Chapter 10

SYNOPSIS

The goal of this final chapter is to stress the most important conclusions arising from the discussions of the previous chapters. Most dealt with natural and man-made lakes (reservoirs) simultaneously, and when the term "lakes" was used without further specification, it referred to both natural lakes and reservoirs. In contrast, Chapter 6 dealt explicitly with the unique characteristics of reservoirs, as well as the differences between them and natural lakes. These features and differences must be considered in attempting to manage reservoir water quality.

10.1 LAKES AND RESERVOIRS AS WATER RESOURCES

By the year 2000, the human population will require about 5500 km^3 of water each year, with a great portion of this volume to be taken from lakes and reservoirs. However, lakes are not only a source of water for human needs. In fact, humans have many contacts with lakes, be it for recreational purposes or even just living close to them. In a deteriorating world environment, we have concerns about water not only contributing to worsening human health, but also recognize that visual factors also have a role. Lakes and reservoirs are valuable, picturesque landscape features. The willingness of people to pay a premium for good water quality continues to rise, with the prices of lakefront properties being about 10–15% greater than of non-lakefront properties. An additional premium is paid for being able to live next to clear water lakes.

Because the quantitative and health safety concerns about water are still dominant in a large part of the world, the authors identify approaches that are considered useful for overall water quality management. Climate change occurring around the world obviously makes the water situation even more critical, not only because of an overall decrease of humidity, but also because of highly-increased weather variability, resulting in higher floods and more severe droughts, with negative consequences for water quality. Thus, the range of concerns comprising water quality management are broadening. These authors attempt to cope with this tendency by stressing both the immediate, everyday concerns of water quality management, as well as the more complex issues. The approach discussed here focuses on moving from classical technology to ecotechnology, the use of nature-friendly technologies with a broader focus, from correction to prevention, from "end-of-pipe" to "start-of-pipe", from a local to global perspective.

The economic value of water is not fully recognized by economists. Some attempts to estimate the value of "ecosystem services" that rivers, lakes and reservoirs provide free-of-charge to humanity have resulted in an astonishing average global value of US $1.7 trillion per year, which is about 10% of the annual world gross national product. This estimate includes both the direct costs (sale of water for human consumption, services provided by self-purification and production of food items, transportation, etc.) and the indirect costs (e.g., hydroelectric power generation). It does not, however, cover the cost of environmental deterioration resulting from changes in water flows, habitat modifications resulting from dam construction, and decreasing quality of outflowing rivers resulting from increased recreational and aesthetic use of water, etc. New approaches to the economic valuation of water, including keeping it clean in the first place, are being developed. The Polluter-Pays-Principle, marketable pollution permits, green taxes and green auditing, and environmental impact assessment for new water developments, are used in developed countries. However, such measures are only just beginning to be used in the developing world. The role of non-governmental organizations (NGOs) also can be very positive in protecting water supplies in general, and lakes in particular, as well as in mobilizing water authorities to protect and conserve water resources.

Distribution of Lakes and Reservoirs

It is estimated that there are about 3–6 million natural lakes in the world, covering an area of about 1.6–3 million km^2. There is no similar estimate for reservoirs. The geographical distribution of lakes and reservoirs is extremely uneven, both with respect to latitude and altitude, as well as continentality. There is generally more water in the vicinity of sea coasts. However, coastal lakes are subject to salinity problems. Dry regions are subject to general water shortages from multi-year drought cycles, many of which also are irregular in occurrence. Geography also can exert major effects on lake physics, chemistry and biology, since lake mixing types are driven by climatic variables. Knowledge of macro- and particularly mesogeographic features is important in managing water quality, since many lake water quality features can be deduced from their geographic location. The geographic differences also lead to the conclusion that the application of experiences from temperate and hydrologically-balanced regions is not necessarily directly applicable to waterbodies in tropical or arid regions. Rather, the specifics of lake behavior in different regions also must be taken into account. As an example, one basic characteristic of lakes in tropical regions is that their daily biological and chemical cycles are usually most significant, while the annual water quality cycles are of more significance for temperate-region lakes. However, even more detailed geographic distinction than temperate versus tropical location also must be considered in the management of lake water quantity and quality.

Uses and Abuses of Lakes and Reservoirs

Individual uses of lakes and reservoirs (Box 1) are treated separately by the authors. However, the reality is that most lakes and reservoirs are used for multiple purposes. This results in the creation of conflicts among various user groups, and the creation of complex water quality management problems. Thus, the positive features of water use are treated simultaneously with their negative impacts. As discussed further below, therefore, wise lake

Box 1. Uses and functions of lakes and reservoirs

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

management must be directed to accentuating the positive features, while also decreasing the negative impacts.

Water supply from natural and man-made lakes is increasing in proportion. Examples are Lake Biwa in Japan supplying water for 13 million people, the European city of London being supplied by a system of embankment reservoirs, and the great world megacity São Paulo getting its water from a system of valley reservoirs.

Irrigation with lake water is growing, creating increasing water quality concerns. One facet of the problem is related to water losses resulting from evaporation and evapotranspiration, and another to salinization. The extensive environmental damage resulting from diversion of the tributary flows to the Aral Sea provides a dramatic example of the need to re-evaluate irrigation projects from both a water quantity and water quality perspective.

