Chapter 4

MEASURES FOR IMPROVING WATER QUALITY

This chapter deals with preventive and corrective methods for improving water quality, both in the watershed and in the waterbody into which it drains. Facilitating the application of preventive methods is the goal. However, corrective methods also can be important if preventive measures already have been applied to the maximum extent. Accordingly, the chapter is divided into four sections; Section 4.1 is introductory, Section 4.2 is devoted to measures applied in the watershed, Section 4.3 summarizes in-lake methods and Section 4.4 focuses on combined and innovative methods.

Section 4.2 discusses methods of water quality management within the watershed in four major categories: pollution prevention from forests and agriculture (Section 4.2.1), clean production by factories (Section 4.2.2), wastewater treatment by municipalities (Section 4.2.3), and ecotechnological methods using absorption of pollution by plant communities in natural and constructed wetlands (Section 4.2.4).

Section 4.3 distinguishes seven groups of in-lake measures, including biomanipulation or eutrophication control based on modifying food chain relations (Section 4.3.1), various methods of lake mixing and oxygenation (Section 4.3.2), hydraulic regulation by modifying the flow through lakes (Section 4.3.3), biomass removal (Section 4.3.4), methods of treating lake sediments (Section 4.3.5), nutrient inactivation methods in the waterbody (Section 4.3.6), methods that treat sediments (Section 4.3.7), and other methods (Section 4.3.8).

Section 4.4 identifies some examples of successfully used combinations of in-lake approaches. It also discusses some innovative approaches that have not yet been verified, but which show promise.

4.1 INTRODUCTION TO REMEDIAL MEASURES

When pollution abatement was discussed during the first green wave in the late 1960s, so-called "end-of-pipe" techniques were the primary consideration. There was a general optimistic view on the possibilities of using technology to solve all environmental problems. A typical statement from the late 1960s was: No dilution, but treatment. Today, almost 30 years later, we realize that environmental management comprises a very complex set of problems, and that only consideration of a wide spectrum of approaches can solve the problems properly. It is not surprising that solving complex environmental problems associated with very complex systems such as lakes will require complex approaches and techniques. Thus, very careful selection of proper management approaches on the basis of substantial knowledge of the system and the problem is necessary.

Thirty years ago, diffuse (nonpoint) pollution did not play any role in the green debate. Since the late 1970s and the early 1980s, however, it has become clear that nonpoint pollution sources, as well as internal sources (e.g., lake sediments), often are more significant pollution sources than the point sources, which often can be reduced significantly by an easily manageable "end-of-pipe" technique. This development has provoked a new type of pollution control approach, denoted *ecotechnology*, which is better able to cope with diffuse pollution sources, which are discussed in this chapter (also see Chapters 5 and 6).

Ecosystems are living systems, and do not react in the same predictable manner as rigid physical systems. In fact, ecosystems have often exhibited surprising reactions to changed impacts, which obviously complicates environmental management considerations. A deeper understanding of systems ecology, therefore, is a prerequisite for a more ecologically-sound environmental management approach, one of the threads unifying this entire document. The state of a lake is obviously dependent on the forcing functions that cause the observed impacts. The history of the lake, however, also is important in assessing its possible reactions to changed water quality or other type of impact. It can be shown that the same impact on a lake (e.g., the same total phosphorus concentration in lake water) may result in two different responses, depending on the structure of the system, which again is determined by the history of the system.

Many failures in lake management can be explained by the omission of the ecological consideration of the waterbody. As an example, an ecosystem resists changes, with a tendency to try to maintain its existing structure. A reduction in external forcing functions (e.g., a pronounced reduction in the phosphorus load entering a lake from wastewater discharges) is often not sufficient to restore a lake or reservoir. If the structure of the food web in a waterbody is adapted to a high phosphorus input, it will require very pronounced reductions in the phosphorus load to shift to a mesotrophic or oligotrophic condition. Thus, biomanipulation is an alternative to support the system in its efforts to shift to another food web structure. In this context it is absolutely necessary to consider the storage of nutrients and other pollutants during the implementation of a management strategy. Significant quantities of nutrients and other pollutants may be stored in the lake bottom sediments. If less-polluted water flows into a lake as a result of proper wastewater treatment, nutrients stored in the sediments may be released if appropriate chemical conditions exist in the water layers at the bottom of the lake and can significantly delay its restoration. This internal pollutant source often may be very significant, dominating over external pollutant sources for an extended period (also see Section 2.2.2—*Eutrophication*).

