Chapter 8

DEVELOPMENT OF WATER QUALITY MANAGEMENT STRATEGY

The goal of this chapter is to bring together the scientific and technical information previously provided in Chapters 1–7 into a form useful for decision-makers and policy-makers. Although these individuals may be generally familiar with water issues, they do not necessarily possess the scientific background needed to fully address the complex mix of chemical, biological and physical factors to be considered in developing water quality management strategies. Accordingly, this chapter attempts to integrate the major scientific, socioeconomic and political concerns that should be addressed in management strategies for the sustainable use of lakes and reservoirs, for those lacking a scientific background, but who nevertheless have major responsibility for managing lake or reservoir water quality.

8.1 INTRODUCTION

That freshwater has a fundamental role in supporting both human survival and facilitating socioeconomic conditions is without question. It is easily observed that people living in areas with scarce freshwater supplies typically exhibit poorer health conditions, more limited economic development, and fewer aquatic ecosystems than those in areas with abundant freshwater supplies. The United Nations reported that, at the present time, approximately one-third of the world's population lives under "water stress" conditions (WMO, 1997). This situation is expected to worsen in future years, with the prediction that two of every three individuals on this planet will live under water stress conditions by the year 2025 *if present water use trends continue*. The dominant role of water pollution in defining the human condition is illustrated by the fact that contaminated water is still the single greatest cause of human illness and death on a global scale. Inadequate treatment of human wastes, and their subsequent discharge to receiving freshwater systems, is the primary culprit in this regard.

Previous chapters of this book deal largely with the scientific and technical aspects of lakes and reservoirs, including the identification of relevant water quality parameters, sampling strategies, the role of models, remedial and control measures and options, etc. As such, they provide information on the biological, chemical and physical characteristics and dynamics of these important waterbodies. However, this type of information does not translate directly or easily into knowledge that can readily be used to manage the water quality of lakes and reservoirs. This is due partly to the fact that fundamental authority for natural resource management (including water resources) typically falls under the responsibility of decision-makers and policy-makers. Such individuals often lack the scientific and technical background needed to understand and apply this information in a water management context. Thus, the "translation" of scientific and technical knowledge into a form that can be readily used by decision-makers and managers is a fundamental goal for the development and implementation of appropriate water quality management strategies for lakes and reservoirs.

To address this gap, this chapter focuses less on the strictly scientific and technical issues related to lake and reservoir water quality, instead moving more to the management aspects. It attempts to consider both the positive and negative vagaries of the human condition as well. This chapter discusses relevant issues and provides a general framework for developing cost-effective lake and reservoir water quality management strategies. It also attempts to identify specific factors to be considered in tailoring action plans that incorporate the physical, social, institutional, regulatory, economic and political realities for a given lake or reservoir drainage basin.

In striving to achieve this goal, there are several caveats regarding the effective development and implementation of water quality management strategies. First, it is difficult to present a definition of a decision-maker that is accurate in all cases. Depending on the individual situation, they can comprise legislators, executives, directors, senior administrators, etc. Further, water resource concerns and priorities often differ significantly within a given country, as well as on a regional and/or global scale. In many cases, water uses also can be conflicting in nature. The specific circumstances in a given case, therefore, may require a decision-maker to consider or interject issues and concerns other than those discussed in this chapter, to identify and formulate solutions to a given lake or reservoir water quality problem.

The goals of water quality management are similar for virtually all freshwater systems, whether they are on the land surface or under it. As discussed below, surface waters must be managed within the context of a drainage basin, including all the water-related components contained therein. These comprise rivers, streams, lakes, wetlands, ponds, etc. These freshwater systems are generally affected by the same water pollutants and their causative factors, and typically suffer the same general impacts, although the magnitude and timing of the impacts may vary. The goals of this chapter, therefore, overlap with the general goals of water quality management, whether directed to lakes, reservoirs, rivers, wetlands or groundwater aquifers.

There is no universal management program for all lakes and reservoirs, and there is no water quality management strategy or program that will address every situation. As discussed below, it is necessary to relate water management programs to human water needs, as well as the water needs of aquatic ecosystems, which can vary widely within and between countries. Further, effective management strategies must consider not only the strictly scientific, technical and engineering issues related to lakes and reservoirs, but also the relevant nontechnical issues. The latter include such elements as legislation, institutions, economics, social concerns, regulations, politics, etc. Experience around the world has repeatedly demonstrated that these latter elements often are the most important components to consider in developing and implementing effective water resource management programs of any kind, because they fundamentally influence *how* humans use their available water resources. An adequate water quality management strategy, therefore, must not only contain elements directed to the physical, chemical and biological characteristics of lakes and reservoirs, but also the socioeconomic aspects that control human uses of these waterbodies as well. To facilitate this goal, this chapter also provides some general principles that can be used as guidance for developing lake and reservoir management programs for their sustainable use (see Section 8.3.6).

8.2 CONSIDERATIONS IN SELECTING MANAGEMENT STRATEGY

There are several factors to consider in identifying and implementing lake or reservoir water quality management strategies, as described in the following sections.

8.2.1 Water and Sustainable Development

As noted earlier in this book, adequate supplies of freshwater are an essential requirement for human survival and socioeconomic development. The notion of sustainable use of natural resources in relation to socioeconomic development focuses on economic development that is sensitive to the size and condition of the available resource base, including freshwater resources (United Nations, 1992; WMO, 1992; Smith and Rast, 1998; Rast, 2003a). To be sustainable, the type and extent of development must be done within the limits and ability of the natural environment to provide the needed resources. For freshwater resources, sustainable economic development would be based on the ability of the natural environment to renew or sustain the water resources for beneficial human uses over the long term. It would not be possible, for example, to grow water-intensive crops over the long term in arid or semi-arid regions, without extraordinary measures being undertaken to supply the water (building reservoirs, interbasin water transfer, etc.). The notion of sustainability, therefore, should be a cornerstone of effective lake and reservoir management as well (WMO, 1992; Rast, 2003a).

The ultimate goal of water resource management in a given lake or reservoir drainage basin should be to maximize the benefits of the water resources to the basin inhabitants. This is in contrast to dividing the available water resources equally among the basin inhabitants. For example, irrigated agriculture uses the largest volumes of water on a global scale. From a hydrological perspective, therefore, it would be more logical for a nation or region characterized by water scarcity to use its existing resources to produce goods of high economic value, and subsequently trade these goods for food supplies, rather than using their scarce water resources to attempt to grow all their food needs (WMO, 1997).

8.2.2 Integrated Water Resource Management

Sustainable use of lakes and reservoirs requires an integrated management approach. Integration refers to "making a whole from the various parts". The notion of integrated management within a technical context was introduced in the previous chapter. For the purposes of this chapter, and consistent with the previous discussion on this topic, the integrated management of lake or reservoir drainage basins means consideration and accommodation of not only the scientific and technical aspects (e.g., water supply and demands, geology, physiography, flora, fauna, land use, pollutant sources), but also the socioeconomic aspects (e.g., legislative and regulatory frameworks, institutional capacity, economic conditions, human health and demography, political structure and activities) that fundamentally control how humans use these resources. Further, these elements must be considered within the context of the long-term development and use of the water resources (see Chapter 7 for more details).

In considering management actions, the focus should be on maintaining or achieving the "average" conditions likely to be encountered over the long-term, rather than attempting to provide for the maximum or worst case condition. Human knowledge and understanding of natural cycles and processes is not sufficient for us to be able adequately to consider all the relevant elements necessary for effective management of natural resources. Addressing worst-case conditions in a given situation, for example, would require a more extensive (and more expensive) management program that one developed to address the long-term, average conditions. Further, there is no guarantee that a given management program, no matter how extensive, could adequately address worst case conditions.