Flood control is exerted naturally by some lakes, with water levels decreasing during dry periods. Many reservoirs are specifically designed for flood control. Unresolved management problems are related primarily to the insufficient natural water retention of present man-made landscapes. Deforestation, destroyed wetlands, artificially straightened and canalized rivers, and large percentages of the land surface made impermeable in urban regions, significantly decrease the water-holding capacity of the land surface.

Aquaculture activities in fresh and brackish water is rising, with more species of fish and wild aquatic animals, including alligators, capybaras and other higher animals, a number of domestic birds and various invertebrates, being exploited and cultivated. High organic pollution is caused by intensive aquaculture. The widespread invasion of exotic species into waterbodies is often driven by positive intentions, but unfortunately its consequences are predominantly negative. In a new environment, the introduced species are free from the balanced competition and natural controls existing in their original habitats. As a result, they can proliferate rapidly in the new environment, often destroying native species. The results are most often negative. Thus, these authors conclude that the introduction of nonnative fish and other organisms must be strictly controlled, and in most cases avoided completely. See exception, Lake Kariba (Chapter 9). Our knowledge of species and habitat interactions is still insufficient to be able to predict in advance all the complex interrelations between native and nonnative organisms that can lead to success or catastrophic consequences, upon the introduction of the latter to a new environment.

Hydroenergy generation is considered the least-polluting means of generating energy. However, it also is not without negative environmental effects, related primarily to large hydroelectric projects. Another use of lakes in regard to energy production is their use as sources of cooling water for power plants, with the negative impact being caused by high water losses due to evaporation, and by pollution resulting from the concentration of materials in the water as a result of the evaporation.

Recreation and transport. There is a general tendency for an increase from the current approximately 13% of all economic spending devoted to travel and tourism. The appreciation of lakes and reservoirs as sites for recreational activities is increasing. A particular requirement for recreational needs is to protect the lake shores and lake fringes. Otherwise, the recreational value of lakes and reservoirs can rapidly decrease.

Transportation, in both an aquatic form (by boats) and a terrestrial form (roads crossing lakes) can create pollution, eutrophication and the unintentional introduction of exotic species to lakes and reservoirs.

Urban lakes receive particular attention because of their major management problems, including protection from pollution from the surrounding city, as well as from various lake-related activities, multiple uses of urban lakes, and conflicts among the various users.

Conservation and biodiversity. More than 100 lakes and wetlands are among the Biosphere Reserves of UNESCO within the Project Aqua. Efficient legislation should be the main management concern for these waterbodies.

10.2 POOR LAKE MANAGEMENT

This section discusses major causes of bad lake management (Box 2), focusing mainly on topographic requirements that have not been achieved, such as the location of new construction outside risk zones along the shoreline or close to the mouth of the inflowing river(s), protection of at least 30% of the area of nearshore zones for self purification, creation of a 50–100 m protected shore zone, the avoidance of conflicting activities in the same location, and proper management of submerged vegetation and avoidance of adverse methods.

Box 2. Major causes of poor lake management

- Rapidly-growing population in sensitive drainage basins
- Rapidly-growing tourism and recreation on lake shorelines, political pressures and profit motivation for actions, poor financial capacity, and lack of awareness of serious problems because of poor education and training
- Complex, multinational problems requiring regional cooperation (pollution in multinational drainage basins, acidification, climatic change, etc.)

Monitoring Lake Water Quality

A typical feature of lake, and water quality monitoring in general, is the "data rich, but information poor syndrome". Monitoring often consists of extensive sampling and determination programs. However, there often is limited utilization of the results because they are not translated into useful information. To avoid this situation, monitoring is treated as a system of activities, with water sample collection being only one. Emphasis is on obtaining maximum information for management purposes with a minimum effort. This can be achieved by distinguishing and analyzing the various monitoring components and their interactions (Box 3).

Monitoring goals often vary and, therefore, must be specified a priori. The monitoring goals are designed for a number of reasons, including:

- Finding the sources of pollution or water quality deterioration,
- Detecting trends of water quality changes resulting from industrial production and land use development, and
- Serving as a background for determining pollution fines, or for estimating the capacity of a receiving waterbody for a given type of pollution.

In each case, the monitoring system components have to be carefully selected to contribute to this goal. A generalized framework for monitoring, based on the type of water use, is suggested in Box 4.

Sound evaluation of each step is essential. A very sensitive, time-consuming method used in a highly variable environment is typically a waste of time. A cheaper method that enables one to sample more stations and detect major pollutant sources is recommended in this case.

Indicators and classifications. The systems of water quality indicators used for flowing water usually are not useful for lakes. Thus, water quality indicators are different for rivers and lakes. For lakes and reservoirs, indicators are based more on chemical composition, biological trophic state indicators, and nutrient concentrations responsible for the resulting trophic state.