The importance of internal pollution sources is closely related to the proper timing of effective management strategies. Because an ecosystem has the ability to reduce the impacts of pollutant inputs by various accumulation processes, accumulation in the sediment being one of the most significant, it becomes very important to reduce the pollution sources at an early stage. Environmental management efforts in Denmark clearly illustrated how a good management strategy, applied at the wrong time, can lead to significant increases in pollution abatement costs. An ambitious environmental management strategy was launched in Denmark in 1976, with the goal of letting the ecosystem determine the best restoration strategy. Consequently, it was necessary to make plans about the use of all aquatic ecosystems. Could discharge of wastewater be tolerated? What were the recreational values of the various aquatic ecosystems? Did some ecosystems have a particular scientific value? Which ecosystems were valuable as water resources? Many more questions became evident. To answer these crucial questions required more than 7 years of interactions between the different levels in the political hierarchy, from the communities to the government, which resulted in excellent environmental plans, but no pollution abatement. The Gordian Not was cut in 1986, when it was decided that all Danish wastewater treatments would meet certain standards, including a biochemical oxygen demand (BOD_5) $\leqslant 10\ \mathrm{mg\ l^{-1}}$, total phosphorus concentration $\leqslant 1.5\ \mathrm{mg\ P\ l^{-1}}$ and a total nitrogen concentration $\leqslant 8\ \mathrm{mg\ N\ l^{-1}}$. In addition, it was possible to assess even more strict requirements for particularly important or vulnerable ecosystems (e.g., lakes of important recreational value). This goal was subsequently widely applied in Danish lake management efforts. The result was that the entire environmental strategy in Denmark was quite successful—except for the timing. These measures should have been implemented 7–9 years earlier! The consequences were that 7–9 additional years of phosphorus (and nitrogen) discharges accumulated in the Danish lakes, making it considerably more difficult to find a management strategy able to return the lakes to the conditions prevailing 30–50 years earlier. A specific example of this failure is Arresø in Zealand, Denmark's largest lake. The lake is very shallow, with a maximum depth of 4 meters, which obviously accentuates the importance of nutrients accumulated in the lake sediments. If a proper environmental management had been implemented in the mid-1970s, the condition of the lake today would have been close to its condition in the 1950s. However, because of the above-noted delay of 7–9 years, so much additional phosphorus had accumulated in the sediments that it may take more than 100 years to bring the lake back to its previous conditions based solely on reduction of its phosphorus load. In fact, it may be necessary to remove the upper 0.5 meters of the lake bottom sediment to significantly reduce the internal phosphorus load, which will cost as much as US $60–80 million based on a sediment surface area of 41 km^2. Under all circumstances it will be necessary to apply restoration methods.

As this example illustrates, lake restoration may be very expensive. It is usually best, therefore, to develop and implement good lake environmental planning at an *early* stage, in order to be able to also take preventive measures that would eliminate the problems of phosphorus accumulation, as well as heavy metals and persistent organic chemicals, in lake sediments. A proper environmental planning also would help identify the pollution priorities that a good strategy should address.

Many developing countries lack the economic resources to undertake appropriate environmental management programs. Nevertheless, the reality is that proper environmental planning can be carried out at a fraction of the costs of major pollution abatement programs. It is strongly recommended, therefore, that development plans include environmental planning efforts at an early stage. This will facilitate their assigning a proper priority to the various steps in the environmental management planning process, and also making better use of preventative preventive measures, both of which will work to enhance the possibilities of moderate-cost solutions over the long term.

As with other ecosystems, lakes and reservoirs are "open systems". Thus, it is not sufficient to consider only the lake or reservoir water basin in a management regime. Indeed, it also is essential to consider the entire watershed of a lake or reservoir, in order to include all the pollution sources in the management considerations. It is often much more cost-effective, for example, to reduce the concentration of a pollutant at its source—a solution that can only be identified by considering a lake and its watershed as one combined system. Further, there are usually many more possible solutions to lake and reservoir problems when we attempt to optimize a large, combined lake–watershed system, rather than focusing only on the lake itself. Including the entire watershed in environmental management considerations is of particular importance for developing countries, which generally have fewer resources to devote to later pollutant abatement efforts than do the developed countries.