8.2.3 Watershed Approach to Pollution Control

The simplest description of a lake is that it is a natural depression in the land surface that became filled with inflowing water over time. In contrast, a reservoir is an artificial lake created by damming a flowing river. Considerable volumes of freshwater, and their biological communities, characterize both natural and artificial lakes. Further, the water quality of these waterbodies is a direct function of the quantity and types of materials entering them from their surrounding drainage basins. The drainage basin is the fundamental freshwater management unit, therefore, for addressing both water quantity and water quality issues. The management of lake and reservoir water quality, as well as their sustainable use, will necessarily focus on the inflowing water and sources of polluting materials entering them from the drainage basin. This means that control measures or programs should be directed to (i) the sources of the polluting materials in the drainage basin, (ii) their transport to lakes and reservoirs and/or (iii) their changes within the waterbody (degradation, transformation, etc.).

A complicating factor with this approach is international basins (i.e., a drainage basin in which the water is used or shared by two or more countries). Nevertheless, a drainage basin approach is equally appropriate in this latter situation. National water needs, priorities and perceptions, however, can differ significantly between the different countries comprising a drainage basin. Further, water use in upstream countries can impact both the quantity and quality of the water reaching the downstream countries in the basin. The water quality of a lake or reservoir that serves as a boundary between multiple countries also can be impacted by all the countries, affecting the quality of the water available for their use.

8.2.4 Linkage between Water Quantity and Quality

Water quality and water quantity are fundamentally related. The pollutant load to a lake or reservoir is a function both of the quantities of the polluting materials being carried by the inflowing waters (i.e., the concentration of the polluting materials in the water) and the volume of the inflowing waters carrying these materials (see Section 7.4).

A main impact of water pollution is to limit or otherwise reduce the possible range of human uses of the water without requiring some type or degree of pre-treatment. Water of the highest quality has virtually no restrictions in regard to its uses. Water of drinking water quality, for example, also can be used for virtually any other purpose. As water becomes more polluted, however, it can only be used for fewer purposes without necessitating treatment of some type. Inadequately-treated municipal wastewater, for example, cannot safely be used as a drinking water supply without pre-treatment to remove disease-causing microbes. Under specific conditions, this partially-treated water also could be used to irrigate food crops. Water used for bathing or washing purposes also could be used for this purpose. However, one would not want to use the latter as a drinking water supply unless it was first treated. Similar considerations exist in regard to using storm-generated water runoff from agricultural and urban areas, which can pick up and transport pollutants from the land surface.

Thus, water pollution does not reduce the absolute quantity of water available for human use. Existing technology is adequate to take care of most water pollution problems. However, depending on the types and quantities of the pollutants of concern, such treatment can be both expensive and time-consuming.

8.2.5 Water Quality and Competing Water Uses

Lakes and reservoirs are used for a wide range of human water uses (see details in Section 2.1), including:

- Drinking water supply (for humans and livestock),
- Cleaning and bathing,
- Growing and cooking food,
- Fisheries and aquaculture,
- Industrial development (both as a basic commodity of goods and for transporting wastes and by-products from the production arena),
- Bathing and water sports,
- Production of hydropower,
- Transportation of goods, and
- Aesthetics.

Each possible water use has its own water quality requirements. In developing a water quality management strategy, it must be recognized that some water uses often compete with other ones. In developing national water quality standards in the United States, for example, the Environmental Protection Agency was charged with the mandate of achieving "swimmable" and "fishable" waters throughout the country. The water quality needed to address these two goals, however, is fundamentally different. One would desire water of high quality for swimming purposes. In contrast, the fisheries of a lake or reservoir would be enhanced by increased nutrient loads, which would increase the possibilities of lake or reservoir eutrophication, the latter being contrary to the goal of "swimmable" waters. Thus, the goals of a lake or reservoir water quality management strategy usually should be based on meeting the primary or most sensitive water use(s).

8.2.6 Differing Perspectives of Desirable Water Quality

There is no universally-accepted perspective for determining "desirable" water quality for lakes and reservoirs. Such factors as the environmental and human conditions in a drainage basin, the existing water sources and the current and anticipated water uses, the current and future economic development plans, the available economic, legal, institutional and political framework, etc., can result in different, and sometimes conflicting, water quality goals for a given waterbody.

This is particularly evident when considering the contrasting water quality situation in developed and developing countries. The inhabitants of lake and reservoir drainage basins in developing countries often face crucial survival issues (Laszlo et al., 1988; Rast, 1999, 2003a). They also suffer from a high level of poverty and other factors limiting their economic development potential. Thus, the daily spectre of simple survival is of high priority. A consequence of extreme poverty is to limit the possibilities of individuals living in a drainage basin. People living in poverty often have few (or no) options to environmental degradation; they do what they must do to survive, regardless of the environmental consequences. This results in continuing, and often increasing, water pollution and associated water-related disease and death. The ability of national governments to adequately address water quality problems in such situations typically is limited by their economic and technological capabilities.

In contrast, inhabitants of the developed world typically do not worry about fundamental survival issues. In fact, even though it typically results in some degree of environmental degradation, a basic level of economic development appears to be necessary to facilitate human consideration of environmental issues (including the quantity and quality of water resources). Thus, many water resources in developed countries are of higher quality than those in developing countries. The latter reflects the increased economic and technological capabilities of developed countries which, in turn, allow for a greater ability to treat and otherwise ensure a higher level of water quality.

The relation of "desirable" water quality, as a function of human water uses, is discussed further in a following section.

8.3 DEVELOPING A WATER QUALITY MANAGEMENT STRATEGY

Considering the above-noted issues and concerns, a general approach for developing a realistic water quality management strategy for lakes and reservoirs would comprise the following:

- Identifying the major water quality problem(s), including current water uses and water pollutants of concern, and establishing water management goals (Section 8.3.1).
- Assessing the extent of data and information available about a lake or reservoir and its drainage basin, including sources, locations and characteristics of water quality problems (Section 8.3.2).
- Identifying the available options for addressing water quality problem(s) (Section 8.3.3).
- Analyzing all the relevant costs and expected benefits of alternative management or control options (Section 8.3.4).
- Analyzing the adequacy of existing institutional, legal, regulatory and political framework for implementing alternative management strategies (Section 8.3.5).
- Developing a comprehensive action plan to address the identified water quality problems, and distributing a summary of the plan to all interested parties prior to implementation (Section 8.3.6).
- Ensuring post-treatment monitoring, and providing periodic progress reports on the water quality management control program to citizens and other interested parties (Section 8.3.9).

8.3.1 Identifying Water Quality Problem and Establishing Management Goals

The need for an integrated view of land, atmosphere and water interactions in a drainage basin is essential in both developing and developed countries (Rast, 1999; Falkenmark et al., 1999). This is necessary because of increasingly serious water quality problems resulting from both point and nonpoint source pollutant loads to surface and groundwater. In arid and semi-arid regions, the problems are even more serious, because the absolute lack of water is ultimately both a basic survival and socioeconomic issue (WMO, 1997).

Identifying water quality management goals

The designation of good (acceptable) versus bad (unacceptable) water quality should be based on the intended water use(s). Humans can use water of varying quality for different purposes. However, as a lake or reservoir becomes more and more polluted, its possible water uses are reduced, without expensive and time-consuming treatment measures prior to its use. Thus, the water quality management goals for a lake or reservoir should be based on achieving the needed quality for the water uses deemed most important.

The desired water quality relative to the eutrophication status of a lake and reservoir provides an example. Ideally, a lake or reservoir used as a drinking water supply should have water quality as close to an oligotrophic state as possible, thereby ensuring that no or minimal treatment would be necessary to produce water suitable for human consumption. Some water uses may require no treatment at all, regardless of the quality of the water, an example being the transport of commercial goods by ship. In some areas with limited water resources, virtually all available water may be used, regardless of its quality. Thus, although humans can use water exhibiting a range of water quality, there usually is a desired or optimal water quality for virtually every use. A qualitative example of the identification of acceptable and unacceptable water quality applied to eutrophication is given in Table 3.3 (also see Section 3.2.2). Because information on acceptable versus unacceptable concentrations of other water quality pollutants also is generally available, a similar approach appears feasible for other pollutants as well. The situation will be complicated by the fact that less is known about the ultimate water quality impacts of some other pollutants (e.g., synthetic organic chemicals).