Box 3. Components to be considered in developing lake monitoring systems

- Determining the specific monitoring goals
- Identifying the relevant indicators of the state of the environment (i.e., the variables to be measured, and the methods for their determination) that will provide information useful for improving the situation
- Developing a sampling schedule (timing, localities, depths, etc.), consistent with reasonable expectations, that leave some time for preliminary evaluation, and yet enable one to derive sound conclusions
- Determining the type of sampling (manual, use of electronic probes, automatic recording, etc.) appropriate for the monitoring goals
- Sample preservation, transport and elaboration
- Information extraction

Box 4. Suggested framework for monitoring

Principal water use	Sampling frequency	Physical and chemical variables	Biological variables
Potable water supply	Continuous, daily to weekly	Temperature, Secchi depth, oxyen, color, turbidity, pH, odor, phosphorus, metals, suspended solids, organics, nitrogen	Coliforms, pathogens, phytoplankton, chlorophyll-a
Industrial water supply	Continuous, daily to weekly	Temperature, pH, hardness, dissolved and suspended solids, major ions	Pathogens
Power generation	Daily to weekly	Temperature, oxygen, conductivity, dissolved and suspended solids, major ions	
Irrigation supply	Weekly to monthly	pH, total dissolved solids, sodium, chloride, magnesium, nutrients	Faecal coliforms
Fisheries and recreation	Weekly to monthly	Temperature, suspended solids, Secchi depth, oxygen, phosphorus and nitrogen, ammonia, pesticides	Phytoplankton, chlorophyll-a, zooplankton
Food control	Monthly to annual	Suspended solids, turbidity, Secchi depth	

Approaches to water quality evaluation are as follows:

- To evaluate individual criteria,
- To use combined, complex, multi-metric, multi-criteria systems.

For most lake and reservoir problems, the first approach is recommended, since it provides detailed information for management decisions. Indices are appropriate for broad comparisons of the state of different waterbodies. However, they do not allow for recognizing pollutant sources, or for performing appropriate corrective management actions. The use of indices may require the same sampling and analytical effort as the evaluation of individual criteria, but the information is lost when the data is condensed into one expression or index number.

Most of the more commonly-used indices are geographically-conditioned, with restricted generality. Thus, it often is impossible or useless to use a classification system for a lake located outside of the area for which the index was developed and/or the goal for which it was developed. Trophic indicators are examples of a classification scheme that would be inappropriate for evaluating waterbodies characterized by naturally-high phytoplankton primary production and chlorophyll levels (e.g., tropical and shallow waterbodies). These indicators would classify almost all such waterbodies in the highest trophic category, thereby not enabling any specific management decisions. Another example is the inappropriate application of an indicator system derived from natural lakes to evaluate reservoirs. Because of the greater turbidity, larger nutrient loads and the effects of water retention time on reservoir water quality, as well as the effects of reservoir operation, systems derived from natural lakes are of limited value for reservoirs.

In addition to classical water quality indicators, newly-developed indicators of ecological quality, which also address conditions for aquatic organisms (particularly fish), are emphasized. Ecotoxicological indicators also are presented. In addition to classic toxicity tests, indicators are based on:

- The use of semipermeable membranes,
- Methods for detecting longer-term sublethal effects,
- Genotoxicity and use of biomarkers,
- Microcosm and mesocosm studies,
- Monitoring of long-term consequences of contaminants in nature, based on species diversity,
- Predictions of toxicity based on molecular structure,
- Tests for changes of morphologic or morphometric characteristics of organisms,
- Detection of pathological individuals.

Thus, a critical evaluation of different approaches to aquatic toxicity is possible.

Automatic monitoring systems are of two main types:

- Depth recording (i.e., monitoring by lowering an electronic probe into different water depths),
- Recording over time.

Depth-profiling instruments are of two types. The first is of slow reaction, lowering an electronic probe to a certain water depth and manually starting the record. The second is a free-falling probe, capable of automatically recording the water quality profile with a very high depth resolution (to millimeters). It is stressed that electronic probes can become unreliable if not frequently calibrated. The reaction time of the probe also must be considered, otherwise erroneous results may be obtained.

Remote sensing is the use of satellite and aerial imaginary to help water quality management decisions, by providing information on:

- Variables such as the temperature distribution at the lake surface,
- Horizontal distribution of chlorophyll-a,
- Areas of low and high phytoplankton concentrations,
- Horizontal distribution of Cyanobacteria blooms,
- Areas of high and low turbidity,
- The horizontal displacement of river plumes carrying pollutants and suspended material into a waterbody,
- Areas of concentrations of suspended inorganic and organic matter,
- Location of mass fish kills in a lake.

With careful analysis and correlation with other variables (e.g., chlorophyll-a, temperature, transparency or adsorption coefficients), the distribution of total phosphorus and nitrogen also can be derived for specific waterbodies. The detection of mean or elevated macrophyte concentrations, areas of severe plant stress, and delineation of groundwater flows into lakes also can be determined in specific situations.

Evaluation of monitored water quality data can be achieved with several data elaboration methods (Box 5).

Conclusions to be derived from monitoring can be divided into three groups (Box 6), each of which was considered in more detail in Chapter 3.