The use of ecological modelling has become much more important over the last 30 years, due to a need for quantification in ecology and environmental management efforts. This is probably the only significant tool available for obtaining a quantitative overview of a complex ecosystem such as a lake or reservoir, which is a prerequisite for selecting an optimum solution to the complex problems facing them. Because solutions to the entire spectrum of environmental problems require quantitative estimation methods to assist in identifying a realistic trade-off between ecological and economic concerns, it is not surprising that ecological models have been used increasingly in environmental management efforts. Chapter 5 provides an overview of models in environmental management of lakes and reservoirs.

From this introductory discussion, several important recommendations may be deduced, as summarized in the following six points:

- Expect that a proper environmental strategy will require a wide spectrum of approaches and techniques,
- Expect that proper environmental management will require the application of a combination of "end-of-pipe" technologies (environmental technology), ecotechnology, cleaner technology and environmental legislation,
- Correct timing in applying the various steps in environmental management efforts is extremely important; thus, it is recommended that a comprehensive environmental management plan be developed at a very early stage, in order to be able to use the available resources in the most optimal manner,
- It is usually very beneficial, particularly from an economic perspective, to consider prevention, rather than correction, primarily because it is often very costly to restore heavily degraded lakes,
- Because of the complexity of ecosystems and their problems, proper ecological knowledge about ecosystems is a prerequisite for ecologically sound environmental management programs; this is the only reasonable method for avoiding unexpected ecosystem responses,
- Optimum solutions to environmental management problems are best obtained if the entire lake–watershed ecosystem is taken into consideration in developing and implementing management actions.

4.2 WATERSHED METHODS

Ecotechnological methods used in the watershed (Table 4.1) can be classified as either preventive or corrective. Preventive methods, directed to the creation of conditions minimizing pollution, are preferable because they are cheaper for society than the implementation of corrective, remedial measures. It is very unwise, from a global perspective,

Table 4.1. Ecotechnological methods applied to reservoir watershed management and recovery (modified from Straškraba et al., 1993; Thornton et al., 1999)

Problem to be solved	Methods
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 the vegetated banks • Natural and constructed wetlands • Pre-impoundments at the inflows • Wahnbach P-reduction plant
Eutrophication and oxygen depletion of rivers:	• River restoration • Re-oxygenation
Reservoir siltation:	• Erosion control • Rehabilitation of river banks • Reforestation • Groundwater recharge • Pre-impoundment of inflows
Heavy metal contamination:	• Reduction of polluted effluents • Wetlands
Acidification:	• Liming • Organic matter additions
Salinization:	• Improved irrigation practices • Decreased fertilizer applications • Decreased road salting
Decreased biodiversity due to reservoir construction:	• Prohibit introduction of foreign species • Reintroduction of native species • Maintenance of wetlands as nursery grounds • Maintenance of preserved areas for native species

to first release pollutants in diluted form into canals and surface waters, and then to extract and treat them with costly methods. All pollution extraction procedures are cheaper when the pollutant concentrations are high. Some approaches will be the same for prevention as for correction—the only difference will be in the timing. Prevention must be done early, before pollution starts. A clear example of the importance of timing was shown above in Section 4.1. A typical corrective group of methods is represented by wastewater treatment. Unfortunately, this is frequently the most often, if not the only, method of pollution abatement considered.

One obstacle to using preventive measures is the sectoral character of infrastructure. It shifts the impacts from water to land, to sectors such as forestry, agriculture and industry. However, because water resource managers typically have the information on the state of the water resources and the costs of corrective measures, they also are responsible for documenting and advertising the societal advantages of preventive, rather than corrective, approaches, as well as the possibilities of other sectors to prevent pollution.

