*Chapter 1*

# LAKES AND RESERVOIRS AS WATER RESOURCES

## 1.1 INTRODUCTION

Many features of natural lakes and artificial lakes (reservoirs) are similar, and the approaches for their use and management also bear great similarity. Therefore, when the words "lakes" or "waterbodies" (without specification) are mentioned in this book, it refers to both natural lakes and reservoirs. However, because reservoirs and natural lakes also have a number of characteristics that differ significantly (Rast and Straškraba, 2000; also see Chapter 6), reservoirs and natural lakes will be identified specifically in this volume where it is appropriate.

This introductory chapter discusses the physical characteristics of lakes and reservoirs, and the roles they play for society. Section 1.2 presents their role from the perspective of how they are perceived by the public (Section 1.2.1), the roles they play for society (Section 1.2.2) and their economic value to humanity (Section 1.2.3). The opposite perspective also is discussed in this chapter; namely, what is the role of society in regard to managing lakes and reservoirs for their sustainable use for humanity and for nature (Section 1.2.4)?

Section 1.3 reviews the distribution of lakes and reservoirs, focusing on their water volumes and surface areas (Section 1.3.1), their geographical distribution, and how their geographic location is reflect in their water quality and related management issues (Section 1.3.2).

## 1.2 THE ROLES OF LAKES AND RESERVOIRS

The large number of reservoirs constructed throughout the world demonstrates that lakes are needed for many purposes, and that they play a major role for society (Thornton et al., 1996; World Commission on Dams, 2000; Rast, 2003). The main need is for greater quantities of continuously available and easily accessible quantities of water of good quality, primarily for its value for meeting the water needs of the population, agriculture and industry.

### *1.2.1 Need, Uses and Public Perceptions of Lakes and Reservoirs*

Lakes and reservoirs are basins filled with water that is often (in the case of natural lakes) and always (in the case of reservoirs) used by humans. Why do humans need such large quantities of water? For daily consumption (drinking), humans only need about two liters of water daily. The remaining quantity is used for human hygiene, for the preparation of

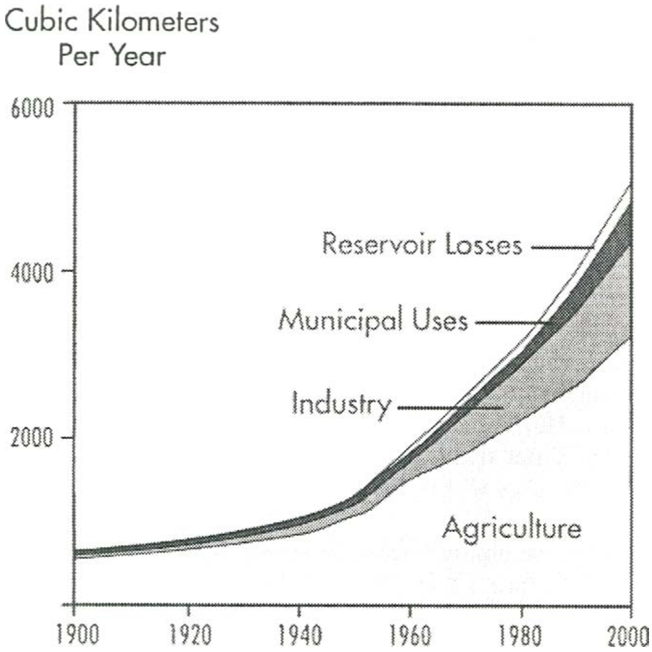

Fig. 1.1. Estimated water usage by different economic sectors for the period 1990–2000 (Atchia and Tropp, 1995).

food, and for the production of food and goods. The average daily water need per person differs significantly in different regions. It depends partly on the availability of water, and generally increases over time as the economic and cultural status of a region increases. Water availability is uneven around the world. Some regions face water shortages, including Africa, the Middle East, Australia and parts of western America. It has been estimated that total annual water use around the world increased tenfold between 1900 and 2000, from approximately 600 km$^3$ to nearly 5500 km$^3$. On a global scale (Fig. 1.1), approximately 69% of water usage is for agricultural purposes (primarily irrigation), 23% is for industrial usage, and 8% is for domestic consumption (Atchia and Tropp, 1995).

Water usage in large urban centers with centralized supplies is particularly high for various reasons, including often-large water losses to leakage from inadequate or broken pipe systems, and to its use in industry, watering of gardens, etc. A distinction is drawn between water that is consumed (i.e., water that is not returned directly to waterbodies) and water used (including water that is returned, usually in a polluted state, to waterbodies). This distinction is made because water that is consumed cannot be used more than once without having to re-enter the hydrological cycle and be returned to the Earth in the form of rainfall and snowfall. In contrast, in many countries water that is not consumed is re-used a number of times. This situation enhances the need to save water more than in situations in

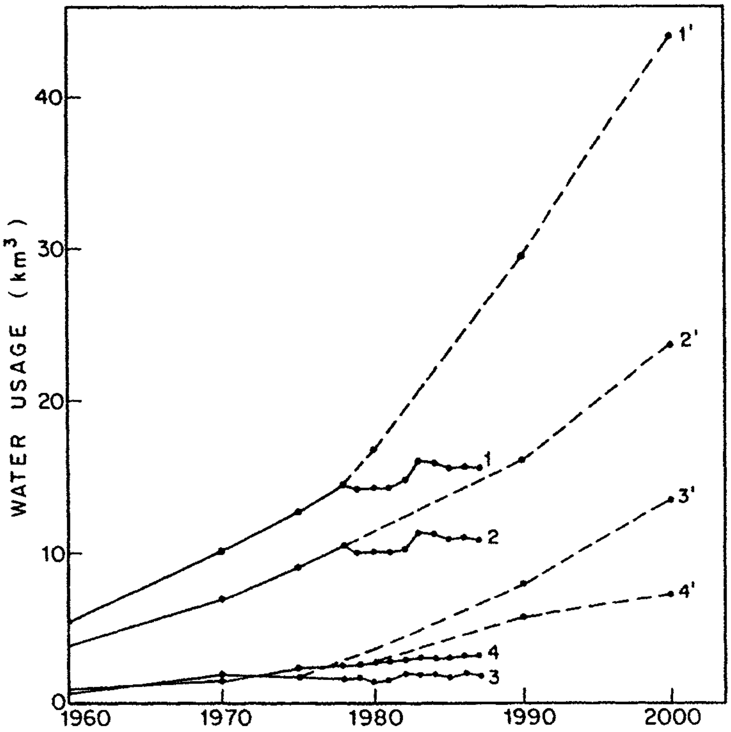

Fig. 1.2. Predicted and actual water usage in Poland, 1960–2000, showing discrepancies from 1976 (modified from Mitchell, 1990). Legend: 1—total users; 2—industry, including energy; 3—agriculture, particularly irrigation; 4—municipal sector.

which water is present in excessive quantities. In spite of rapidly increasing water needs on a global scale, it is fortunate that the rise is exponential in nature. In fact, per capita water need often decreases in developed countries to the extent that there can be a discrepancy between water needs predicted on the basis of simple extrapolation of trends and actual water consumption (Fig. 1.2).

Lakes represent a large proportion of the world's readily available water supply, following rivers. The importance of lakes in a given region depends partly on their numbers and distribution. In Scandinavia, for example, lakes occupy almost 10% of the total land area, while lakes occupy less than 1% of the total land area in China and Argentina (see Section 1.3.1).

Lake water is not used only for human consumption. Other water uses include industrial applications and processes, transportation, and generation of hydropower (particularly reservoirs), as discussed further in Chapter 2. Both the production of food and of industrial products, for example, requires water. Plants and animals consume water. Industry requires water for purposes such as facilitating chemical reactions, cleaning and cooling (Ryding and Rast, 1989; Rast and Thornton, 1999).

The public perception of lakes and reservoirs in different regions of the world depends on the economic and cultural state of the regions. This perception is closely related to the concept of the "quality of life" (Galloping and Oberg, 1991; also see Glantz, 1999). By definition, the quality of life (QOL) is a subjective concept, dependent on cultural perspectives and values. There is a tentative consensus, however, on some of the factors considered essential for a good life, including (i) access to clean water for domestic purposes; (ii) sufficient food; (iii) adequate shelter; (iv) security; and, with respect to health, (v) access to adequate medical care. It is also suggested that education and gender equality be added to this list (Daly and Cobb, 1989).

Applied to lakes and reservoirs, the basic demands for quality of life include (i) protection from floods and drought; (ii) protection from water-based and waterborne diseases; (iii) clean water; and (iv) protection of food (protein) in lakes and reservoirs. The latter also may include satisfaction with work, such as irrigation, fisheries and production of huts, mats, boats, etc., from macrophytes (aquatic plants). Direct access to a lake or river also was a preferred condition in situations of early development, be it in historical periods for the developed regions, or more recently for the developing regions. The public perceptions of lakes, however, do not depend only on how they are used. They also have a role in the aesthetics of the natural landscape, representing important natural beauty for satisfying human needs and feelings. This is seen not only from many earlier and recent paintings of artists, but also from the recent appreciation of both residential and recreational housing along lake shorelines. The prices of such housing are typically much higher than elsewhere. The will of people to pay higher prices for water also is seen in places with good central water supply systems, and with people who utilize water for sports and recreational purposes.

Recreation along lake shores is quite desirable, as can be seen from the high concentrations of recreational housing along lake shorelines. There are many water-based recreational activities in lakes and along their shorelines. The negative effect of recreation, however, is obvious with mass tourism, which can significantly degrade landscapes along lake shorelines and which, so far, have largely been planned carelessly and often irresponsibly (Ostendorp and Krumscheid-Plankert, 1993).

People that live close to lakes, or who like visiting them, typically appreciate not only the lake scenery, but also its water quality. Good water quality is an obviously desirable trait, while degraded water is not. Particularly negatively impressions are observed among swimmers when lake water is turbid, the quantity of algae in the water is high, and where filamentous algae overgrow the shallower lake areas. Swimmers typically feel a physical disgust when such algae touch their skin or when it accumulates in their swimming apparel. Dense growths of aquatic plants can be disturbing to swimmers, as well as boaters, particularly when they become tangled in the propellers of boats. In fact, dense stands of tropical aquatic plants, such as *Eichhornia* or *Azolla*, can prevent the movement of boats. The appreciation of clean water can be simply demonstrated by the statistical patterns of visitors when they have a choice between clean lakes and lakes beset with algae and aquatic plant problems. This is due not only to negative perceptions as cited above, but also to negative experiences with waterborne diseases and infections (Section 2.2.3) and water pollution.

A quantitative indication of the public perception of water quality is represented by the willingness of consumers to pay a premium for water. The values assigned by the buying public to bottled water, and to home sites located on "clean" lakes and reservoirs, are indicative of the complex relationship between human perceptions (i.e., the objective assessment of a situation) and human behavior (i.e., the objective response to the situation). Interestingly, Thornton and co-workers (Thornton et al., 1989; Thornton, 1993) reported that, in studies including temperate zone lakes and rivers, as well as subtropical reservoirs and lagoons, few respondents indicated any interference with their use of the waterbodies for water-based recreational purposes (e.g., their behavior), despite indications that water quality conditions may have influenced their enjoyment of the recreational experience (e.g., their perceptions).

In these and other studies (David, 1971; Kooyoomijian and Clesceri, 1974; Heiskary, 1989; Quick and Johansson, 1992; Wiseman and Sowman, 1992), public perceptions of water quality were based upon visual factors as primary determinants of water quality. In studies on African lakes, enriched reservoirs generally attracted a wider range of negative responses than other types of lakes, especially in terms of odors and tastes where the waterbodies were used for drinking water supply. In contrast, there was little unanimity, in terms of behavioral responses, with the limnological differences between waterbodies playing a part in determining user responses. In reservoirs dominated by algal growth, for example, few respondents expressed concerns over aquatic macrophyte growths. In addition, the types of water use played a role in determining human behavioral responses. In lakes where recreational boating and swimming were the primary uses, the presence of excessive quantities of algae and aquatic plants resulted in more frequent negative expressions among respondents than for lakes where recreational angling was the primary use, despite similar or even more abundant growths of plants and algae in the latter lakes. Such use-specific behavioral links were reported by Kooyoomijian and Clesceri (1974), who found that lake contact recreational users (e.g., swimmers and anglers) had more negative impressions of water quality than from noncontact recreational users (e.g., picnickers and sight-seers). Similar judgments also were identified in relation to the proximity of the respondent's residence to a waterbody, with persons living closer to a waterbody being more severe judges of water quality (David, 1971).

### *1.2.2 The Roles of Reservoirs and Lakes in Society*

The water requirements of people vary greatly around the world. Populations are even found inhabiting deserts, semi-arid regions and other localities with limited water resources. At least a limited quantity of water must be available in all such locations, however, either as surface water or groundwater, if people are to survive. The hydrological reality is that where there is no water, there is no life. This applies to all life, plants, animals and humans. Under hot dry conditions, humans will survive only few days without drinking water, and the same would be true even at the seacoast, which is characterized by access to large quantities of water, but of high salinity, rendering it unfit for human consumption.