The most important water quality changes within the lake, compared to the inflowing water, include the processes given in Box 7. Methods for quantification of these processes are given and some general comparisons are made possible.

Management Approaches

Approaches to water quality management are based on the methodological perspectives of three basic management approaches:

Box 5. Data elaboration methods

- Characterization of the type of statistical distribution of individual water quality variables
- Determination of water quality trends
- Correlation between variables
- Multiple regression
- Spectral characteristics of the data by means of spectral analysis (i.e., time series analysis)
- Cross-spectral analysis of several variables, and detection of time lags between signals
- Creation of statistical input–output models
- Use of data for dynamic models

Box 6. Types of conclusions from monitoring

- Conclusions concerning management of the drainage basin
- Conclusions concerning management of the waterbody
- Conclusions concerning water treatment plants

Box 7. Processes causing water quality changes in lakes

- Mineralization of organic compounds, indicated by a decrease in biochemical oxygen demand (BOD), chemical oxygen demand (COD) and water color
- Improvement of water quality, based on decreased phosphorus, organic substances, and non-dissolved (particulate) matter, due to sedimentation of the particulate matter, and because of dissolved matter becoming particulate in the waterbody (e.g., as algal cells)
- Deterioration of water quality due to intensive decomposition of organic compounds, and the related processes of either releasing or binding certain substances (e.g., release of iron, manganese, ammonia, hydrogen sulfide and nitrites, or the binding of nitrates, especially under anoxic conditions)
- Deterioration of water quality, due to an excessive production of organic matter in the form of phytoplankton (eutrophication)

- Preventive,
- Corrective,
- Sustainable.

The use of preventive ("at-the-source") approaches over the corrective ("end-of-pipe") approaches is emphasized. Preventive methods are typically cheaper, have no negative side effects, are long lasting, and are much closer to the final goal of sustainable water use. The present commonly-used approach of first diluting materials (organic matter, nutrients, metals) in water (thereby creating pollution problems and high costs), and subsequently removing it again prior to water use at even higher cost, is considered completely irrational.

The location for application of management actions is categorized into two main groupings:

- Management options used in the drainage basin,
- Management methods applied in the waterbody (i.e., in-lake approaches).

Although individual options typically are performed either in the drainage basin or in the waterbody, management activities should ideally be integrated (i.e., covering both environments). The "at-the-source" methods belong largely in the *drainage basin* category. The in-lake methods predominantly comprise *corrective* methods. There are only a few in-lake methods belonging to the preventive category (e.g., epilimnetic mixing) and these methods should receive more consideration. Although the "corrective approach" typically is used within the sphere of aquatic resources, water quality managers have an obligation to consider any realistic means for preventing water pollution.

Approaches for Drainage Basin Management

The drainage basin-based management approaches considered are listed in Box 8. New developments include life cycle analysis and cleaner technology, approaches used by the industry to increase profits, by facilitating decreased use of water, energy and resources, and by decreasing pollution. These approaches must be strongly fostered by water managers, since they can significantly contribute to saving water supplies and decreasing pollution. The critical causative factors for dominant groups of problems and corresponding approaches also are mentioned.

Wetlands are treated separately as the most universally-applicable approach, as evidenced from their frequency in Box 8. Wetlands appear in two basic forms in Box 9:

- *Natural* (including regenerated or created) *wetlands*—representing ecotones (the natural transitions between lakes and their terrestrial surroundings),
- *Constructed wetlands*—representing purification plants that utilize the cleansing and pollution-retention capacity of vegetation.

Prevention of water pollution can take many forms, some being technical and others being educational in nature. It is stressed that water managers must be active in the educational incentives aimed at convincing both town and country people, farmers, industrialists and politicians about the importance of their daily activities and their decisions in regard to keeping water supplies safe and clean (Box 10).

Box 8. Water quality problems in reservoir drainage basins, and ecotechnological methods applicable for their management

- *Organic pollution*—Clean production, diversion of effluents, purification plants, wetlands
- *Excess nutrients and eutrophication*—Diversion of wastes, tertiary treatment plants, progressive agricultural practices, meadow and riparian forest zones on vegetated banks, natural and constructed wetlands, pre-impoundments at the inflows, Wahnbach phosphorus-reduction plant
- *Eutrophication and oxygen depletion of rivers*—River restoration, re-oxygenation
- *Siltation*—Erosion control, rehabilitation of river banks, reforestation, groundwater recharge, pre-impoundment of inflows
- *Heavy metal contamination*—Clean production, life cycle analysis, reduction of polluted effluents, wetlands
- *Acidification*—Life cycle analysis, clean production, liming, addition of organic matter
- *Salinization*—Improved irrigation practices, decreased fertilizer applications, decreased road salting
- *Decreased biodiversity due to reservoir construction*—Prohibiting introduction of foreign species, reintroduction of native species, maintenance of wetlands as nursery grounds, maintenance of preserved areas for native species