A prudent approach to setting water quality management goals, therefore, is to determine the minimum acceptable water quality for the primary or most sensitive use(s) of the water, and attempt to manage the waterbody to achieve these desired conditions. The situation is more complicated if multiple pollutants must be simultaneously considered. If the existing water quality is not adequate for the intended uses, it will be necessary to develop and implement a remedial program to achieve the desired water quality.

Who should be involved in addressing the problem?
The nations of the world comprise a range of governments and socioeconomic conditions. It is difficult, therefore, to provide unequivocal guidelines regarding the role of governments in environmental protection programs that would cover all social, economic and political conditions likely to be encountered. Nevertheless, virtually all governments have some type of civil service infrastructure that could be used to attempt to facilitate governmental activities related to sustainable aquatic resources. Further, many water quality management programs are typically developed and implemented by a governmental body at the local or national level. Thus, all affected government agencies should be consulted in developing lake and reservoir water quality management programs. Relevant agencies include those involved in issues related to environmental quality, water quality, water supply, natural resource management, fisheries, energy production, agriculture, industry, and public health. This inter-governmental consultation also is a good proactive planning strategy, and should facilitate cooperation, rather than confrontation, between governmental units. It also will focus more energy and resources on developing and implementing environmental problems. Ryding and Rast (1989), Smith and Rast (1998) and Thornton et al. (1999) provide examples of specific expertise to consult regarding the management of lakes and reservoirs undergoing varying degrees of eutrophication.

Citizen involvement
It is usually always helpful to seek the view of the citizens in lake and reservoir drainage basins regarding water quality problems and their possible solutions. A readily-accessible and "user-friendly" forum to obtain this input should be established to facilitate citizen input (e.g., formation of a citizen's advisory group or committee). Further, the decision-maker typically must balance the interests of advocates of long-term benefits against those wishing more politically-expedient solutions. Citizen inputs can sometimes provide decision-makers with a buffer against the latter solutions.

Knowledge gained from citizen fora also can be disseminated among the general population, facilitating more informed future judgments and actions on its part. Effective public participation, however, requires that government officials be honest in their dissemination of information, as well as responsive to the public views presented to them. Whether true or perceived, the belief that government officials are not paying appropriate attention to those providing input and advice can seriously damage citizen confidence in a government-sponsored initiative, even if the latter has positive results to offer.

As an illustration of the potential value of citizen participation, many developing countries may be under such financial constraints that the implementation of large structural solutions to water quality problems (e.g., building municipal wastewater treatment plants) is beyond their means. In such situations, governments can strive to make maximum use of community-based public awareness and information programs on water pollution control measures, especially if citizens can directly participate in developing and/or implementing community-based control measures.

8.3.2 Assessing Available Information and Data

Accurate data and information on the full extent of the problems are essential if one is attempting to address a lake or reservoir water quality monitoring or management program with confidence. Previous studies on similar problems in other lakes and reservoirs, as well as relevant case histories, should be identified and reviewed prior to developing management programs. Relevant information sources include government ministries and agencies, universities, research centers, professional organizations, and scientific and technical literature. The increasing availability of computer-based information sources in many places around the world also should facilitate the identification of such data and information.

Identifying such data and information is necessary for several reasons, including:

- Establishing past and present baseline water quality conditions,
- Identifying significant data and information gaps,
- Facilitating the development of cost-effective monitoring programs.

If the existing data are not adequate to provide the needed information for assessment or management purposes, it may be necessary to establish a drainage basin and/or in-lake monitoring program to obtain the data. However, with careful scrutiny of the data and information needs, and the requirements for obtaining them, an initial monitoring program can be modest in nature, while at the same time allowing for progressive expansion and revision as necessary. Cale and McKown (1986) previously developed a simple methodology for estimating the costs of such monitoring programs, based on the specific data needs, knowledge of the water quality variability in a lake or reservoir, and the costs of individual chemical analyses, relevant personnel and sampling trips.

8.3.3 Identifying and Evaluating Available Options for Addressing Problems

Identification of pollutants

The remedial program or action plan ultimately implemented will be a function of the water quality pollutant or range of pollutants to be addressed, as well as the number and locations of the pollutant sources in the lake or reservoir drainage basin.

Many United Nations organizations (WMO, 1997; UNEP, 1997, 1999) identified inadequately-treated human wastewater as the most serious water-related health problem faced by humans. The most pervasive water quality problem affecting lakes and reservoirs on a global scale is cultural eutrophication (Rast and Thornton, 1996). Water quality problems resulting from related to excessive concentrations of heavy metals are found in both developed and developing countries, particularly in heavily-industrialized areas. Synthetic organic materials have become an especially serious problem in recent years throughout the world, prominent examples being DDT and other pesticides, PCBs, and some organic solvents. Many are suspected human carcinogens, although our knowledge about the conditions under which they are transported, how they partition themselves into various environmental compartments (e.g., water, soil, atmosphere, living beings), and their short-term and long-term human and environmental impacts, is inadequate in many cases.

For lake and reservoir water quality management programs, the range of pollutants to be considered for most remedial programs includes:

- Particulate matter, including large debris,
- Plant nutrients (phosphorus, nitrogen),
- Biodegradable organic matter (biochemical oxygen demand (BOD), chemical oxygen demand (COD)),
- Heavy metals (lead, mercury, cadmium, chromium, nickel, etc.),
- Synthetic organic chemicals (pesticides, herbicides, organic solvents, etc.),
- Dissolved solids (salinity),
- Biological pollution, particularly by microorganisms,
- Acidifying compounds.

More detailed information on pollution is found in Section 2.2.2.

Large nutrient loads usually are generated from municipal wastewater treatment plants and large stockyards, as well as in storm-generated drainage or runoff from agricultural and urban areas. Agricultural runoff and construction sites, particularly in erosion-prone areas, also are major pollutant sources. Significant heavy metal loads are found in storm-generated runoff from urban and agricultural areas, particularly in industrialized regions. Synthetic organic materials are products of agricultural and urban storm-generated runoff, as well as industrial discharges, and also are transported via the atmosphere.

The locations of the "traditional" pollutants (e.g., nutrients, sediments, microbes) in a drainage basin are a significant factor in selecting a remedial or control strategy. These pollutants are subjected to various biological and chemical reactions and transformations in their transport from their sources to lakes and reservoirs. As a general rule, initial attention should be given to the pollutant sources closest to the location at which the water is to be withdrawn.

This general guideline, however, is not necessarily true for persistent pollutants, or pollutants that are capable of undergoing biotransformation to more toxic forms. The latter would include some heavy metals (e.g., lead, mercury) and some synthetic organic chemicals (PCBs, some pesticides and herbicides). The sources of these pollutants throughout the entire drainage basin must be considered in developing effective water quality management programs in such cases. For synthetic organic chemicals, the very nature of the sampling program must reflect the fact that such pollutants are hydrophobic (water-avoiding) in nature. As a result, they typically are present in very low or nondetectable concentrations in the water column. Instead, they tend to concentrate in the fatty tissues of fish and other aquatic organisms and organic-rich sediments in a lake, and must be measured in these components.

An effective remedial program or action plan, therefore, must be developed on the basis of the types, magnitude and sources of pollutants within the entire drainage basin. A general guideline to follow in developing and implementing an effective remedial program is to identify the sources of the greatest quantities generating biologically-available chemical forms of the water pollutants of concern, and to direct major attention to these sources.

Treating the causes versus the symptoms

Considerable past experience indicates that it is inevitably more cost-effective over the long term to treat the underlying, and most readily-controlled, *causes* of water quality deterioration, rather than attempting to alleviate the negative *symptoms* of such deterioration. In most cases, this means reduction or elimination of the pollutant inputs causing the degraded water quality in the first place.