Many new ecotechnological methods use the capabilities of natural systems to adsorb or otherwise neutralize pollution. However, mastering these methods requires "fine-tuning" between technical and natural means, as well as the need to use more, and until now less understood, knowledge. In a way, they substitute the brute force of modern technology with specific knowledge and, in this way, are representative examples of the informational revolution currently underway. A typical example is the use of wetlands for water purification. Wetlands are considered less reliable than classical wastewater treatment for such purposes, mainly because they are affected by weather and other conditions, and because we know less about how wetlands work to produce their effects. However, such factors as their low price, their natural availability in many places around the world, and their high purification efficiency make natural wetlands ideal tools for pollution prevention, and constructed wetlands ideal for pollution abatement.

4.2.1 Pollution Prevention from Forests and Agriculture

Pollution sources from forested and agricultural areas are primarily nonpoint or diffuse in character. The newest experiences with diffuse, nonpoint source pollution and the possibilities for its abatement, are summarized by Thornton et al. (1999). Fertilizers applied to fields (and sometimes to forests) and post-harvest protection chemicals (and the heavy metals they contain) are major polluting substances. The resulting pollution primarily impacts ground and surface waters. However, increasing importance also is being given to air pollution by ammonia from animal husbandry operations. There are also point pollution sources from agriculture, examples being pollution from concentrated husbandry units or agricultural product enterprises. However, the later ones can be considered industrial enterprises, the food industry being just one type.

Specific methods for treating diffuse pollution from agriculture and forestry fall into the following groups:

(i) Methods associated with crop cultivation,
(ii) Methods directed to forestry,

(iii) Methods directed to controlling the application of herbicides and pesticides,
(iv) Methods directed to decreasing the quantity of agricultural and forest pollution reaching surface waters.

Diffuse pollution from different types of agricultural cultivation
Agricultural components leading to water pollution may be of three kinds: crop production, pastures, and animal production. Diffuse pollution from agricultural crop activities consists mainly of nutrients, heavy metals and salts from fertilizers and organic chemicals used for crop protection. Pollution from livestock cultivation comes mainly from animal faeces, urine, and pasture erosion. The focus in this section is on nutrients, although they are often accompanied by heavy metal and mineral (salt) pollution. Salts represent a large percentage of applied fertilizers and are a significant component of the generally-increasing salt concentration in natural waters (see Section 2.2.2—*Salinization*). Although the quantity of heavy metals in applied fertilizers is low, their influence on the environment is very negative (see Section 2.2.2.—*Metals*).

Soils deprived of nutrients during harvesting are often fertilized with either manure or chemical fertilizers. Fertilizers are typically in the form of nitrogen, phosphorus and potassium (N–P–K), but only nitrogen and phosphorus are aquatic pollutants, provoking lake and reservoir eutrophication. There is a difference between the two elements in regard to their retention in soils. The retention of phosphorus is high, while nitrogen is retained to a lesser degree. There also is a difference between temperate and tropical soils in this respect; nitrogen retention in soils in tropical regions generally is higher than in temperate regions. Nitrogen also has an additional function, relative to its role as a plant nutrient; namely, it represents a possible cause of human illness (see Section 2.2.2—*Eutrophication*). Different crops have different nutrient needs, as do different varieties of the same plant, with the need being irregular in time and dependent on soil type.

The degree of cropland pastures and forest pollution depends mainly on the type of crop, soil type and soil erosion, type of fertilizer and the method of fertilizer application.

Crop types and field cultivation methods
Different vegetation formations have differing abilities to retain nutrients. A major method of minimizing pollution is to retain forests because they possess the highest retention capacity for pollutants, and to use meadows wherever possible. In regard to cultivated crops, those having dense growths should be used, although those whose use will produce strips of bare soils should be omitted, or else the bare strips should be filled with other vegetation. The general functions of forests, meadows, and dense vegetation are two-fold: high nutrient retention and prevention of soil erosion, thereby also preventing erosion-associated nutrient losses.

Different agricultural crops produce different quantities of nutrients exported to receiving waterbodies, depending primarily on their nutrient needs. Row crops produce larger nutrient exports than non-row crops. Low nitrogen pollution can be achieved by using the nitrogen-fixing ability of some plants, resulting from symbiotic nitrogen-fixing bacteria (particularly in the plant family Fabacae). Research in Brazil lead to the discovery that some varieties of mass-cultivated plants grown on low nitrogen soils also possess symbiotic nitrogen-fixing bacteria, thereby having a low need for fertilizer nitrogen. Particular attention is given to sugar cane, which is used as a source of alcohol for cars. These results have great potential for improving water quality.