Box 9. Use of natural and constructed wetlands

- Maintenance and preservation of the transition zone between terrestrial ecosystems and the lake ecosystem functions as a buffer zone for pollution, and preserves the species diversity in both ecosystems
- Building and maintaining constructed wetlands is much less costly than building and maintaining classical purification plants
- Wetlands, both natural and constructed, have a high adsorption capacity for many pollutants (e.g., nutrients, heavy metals, toxic organic compounds)
- Wetlands are able to denitrify up to several tons of nitrate-nitrogen per hectare and year
- Recovery of natural wetlands, and creation of constructed wetlands, are crucial abatement methods for diffuse pollutants originating from agriculture
- Constructed wetlands represent an attractive wastewater treatment method for recreational areas adjacent to lakes, for areas with low population densities, and as post-treatment of purified effluents from cities
- The application of quantitatively-based management of all types of wetlands, including the use of models for these ecosystems, is recommended

Box 10. Desirable educational activities of water managers

- Water quality managers must stress the usefulness of cleaner production techniques, and the product life cycle evaluation procedure, and strive for such evaluations. Local water management councils can be very helpful in this direction
- Saving energy has positive consequences for water quality, since energy generation can be the cause of environmental degradation, including water pollution
- Saving water in households improves water quality, since existing wastewater treatment plants function better with less incoming wastes, thereby reducing the need for upgrading, renovation and new construction

Box 11. Methods of agricultural pollution prevention

- Agriculture is one of the major sources of diffuse pollution in many places of the world. Diffuse pollution from agriculture should be minimized. Among other concerns, it is economically beneficial to ensure that expensive fertilizers do not end up unutilized by crops
- Application of fertilizers in the most efficient manner for uptake by crops usually is also most favorable for enhancing good water quality, since it creates the least water pollution. Water quality difficulties are often caused by unutilized (but nevertheless expensive) and lost fertilizer. Agricultural best management practices are the most useful practices for addressing water quality problems
- Losses of fertile soils as a result of improper agricultural practices and other land uses are related to major water pollution problems. It is to the benefit of both agriculture and water quality to minimize erosion by contour plowing, terracing, and leaving soil bare of vegetation for the minimum time
- Forests generally enhance good water quality, while deforestation typically results in water quality deterioration
- The use of plant protection agents must be strictly controlled, because some are highly toxic to aquatic life and humans
- Buffer zones, riparian forests and vegetation strips along stream and lake shorelines, together with wetlands, are efficient in reducing the loads of nutrients and some other chemical compounds to lakes and reservoirs

Agricultural activities represent one of the most severe nonpoint (diffuse) pollution sources. Methods for preventing this type of pollution are reviewed (Box 11). Natural forests generally have positive water quality impacts, although the effects of intensive cultivation of introduced tree species (e.g., *Eucalyptus*), and improper forestry practices and forest fertilization, may be significantly negative.

In-Lake Management Methods

There are a multitude of in-lake management methods (Box 12). Examples for each method are provided, conditions and limitations of their use are enumerated, positive and negative effects mentioned, and some indication of costs given.

Artificial mixing is used for:

- Oxidation of a deoxygenated hypolimnion (*destratification, propeller mixing, hypolimnetic aeration* and *hypolimnetic oxygenation*),
- Improvement of the water quality of specific water layers in a stratified waterbody (*layer aeration*),
- Inhibition of phytoplankton growth (*epilimnetic mixing*).

Epilimnetic mixing is based on decreasing phytoplankton primary production, and increasing its respiration in the water column, by mixing surface water layers to a depth where respiration compensates for production on a daily basis. This method, therefore, belongs in the very efficient *preventive* category. It was successfully used to protect the drinking water supply of London and some major towns in The Netherlands. Another way

Box 12. In-lake management methods

Methods based on artificial mixing and oxygenation:
• Destratification by total mixing of the water column
• Mixing and re-aeration of the hypolimnion
• Epilimnetic mixing
• Layer aeration
• Hypolimnetic oxygenation
• Metalimnetic mixing
• Propeller mixing
Methods based on treating sediments:
• Sediment removal
• Sediment capping
• Sediment oxygenation by the RIPLOX procedure
• Phosphorus precipitation with sediment sealing
Other methods:
• Hydraulic regulation (selective water withdrawal)
• Diversion of polluted inflow water
• Extraction of hypolimnetic water (hypolimnetic siphoning)
• Biomanipulation
• Macrophyte removal

to decrease algal production is by decreasing light penetration into the water column. This has only been performed in a few instances by shading, and by the application of surface covering, soot, and color. The cheapest in-lake option is *hydraulic regulation*, or selecting the water layers with the best water quality for drinking water treatment by:

- Releasing poor-quality water layers near the lake bottom (also achievable with bottom water siphoning),
- Decreasing phytoplankton biomass by releasing surface water layers,
- Using density currents to get rid of by short spikes of water pollution.

Hydraulic regulation can be performed by means of selective offtakes, or their substitution by plastic curtains.