The alternative strategy is to treat the symptoms of water quality deterioration. For a lake or reservoir suffering from excessive growths of aquatic plants (macrophytes) as a result of excessive nutrient loads (e.g., phosphorus), for example, one could mechanically harvest or remove the macrophytes from the waterbody. This is in contrast to treating the nutrient sources that are stimulating the macrophyte growths in the first place. In fact, such mechanical harvesting may be the most logical, and perhaps the only option to consider if the costs of reducing the nutrient inputs (the root cause) are too high, or if additional treatment may be necessary in a given case.

Other possible reasons for treating the symptoms of water quality degradation, rather than their underlying causes, include:

- The absence of an institutional or regulatory framework for identifying and treating the causes,
- An inability of government or other bodies to formulate and implement an effective management program directed to reducing pollution inputs, and/or
- Inadequate financial or human resources to carry out the management program (Rast, 1999).

In some cases, direct treatment of water pollutants in a lake or reservoir basin can offer temporary relief from the symptoms of water quality degradation. An example in regard to eutrophication would be the direct addition of chemicals (e.g., alum) to precipitate the nutrients in the lake water, thereby reducing excessive phytoplankton biomass. The direct addition of acid-reducing materials has been attempted in some Scandinavian lakes to reduce the impacts of acid rain on water quality and biological communities. Treating the symptoms, however, rather than the underlying causes or sources of water pollution usually only offers temporary relief. The water quality problems typically will re-occur as additional pollutants enter the waterbody over time.

Reducing pollutant loads

The nature of the pollutant sources is a major factor in designing an effective remedial program or action plan for managing a lake or reservoir. A first priority usually is to limit or reduce the pollutant load to a lake or reservoir from the sources in the drainage basin that contribute the greatest quantities of the "biologically-available" forms of the pollutants. This refers to the chemical forms of a pollutant that are readily assimilated or taken up by organisms in a waterbody.

Water pollutants can enter a waterbody from both distinct (point) and diffuse (nonpoint) sources in the drainage basin. Examples of nonpoint pollutant inputs to waterbodies include storm-generated runoff from agricultural or urban areas. Consideration of basic differences in the characteristics of the pollutant inputs from point and nonpoint sources are major factors in designing an effective water-pollution control program for lakes and reservoirs (Table 8.1).

Nonpoint pollutant sources are more difficult to identify and quantify than pollutants from point sources. Further, control of storm-generated runoff typically involves multiple administrative units and departments. In contrast, it usually is easier to reduce point-source pollutant loads by initiating control measures at their sources (Novotny and Olem, 1994; Thornton et al., 1999).

Table 8.1. Comparison of point and nonpoint sources of pollution and their management implications (modified from Thornton et al., 1999)

Point sources	Nonpoint sources
Fairly steady volume and quality	Highly dynamic; occurs at random intervals closely related to hydrologic cycle
Variability of values typically is less than one order of magnitude	Variability of values can range across several orders of magnitude
Most severe water quality impacts occur during low-flow periods	Most severe water quality impacts typically occur during or after storm events
Pollutants enter receiving waters at identifiable points, usually via pipelines or channels	Pollutant entry point to receiving waters cannot easily be identified; sources typically arise from extensive land areas
Pollutant loads can be quantified with traditional techniques	Pollutant loads are difficult to quantify with traditional hydrologic techniques
Primary water quality parameters of concern include biochemical oxygen demand (BOD), dissolved oxygen, nutrients, suspended solids, and sometimes heavy metals and synthetic organic chemicals	Primary water quality parameters of concern include sediments, nutrients, heavy metals, synthetic organic chemicals, pH (acidity), and dissolved oxygen
Pollution control programs are typically applied by government agencies	Effective pollution control programs involve individuals not normally considered in such programs (e.g., farmers, urban homeowners)

The magnitude of nonpoint-source pollutant loads arising from storm events depends on a number of factors, including:

- The physiography of the drainage basin,
- The soil type and chemistry in the drainage basin,
- The type and extent of vegetative cover,
- The density of drainage channels in the drainage basin,
- The types and quantities of the materials applied to the land surface,
- The duration of the dry period preceding a rainfall event, and
- The volume, intensity and quality of storm-generated runoff.

Using eutrophication as an example, Ryding and Rast (1989) and Thornton et al. (1999) discussed human and animal wastewater, which contains large quantities of biologically-available phosphorus and nitrogen, as primary targets of pollution control programs. Treatment to reduce these nutrients in wastewater is a cost-effective approach to reduce the nutrient loads to lakes and reservoirs, at least up to a certain advanced treatment level, after which some degree of nonpoint-source control may increase the cost efficiency. It is noted, however, that phosphorus and nitrogen are not the only nutrients needed by algae and aquatic plants for growth and reproduction. In specific cases, other elements or compounds may limit algal growth. Examples of other limiting factors controlling the maximum algal biomass in specific cases include silicon, molybdenum, specific vitamins, etc. Nevertheless, from the perspective of development and implementation of cost-effective eutrophication management programs, phosphorus and nitrogen are the most important nutrients, primarily because their input to lakes and reservoirs, particularly from point sources, can be readily controlled with existing technology.

An alternative method of reducing pollutant inputs to a lake or reservoir is to divert the inflowing waters from the drainage basin into a downstream basin. Although this approach often is effective for the lake or reservoir of concern, it will not eliminate the basic problem. It simply transfers it to a downstream waterbody which may (or may not) be more susceptible to the problem.

The possibility of structural versus nonstructural control options also must be considered. Studies in the North American Great Lakes, for example, indicated that the construction of new municipal wastewater treatment plants, or implementing greater levels of phosphorus removal at the existing plants, was a viable option for significantly reducing phosphorus loads to the lakes (PLUARG, 1978). In some cases, however, nonstructural control measures also offered a viable option for controlling nonpoint phosphorus sources in the Great Lakes drainage basin. The PLUARG study, for example, found that simple changes in agricultural practices could significantly reduce phosphorus inputs from agricultural runoff. Such factors as (i) the quantity of fertilizers or pesticides being applied, (ii) the time of their application and (iii) the degree of treatment after their application (e.g., being plowed into the soil versus simply being applied to the soil surface) were of considerable importance in demonstrating good land stewardship (see Section 9.2). It was possible to demonstrate to farmers that plowing manure into the soil as fertilizer, rather than dumping it onto the land surface to be washed into receiving waters in storm-generated runoff, was effective in reducing inputs of nutrients and other pollutants to the Great Lakes.

Further, implementing soil fertility tests not only allowed farmers to reduce their fertilizer applications, and still produce a crop yield similar to applying larger quantities, but also saved money for farmers that previously used excessive quantities of fertilizers.

The PLUARG study also explored the option of removing water pollutants from urban streets by use of sweeping versus vacuum removal. It found that neither approach was successful in removing the smallest-sized particles, which comprise the major source of many pollutants entering lakes and reservoirs. For urban areas reducing the generation of pollutants at the source was found to be an effective approach over the long term. Thus, actions directed to change human practices in rural and urban areas have the potential to significantly reduce the pollutant loads to lakes and reservoirs.

The option of doing nothing

The environmental, social and economic consequences of doing nothing also should be considered in evaluating management options. Considering the consequences of doing nothing can actually be useful in helping decide whether or not to implement such a program in the first place. The environmental and socioeconomic consequences of doing nothing offer a basis for comparing the potential impacts of initiating a control program.

Nevertheless, experience to date indicates that a proactive approach to addressing water pollution *before* it becomes a major problem results in greater environmental and socioeconomic dividends over time than attempting to treat a lake or reservoir *after* water pollution has become a major problem. Doing nothing usually is not a satisfactory solution to water quality problems. An inevitable consequence of the human settlement of a drainage basin is a deteriorating water quality over time, especially if the deterioration continues to be ignored. Ignoring lake or reservoir water quality deterioration will likely result in the situation becoming worse over the long term, thereby necessitating even more expensive control programs at a later date. It also will reduce the number of water use options. Further, some prevention or control measures actually may result in monetary savings over time, an example being the use of nutrient-rich waters for irrigation or aquaculture purposes (Ryding and Rast, 1989).