Throughout history, ancient civilizations flourished, particularly on or near lakes, which provided water for drinking, cooking, cultivation of plants and domestic animals, washing of clothes, a medium for transportation, and sometimes even a hydrological barrier that protected them from their enemies.

At the community and national scales, the cultural importance of water is reflected in the basic human need for it. Most large cities and, indeed, the majority of human settlements around the world, lie in close proximity to water resources. Almost all the large cities of the world lie within 100–200 km of rivers, lakes and seas. The cultural importance of waterbodies extends to the demarcation of boundaries, ranging from the most elementary moats surrounding European castles to the most elegantly negotiated international boundaries between countries. In such situations, waterbodies assume the role of protector, isolating the community from its potentially-hostile neighbors. Indeed, the construction of protective moats is one of the earliest uses of water diversionary structures. At this scale, waterbodies often have a role as landscape features, exclusive of their other societal roles (drinking water supply, irrigation and industrial water source, recreational resource, transportation corridor, etc.).

Lakes and reservoirs are landscape features with great significance for people that extends far beyond their geographic existence or their immediate economic values. This significance is both cultural and aesthetic, and much is deeply ingrained in society. Brakke (1996), Khaka (1996), Chiu (1996) and Paszkowski (1996) all relate various cautionary and fantastic tales among all cultures of the world, wherein water plays a central, and often sinister, role in society. However, such tales always contain a valuable moral that generally reinforces a positive societal characteristic deemed desirable by the culture within which it was created.

While waterbodies in folklore may have sinister overtones, waterbodies often assume a cleansing connotation in regard to their religious significance. Virtually all of the world's great religions utilize water as an essential element of their religious ceremony, both publicly and privately. This role is partly a basic recognition of water's attribute as the universal solvent. This role also recognizes the basic societal concern over personal hygiene and the universal use of water for ablutions.

Over time, the role of water and waterbodies has permeated other societal aspects, ranging from its practical scientific and technical uses and concerns to the more esoteric realms of arts and literature. Upon reflection, although the role of water in art and literature should not be too surprising, given the more fundamental role of water in religion and daily life, rivers, lakes and reservoirs form the basis for numerous works of art. Examples include the landscape works by John Constable and others, and the literature of Samuel Clemens (Mark Twain) and others.

The varied role of lakes in society not only highlights their great value, but is also the cause of water controversies and management difficulties. As an example, reservoirs originally constructed for a single purpose are becoming multipurpose in their use, with correspondingly increasing conflicts among their different users. The conflicts include the allocation of the available water for individual uses, as well as water quality concerns. Water quality degradation by one can limit water use by others. Because of the dependence of water quantity and quality not only on proper water management, as well as landscape management (Falkenmark et al., 1999), the recent tendency is toward the integrated management of both resources (see Chapter 7) directed to air, water and land (United Nations, 1993; Thornton et al., 1999; Rast, 2003; Rast and Holland, 2003).

Climatic conditions are one important variable dictating consumptive water use. If the climate conditions in a region can be characterized by the aridity index, there is a positive relationship with consumptive water use (Fig. 1.3). The continental differences in the figure are due to the differing physiographic and economic status of the continents.

With few exceptions, most industrialized countries can provide their citizens with a sufficient supply of good quality drinking water. In contrast, measures such as river diversion (e.g., Greece, South Africa, Australia), reservoir and aqueduct construction, use of groundwater reserves, etc., often at high cost, are employed in semi-arid and arid regions. Many Middle Eastern countries (Saudi Arabia, Emirates, Israel, etc.) employ expensive electrodyalitic desalinization, and may also use solar heat to produce drinking water. In most industrial countries, high-quality water (drinking-water quality) is still used for industry, irrigation, cleaning of city streets, etc. In fact, water used for such purposes collectively in Norway, Switzerland and Austria could provide drinking water for at least half the European population. In contrast to this group of countries with abundant supplies of good quality, or the financial resources needed to provide it, about 30 developing countries face drastic deficits of safe drinking water. According to estimates, 60 more countries will face this shortcomings in the year 2000 (World Meteorological Organization, 1997). Rapidly increasing population densities, desertification and inadequate financial resources for water development are primary reasons for this situation (Rast, 1999, 2003).

On the basis of political boundaries existing prior to 1990, nearly 40% of the world population lives in international watersheds, with 23 of these watersheds being shared by 4 to 12 countries. In approximately 50 countries, 75% or more of the national territory falls within an international water basins (Shiklomanov, 1997). On a global scale, there are currently 261 international river basins (Wolf et al., 1999). Collaborative efforts to adequately managing these basins for sustainable water use is frequently obstructed by ongoing political differences, poor international relations, competition for the resource, and differences in social and economic goals. The conflicts about water resources in general, and lakes in particular, are becoming major issues in countries with water shortages. It may become the cause of local wars where countries share joint water resources (Atchia and Tropp, 1995). Water shortages are expected to increase in various locations in the future because of population growth and global climate change. The present status of water shortages for European countries, for example, and some estimates of future shifts in water demands, are given in Figure 1.4.

Some international watersheds are likely to be sources of political tensions, either presently or in the future, between the upstream and downstream countries in river basins. Former Egyptian Foreign Minister, and later U.N. Secretary-General, Boutros Boutros

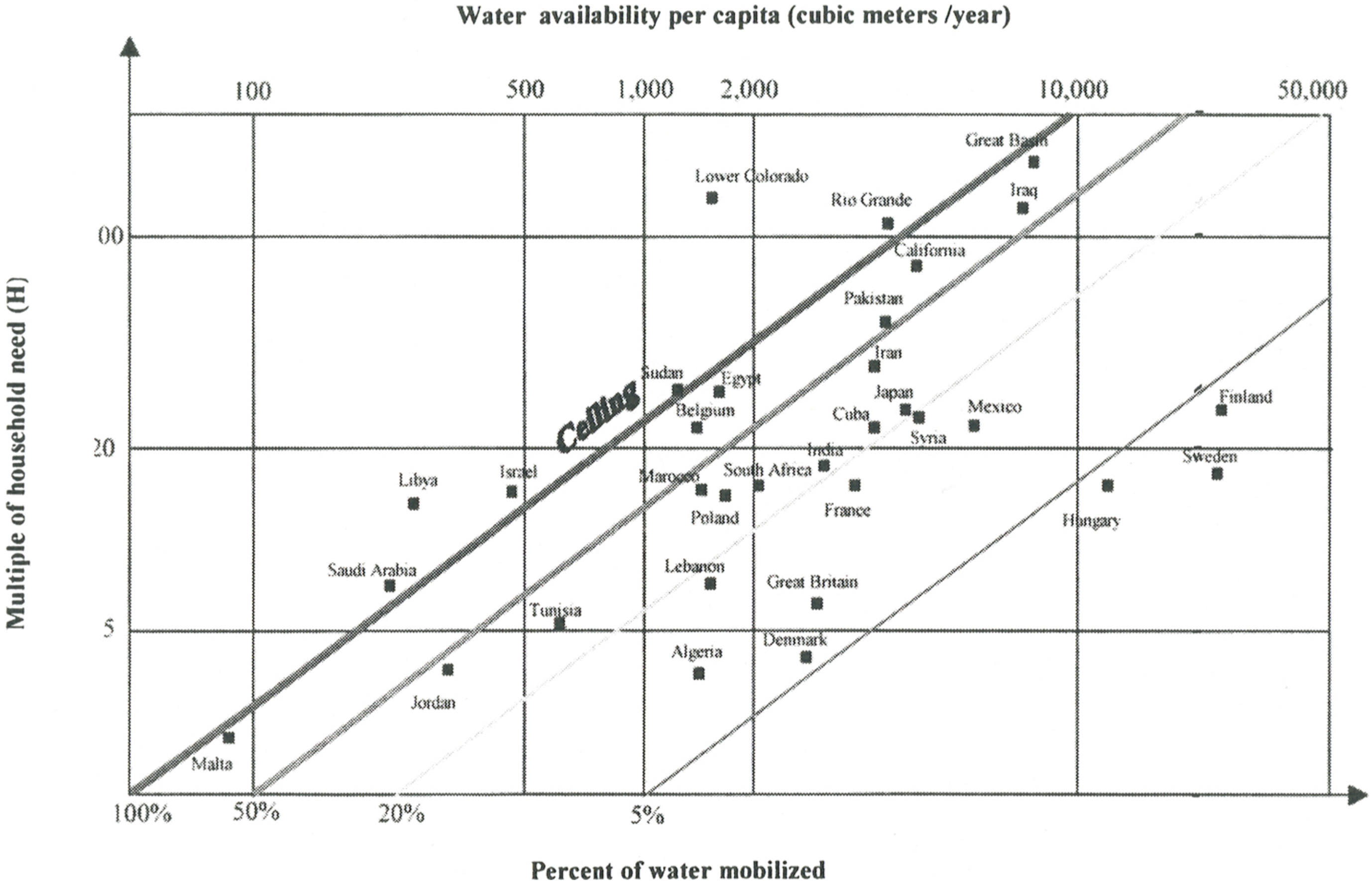

Fig. 1.3. Water availability per capita ($m^3 yr^{-1}$) and percent of water utilized in different countries (Falkenmark and Widstrand, 1992).

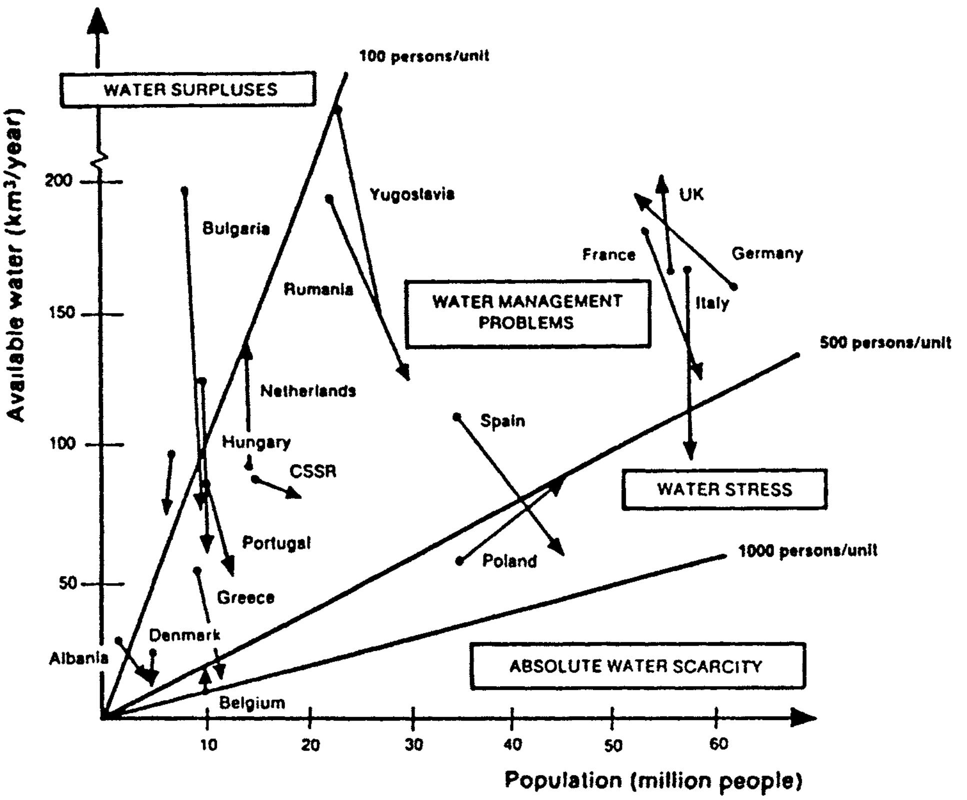

Fig. 1.4. Shifts in relative water availability of European countries in response to climate change and population growth (Falkenmark et al., 1999).

Ghali previously expressed this concern with the statement, "...that future wars in the Near East will not be connected with oil but water".

In the Hamun Basin in eastern Iran, damming activities in the lower Hilmand River section, the only tributary of the large shallow lake and its vast reed areas, have resulted in a critical drought, which may eventually cause the extinction of traditional "Gaw-dar" (cattle herdsmen) culture. With its Southeast Anatolia Project, Turkey has planned for 22 dams and 19 hydroelectric power plants in the upper Euphrates and Tigris Basin. With this ambitious plan, about 20,000 $km^2$ of dry country will be irrigated. This possibility has resulted in critical reactions by Syria and Iraq. Turkey is trying to mitigate this negative reaction with such promises as the construction of aqueducts from the Seyhan and Ceyhan Rivers, which enter the Mediterranean near Adana. In addition to the Jordan River concerns of Israel, Jordan and Syria, the Nile River Basin (3.1 million $km^2$) is the source of large-scale regional conflicts involving the annual discharge of the Nile (84 $km^3$) into the Mediterranean, with about 85% of the discharge arising from the Blue Nile, whose headwaters are in Ethiopia. Other than fossil groundwater, Egypt, with its more than 60 million people and a fast-growing population, depends almost entirely on Nile River water. Egypt has been storing Nile River water in the up to 6000 km$^2$ Aswân Dam since 1970. This large reservoir not only provides 60% of Egypt's electricity, but has also increased the country's irrigation capacity. Nevertheless, Egypt is facing critical water problems in the near future. Moreover, the sustainable water supply of the Nile River depends on Ethiopia and Sudan, countries also in need of water for an expanding irrigation system. In 1983, several Nile River Basin states attempted to form an economic grouping that could have smoothed the path for a basin-wide Nile Water Authority. Kenya and Ethiopia refused to join, however, stating their governments would only negotiate such an agreement on a bilateral basis. Despite their reluctance, these two nations may eventually participate in a basin-wide authority. At the same time, in order to guarantee itself a certain portion of Nile water, Egypt also will be required to acknowledge the water rights of all the upstream riparian nations (Anonymous, 1994).