Biomanipulation is a procedure based on enhancing the suppression of phytoplankton by zooplankton, and control of fish populations in a manner so as to achieve efficient phytoplankton reduction by zooplankton filtration. This can be achieved by manipulating the fish populations in a lake. However, this method is applicable only when the in-lake phosphorus concentrations are below a certain level. For very eutrophic waterbodies, it is necessary to combine biomanipulation and nutrient reduction by other methods. Successful application of this method is generally more pronounced in shallow and smaller waterbodies, mainly because controlling fish populations is easier under such conditions. The procedure cannot be considered a routine method, however, since it should only be performed with the participation of skilled limnologists. Further, the present experience with biomanipulation is based primarily on conditions in the northern part of the temperate region, which is characterized by a relatively uniform, well-known species composition of fish and zooplankton populations.

Macrophyte harvesting by means of mechanical collection, and by use of plant-eating fish and other vertebrates, is recommended. Successful examples of eradication of tropical floating plants by some species of aquatic insects are available.

Managers may note that little attention was given in this book to the commonly-used corrective method of killing algae with copper sulfate or other algicides. This is because the negative side effects may easily exceed the positive benefits, particularly because the toxic materials used may accumulate in the sediment and organisms. As has been seen in a few cases, a lake may become useless for the desired water uses, and the fish become inedible, after many years of application.

A combination of these approaches is recommended, since one method may not necessarily achieve complete success in all situations or regions.

To address lake *acidification*, two options are considered useful; namely, the addition of lime or organic matter to waterbodies impacted by acid rain. These materials work to neutralize the acidic water.

Modelling Water Quality

Although modelling is an activity best done by specialists, it is important for managers, and for those concerned with water quality in general, to know about their existence, possible uses, capabilities and limitations, and possibly about how to evaluate and apply the modelling results. From this perspective, it is important to understand possible model uses (Box 13).

Box 13. The use of models in water quality management

General—To estimate pollution sources in a drainage basin by means of simple calculation models

For lakes and existing reservoirs:

- To predict future water quality conditions resulting from human activities in a drainage basin
- To provide estimates for decisions between different water quality options in long-term planning efforts, and to support short-term operational management decisions
- To optimize sampling schedule investigations and water quality controls, and to assess the environmental risks associated with the discharge of micro-pollutants

Prior to reservoir construction:

- To estimate the loads of major water quality components of rivers entering a reservoir, those existing in the main body of a reservoir, and those in the reservoir outflows
- To provide information for evaluating alternative construction sites, dam heights, and outflow and outlet structures
- To predict the conditions in future reservoirs, and the consequences of different management options for water quality within a drainage basin

Models available for helping management decisions are categorized on the basis of differing criteria, depending on form, scope, and the water quality problems to be solved. The differentiation of models according to their forms is important, as shown in Box 14.

The most advanced modelling approach is represented by the Decision Support Systems (DSS), representing specifically-constructed interactive guides for management decisions. The word *support* in this descriptive name stresses the notion that no decision is made by the model. Rather, quantified information is supplied to a manager, in order to facilitate basing the management decisions on the basis of the maximum background information. In fact, the approach combines all (or at least most) of the other model types named in the list. Extensive databases and connection to monitored information sources are components of such systems. Each DSS has a specific goal, and there is a rapid development of this type of system recently for water quality management.

The specific models directed to different water quality problems are classified into the categories identified in Box 15. Further, the formalization of Environmental Risk Assessments is treated in Chapter 5.

The group of models identified last in Box 15 represents complex lake and reservoir water quality models that have been most recently used in water quality management activities. The relevant DSS for such purposes are enumerated in Chapter 5.

Box 14. Classification of models useful for water quality management

- Simple static calculation models, consisting of algebraic equations or graphs
- Complex dynamic models for analyzing the timing aspects of water quality
- Geographical information systems for analysis of problems requiring spatial resolution
- Prescriptive models for calculating water quality conditions without indicating appropriate management options for a given situation
- Optimization models for incorporating a selection procedure to choose the most suitable option on the basis of a set of criteria
- Expert Systems, using qualitative and quantitative expressions to guide the user toward relevant answers to complex water quality questions
- Decision Support Systems (DSS), representing the most advanced and most helpful decision aids, incorporating various computer software relevant for a specific water quality decision problem facing managers—a computer is typically used with these systems

Box 15. Models applicable to different management problems

- Eutrophication models
- Toxic substance models
- Acidification models
- Wetland models
- Fisheries models
- Biomanipulation models
- Commonly-applied water quality models

Reservoir Water Quality Management

Reservoirs are artificial waterbodies constructed for many diverse purposes. Thus, although there are many types, they are often treated from both a theoretical and management perspective, in the same manner as natural lakes. This is not justified, however, because reservoirs are operated for the purposes for which they were constructed, a condition not possible for natural lakes. Human operation of reservoirs has considerable influences on their water quality. Thus, understanding their specific characteristics enables a considerable extension of their management possibilities.

Considering deep river valley reservoirs and deep lakes, basic differences between natural and artificial lakes are specified in Box 16. On the other hand, shallow, unstratified reservoirs, particularly riverine ones, are not much different from shallow lakes. Reservoirs can be categorized into impounded lakes, valley or dam reservoirs, off-river reservoirs and embankment reservoirs.

Stratification, mixing and other variables of deep valley reservoirs depend strongly on the water retention time (RT = volume/flow), in addition to variables that determine lake stratification (Box 17). Quantification of some relations is developed in Chapter 6.