8.3.4 Analyzing Costs and Benefits of Alternative Management Options

The costs and effectiveness of alternative pollution control options can vary significantly. The costs of pollutant removal at treatment plants, for example, vary as a function of the treatment process, the age of the plant, the pollutants to be removed and to what level, etc. Nonpoint-source control measures also exhibit a wide range of costs and effectiveness.

Compare the available resources and goals

There is no point in developing a water quality pollution control program if the available resources or administrative structure are inadequate to implement the program. Thus, the available resources should be clearly identified and compared with the needs of the control tasks to be undertaken. These resources include such items as technical expertise, administrative framework, and financial and human resources.

An initial assessment of existing resources also can help identify what new resources are needed before an effective pollution-control program can be implemented. A well-formulated statute or regulation, for example, is useless if not supported by an adequate administrative structure. On the other hand, the results obtained from a well-structured monitoring and assessment program are of no value if the necessary legislative base and/or the institutional framework to ensure that corrective or remedial actions are implemented are not adequate.

Experience suggests that an initial pollution control program should not be unnecessarily elaborate. Rather, it should be sufficiently flexible to have a realistic possibility of achieving its management goals. A small, successful program can be expanded as knowledge and experience is gained, and as new resources are made available, thereby building on success already achieved.

As noted above, if the management goal is to reduce the negative impacts of water quality deterioration, the most cost-effective approach is to reduce the pollutant load from the drainage basin to the lake or reservoir of concern. The control program should be directed to the major sources of the pollutants in the basin.

As previously noted, some land use and/or land management practices offer a nonstructural means of reducing some pollutant loads associated with storm-generated runoff. The implementation of some nonpoint source control methods, however, may require basic public education or changes in public attitudes regarding land use. Without proper public awareness efforts, for example, a farmer located a long distance from a lake or reservoir may not appreciate his/her role in generating pollutant runoff from his land to a waterbody. Thus, the farmer may understandably resist the suggestion that a change in fertilizer or pesticide application patterns, or in the methods of plowing, can help reduce pollutant loads to a lake or reservoir from agricultural runoff.

The role of cost-benefit analysis

There are a number of scientific and technical elements to be considered in developing effective lake and reservoir pollution control programs. Nevertheless, experience suggests that the scientist or engineer cannot ignore the economic, institutional or political realities of the program in favor of developing a strictly science-based solution to the problem. Likewise, the decision-maker or policy-maker cannot ignore the environmental realities.

Because of the tremendous growth in the size, complexity and expenditures of governments, the public reaction in many developed countries has been a reluctance to fund new environmental protection programs without first conducting a thorough social and economic analysis of such programs. The basic approach for assessing the desirability or worthiness of alternative management options is cost-benefit analysis, which has its basis in a branch of economic theory called welfare economics. Although a thorough discussion of welfare economics is beyond the scope of this chapter, Baumol and Oates (1975) provide a basic introduction to this topic.

In the broadest sense, cost-benefit analysis refers to a comparison of all the positive and negative elements of a decision, even if all the elements are not directly measurable in strictly monetary terms. In practice, cost-benefit analysis usually means comparing:

- The economic gains to be realized by implementing a particular program or activity, and
- The costs expected to be incurred by implementing the program.

If this type of analysis indicates that a "unit value" (e.g., dollars) required to implement the program is spent such that it generates more wealth than is sacrificed, the overall social welfare is increased. In regard to pollution control, this means that if the costs of a necessary remedial program do not exceed the expected benefits (e.g., enhanced water quality), it is usually desirable to proceed with the program.

Governments must normally choose between many potential projects and programs, including such concerns as national defense, food security, economic development and environmental protection. Using solely economic criteria to assess the worthiness of such programs must stress efficiency in assessing competing alternatives. Thus, the most effective use of scarce resources is required to maximize their benefits.

The economic costs are primary factors in evaluating the efficacy of national, regional and even global programs. A significant shortcoming with a strictly monetary-oriented approach in selecting between alternatives, however, is the assumption that a positive benefit: cost ratio alone is sufficient rationale to justify proceeding with a given program or project. Indeed, it is difficult to offer a good argument contrary to the notion that a cheap or inexpensive solution to a water quality problem is economically desirable. Unfortunately, such an approach also can be environmentally short-sighted because some program elements are not easily quantified, or else can only be quantified in an artificial or unrealistic manner. Examples of the latter include such diverse elements as cultural values, long-term sustainability of natural resources, political realities, and societal and/or government structure and stability. These components can be fundamental considerations to the inhabitants of a lake or reservoir drainage basin when they are deciding how (or whether) to address a given water pollution problem.

A significant step was undertaken by Costanza et al. (1997), in developing estimates of the economic value of life-supporting ecosystem services provided free-of-charge to humans (e.g., water supply, water regulation, waste assimilation, nutrient cycling) from a number of different types of ecosystems (wetlands, oceans, forests, rangelands, etc.) around the world. Such estimates, even with admitted limitations and uncertainties, provided initial information on the economic value of preserving and protecting rivers, lakes, wetlands and other freshwater and marine systems. The "value" of the human services provided in water systems, estimated to be approximately US $33 trillion annually, is especially impressive, particularly because the estimated combined Gross National Products of all the countries in the world at the time of their calculation was approximately US $18 trillion (also see Section 1.2.3).

Governments should proceed cautiously in using a strictly monetary-oriented cost-benefit analysis as the sole decision-making tool. This approach will preclude realistic consideration of the long-term environmental, social and/or public health consequences of a given pollution control program. By comparing the expected benefits of alternative pollution control programs, one can attempt to select the most preferable option either by:

- Comparing the benefit: cost ratios of alternatives programs and levels of expenditure,
- Comparing the absolute values of the expected benefits of alternatives, using a fixed level of monetary and other resources, and
- Determining the minimum cost program for achieving a specific water quality goal or benefit.

Ryding and Rast (1989) describe a simplified approach for conducting a cost-benefit analysis that addresses alternative technical and social concerns regarding the development of eutrophication control measures for lakes and reservoirs.

8.3.5 Analyzing Legislative and Regulatory Frameworks

Institutional concerns

The nature and adequacy of existing institutions dealing with water resources are fundamental concerns. Because a range of different forms of governments, national priorities, customs and socioeconomic frameworks exist around the world, however, guidelines for addressing institutional and regulatory concerns in one country or region may not be appropriate for another country or region. A substantial water quality monitoring and assessment program for identifying pollution and its sources in a drainage basin, for example, would be largely worthless if not accompanied by a regulatory framework for enforcing pollution control programs. Likewise, a fundamentally-sound institutional base will be ineffective in controlling the pollution of a lake or reservoir if it does not have accurate information on the nature, extent and impacts of pollution problems. The latter typically require an adequate monitoring program.

As a practical matter, it usually is more efficient at the central government level to assign environmental protection programs to a single agency structured to manage multiple environmental concerns (e.g., air, water and land resources) than to create a separate government unit to deal with each problem as it arises. The responsible agency or institution for carrying out such programs must be clearly identified, for the benefit of other government agencies and for the citizens in a drainage basin.

In order to avoid overlaps regarding political boundaries, agency mandates, etc., if an agency with a mission compatible with the goals of a pollution control program already exists, it would likely be the most logical one to carry out the new pollution control function. Care must be taken, however, not to assign a new program to an existing government agency with conflicting purposes or goals. If a control program is given to an agency with conflicting purposes, much effort will be wasted in resolving the conflict, rather than addressing the problem, or else one purpose or goal may advance at the expense of the other. The example of the conflicting goals of providing both "swimmable" and "fishable" waters was noted in the previous section.