The 4200 km Mekong is the tenth largest river in the world, carrying about 5000 km$^3$ of water each year into the sea. The river flows from the Tibetan Himalayas southward through China, passes north of Burma, its watershed encompassing nearly all of Laos, northeast Thailand, most of Cambodia and the South Vietnamese delta. Thailand is interested in allocations of Mekong River water for irrigation in its northeast. Vietnam is concerned, however, that such diversions will further reduce the river's low flows between March and May. Laos is interested in hydropower development. The Mekong River Commission might be best served by emphasizing smaller-scale development alternatives, putting aside plans for large, main stem dams that are part of the development designs of the 1950s and 1960s.

### *1.2.3 Economic Value of Water*

Water represents a renewable resource whose economic value began to be recognized only after water shortages materialized. Economists have only recently recognized that one major reason for inefficient use of water resources is that many considered them to be "free" resources with no monetary value. This has subsequently led to the establishment of an "ecological economy" which attempts to overcome this deficiency, and which establishes the economic value of natural resources. Costanza et al. (1997) recently estimated the value of the "ecosystem services" provided to humanity by and rivers, considering such functions as water regulation, water supply, natural waste treatment, food production, recreation, etc. The estimated values of these services, provided free-of-charge by nature to humans, are given in Table 1.1. It is noted that in calculating the total world economic value for lakes and rivers, Costanza and coworkers assumed a total area of only $2 \times 10^8$ hectares, a value that may be highly underestimated, based on new data provided by Meybeck (1995) for lakes. This latter estimate of total lake area corresponds to $2400 \times 10^8$ hectares, about three orders of magnitude higher than that used by Costanza and co-workers. And this latter estimates includes only lakes, not reservoirs or rivers. If a raw estimate of the total area of lakes + reservoirs + rivers is taken to be only 1.2 times higher than the estimated

Table 1.1. The economic value of selected ecosystem services provided by lakes and rivers per hectare (according to Costanza et al., 1997) and the total global value (according to the estimate by Meybeck, 1995)

| Value of ecosystem service (1994 US \$ $ha^{-1}yr^{-1}$) | | | | | Total value per hectare | Total global value |
|---|---|---|---|---|---|---|
| Water regulation | Water supply | Waste treatment | Food production | Recreation | (US \$ $ha^{-1}yr^{-1}$) | (US \$ $10^{15}yr^{-1}$) |
| 5445 | 2117 | 665 | 41 | 230 | 8498 | 4.9 |

lake area, the estimated value of the ecosystem services provided to humans by these water resources is 1440 times higher than the estimate given by Costanza et al. (1997). The recalculated value of US $\$2.4 \times 10^{15}$ per year for the whole world using these latter figures is in sharp contrast to the much lower value of US $\$1.7 \times 10^{12}$ per year estimated by Constanza and co-workers.

It is becoming evident in developed countries that increased water prices, covering not only the costs of treating and distributing water, but also the cost of the resource itself, has led to a considerable lower of water consumption in many cities. Both the quantity and quality of lake and reservoir water is conserved in this way. This is because increased water usage also leads to more water to be treated. Any treatment is only partially effective, however, and complete treatment of all effluents is not feasible in virtually any country. In many regions of the world, only a small part of water is treated, if at all. And both partially treated and untreated water reaches the waterbodies, including lakes and reservoir, with their polluting consequences.

The economic value of water is both direct and indirect. Direct values relate to the sale of water for human consumption and production. In such situations, water is a commodity. It is a phenomenon of our time that bottled water, which is commonplace in the developing countries because of inadequate water treatment and delivery systems, has become a major industry in developed countries. In part, this reflects trends within society, but also the reality that much of the freshwater of good quality previously available in large quantities is now less abundant. In the United States, for example, outbreaks of waterborne diseases in recent years has increased alarmingly, suggesting that potable water treatment techniques have failed to keep pace with the rate of decline in the quality of surface and groundwater. As a result, consumers have indicated a willingness to pay a higher cost per unit volume for water, with the cost differential reflecting their belief that bottled water is safer than public supplies. In contrast, the water consumed for agricultural services is often heavily subsidized by society, in order to minimize the cost of foodstuffs produced in irrigation schemes. These subsidies are often in the form of reduced water prices that allow agricultural producers to purchase water at rates below market value. The allocation of water between consumer groups, specifically the agricultural producers and urban dwellers of the American west, also has resulted in tensions that, at times, have taken on violent overtones (MacDonnell et al., 1995; Krannich et al., 1995; Coggins and Glicksman, 1998; Smith and Rast, 1998).

In addition to the direct costs, consumers also purchase water indirectly. Examples of such indirect costs include the nonconsumptive uses of water for hydroelectric power generation, where the cost of using water is hidden in the cost of the electric power produced, and for recreational or aesthetic uses. In the former case, the price paid for the use of the water does not involve the transfer of water to the consumer, but rather the transmission of electric power. Contained within the nonconsumptive use of water for power generation is the hidden cost of the environmental impacts of aseasonal water flows and habitat modification associated with dam operations. In the latter case, the consumer pays the price for the largely intangible benefits associated with the ambiance of lakes and rivers. In some cases, the incremental costs can be significant. In Maine (USA), a recent study indicated that a premium of approximately 10–15% of the total value of lakefront property was associated with perceived water clarity benefits (Michael et al., 1996). For clear water lakes, this premium was positive, increasing the purchase price that consumers were willing to pay. In contrast, for turbid or humic lakes, this premium was negative, decreasing the purchase price. Public perceptions of water quality, therefore, can have a major role in public economic activities.

An increasing number of industrialized countries are now using the "polluter-pays-principle", although the principle is unfortunately not used consistently or completely. An example of a complete application of the polluter-pays-principle is seen with the discharge of wastewater in Denmark. Based on analysis of the wastewater, a factor ($F$) is calculated. Although the equation used is dependent on the local conditions, the following equation is representative for the considerations:

$$F = BOD_5/(400 + BOD_5) + P/(10 + P) + N/(30 + N),$$

where: $BOD_5$ = biological oxygen demand (5 days) at 20°C;
$P$ = phosphorus concentration (mg $\mathrm{l}^{-1}$) in wastewater; and
$N$ = nitrogen concentration in wastewater (mg $\mathrm{l}^{-1}$).

The factor $F$ identifies the extra charge that industry must pay to the community to discharge wastewater. Thus, if the normal discharge price per cubic meter for municipal wastewater is $PD$, industry must pay $(F + 1)PD$. As can be seen, the equation considers the nutrient and BOD content of the discharged wastewater. This extra charge has encouraged many industries to at least partly treat their wastewater, because it was a less costly solution to treat it where it is most concentrated than to discharge highly polluted wastewater to the municipal treatment plants, where it will be considerably diluted. The introduction of the extra charge implied that the wastewater is treated at the site, where it is most cost efficient, and by the cheapest method. The discharge of toxic wastewater, on the other hand, should be completely prohibited, as it is harmful to the biological treatment processes at the wastewater treatment plants and to the waterbodies receiving the effluents.

The requirement for deposits for reusable bottles and tins is another economic means of reducing pollution. Recycling is in many ways a very attractive method to abate pollution, because it imitates the way nature handles the combined discharge and resource problem.

The use of so-called "green taxes" attempts to direct resource consumption toward more environmentally-friendly processes and products. For example, the most polluting energy sources, coal and other fossil fuels, are subjected to taxes in many industrialized countries. The heavy tax on gasoline in European countries is another example. If a polluter must pay more than the actual treatment cost at a municipal waste water treatment plant, for example, this may be considered a green tax.

It is expected that the use of green taxes will increase rapidly in coming years, particularly in industrialized countries. They will likely be applied increasingly as an instrument in resource management, as they are able to reduce the utilization of depleted resources. The renewable resources can be utilized in a sustainable manner by adjusting the rate of application to the rate of recovery. The application of green taxes can be a very powerful tool to obtain this balance.

A possible trend in the industrialized world toward replacement of income taxes by green taxes may be facilitated by the recognition that green taxes may be better able to adjust consumption patterns in society toward more sustainable resource management. Developing countries also can learn from this experience, and consider introducing green taxes, rather than income taxes, to cover the increasing income needs of the state.

Other recent developments of significant economic impact are the application of "green auditing" (Curran, 1996), "life cycle analysis" and "cleaner technology" (Section 4.2.2). It has been possible to demonstrate in numerous cases that production costs can be reduced simultaneously with environmental considerations, using these technologies. Application of such environmental technological changes in industry often results from the use of environmental certification in accordance with the ISO-standard 14000. Of particular interest for lake management is the possibility of upgrading existing wastewater treatment facilities at relatively moderate costs (Henze and Ødegaard, 1995).

### *1.2.4 The Role of Society in Lake and Reservoir Management*

The public response to the perceived degradation of rivers, lakes and reservoirs, like their perceptions of water quality, vary more as a matter of degree than as a matter of fact. Most countries of the world, for example, have some form of water resources legislation that includes elements regarding the prevention of pollution (Schlickman et al., 1995; United Nations Environment Programme, 1997, 1999). To a degree, such statements reflect the relative availability of water resources, and the range of uses to which the water resources are put, with countries that experience more severe water shortages generally having stricter water quality standards governing the discharge of materials to rivers and lakes (e.g., McKendrick, 1982).

In addition to this regulatory approach of governments on behalf of all its citizens, communities and individuals have adopted other strategies for managing lakes and reservoirs. Community actions are generally undertaken by governmental or other corporate organizations. In Wisconsin (USA), for example, citizen organizations include public "inland lake protection and rehabilitation districts", which are special-purpose governmental units formed by petition of the landowners. They have specific, but limited, authority to raise funds through taxation and other charges for lake water quality management (Dresen and Korth, 1994). Such districts undertake water quality monitoring activities, lake management planning, aquatic plant management, and informational programming. Citizen organizations in Wisconsin include lake associations, or nongovernmental organizations with a waterbody focus (Dresen and Korth, 1994). These organizations have a voluntary membership, and may or may not be incorporated as a body corporate under state law. Funding of these organizations is also voluntary, except in situations where membership in the association is a requirement of residence within certain planned communities (membership in this situation is a requirement outlined in specific clauses in the property's title deed). Incorporated organizations have access to the same state-funded grant programs as lake districts, although they lack the taxation ability. These NGO's undertake many of the same activities as lake management districts.

Similar organizational bases exist in other locations. In many cases, the same concept of public–private cooperation has proven to be a successful mechanism for engaging and directing public involvement in lake management projects. This model is reflected in actions taken by the City of Cape Town in the management of Zandvlei (Thornton et al., 1995), and in the formulation of the recently adopted water law of Brazil (Anonymous, 1997). In the former case, the City of Cape Town, for example, worked cooperatively with the Zandvlei Trust, a citizen-based nongovernmental organization (NGO), to define the perceived problems to be addressed and to refine proposed management actions. Watershed-based management measures, especially those involving substantial informational programming, also were implemented in cooperation with other NGO's within the metropolitan Cape Town area. Their efforts included such activities as anti-littering initiatives sponsored by The Fairest Cape Association. In the latter case, the Government of Brazil recognized the need for broadly based representation and public "buy-in" as the basis for successful river basin management. A key feature of this law is the creation of river basin committees, comprised of federal, state, municipal and NGO representatives, for the purposes of promoting the discussion of water resource issues, arbitrating water resource conflicts, approving water resource plans, monitoring plan implementation, proposing exemptions from water-use rights awards, establishing water charges, and promoting the equitable funding of multiple-use water resource projects within specific river basins. Thanh and Biswas (1990) and Rast and Holland (2003) summarize similar public, private and public–private water resources management approaches used elsewhere in the world.

In addition to corporate or community level actions, individuals can participate in the water resource management process. In the United States and elsewhere, citizen participation ranges from volunteer lake monitoring (Ely, 1997) to watershed-based clean-up activities (Harding, 1997). Many multiple purpose options also exist, an example being the Wisconsin Adopt-A-Lake program (McCann, 1997). In this program, schools are encouraged to take an active role in their communities by learning about, monitoring, and helping clean a waterbody within their community. These programs are designed to be fully integrated into the classroom experience and can provide a vehicle for articulating and re-enforcing many previously identified societal values embodied in rivers, lakes and reservoirs. Individual participation within such programs also can lead to a more informed and knowledgeable citizenry which supports community-based decision-making and citizen-participation within water resources management projects. Such public involvement is a key to successful environmental solutions (Davis, 1997).