Box 16. Differences between deep reservoirs and deep lakes

- For similar situations, pollution of reservoirs can be higher than for natural lakes, because reservoirs are constructed to have greater drainage basin/waterbody area ratios than lakes, in order to fulfill their intended purposes. Thus, reservoir water is generally more throughflowing than for lakes, and reservoirs have shorter theoretical water retention times
- Longitudinal differentiation of the water quality of deep reservoirs is due to the continuous slope of the original river bottom from the inflow to the dam. Four regions are distinguished:
  The inflow region is usually shallow and narrow, characterized by rapid unidirectional flows, with flow rates distributed similarly to that of the river. This is usually the most polluted region
  The transition region is where the water flow decreases as the reservoir gets deeper and broader. The river water plunges into deeper water strata. Maximum concentrations of suspended sediments, nutrients and algae occur in this zone, as well as maximum sedimentation
  The lake region closest to the dam usually has the best water quality, with vertical stratification characterized according to the rules mentioned above
  Bays with the longitudinal pattern observed in the main inflow sometimes repeated to a certain degree, with modifications due to density conditions and inflow intensity and composition
- Water level fluctuations in reservoirs are higher than in natural lakes. The degree of the fluctuations is related to the natural inflow variability and operation of the reservoir
- The phosphorus retention capacity (both particulate and dissolved) of deep reservoirs is very high in both temperate and tropical reservoirs (average around 80%, but can reach more than 90%), and increases with the areal phosphorus load. Some other elements also are retained in the reservoir basin, and the water leaving a reservoir is cleaner than its inflows
- The beginning of a reservoirs existence (period of aging) is characterized by poor water quality for several years. Two causes are shown to determine aging, including external (physical, chemical) and internal (biological)

Box 17. The effects of increasing the water retention time on different variables in deep reservoirs

- Decreasing hydraulic loading and pollution loading
- Increasing degree of stratification up to a water retention time of about one year, with additional dependency on geographic location
- Increasing surface temperature up to a water retention time of about one year, being unaffected thereafter
- Decreasing bottom temperature
- Increasing longitudinal differentiation up to some water retention time, decreasing thereafter
- Decreasing quantity of sediments (at comparable inflow concentrations)
- Asymptotically-increasing nutrient retention, most rapidly at a water retention time less than 200 days
- Increasing phytoplankton biomass up to some water retention time, decreasing thereafter
- Increasing trophic state, followed by a decreasing state
- Increasing occurrence of Cyanobacteria under comparable inflow nutrient concentrations
- Decreasing bottom fauna, but highly dependent on near-bottom oxygen conditions
- Increasing hypolimnetic anoxia increases up to some water retention time, decreasing thereafter
- Increasing zooplankton increases up to some water retention time, decreasing thereafter
- Increasing fish biomass
- Increasing length of period of aging

Management techniques specific to reservoirs include *selective withdrawal* (= hydraulic regulation), which is realized by selective water offtakes or, in the absence of selective offtakes, by plastic curtains. Construction of *pre-impoundments* at the reservoir inflow site decreases pollution of the main reservoir by utilizing the phosphorus retention capacity of the pre-impoundment. Conditions for their efficient functioning are quantified in Chapter 6.

Level and flow operation enables water quality improvements. Several approaches exist for the water quality management of outflows. Special attention should be devoted to management of reservoir systems.

Construction of new reservoirs typically has both positive and negative consequences for the local population and the outflowing river. Thus, careful consideration of the positive and negative sides of new reservoir construction must be performed by means of Environmental Impact Assessments (EIA).

Based on comparative studies of reservoirs, guidelines for the construction of new reservoirs have been developed, particularly for drinking water reservoirs that are most sensitive to water quality concerns.

Integrated Management

Integrated management is the management of a system of functions under a single general control in a way that seeks a compromise to simultaneously maximize the combined benefits from the individual functions. Guidelines for integrated management are defined in Box 18, and elaborated in Chapter 7.

Ways to facilitate achievement of these general guidelines are presented in Box 19.

Indeed, it is readily evident from the above that a major change in thinking and attitudes is necessary on the part of both water quality specialists and water managers. The rationale for this statement is that traditional water management methods are no longer sufficient in many cases (Box 20).

Possible solutions to promote sustainable water resources are summarized in Box 21.

Box 18. Guidelines for integrated water resource management

- Develop methodologies for integrated river basin management that include land-use management and water planning
- Improve the volume and accuracy of national and global assessments of water resources
- Develop, promulgate, and implement new, innovative approaches to water supply and sewage treatment
- Develop, promulgate, and implement waste minimization and recovery techniques
- Develop low-tech, low-cost treatment options
- Increase application of use-related receiving waste standards
- Develop and apply economic evaluation tools to both environmental costs and benefits
- Inform, educate, and train water professionals and public

Box 19. Realization of integrated water resource management rules

- Identify drainage basin-wide issues
- Prioritize subcatchments for action
- Identify specific areas and variables of concern
- Prioritize pollution sources according to the magnitude and the possibility of management
- Screen types of controls, and propose strategies
- Screen practices, rank and develop the action plan
- Implement actions
- Monitor results and revise strategy
- Audit action plans