On the one hand, conventional tillage methods (e.g., fallow land during nongrowth season, harvest removal of crop residues) results in large nutrient exports. On the other hand, conservation tillage practices reduce nutrient export. Unfortunately, however, the latter also results in increased herbicide usage and runoff.

Pastures typically do not produce large quantities of aquatic pollutants, except when fertilized. Limiting livestock grazing time on a given parcel of land also reduces nutrient export. The greater the animal density, the greater the potential for increased pollution.

Soil types, quantities and erosion

Regional differences in the percentage of nitrogen released from applied fertilizers are related to the character of soils, and particularly their water permeability. Less water-permeable soils retain more nutrients (e.g., phosphorus export from sandy or gravel soil generally is small, compared to a large export from clay soils and organic soils).

Because erosion plays a major role in increasing pollutant loads to waterbodies, techniques to prevent erosion must be applied in such cases. On land with slopes of more than a 15% gradient, the field orientation must be shifted to contour strip-cropping, with proper selection of crops. Dense, permanent vegetation is the best means for protecting watersheds against erosion and the release of nutrients, particularly phosphorus. Applying purely technical means to prevent erosion can be costly.

Fertilizer type

The use of manure is preferred over the use of artificial fertilizers in regard to preventing water pollution. This is because the nutrients are released from manure only slowly, thereby allowing plants to keep pace with the released nutrients. Straw, which is a considerably component of manure, also can be used as a retarding element for nutrients. A general observation is that the inefficient use of nutrients simultaneously represents losses for agriculture and additional expenses for addressing water pollution. In addition to its nutrient content, the other components of fertilizer also are important in regard to water pollution concerns. For example, the availability of fertilizers for plants, and therefore the magnitude of the resulting pollution, depends on the compound in the fertilizer to which the nutrient is bound. Additional pollution problems are created by the salts contained in fertilizers. Water salinity is now generally increasing around the world, a primary reason being the increased used of fertilizers. Fertilizers also must be checked for the presence of components toxic to humans.

Fertilizer application

Crops are able to utilize fertilizer nutrients only up to certain doses of fertilizer application (Fig. 4.1). Thus, farmers must be shown that the application of fertilizers above a certain

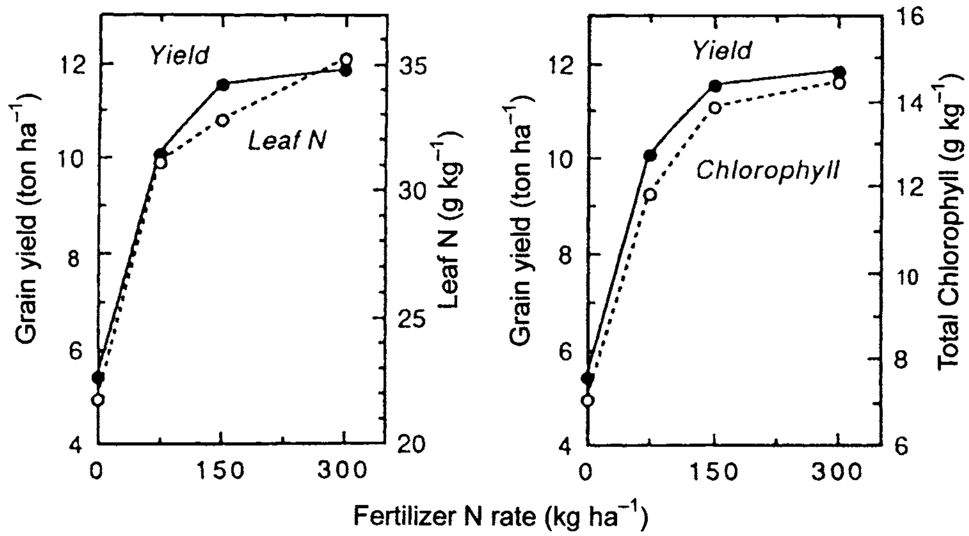


Fig. 4.1. Effect of fertilizer nitrogen rate on leaf chlorophyll and nitrogen concentrations and yield of three corn hybrids, showing the saturation effect at some 150 kg per hectare.