## 1.3 GLOBAL REVIEW OF LAKE AND RESERVOIR DISTRIBUTION

The distribution of lakes and reservoirs around the world is irregular. Regions with water surpluses often have many natural lakes, while those with water scarcity typically have fewer natural lakes. Reservoirs, on the other hand, are build extensively in regions of water scarcity. Nevertheless, countries with many natural lakes also may build reservoirs, mainly for power generation, water regulation and navigation purposes.

### *1.3.1 Volume and Area of Lakes and Reservoirs*

Estimates of the total volume of water contained in lakes and reservoirs depends on the definition of lakes and reservoirs, and the size taken as the lowest limit considered in the estimates. Thus, the estimates vary on the basis of these differences and how they are interpreted. The total water volume of lakes and reservoirs existing prior to approximately 1975 was estimated by Margalef (1983) to be approximately 229,000 km$^3$. Another estimate made at approximately the same time was 280,000 km$^3$, which has been confirmed most recently (The Lakes Handbook, 2003). The time period of the estimate is important, since new reservoirs are continuously being constructed, while the volumes of some lakes is diminishing significantly because of mismanagement and unsustainable use (e.g., Aral Sea, Lake Chad). With the further shrinking of Lake Aral, the number of lakes exceeding 1000 km$^3$ drops from 13 to 12 (still including 4 lakes with more than 10,000 km$^3$).

The most recent estimate of the area and volume of natural lakes by Meybeck (1995) is based on a revision of earlier estimates for the 253 lakes whose surface areas exceed 500 km$^2$. The total water volume of natural lakes with areas exceeding 0.1 km$^2$ is estimated as 178,000 km$^3$, with the values for lakes with areas less than 1 km$^2$ and the values for some regions with lakes with areas between 1–10 km$^2$ and between 10–100 km$^2$ being the least-confident components of this estimate. About half (82,500 km$^3$) of the total lake area is represented by saline lakes, with the Caspian Sea comprising 95% of the latter. The distribution of lakes based on their surface areas and the number of lakes comprising the total lake areas and volumes in different size categories is illustrated in Figure 1.5.

The figure indicates there is only one lake of the size class 10$^5$–10$^6$ km$^2$, but over one million lakes less than 0.1 km$^2$ in surface area. The smallest lakes represent a very small fraction, however, of the total lake area and total lake volume. The total area of lakes in the regions for which direct estimates are available is estimated to be about 1,610,000 km$^2$, with one-half being in Canada and one-quarter being in the territory of the former Soviet Union. The total area of natural lakes on the globe, however, is estimated to be about 3 million km$^2$, which represents approximately 2% of the Earth's land surface. There are large

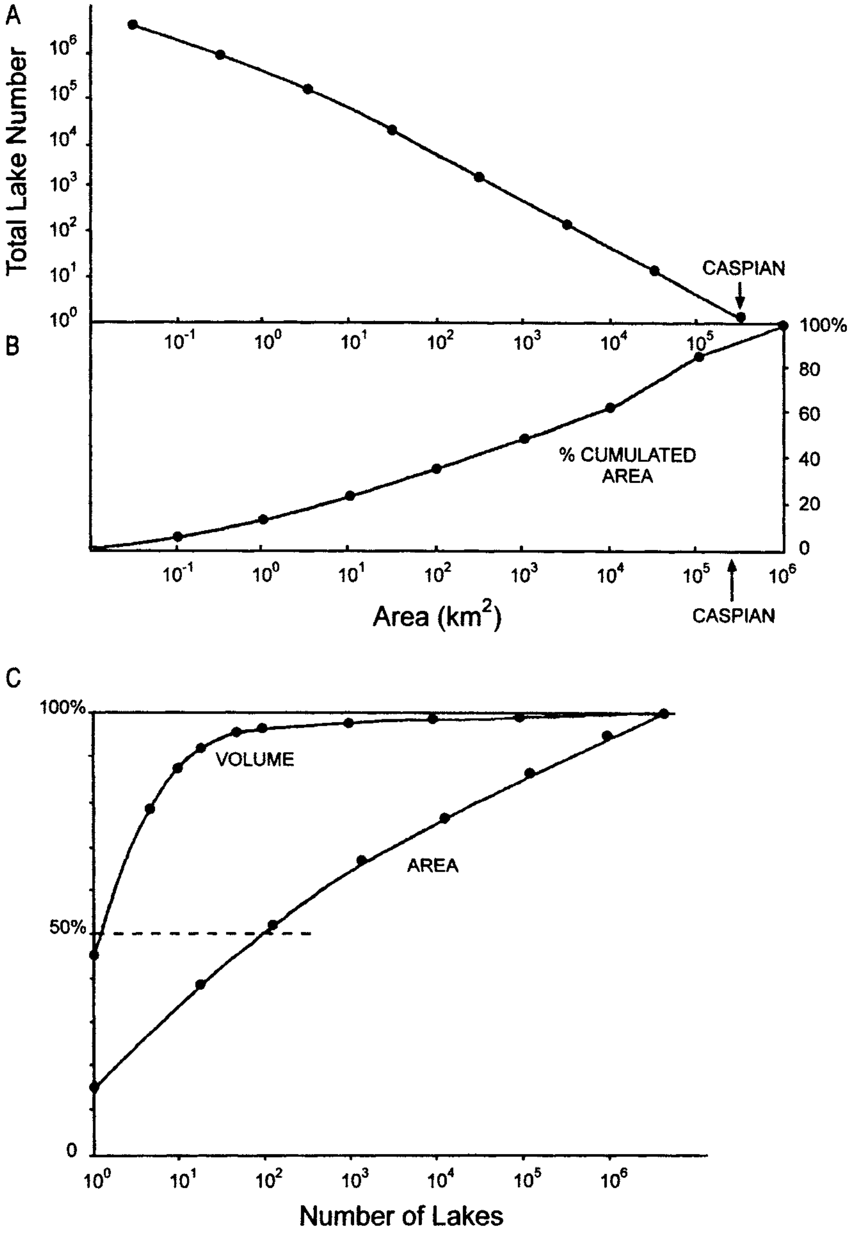

Fig. 1.5. Cumulative lake volumes and area with increasing lake numbers and cumulative area and total lake numbers, based on sizes of natural lakes (Meybeck, 1995).

differences between countries (e.g., 9.4% in Scandinavia, 0.88% in China and Argentina, 0.09% in France). The number of lakes exceeding 10,000 km$^2$ has been reduced to 17 from 18 due to the shrinkage of the Aral Sea. Geographically, most lakes are located in the deglaciated climatic zone (Table 1.2). The total number of lakes is estimated to be about 6.1 million. Lakes with surface areas between 0.1–1 km$^2$ represent about 5 million of the total.

From the perspective of water quantity management, the larger lakes would be the most logical choices for addressing large-scale human water needs. The hydrological reality, however, is that this use is constrained by their limited numbers and irregular distribution.

Reservoirs (artificial lakes) have existed for more than 6000 years (e.g., Kosheish Dam during the first Pharaoh Menes, 4900 BC) and have rapidly increased in number and size in the 19th Century, mainly in response to increased water demands for irrigation and energy. The most accurate reservoir data exists only for the larger ones. The World Register of Dams (International Commission on Large Dams, 1998) classifies large reservoirs as those (i) with dam heights of lists reservoirs with dam height of at least 15 meters and any volume

Table 1.2. Lakes of different size classes in major geographic regions (modified from Meybeck, 1995)

| Climatic zone | Lake class based on surface area | | | | Total lake area ($10^3$ km$^2$) |
|---|---|---|---|---|---|
| | 0.01–0.1 | 1–10 | 100–$10^3$ | $10^4$–$10^5$ | |
| Deglaciated regions | | | | | |
| *A* | 229 | 340 | 333 | 345 | 1247 |
| *n* | 3805 | 69.8 | 0.76 | 0.009 | |
| *dt* | 210 | 388 | 0.04 | 0.005 | |
| Temperate regions | | | | | |
| *A* | 20 | 34 | 103 | 31.5 | 188 |
| *n* | 310 | 5.8 | 0.17 | 1 | |
| *dt* | 12 | 0.23 | 0.008 | 0.004 | |
| Dry and arid regions | | | | | |
| *A* | 15 | 27.5 | 85 | 475 | 602 |
| *n* | 283 | 4650 | 0.147 | 6 | |
| *dt* | 67 | 0.115 | 0.09 | 0.0012 | |
| Wet tropical regions | | | | | |
| *A* | 39 | 52 | 50 | 81.47 | 223 |
| *n* | 600 | 11 | 0.11 | 0.002 | |
| *dt* | 25 | 0.44 | 0.084 | 0.00008 | |
| Desert regions | | | | | |
| *A* | | 7 | 55.6 | 64 | 127 |
| *n* | | 0.96 | 0.049 | 0.001 | |
| *dt* | | 0.04 | 0.02 | 0.0004 | |

Explanation: The temperate region is divided into two subregions, based on the extent of glaciation. Each value represents the center of the class in km$^2$.

*A* = area ($10^3$ km$^2$); *n* = number of lakes (thousands); *dt* = ratio of total area of region covered by lakes.

or (ii) a minimum dam height 10 meters and a volume of at least one million $m^3$. Some regions have many reservoirs, an example being Spain with more than 1000 reservoirs with volumes exceeding 40 $km^3$ on a territory of about 500,000 $km^2$, primarily because of its arid climate. Countries with many natural lakes, however, also may build reservoirs. An example is Finland, with about 10% of its land surface covered with natural lakes, but which also has built many reservoirs, some of considerable size (e.g., Porttipahta, containing about 1.35 million $m^3$ of water). Another example is Canada, with a high proportion of natural lakes, relative to its land surface area. Nevertheless, its Southern Indian Reservoir Complex, built mainly for hydropower generation, covers 2391 $km^2$ and contains a water volume of more than 23 $km^3$. As shown in Figure 1.6, the historic trends of reservoir construction are relatively similar in different countries. As seen from the comparison of the number and volumes of reservoirs in a few countries, smaller reservoirs were built in earlier periods, while the construction of larger ones has mainly been since the 1970s. Although reservoir construction continues in various locations around the world, during the last periods covered by these surveys, both the number and volumes of reservoirs have leveled off, and the rate of reservoir construction is decreasing dramatically, when one compares reservoir construction patterns between 1940–1950 and 1980–1990.

The geographic differentiation of reservoirs also is informative. Data for single regions indicate that, while there are few natural lakes in regions of water scarcity, many reservoirs have been built in such regions to compensate for water shortages. Far fewer reservoirs are generally found in regions with many natural lakes, and vice versa, as seen with the situation in the United States (Fig. 1.7). Intensive reservoir construction began only after 1900, with the two world wars interrupting this trend. After 1945, another boom or reservoir construction took place. After 1985, however, reservoir construction showed a marked decline, and very few new large reservoirs are now being planned. Virtually all the large reservoirs being constructed now are in developing countries (Rast, 2003; Rast and Thornton, 1999).

### *1.3.2 Geographical Conditions and Their Effects on Lakes and Reservoirs*

As shown in the previous section, the geographical distribution of lakes and reservoirs is uneven. This is due to major geographic differences in physical characteristics, first of all being their hydrological budgets. The consequences of hydrological budgets and other geographically conditioned variables are significant, not just for the existence of lakes and reservoirs, but also for other water quality processes. This is reflected in lake thermal structure and water mixing via the distribution of radiation, temperatures and winds, in aquatic chemistry via changes in soil and vegetation, and in the aquatic biology via temperature and other influences. The distribution of human populations also is an indirect effect, although is becoming a very strong influence in many places.

Another consequence of the geographical differentiation is the varying species composition of local flora and fauna from region to region, with more detailed differentiation than that based on the ecoregions defined below. This has consequence for biological monitoring, in that any system based on the presence of individual species is only local, and should not be used in other regions.