Regulatory concerns

A well-formulated statute or regulation is of little value if the necessary monitoring program or pollution-alert network for determining compliance with it is inadequate or nonexistent. Further, lengthy, complex regulations should be discouraged, because of the potential difficulty in both understanding and administering them. A proliferation of agency-oriented regulations that can burden many environmental protection programs also should be avoided. If a new statute or regulation cannot be properly implemented or enforced because of unrealistic components or expectations, achievement of the worthwhile objective also is delayed. In such cases, respect for the timely compliance with laws also is generally eroded.

An orderly progression in statutory complexity and development is preferred to the confusion that can result from attempting to accomplish too much, too soon, and with too little information, manpower and funds. As previously noted, initial regulatory statutes should contain provisions for securing sufficient data and information to allow the responsible agency to periodically re-evaluate a given water quality control program, and revise it as necessary over time.

8.3.6 Selecting a Water Quality Control Strategy

There is no universal program to address all lake and reservoir water pollution problems. Our scientific knowledge of the characteristics and dynamics of lakes and reservoirs (particularly cause-effect relations for extreme events) is not yet adequate to be able to develop and implement a flawless water quality control program. Nevertheless, we do have sufficient knowledge and experience to develop a generalized approach which, if used in conjunction with an adequate monitoring program and continuing evaluation of the measured data, will likely work for the majority of cases to be encountered.

The most feasible control program in a given situation will vary from location to location, depending on the nature and magnitude of the problems, the resources available to address it, the management goals, etc. Nevertheless, the reduction of pollutants loads from their sources in a drainage basin represents the most effective, long-term strategy for attempting to control or reduce water quality deterioration of lakes and reservoirs. As noted previously, some in-lake treatment methods also can offer temporary relief from some pollution problems (e.g., nutrients, heavy metals).

Related water quality and desired water use

It was previously suggested that "good" (acceptable) or "bad" (unacceptable) water quality must be defined in terms of the degree of impairment of human use of the waterbody. In this way, it is possible to relate desired water uses to the minimally-acceptable and/or optimal water quality for these uses. Thus, a logical management approach is to determine the needed water quality for a given water use or uses, and then design the control program to achieve the needed quality.

This approach is prudent for lakes and reservoirs. However, many reservoirs have dendritic shapes and multiple "arms" with many possible pollutant inputs. In contrast to the bowl-like shape of most natural lakes, reservoirs exhibit a depth gradient from their shallow upstream end to the deeper, more "lake-like" end at the dam site (Thornton et al., 1996; Rast and Straškraba, 2000). As a result, reservoirs often exhibit water quality gradients along their length (Fig. 8.1). Nevertheless, experience from around the world suggests that

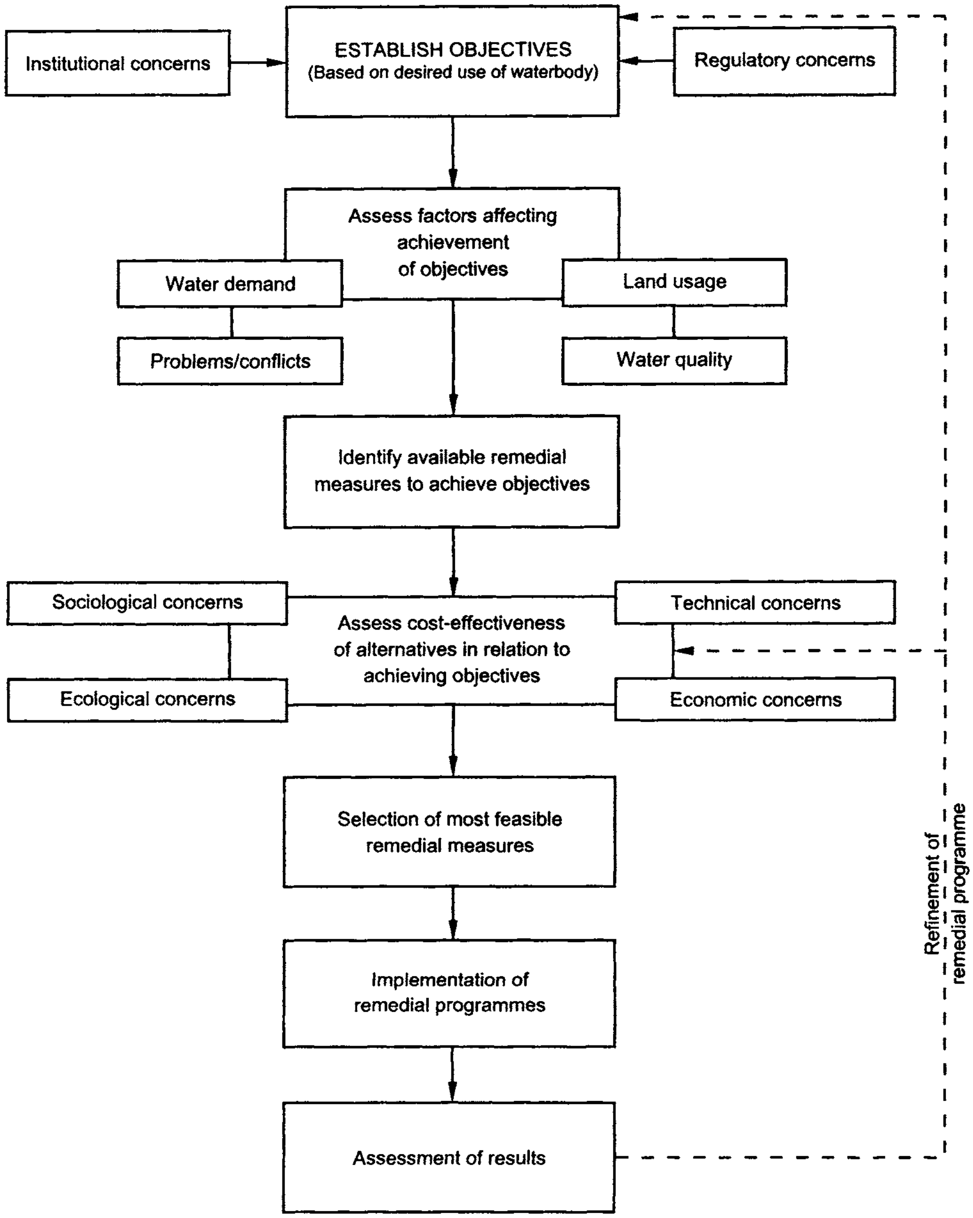

Fig. 8.1. Sequence of relevant decisions to be made by water managers in designing and implementing remedial programs to address water pollution (from Ryding and Rast, 1989).

the primary focus of reservoir water-pollution programs is the deeper, downstream end of the waterbody at the dam. Most water withdrawals are normally taken from this end. Thus, even though the shallower, upstream end of a reservoir may exhibit poorer overall water quality, the quality of the water at the downstream end is the usual focus of water-pollution management programs.

Selecting a water quality control program

As previously noted, an individual lake or reservoir water-pollution control program will depend on a number of factors, including the severity of the problem, the pollutants of concern, the number, types and locations of their sources in the drainage basin, the legislative and regulatory framework, the available institutions to carry it out, etc. Thus, it is difficult to provide unequivocal guidelines to be used in all cases. Nevertheless, a generalized sequence of decisions to be made by a decision-maker or water quality manager is illustrated in Figure 8.2. A practical, step-by-step application of the scientific and technical aspects of achieving the desired water quality in lakes and reservoir undergoing cultural eutrophication is provided in Figure 8.2. It is emphasized that virtually every component in this process, even if determined on the basis of the most rigorous scientific standards and criteria, also will necessarily involve the integration of a range of relevant socioeconomic elements as well. This is particularly true in regard to developing an effective water quality management program for the sustainable use of a lake or reservoir. As illustrated in Figure 8.2, these components include determining the nature of the problem, defining the control goals, assessing the adequacy of the current water quality, identifying logical and practical control measures, etc. Greater efforts also may be required to identify safe (acceptable) versus unsafe (unacceptable) pollutant concentrations, and the necessary reduction of the pollutant load needed to achieve desired in-lake conditions.