Box 20. Reasons for inadequacies of traditional water management methods

- They are very expensive
- They concentrate almost exclusively on "end-of-pipe" solutions
- They are often unable to provide sustainable solutions to problems
- They cannot cope with changing environmental conditions
- They often simply move environmental degradation problems from one place to another, producing new environmental deterioration in the other areas and creating new environmental problems

Box 21. Suggested solutions for achieving sustainable water resources

- Decentralized decisions and management
- Reduced water use
- Recycling water
- Sanitation procedures that do not require water
- Recycling organic matter
- Introducing new wastewater treatment technologies
- Introducing low-tech, nature-friendly methods of ecological engineering and ecotechnology
- Placing more emphasis to the prevention of pollution and deterioration before utilizing purification and other corrective measures
- Emphasizing "start-of-pipe" rather than "end-of-pipe" methods
- Giving more emphasis to imission rather than emission criteria
- Giving more attention to methods for abatement of diffuse pollution sources
- Increasing the use and elaboration of mathematical models for different specific problems and evaluation of various approaches
- Emphasizing the adaptation of approaches to local social, material and other conditions
- Elaborating, introducing and evaluating methods of monitoring "global changes" from the hydrodynamic, chemical and biological perspective
- Increasing the availability of information to managers, and to the local rural population, about the consequences of their activities on water quantity and quality
- Promoting closer collaboration between managers, engineers, scientists and decision-makers
- Increasing community participation
- Encouraging water quality specialists to be more aggressive in stressing the need of "clean technology" and pollution prevention, rather than water purification
- Encouraging application of the "life cycle evaluation" of products, which consists of considering the environmental consequences of a product throughout its entire life cycle (creation to disposal). Considerable financial savings enhance the economic competitiveness of products, accompanied by considerable savings in water and energy resources, and reduced pollution
- Simultaneously evaluating possible alternative options. The capabilities of nontraditional ecotechnological approaches also must be stressed
- In evaluating management options, considering the global, rather than just the local, "cost" (damage) to the environment
- Emphasizing the goal of the long-term horizon sustainability of clean water resources
- Intensifying environmental education

10.3 SELECTION OF BEST MANAGEMENT STRATEGIES

A detailed outline to the development of appropriate management strategies is given in Chapter 8, to enable higher-level managers that do not need the technical details given in Chapters 1–7 to utilize this book. Only the most important recommendations concerning management approaches are summarized here (Box 22).

10.4 CASE STUDIES

An overview of situation and management problems of a few selected lakes is given in Chapter 9. The case studies (Box 23) cover a broad geographical range, lakes and reser-

Box 22. Recommendations for lake/reservoir water quality management

- Proper environmental strategy usually requires a range of approaches and techniques
- It ideally requires the application of a combination of "end-of-pipe" technologies (environmental technology), ecotechnology, cleaner technology, and environmental legislation to be most successful
- The correct timing of steps is very important. A complete environmental management plan should be established at an early stage, as a means of utilizing the available resources in the most optimal manner
- From an economic perspective, it is very important to consider *prevention* over *correction*, since lake restoration efforts can be extremely expensive
- Because of the complexity of aquatic systems and their problems, sound ecological knowledge is a prerequisite for an ecologically-sound environmental management programme. This is the only appropriate means of avoiding unexpected results from treating the ecosystems of concern

Box 23. Case studies presented

- *Neusiedlersee (Austria and Hungary)*—Very shallow lake overgrown by vegetation; the recreational interest is in conflict with nature protection because the lake has been declared a Biosphere Reserve by UNESCO
- *Great Lakes of North America*—Huge, densely-populated territory where intensive analysis, modelling and control of point and nonpoint source (agriculture, urban areas) pollution, conducted by the U.S.–Canada Pollution from Land Use Activities Reference Group (PLUARG) has resulted in considerable eutrophication abatement
- *Lake Fure (Denmark)*—Lake located in a highly urbanized area, an example of major water quality improvement based on community activities
- *Lake Ichkeul (Tunisia)*—Also a UNESCO Biosphere Reserve, a shallow lake endangered by increasing salinity due to the damming of some of its inflows
- *Biesbosch reservoirs (The Netherlands)*—A system of three embankment reservoirs, supplying drinking water to major towns. Problems with water pumped from lower reach of an European River are successfully solved with a combination of engineering and biological methods
- *Rímov Reservoir (Czech Republic)*—A small, stratified drinking water supply reservoir with multiple outlets, with application of hydraulic operation and biomanipulation management methods.
- *Lake Kariba (Zimbabwe and Zambia)*—One of the largest reservoirs exposed to an invasion of macrophytes over many years. The reservoir also is a rare example of a successful fish introduction
- *The River Tietê Reservoir system (Brazil, São Paulo State)*—Six reservoirs with 50 million people in the headwaters of the river; an example of management problems in an economically rapidly-developing region

voirs, developed and developing countries, temperate and tropical regions, and shallow and deep waterbodies, used for different purposes. The situations and management solutions used are given for each example.