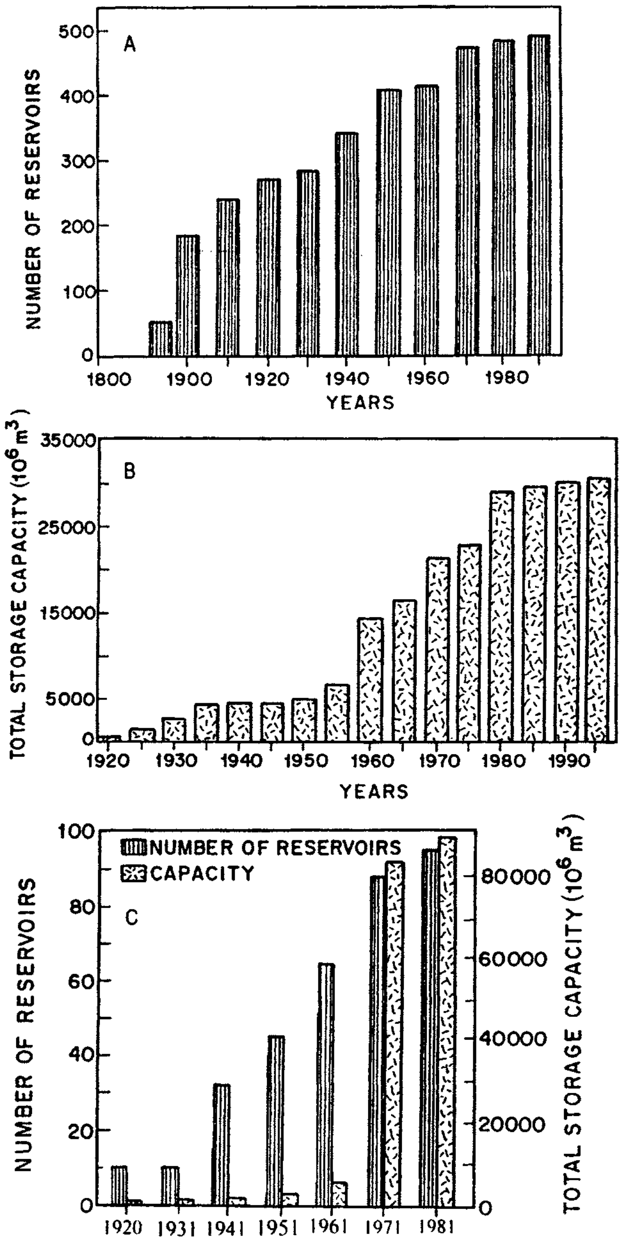

Fig. 1.6. Historical development of number and volumes of reservoirs in different countries. A—Number of reservoirs in United Kingdom (Stanners and Bourdeau, 1995); B—Reservoir storage capacity in Murray–Darling Basin of Australia (Blackmoore, 1995); C—Numbers and/or storage capacity of reservoirs.

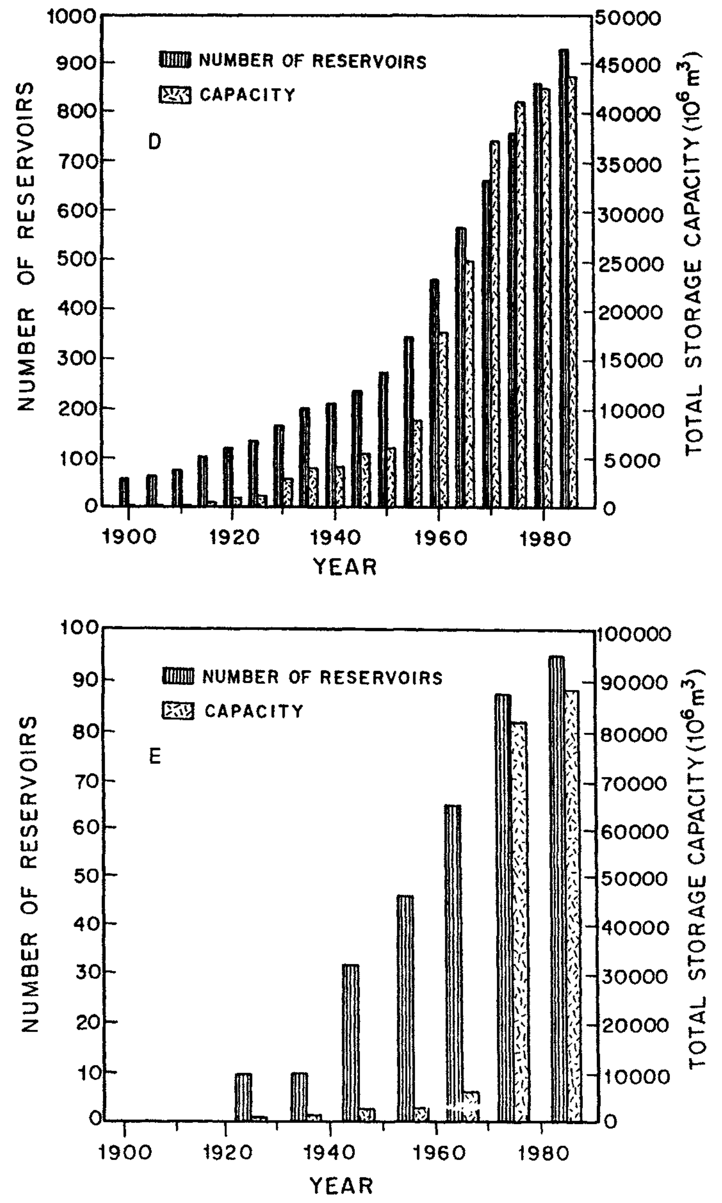

Fig. 1.6 (*continued*). D—Number and volume of reservoirs in Spain (Riera et al., 1992); E—Number and capacity of reservoirs in Germany.

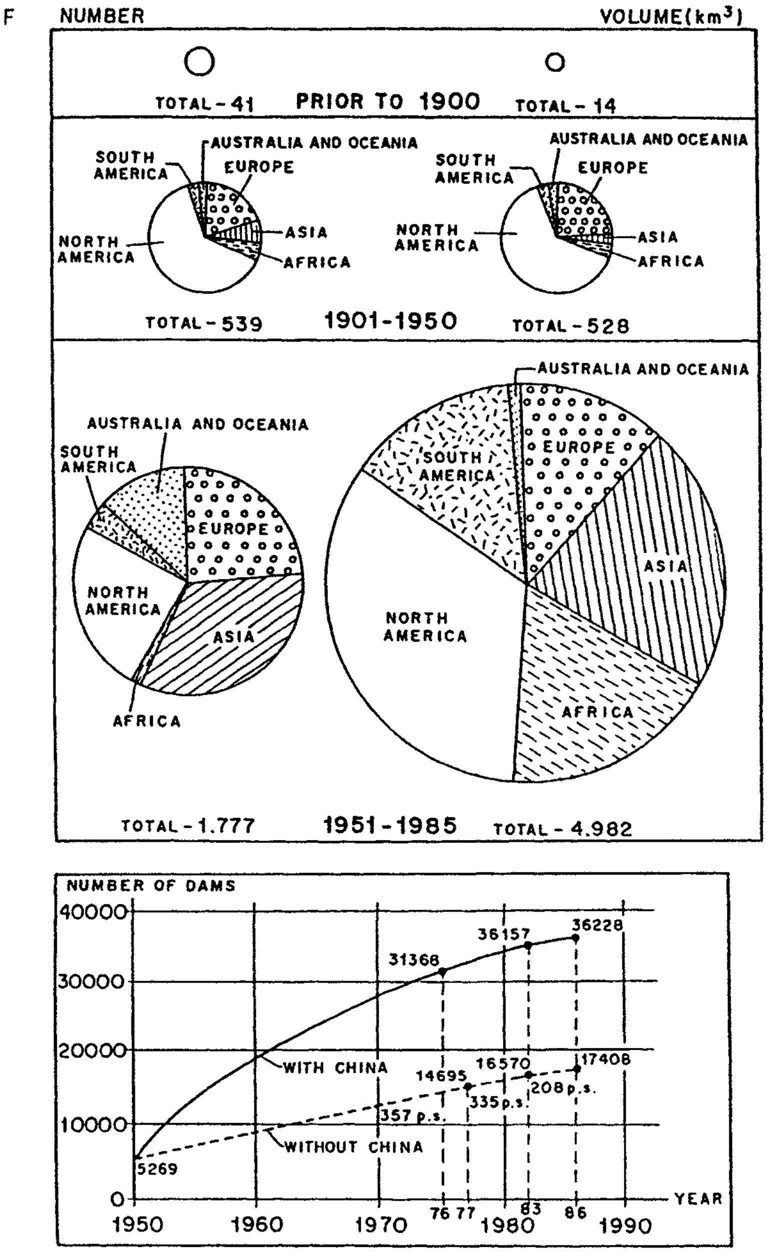

Fig. 1.6 (*continued*). F—Comparison of reservoir developments throughout the world (Mermel, 1991).

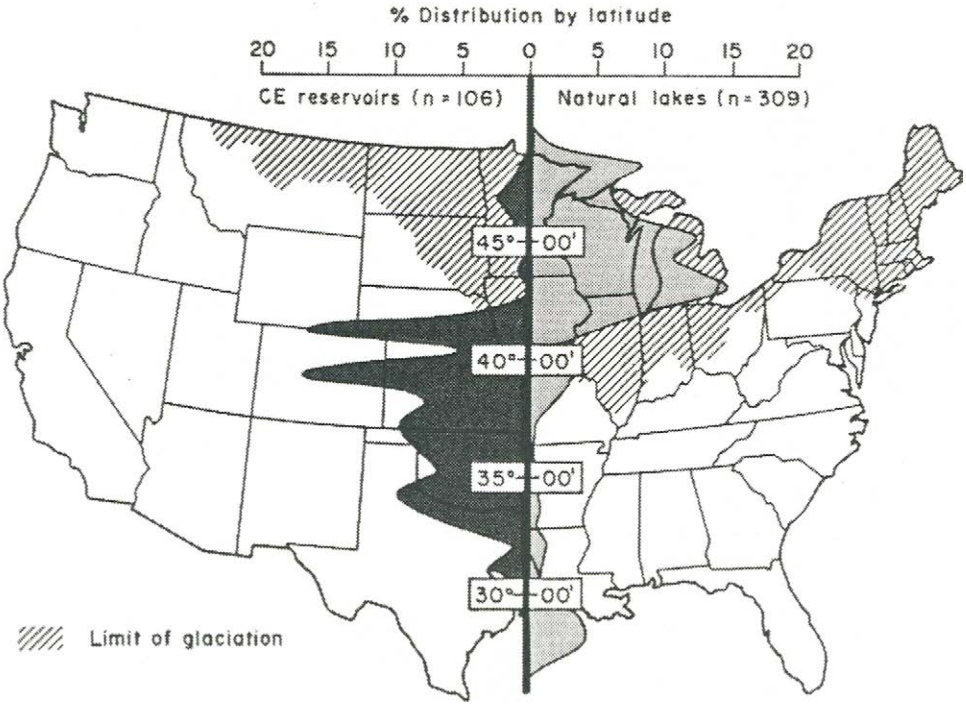

Fig. 1.7. Distribution of natural lakes and reservoirs in the United States (Walker, 1980).

A short description of the basic ecological zonation around the world is given in the following section, along with a discussion on how it is reflected in lake and reservoir water quality variables. Effective water quality management efforts must consider and reflect these differences.

### *Major ecoclimatic regions*

Figure 1.8 illustrates a gross differentiation of the world's major ecoregions. The physical conditions of the major global ecoregions relevant to a water quality perspective are based on patterns of precipitation, evaporation and the resulting flow, solar radiation, wind speed and direction, cloudiness and air temperatures. These are summarized in Table 1.3, along with the resulting major characteristics of lakes and reservoirs of given regions. It is evident from Figure 1.8 that, although the zonation is largely latitudinal, major modifications also exist because of the distribution of continents, mountain ridges, and the effects of the oceans. The zones are located approximately symmetrically in respect to the Equator. Differences between the Northern and Southern Hemisphere, however, are due largely to the much smaller land mass in the South (except for Antarctic). Thus, the values given in the table and following figures are only approximations.

Table 1.3. Four major geographical zones and resulting lake and reservoir characteristics

*Humid tropics* (0–15° latitude)

Radiation—Highest annual average radiation with very low seasonal and stochastic component

Photoperiodicity—Constant

Mixing—Deepest from all regions

*Dry regions* (15–35° latitude)

Hydrological budget—Negative, leading to extreme stochastic variability of precipitation and flow rates

Mineral turbidity—Extremely variable, related to above

Chemical composition—Extremely variable

*Temperate regions* (35–60° latitude)

Radiation—Largest seasonal component of incident solar radiation variability and radiation available to lake phytoplankton

Air and surface temperature—Largest seasonal and stochastic components of variability

Minimum surface temperature—Reaching to freezing point

*Subarctic and polar regions* (> 60° latitude)

Zone of continuously-frozen lakes

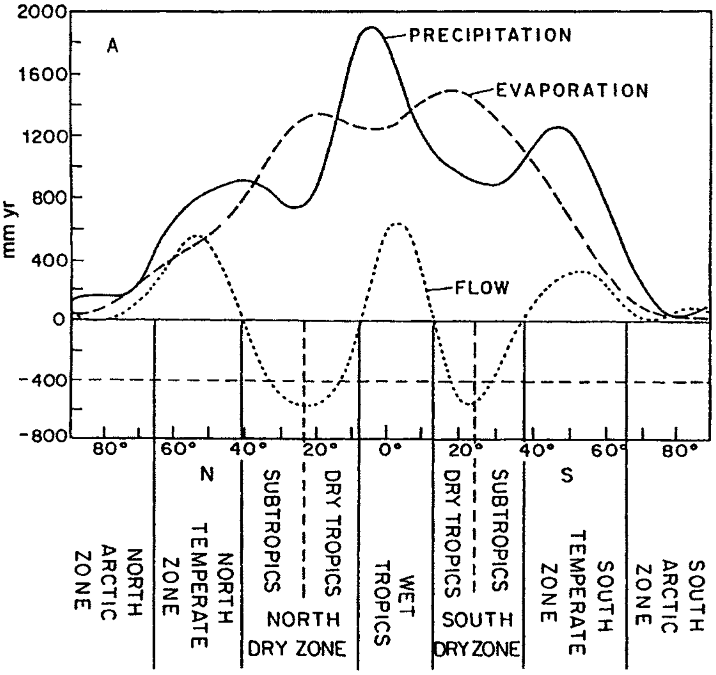

Fig. 1.8. The distribution of water budgets and soil characteristics. A—Annual average precipitation, evapotranspiration and runoff, based on latitudinal zones (Straškraba and Tundisi, 1999).