A similar approach should be feasible for other water pollutants as well, although the elements, particularly for evaluating the pollutant sources and impacts, and the possible control measures, will be unique to the problem.

The final decision on an appropriate water quality control program should be a "multi-judgment" decision, based on the relevant scientific, social, institutional, economic and political aspects of the problem. It is very important to set up a responsible monitoring program as well, both for defining the necessary condition of the waterbody prior to implementing the management program, and for evaluating the final outcome of the program after it is implemented.

Another point is reiterated here; the most prudent approach is to start with a simple management program, and increase its complexity as further knowledge and experience are gained. In this way, one can build on successes and generally reinforce the ultimate goals of the program.

As noted in Chapter 6, although they should never be used as the sole decision-making tool, mathematical models for predicting future trends in lake or reservoir water quality under a changing pattern of pollutant loads can be useful tools in the management and policy-making arena. Such models can be used to predict average values for specific time periods, as well as extreme or worst case conditions in some cases, depending on the

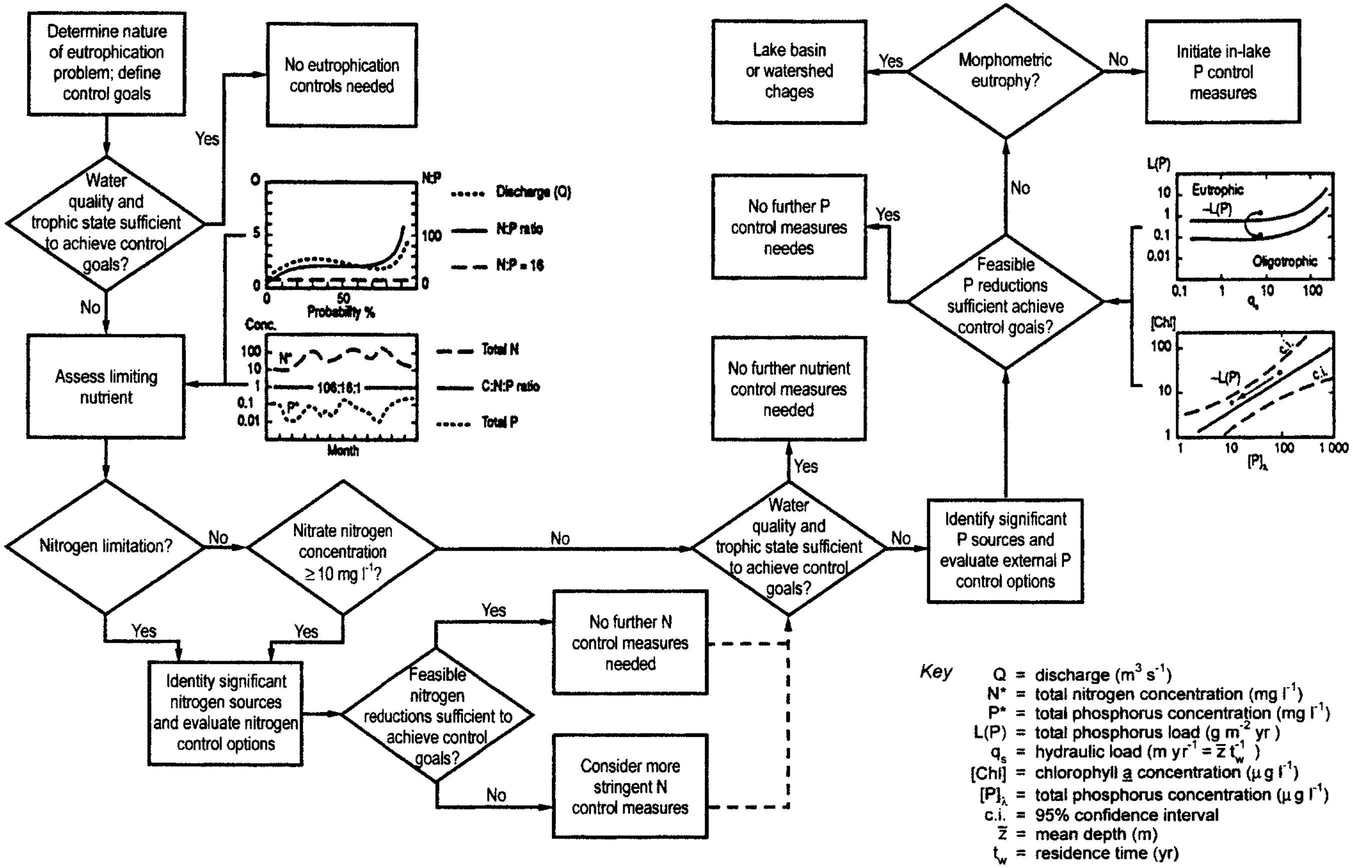

Fig. 8.2. Practical application of a control program for addressing lakes and reservoirs undergoing cultural eutrophication (from Ryding and Rast, 1989).

pollutants of concern. It is also noted that, in most industrialized countries, the main citizen interest in lakes and reservoirs tends to focus on the water quality conditions existing during the period of maximum direct human contact use of the waterbodies and the period of worst water quality. In flowing waters, however, recreational use may be prolonged throughout the year.

The problems to be identified and addressed, and the remedial programs to be developed and implemented, will necessarily dictate the elements that must be considered in developing a comprehensive, cost-effective water quality management program. Nevertheless, a number of principles exist that can be used to guide water quality management programs. These principles were developed as a collaborative effort of an international group of stakeholders concerned with the sustainable use of lake and reservoirs, including representatives of governments, non-governmental organizations, citizens organizations, international scientific organizations, academia and scientific institutions. As identified and discussed in the *World Lake Vision: A Call for Action*, these general principles are as follows (Rast, 2003b):

Principle 1. *A harmonious relationship between humans and nature is essential for the sustainable use of lakes.*

Principle 2. *A lake drainage basin is the logical starting point for planning and management actions for sustainable lake use.*

Principle 3. *A long-term, preventative approach directed to preventing the causes of lake degradation is essential.*

Principle 4. *Policy development and decision making for lake management should be based on sound science and the best available information.*

Principle 5. *The management of lakes for their sustainable use requires the resolution of conflicts among competing users of lake resources, taking into account the needs of present and future generations and of nature.*

Principle 6. *Citizens and other stakeholders should be encouraged to participate meaningfully in identifying and resolving critical lake problems.*

Principle 7. *Good governance, based on fairness, transparency and empowerment of all stakeholders, is essential for sustainable lake use.*

Coupled with consideration of the relevant scientific, socioeconomic and political realities, these principles provide valuable guidance to decision-makers and policy-makers involved in lake and reservoir water quality management.

8.3.7 What if a Lake or Reservoir Does Not Respond as Expected

In some cases, even with the development of a seemingly-comprehensive water quality management program, a lake or reservoir will not respond as expected to the implemented control measures. In these instances, there are several factors that can be examined to determine why the expected results did not materialize.

Assess the lag period for lake response

A lake or reservoir will not necessarily respond immediately to a pollution control program, especially those directed to reducing external pollutant loads to the waterbody. Rather, there typically is a time interval or "lag period" between implementation of a control program and the expected, measurable results. The lag period is the time necessary for the lake or reservoir to flush itself, or otherwise neutralize the effects, of any internal stores of a pollutant, particularly in the sediment at the bottom of the waterbody, once their input has been reduced or eliminated. A prominent example is the phosphorus in the bottom sediments of lakes undergoing cultural eutrophication. If the oxygen in the water layer overlying the bottom of the lake is depleted, the phosphorus in the sediments can be re-mobilized back into the water column. In contrast, in-lake methods, such as harvesting of aquatic weeds and precipitation of nutrients in the waterbody, may show smaller or no lag periods, since the symptoms are being directly treated in these cases. However, for in-lake methods, the negative symptoms may reappear after a short time period.

