 57–83.

Thomas, E.A., 1960. Rotalgenrasen und Blaualgenteppiche im Zürichsee. Viertel-jahresschrift naturforschende Gesellschaft Zürich, 105: 297–305.

Thomas, E.A., 1972. Phosphate removal by circulating iron sludge. J. Water Pollut. Control Fed., 44(2): 176–182.

Thunmark, S., 1948. Sjöar och myrar in Lenhovda socken. Lendhovda, en värendssocken berättar, pp. 665–710.

Tölle-Kastenbein, R., 1990. Antike Wasserkultur. Beck, München, 231 pp.

Toombs, M.R., 1997. Agricultural pollution control: Trends and innovations in the Lake Simcoe watershed. Lake Reser. Manage., 13(3): 240–245.

UNEP and UNESCO (United Nations Environment Programme and United Nations Education, Scientific and Cultural Organization), 1990. The Impact of Large Water Projects on the Environment. Proceedings of an International Symposium. Paris, 1986. The UNESCO Press, Paris.

UNESCO and UNEP, 1992. Water-Related Issues and Problems of the Humid Tropics and Other Warm Humid Regions, pp. 15–17.

Verweij, W., 1991. Speciation and Bioavailability of Copper in Lake Tjeukemeer. Diss. Thesis. Wageningen, The Netherlands.

Vezie, C., Brient, L., Sivonen, K., Bertru, G., Lefeuvre, J.-C. and Salkinoja-Salonen, M., 1997. Occurrence of microcystin-containing cyanobacterial blooms in freshwaters of Brittany (France). Arch. Hydrobiol., 139(3): 401–413.

Vollenweider, R.A., 1979. Das Nährstoffbelastungskonzept als Grundlage für den externen Eingriff in den Eutrophierungsprozess stehender Gewässer und Talsperren. Z. Wasser-Abwasser-Forschg., 12(2): 46–56.

Waid, J.S. (Ed.), 1986. PCBs and the Environment, Vols 1–3. CRC Press, Boca Raton, FL.

Watanabe, T., Ives, J.D. and Hammond, J.E., 1994. Rapid growth of a glacial lake in Khumbu Himal, Himalaya: Prospects for a catastrophic flood. Lake Reserv. Manage., 14 (4): 329–340.

Willen, T. and Mattsson, R., 1997. Water-blooming and toxin-producing cyanobacteria in Swedish fresh and brackish waters, 1981–1995. Hydrobiol., 353: 181–192.

Williams, W.D., 1993. Conservation of salt lakes. Hydrobiol., 269: 1–17.

Williams, W.D., 1996. The largest, highest and lowest lakes of the world: Saline lakes. Verh. Int. Verein. Limnol., 26: 61–76.

Williams, W.D. and Aladin, N.V., 1991. The Aral Sea: Recent limnological changes and their conservation significance. Aquatic Conservation: Marine and Freshwater Ecosystems, 1: 3–23.

Wilson, R. and Jones, B., 1995. Swedish Phosphate Report. Landmark Environmental Research and Consulting.

Wolf, W., Soeder, C.J. and Drepper, F.F. (Eds), 1988. Ecodynamics: Contribution to Theoretical Ecology. Proceedings of an International Workshop, 19–20 October, 1987, Julich, Germany. Springer-Verlag, Berlin.

Zaret, T.M., 1980. Predation in Freshwater Communities. Yale Univ. Press, New Haven, CT.