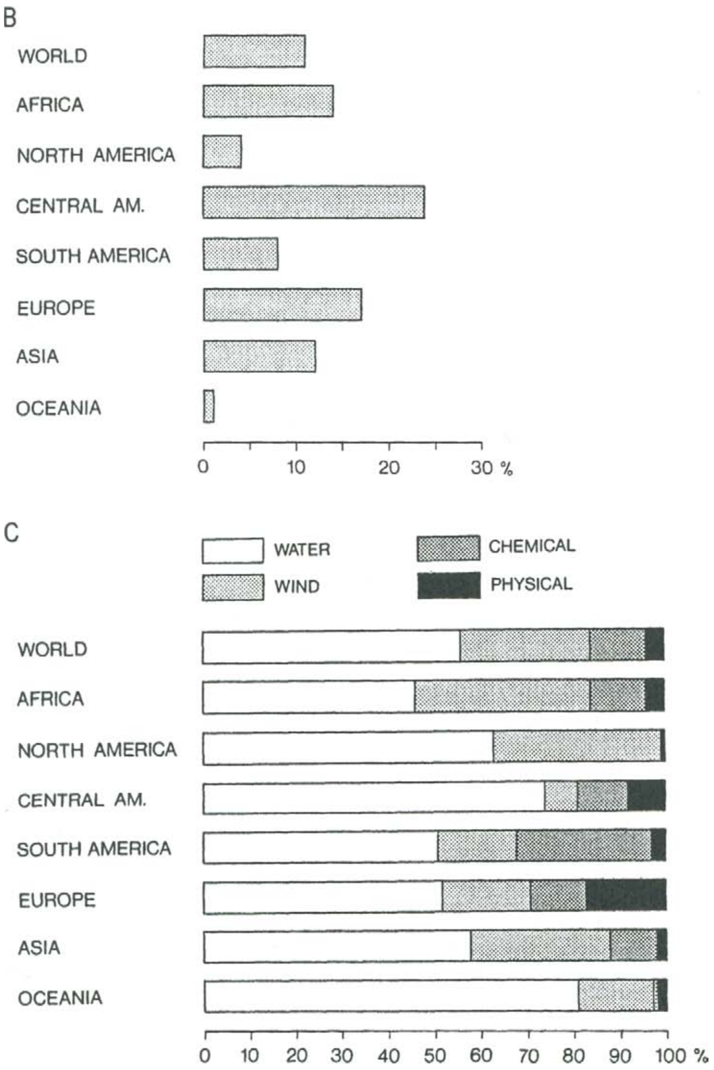

Fig. 1.8 (*continued*). B—Soil degradation as percent of vegetated land, 1945–1990 (Hebel, 1995); C—Types of soil degradation by region, 1965.

The distribution of the average annual water budget around the globe shows an approximate regularity on both sides of the Equator. Extremely dry regions are found mainly at latitudes around 20°C (the trade winds zone), with highly negative water budgets where evaporation greatly exceeds precipitation. Negative water budgets occur at latitudes between about 10 and 35 degrees. There is a smooth transition of water budgets along the latitudinal axis, and exact boundaries between zones do not exist, except where

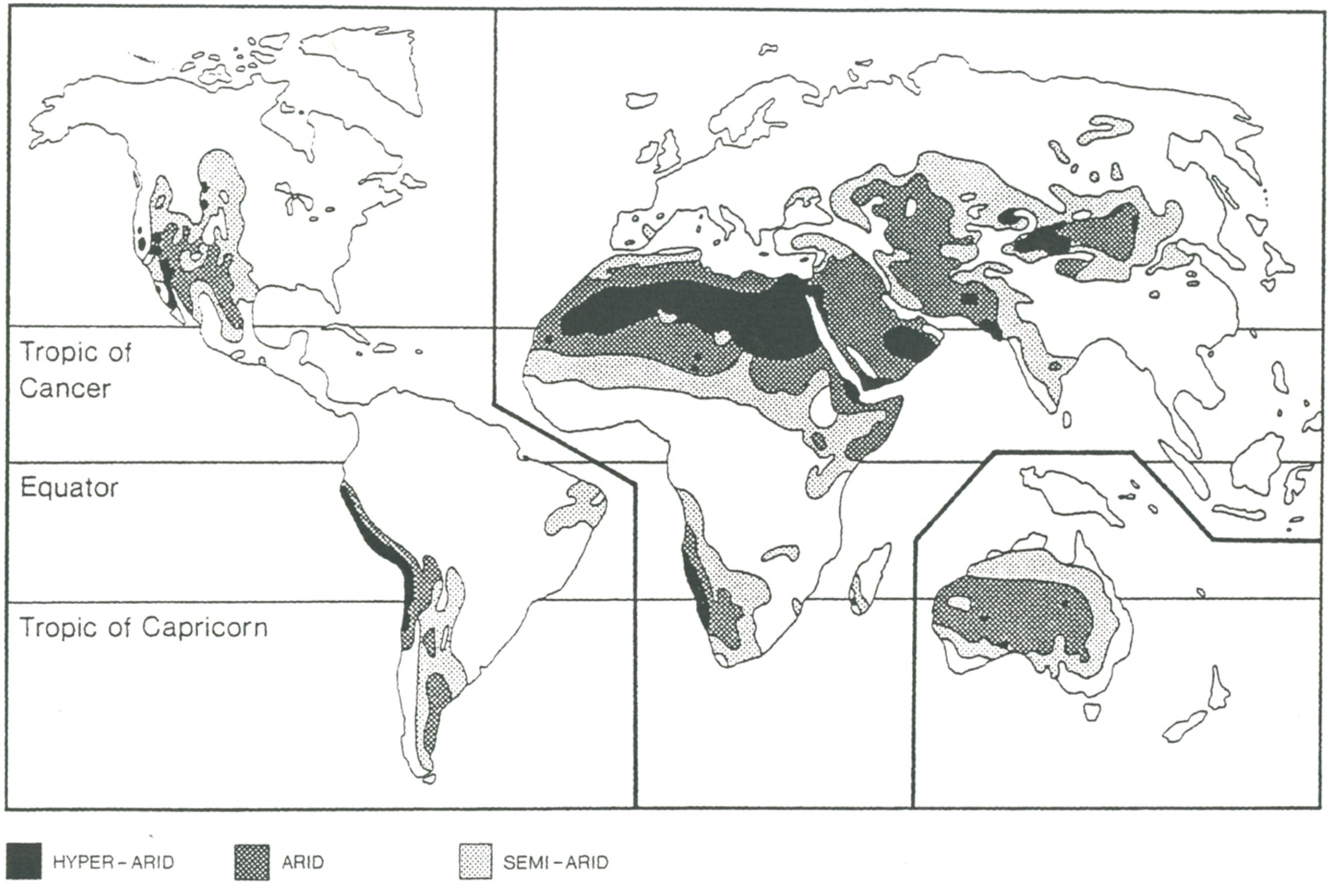

Fig. 1.9. Major arid regions of the world (Bailey, 1996).

supplemented by more clear-cut boundaries among vegetation types and mountains, such as in East Asia or along the Americas.

The same approximate regularity is seen for other variables. Thus, in the following text, latitude is considered independently of its position on the Northern or Southern Hemisphere. The half-year time shift in the position of seasonal maximum and minimum as shown schematically for temperatures in Figure 1.10, however, should be kept in mind. Some differences between the Southern and Northern Hemisphere are caused by different proportions of land and sea; in the North there is more land area, while the sea is more extensive in the South.

In addition to the major latitudinal zones for the existence of lakes, there are more subtle differences within individual countries that may be of great interest to water managers.

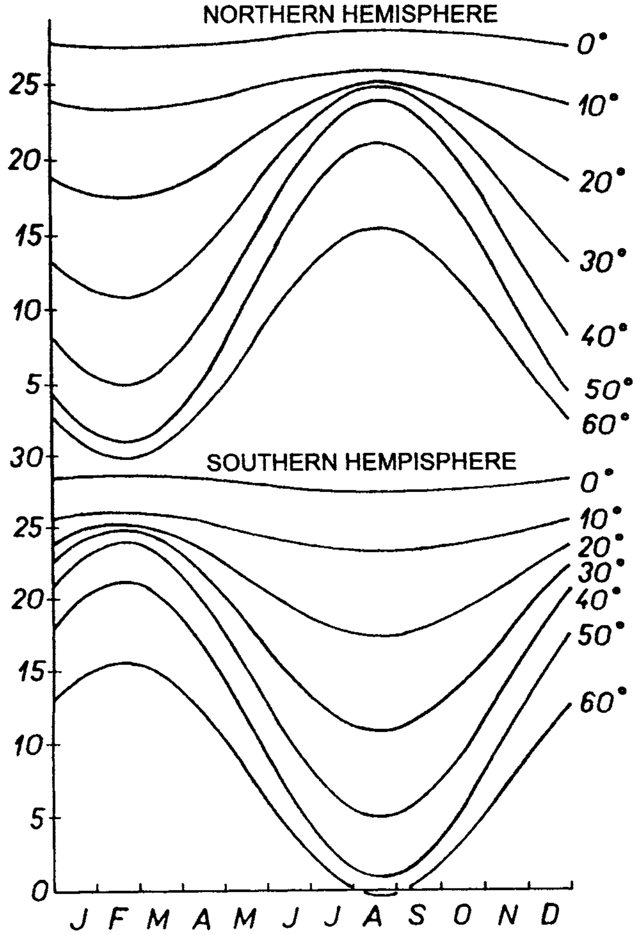

Fig. 1.10. Average global temperature distribution by continent and globally (Straškraba, 1980).

These are due primarily to the effects of continentality, elevation, orography and geology, with the associated soil and vegetation types.

Continentality expresses the distance of the land area from the sea. Its effect on the extremity of temperature fluctuations is well known, with nearshore areas being known for milder temperatures, and inland areas for harsher temperatures. This difference is reflected in air temperatures, with the annual temperature amplitude increasing about 1.6 times in the first 10 km from the shores, but progressively rising to 2.6 times at a distance of 100 km and to 4.6 times at 1000 km from the shores (Straškraba, 1993). Lake temperatures change correspondingly, with increased summer temperatures. There also is a decrease of lake salinity inland, although this effect is restricted to a several kilometers range along the shoreline.

Altitudinal differences are to some degree equivalent to latitudinal differences. The annual average water temperatures seem to decrease with altitude, at a rate of about 0.4–0.8°C per 100 meter elevation. Precipitation, solar radiation intensity and wind speeds generally increase with altitude. The effect of higher wind speeds on lakes are often compensated by more complex orography in mountainous regions. Some differences in population densities and land use also will be associated with altitude, with less people and less intensive land use generally occurring at higher altitudes.

In addition to factors that are closely related geographically, other factors also show geographic trends. The relation to geography, however, is indirect and less pronounced. The trends are loosely related geographically (e.g., water turbidity is much higher in drier regions and regions with intensive rains). Variables unrelated to geography, such as the nutrient loads resulting from human activities, or differences in biological composition due to fisheries and pollution, may override the geographical dependencies.

A recent development in a number of countries is to distinguish "ecoregions", characterized by general ecological conditions (Omernik, 1992, 1995). A regionalization based on total phosphorus concentrations in waterbodies in the United States, for example, was made by Rahm et al. (1995).

*Relation of geography to water quality*

In Figure 1.11, the macro-geographical differences in physical forcings relevant for the water quality of lakes and reservoirs are diagrammed for locations at given latitudes, irrespective of their North or South location. Three components are distinguished, including (i) annual average values; (ii) seasonal variability; and (iii) degree of stochastic, irregular component. The three components together best characterize conditions at any given latitude.

The aquatic chemistry of lakes and reservoirs also is dependent on geography, although the differentiation is less clear because of the interference of local geological formations. The ratio of precipitation to evaporation plays a role not only in diluting or concentrating chemical species, but also in determining the dominant minerals in the water.