Citizens should be informed of possible lag periods. Otherwise, they may erroneously conclude that a control program has failed to achieve its pollution control goals, when the reality is that there simply has not been sufficient time after implementation of the program for the positive results to become visible. Sonzogni et al. (1976) and Ryding and Rast (1989) outline methods for calculating the expected duration of the lag period needed to show positive results from reducing the external phosphorus loads to lakes and reservoirs.

Reassess the pollutant load estimates

Another possible reason for a lake or reservoir not responding to a pollution control program may be inaccurate estimates of the pollutant load to the waterbody. Further, as noted above, a lake or reservoir can contain significant quantities of a pollutant in its bottom sediments that can be re-mobilized back into the water column under oxygen-depleted conditions in the bottom water layer in the waterbody. These latter sources must be considered in estimating their total load to a lake or reservoir.

As a general rule, direct measurement is the most accurate means of determining the pollutant load to a lake or reservoir. If it is not possible to directly measure the loads, one can estimate the load using unit area loads for specific pollutants and types of land uses in a drainage basin. Unit area loads provide an estimate of the average pollutant load expected to be generated from a given area of land surface over the annual cycle under average hydrologic conditions. As a simple example, a unit area load for a water pollutant might be one kilogram/hectare of agricultural land/year. Multiplying this value by the total number of hectares of agricultural land in a drainage basin provides an estimate of the annual load of the pollutant of concern expected from agricultural areas in the basin. The unit area load, however, must be used with caution, because "wet" or "dry" periods can significantly influence the quantities of a given pollutant generated in a given situation. The time interval between precipitation events also can influence the pollutant load (Thornton et al., 1999).

Although the most accurate values are obtained from direct measurements, the unit load approach also can be used for some point sources. One example is the phosphorus discharge from municipal wastewater treatment plants. Knowledge of the average production of phosphorus from each individual in a given area, and the number of people being served by a treatment plant, can provide an estimate of the total phosphorus load from the plant. A similar approach could be applied to pollutant discharges from specific industries and manufacturing processes.

The multi-year, international study of nonpoint-source pollution of the North American Great Lakes Basin provides unit area load estimates for a number of water pollutants (PLUARG, 1978) affecting the Great Lakes. Rast and Lee (1983), Ryding and Rast (1989) and Thornton et al. (1999) also discuss methods for estimating the accuracy of phosphorus loads to lakes and reservoirs.

Reassess the water quality sampling program

Lakes and reservoirs can exhibit large, intermittent variations in water quality. Thus, an efficient, representative and economically-feasible sampling program is not always readily attainable unless such variations are incorporated into the program. This typically means more frequent sampling during periods of water quality changes, including during and after precipitation events.

Further, accurately forecasting hydrological and meteorological conditions from one year to another, especially because of low flow and flood periods, and for "ice-breaking" periods, is difficult over the long term. There is a need, therefore, for appropriate water quality sampling intervals both in a lake or reservoir, and in the major input streams, over the annual cycle as a baseline monitoring program. As noted above, flood and major rainfall events should always be sampled. A sampling period of at least three years should be considered a minimum sampling effort for the most accurate assessment of a waterbody. To this end, Ryding and Rast (1989), Thornton et al. (1996) and Rast and Thornton (1999) provide guidance for addressing water quality gradients in lakes and reservoirs.

Reassess the geographic factors

Physical factors such as mean air temperature, rainfall, snow cover, overland flow and soil erosion can significantly affect the water quality conditions to be found in a lake or reservoir. Further, because of their generally higher average water temperatures, waterbodies in tropical regions can exhibit considerably different chemical conditions and biological communities (also see Section 1.3.2—*Consequences of Geographic Differences for Water Quality Management*).

Reassess the lake morphometric factors

The shape or configuration of a lake or reservoir can significantly influence its response to reduced pollutant loads. It is generally difficult, for example, to accurate define the average conditions for reservoirs with substantial longitudinal gradients in water quality (Rast and Straškraba, 2000). As previously noted, the main sampling sites for reservoirs are normally situated at the dam end of the waterbody. In waterbodies containing multiple sub-basins, it is difficult to determine the "average" water quality conditions for the entire waterbody. Further, reservoirs subjected to periodic drawdowns also can experience widely-differing morphometric characteristics over the annual cycle. These factors can result in erroneous conclusions regarding the overall water quality of a lake or reservoir.

Reassess the hydrodynamic factors
The mixing regime in a lake or reservoir involves elements such as the wind-induced mixing of the water (and its "fetch") during different seasons, the ratio between the volumes of the bottom and surface water layers (hypolimnion: epilimnion ratio), the ratio between the mixing depth and the mean depth in a waterbody, and the ratio between the shoreline waters and the surface waters (littoral area: epilimnion ratio). These elements also can facilitate the remobilization of pollutants in the bottom sediments back into the water column, particularly with wind-induced water mixing.

Duration of expected results
Even when such factors are appropriately considered, a pollution control program still may not achieve the desired results. The only alternative in such cases may be more stringent control measures. Alternatively, one can simply accept the results obtained with the original program as the best that can be obtained for the lake or reservoir with the existing resources and efforts.

Fortunately, however, even when a pollution control program does not produce the desired results within the expected time period, such programs still generally work to the positive benefit of a lake or reservoir. An additional factor to consider in developing a pollution control program, therefore, is the expected duration of the program. Programs designed to be effective over the long term usually are preferable than programs designed only for short-term results.

8.3.8 Summarize Selected Control Strategy

After developing a pollution control program or strategy, it is useful to develop a detailed working plan. The goal is to ensure that regulators, implementers and all other interested parties and individuals have adequate documentation of the program objectives, and the tasks necessary to achieve them. This approach also will foster cooperation, rather than confrontation, between the involved government units, and between government agencies, the citizens and other relevant stakeholders in the drainage basin. The program summary should identify the goals of the control program, and the obligations of the involved governmental agencies and other relevant stakeholders.

A brief control program overview also can be prepared for all interested parties inside and outside the government. It should contain a clear re-statement of the problem to be addressed and the goals of the program, and should be widely disseminated prior to its implementation.

8.3.9 Post-Project Monitoring

It is essential to ensure appropriate monitoring efforts and studies continue for at least several years after implementing a lake or reservoir pollution control program. This will allow comparison of the conditions of a lake or reservoir before and after the implementation of the program.

Post-treatment monitoring also will allow governments, citizens and other interested parties to ascertain whether or not the expected results, often based on model calculations and predictions, have been achieved. Even if the measured results of a pollution control program fall short of the expectations, a post-project monitoring program still can be used to improve the predictions in question, and to reduce the uncertainty of model predictions for future planning purposes.

8.3.10 Periodic Progress Reports to the Public and Other Stakeholders

Wherever feasible, citizen participation in developing and implementing water pollution control programs can be very valuable. Further, providing progress reports to citizens on the results actually achieved for a pollution control program are extremely useful.

The type, extent and format of the information will vary considerably on the basis of the target audience. Appropriate media include the press, television, radio and the Internet, as well as popularized science and technical publications. In view of the lay audience's nontechnical background, general information is usually more informative than highly-technical or scientific descriptions. Appropriately-illustrated information also is useful in communicating to citizens, with technical jargon kept to a minimum. Detailed technical discussions can be presented in appropriate scientific and technical reports and journals.

Experience has generally demonstrated that, if citizens can be persuaded of the severity of a water quality problem, and the environmental, health and economic consequences if the problem is ignored, they can more easily and readily appreciate the need to implement a control program. It also can result in the development of a proprietary interest on the part of citizens in the work involved in the control program. In many cases, it can assist in making citizens more amenable to the associated expenses of the program.

Rast et al. (1990) and Thornton et al. (1999) provide detailed discussions of these various principles as applied to control nutrient loads to lakes and reservoirs undergoing cultural eutrophication. Their approach can be generalized to other pollutants as well.

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