The sediment load to lakes and reservoirs is typically determined by runoff conditions in their drainage basins, and is an important variable affecting the operational life of a

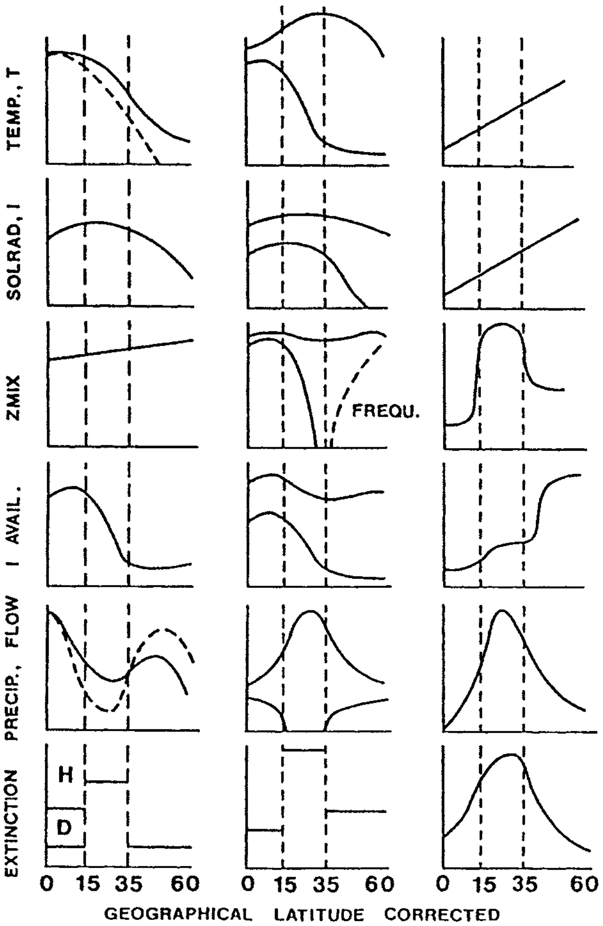

Fig. 1.11. Macro-geographical differences in physical forcings: Average, seasonal and stochastic components of latitudinal variations in solar radiation, air and water temperature, precipitation, water flow, turbidity and light availability for phytoplankton in lakes and reservoirs (Straškraba, 1993).

reservoir. The development turbidity is parallel to the ecoclimatic regions, with highest turbidity in dry regions.

A lake located high above sea level, therefore, will on average have conditions similar to a lower latitude lake situated at higher latitudes. Differences of only several hundreds of meters in elevation can play a significant role in influencing these conditions.

A characteristic feature for lakes in any geographical position is the annual water mixing cycle, a very important property influencing the development of water quality over the annual cycle. Mixing types have been found to be related to geographical latitude and altitude (Hutchinson and Löffler, 1956). The effect of altitude reflects altitudinal changes in temperature and other previously-described variables. The overall effect is that the geographical boundaries for different mixing types are related to altitude as one moves toward the higher latitudes.

The only mixing type almost independent of geography, and which occurs in most regions of the world, is the polymixis, or transitory complete mixing of shallower waterbodies. The delineation of the depth of polymictic lakes is due to their relative, rather than absolute, depth. Thus, it cannot be unequivocally said, for example, that lakes with depths greater than a certain number of meters will mix, while lakes deeper than this depth will not. The mixing is basically due to two forces; namely, the force of the wind, and its counteraction by buoyancy related to the potential kinetic energy of the water mass in the lake or reservoir corresponding to its temperature structure. The wind starts to act on the water surface essentially on the basis of the 1 : 8 rule, which means that the wind blowing over a landscape reaches the water surface approximately in the distance from the shore that is 8 times the height of obstacles on the shore. The wind fetch, the force with which wind creates water movement and mixing, is related nonlinearly to the distance the wind travels over the lake surface. The wind gains speed over flat, smooth water surfaces. Thus, lake mixing depends on the size of a lake, rather than its absolute depth. Because wind-induced mixing penetrates just to a certain depth, it is the ratio between the depth of wind mixing for the particular size and wind exposure of the lake that is decisive for its hydrological shallowness and polymixis. The second defining variable for wind mixing is the thermal structure of the waterbody, mainly the air–water temperature difference and the development of internal density gradients. The same wind fetch will cause much deeper mixing when the gradients are low. This is why polymixis will be restricted to waters only a few meters deep in temperate regions, while polymixis also is common for very deep lakes in high altitude tropical regions. Polymictic waterbodies are intermittently mixed and stratified, depending on the existing weather conditions. On calm days, particularly with nights when the air temperature remains higher than the surface water temperature, and no wind stirs the water surface, stratification of the water column begins and can persist for a few days, until the wind starts to blow and the temperature grows colder. When this happens, the surface water cools down, sinks because of its greater gravity, and mixes the waterbody via convective mixing. Anoxic conditions in polymictic lakes are more detrimental to water quality than for lakes of other mixing types because it developed very rapidly (within a few days), unlike other mixing types. The onset of thermal stratification prevents mixing between the deeper and shallower water layers in lakes and reservoirs, and the ratio of the water–sediment contact zone to the water volume of the layers that are isolated from contact with air is much lower. Thus, the oxygen consumption in this small volume can result in rapid oxygen depletion.

Outside the tropical belt, where seasonal climate dominates, three mixing types with respect to full circulation of the waterbody may be distinguished. Cold monomictic lakes are connected with high latitude and altitude, and are frozen over most of the year. They are fully mixing only during summer if their surface temperatures do not exceed 10°C, which implies only small density differences. Inflow from glaciers or frequent cloudiness are most likely essential to provide for the low temperature. Otherwise, the twenty-four-hour period at high latitude and the strong insolation at dry high altitude areas may easily heat the upper layer of lakes and thus suppress full circulation. Due to the ongoing climatic change, cold monomictic lakes are obviously extremely rare and most likely absent from the Southern Hemisphere. There are some indications that during certain periods of the (early) Holocene they might have been common (Löffler, 1998). Lakes with two circulations—after cooling during autumn followed by the break down of the thermal stratification and after the melting of the ice during spring or at least the inverse winter stratification—are designated dimictic and most common throughout the Northern Hemisphere. Most likely among deep lakes they even present the majority on our globe. However, they are almost missing in the Southern Hemisphere where they obviously are limited to the southern Andean region. This is mainly due to the oceanic predominance, which is also responsible for their absence in most of Japan and in Ireland. Finally, warm monomictic lakes undergo circulation during winter at temperatures well above 4°C. They are typical of the Mediterranean type of climate, as well as regions with strong oceanic influence. Ireland and most of Japan are examples where this climatic type, which dominates in the Southern Hemisphere, prevails.

Within the tropics, distinguished by preponderating diurnal climate, lakes at great altitudes (mostly well above 4000 m) lack any persistent thermal stratification. Cooling during the night (typical of altitude ranges with regular change of frost and thaw) results most often in complete mixing, followed by only feeble stratification during the day. This kind of lake has been labeled cold polymictic (Hutchinson and Löffler, 1956). The majority of this type is known from the tropical Andes (Löffler, 1960), high mountains in East Africa and New Guinea. In contrast to the proposition made in 1956 (Hutchinson and Löffler, 1956), tropical lakes at low altitude have a tendency to mix completely once a year (instead of several times), most often during the dry season. In East Africa, Lake Victoria is a remarkable example of this phenomenon. Therefore, they are denoted monomictic lakes which must be distinguished from temperate warm monomictic lakes. Warm polymictic lakes as described by Hutchinson and Löffler (1956) may be connected with regions where sudden cold rain events or even hailstorms are frequent events. With their high density gradient and only a few degrees difference between surface and maximum depth, such climatic impacts can easily release complete mixing of a lake. Another rather hypothetical group suggested by Hutchinson and Löffler (1956) comprises an oligomictic type characterized by very infrequent circulations at irregular—not even annual—intervals.

Finally, it should be mentioned that the globally distributed amictic lakes, which are sealed by ice from any climatic influence since the onset of climatic warming, have become increasingly rare. They were known from glaciated high mountain areas, such as the Alps, the Andes and Mt. Kenya (Curling Pond, at least until 1960). At present, only a few examples exist in the polaric regions. The most prominent one, Lake Wostok in Antarctica, may be frozen over since the late Pleistocene Era. It should be stressed that, along with climatic warming in our time amictic lakes within the tropical belt turn into cold polymictic ones, and outside the tropical climate turn into cold monomictic, if not immediately into dimictic types. The latter can then turn into warm monomictic ones. Within the tropical belt the cold polymictic lakes will be shifted increasingly to higher regions, whereas the other types mentioned will probably be more subjected to regional climatic changes.

Among these climatic types of fully circulating (holomictic) lakes, the warm monomictic, monomictic and dimictic ones are most likely to undergo oxygen deficiencies even under natural conditions. This is much more so in lakes with a permanent density gradient, which results in partial circulation (meromictic lakes) and in anoxic conditions in the deeper water layers. The most prominent example of this phenomenon is Lake Tanganyika, with a maximum depth of 1471 m, but devoid of oxygen below about 110 m. In small lakes the anoxic deep water ("monimolimnium") below the upper circulating layer ("mixolimnium ") can be, if desirable and feasible, reduced or even removed by means of the Olszewski-tube (a siphon technique).

Most of the described climatic types of deep lakes—although less so for the reservoirs—are located in exorheic regions connected to the sea. Within endorheic basins, any connection with the sea, they are most often confined to the boundary region of such regions, with their main distribution in Australia, Asia and Africa. They are much less presented in the Americas and Europe. Endorheic regions are recognized by their great diversity of hydrological and chemical features, and need significant attention with respect to their water management. The catastrophe of the Aral Sea, and the rapidly increasing problems of the endorheic region in Iran are dramatic examples of mismanagement of lakes which can hardly be restored. In both cases, large scale agricultural projects were responsible for the observed disastrous conditions. Similarly, agricultural activities in dry regions (both, endorheic and exorheic) require the use of lakes for irrigation, causing hydrological and pollution problems. Examples of such impacts are numerous. In Europe, they are well known in the Mediterranean region (e.g., Lake Prespa, shared by Albania, Greece and Macedonia). Some regions are also characterized by large scale water transfer projects (e.g., South Africa, Mexico, Greece, etc.) which often are combined with the construction of reservoirs, but also contribute to the devastation of lakes and wetlands (e.g., Jonglai-Canel, Sudan-section of the Nile).

### *Consequences of geographic differences for water quality management*

The geographical differences of a number of water quality variables are great. It would be erroneous to use experiences from one region for managing lakes and reservoirs in other regions, without taking such differences into account. The material below describes some of the relevant rules to be considered in this context.

*Regions with low and high population densities.* Although directly and indirectly related to geography, there are major regional differences in population density and its economic wealth. Summarizing investigations show that a strong correlation exists between pollution and population density for a number of water quality variables. Figure 1.12 illustrates the relations between some water quality variables and population densities in different regions. It would be erroneous, therefore, to use estimates made in a region with low population density to another region with high population densities. The differences are not just related to the population density itself, but also to the differing practices of peoples living in the different regions.

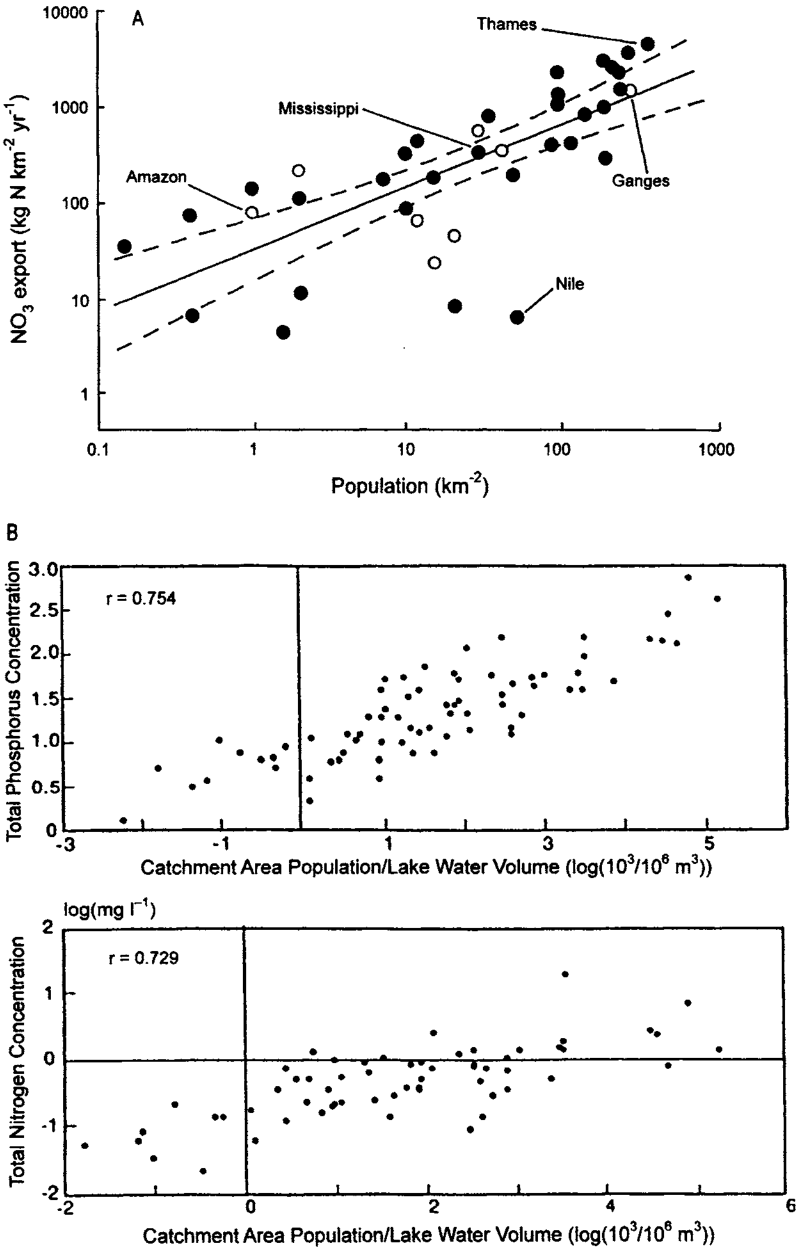

Fig. 1.12. Population density and water quality variables. A—Average annual export of nitrate as a function of human population density in the catchments (open circles—tropical rivers; filled circles—other rivers; Howarth et al., 1996); B—Relation between total phosphorus and total nitrogen concentrations in catchment areas and lake volumes (Kira, 1993).

*Temperate and tropical regions.* Experiences from temperate regions, from which most lake and reservoir knowledge has been gained, are often applied to tropical conditions. This error can happen both to experienced temperate zone limnologists and water quality managers with no experience in tropical regions, and to tropical specialists trained in a temperate country. The domination of the daily cycle over the annual cycle, typical of tropical conditions, is often ignored since nothing similar occurs in the temperate regions. The domination of the annual cycle in temperate lakes also is reflected in phytoplankton production as the primary source of eutrophication difficulties (Fig. 1.13). Inaccurate conclusions are easily made from water quality measurements taken in shallow tropical waters during morning hours when the water is mixed, while it may become stratified and anoxic during the day. Lake and reservoir water quality monitoring must consider these daily differences much more strictly than in the temperate regions, where differences in some variables such as pH, oxygen and nutrient concentrations are not very pronounced over a period of a few hours. Anoxic conditions can occur in tropical regions at lower external organic loads because of higher temperatures and higher production of allochthonous

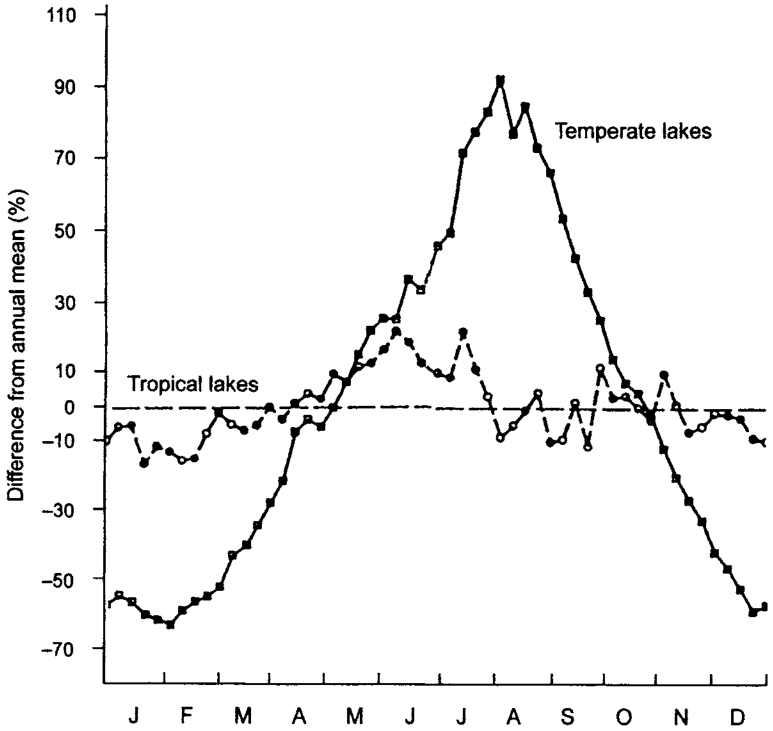

Fig. 1.13. Seasonal variation of primary production by phytoplankton in temperate and tropical lakes (mean percentage difference from annual mean values; modified from Alvarez Cobelas and Rojo, 1994).

organic matter by phytoplankton. One feature easily overlooked because of similar effects on lake and reservoir water quality, but with completely different consequences for their management, is the differing nature of the problem of general pollution and eutrophication (Rast and Thornton, 1996). While in-lake methods may be effective in treating eutrophication symptom in some cases, efforts to treat pollution typically must concentrate on the drainage basin.

*Dry and wet regions.* Major differences also exist between the wet, near-Equator part of the tropics and the dry belts around it. Similar, but less pronounced, differences exist between regions with more balanced hydrological budgets (i.e., evapotranspiration approximately equals precipitation) and more arid and semiarid regions. Much greater variability in water quality can be expected in a dry region than in regions with balanced water budgets (Thornton and Rast, 1993; also see Glantz, 2001). Multiyear cycles of drought can cause decreased water quality during periods of reduced flows and reduced lake volumes. On the other hand, more intensive short-term flushing by strong precipitation events brings more silt and pollution from the landscape to lake waters. Major differences also can occur because of population density, which is naturally reduced in a dry country compared to regions with greater precipitation. The situation in certain regions of India with very high population densities, which are also dry because of water mismanagement, does not appear to follow this observation. The consequences of flow irregularities, resulting in higher pollutant loads, can lead to underestimates of load coefficients valid for hydrologically-balanced regions, which usually also have well-developed vegetation.

*Forested and agricultural regions.* Major differences in water quality are to be expected in forested and deforested regions. The reason is twofold:

- Forest conditions are usually closer to natural conditions, in which the least disturbance of vegetation takes place, and the population density is low; and
- No fertilizers or pesticides are usually applied, and no agricultural practices that increase erosion are used.

*Economically developed and rapidly-developing countries.* The natural geographical situation in the present world is largely modified by human activities, and socioeconomic development plays a very important role for the landscape and waterbodies. Figure 1.12, for example, illustrates the role of population density. Population density is not only directly related to various components of water pollution, but also to other socioeconomic changes that can indirectly affect waterbodies. Other major differences in water use and water quality are related to different kinds of industrial activities, in regard to both the extent and magnitude of sophistication. From this perspective, the strongest differences exist between the developed part of the world and the rapidly-developing so-called "Third World". The politico-economic differentiation into "NORTH" and "SOUTH" (Fig. 1.14) characterizes these differences, which are strongly reflected in the waterbodies of the two regions, making the understanding of complex water problems more difficult.

*Global changes.* To further complicate the tasks of water managers, the present physical world is not static. It undergoes relatively slow, but continuous, changes, usually summarized under the term of "global changes". One component is global climate change,

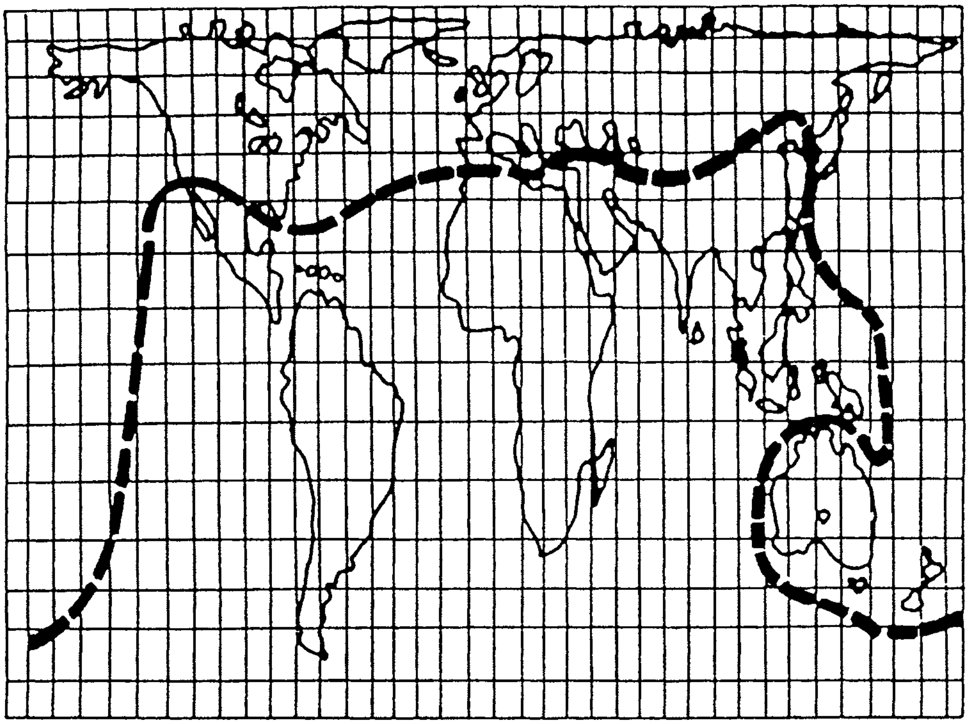

Fig. 1.14. Global political-economic distinction of North and South (Goldemberg et al., 1987).

with global warming being the most broadly-known element. It is misleading, however, to reduce the observed changes just to the issue of global warming. Temperature rises are observed on average throughout the world (Fig. 1.15A), but it is not regularly realized in all locations. In fact, although warming prevails on average for the whole globe, in some regions, there is to be expected a significant cooling rather than warming. Even more misleading than the local differentiation is the increase of short-time temperature irregularities. Some years can be rather cold, while others are much warmer. For waterbodies, therefore, it is not just the solar radiation and resulting temperature regime. The changed hydrological budget also is of great importance. In this latter case, we are speaking about global climate change. Observations of these phenomena in places remote from direct human interference (Fig. 1.15B) demonstrate how significantly waterbodies are already changing. And, in addition to temperature and climate changes, there are other global changes associated with the manufacture and spread of different products and processes that can change the environment. Some may represent environmental "time bombs", with direct effects of climate on human cultures, on vegetation in general and on crops in particular.

For water managers, therefore, it is necessary to take ongoing changes into account, considering the world to be in a state of dynamic development (Smith and Rast, 1998).

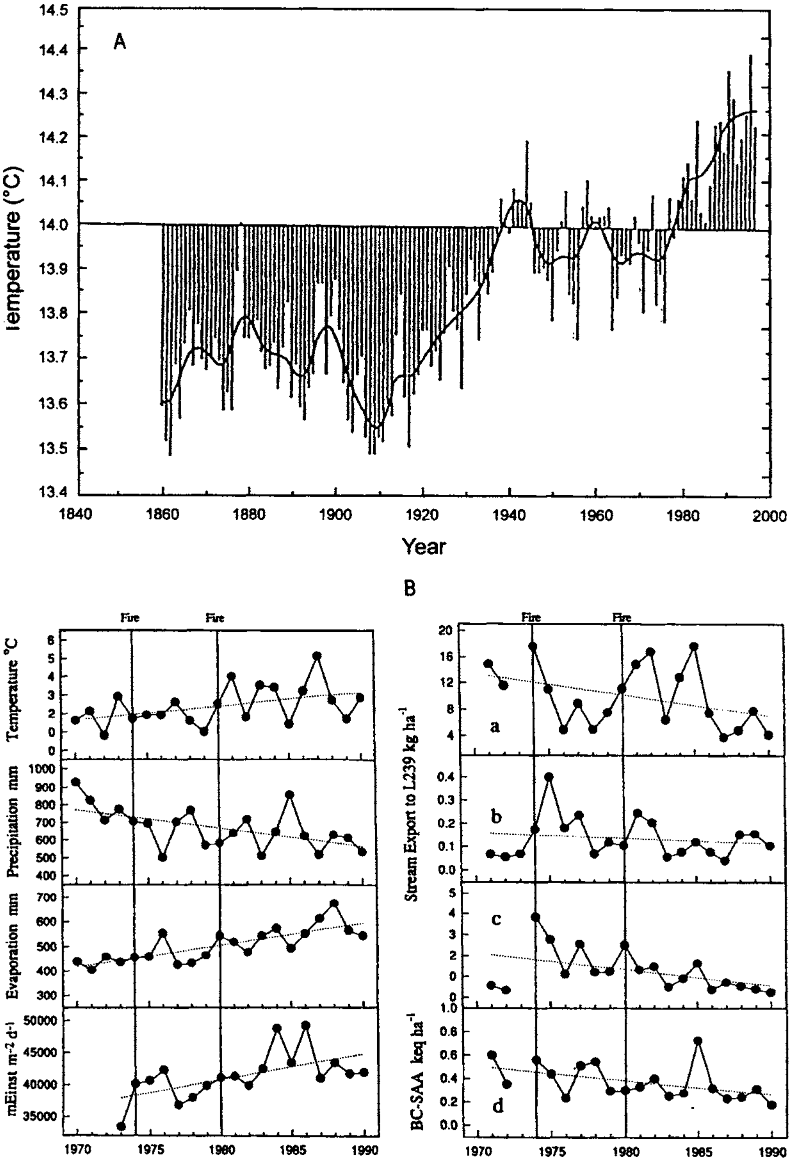

Fig. 1.15. Global changes and their consequences for lakes. A—Average global air temperatures near the ground (land and sea) (horizontal line—average determined from measurements on the whole globe. The horizontal line represents average from period 1961–1990; B—Climatic conditions (left) and loads to a lake in Northern Canada (right). (Other changes—increase of thermal capacity of lakes; high increase of retention time (from about 4 years in 1970 to about 20 years in 1990 in one lake); decrease of runoff and increase of the number of days without flow; Schindler, personal comm.)

Water resource development projects typically have rather long planning and construction phases. Thus, what is valid now may be very different from what actually happens after they have been realized.

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