limit inevitably leads to fertilizer and financial losses, with the excess fertilizer also causing pollution of ground and surface water. The curvilinear dependence seen in Figure 4.1 also indicates that, as the upper limit of plant reactions to fertilization is approaching, the crop return becomes lower and, therefore, application of fertilizer up to this limit is inefficient. The respective fertilizer should be applied in a form that facilitates maximum nutrient utilization by the crops. Fertilizer in the form of pellets, particularly of certain types, is superior to powders. Airplane application during dry weather should be avoided, as it creates greatest spreading of fertilizers to waterbodies. The timing of fertilizer application should be synchronized with plant needs. Fertilizers should never be applied on bare field without vegetation. The greatest fertilizer nutrient losses are associated with winter application on snow, since much of the nutrient movement to watercourses occurs during the thaw period. Incorporating applied fertilizers into the soil also results in reduced nutrient exports. Fertilizer storage areas should not be located in the vicinity of watercourses, and should ensure protection against the dispersion of stored manure.

Animal production

Nutrient exports increase with increasing animal density. Nutrient exports also increase with the extent of impervious substrates in feedlots. The use of detention basins decreases nutrient export. It appears that nutrient export decreases with an increase in the roof area : feedlot area ratio (Thornton et al., 1999). Innovative ecotechnological protection methods, such as vegetative filter strips, should be used (Toombs, 1997).

Control measures for nonpoint source pollution from agriculture

Various control options follow from the above evaluation of different diffuse pollution sources, as summarized under the following headings (Thornton et al., 1999):

- Conservation tillage (crop residues not removed, field continuously covered),
- Contour farming/strip cropping (plugging along contours, no large bare strips),
- Integrated pest management (low pesticide use, good chemical selection, biological methods),
- Management of pasture/range lands,
- Crop rotation (with respect to differential nutrient needs; nitrogen fixing plants),
- Terraces (no steep slopes),
- Management of animal wastes (prevention of leakage to waters),
- Fertilizer management (protection of stores, application form and timing),
- Livestock exclusion.

Preventing pollution from forest cultivation

In addition to their positive effects on water quantity, forests also have positive effects on water quality. They not only do not release polluting substances, but are able even to retain pollution entering them from outside the forest. The only negative influence of deciduous forests on water quality is represented by the humic substances released into water, so that both streams and lakes have low pH and a brown color. Treating such water for drinking water purposes requires special care. This positive effect turns into a negative one in the case of forests damaged by acidification, when the extremely low pH causes the release of aluminum in a toxic form. Further, some forests used for very rapidly growing wood production can have negative effects on water quality. This is particularly true for the Australian *Eucalyptus*, which exists in many parts of the world.

The methods of managing forests with regard to protection of water quality, therefore, are consistent with balanced forestry practices aimed at multigoal forest functions, but not with the one-sided wood production technology: keeping a healthy mixed forest, no clear cutting, sensitive use of machinery. Forest burning caused by natural events and local pests attacking trees causes less damage than spraying forests with pesticides or the mass eradication of damaged trees using heavy machinery. Fertilizing forests should especially be avoided in watersheds used for drinking water supply.

Special attention should be given to riparian forests on the slopes of river valleys and other steep slopes. Their buffering and nature protecting function is manifold, including,

- Protection against erosion,
- Capturing silt, nutrients and other pollutants originating from fields, thereby preventing water pollution,
- Serving as migration corridors for animals,
- Protecting biodiversity by serving as refuges for different groups of plants and animals,
- Keeping landscape heterogeneity.

Recent research devoted to the quantification of forest riparian buffer zones (e.g., Lowrance et al., 1997; Snyder et al., 1998) demonstrates their efficiency for surface water protection.

Control measures to prevent water pollution from forestry can be summarized as follows (Thornton et al., 1999):

- Maintenance of ground cover,
- Management of roads and trails,
- Management of riparian zones,
- Management of biocides.

Preventing water pollution from application of herbicides and pesticides

Herbicides and pesticides also can be toxic to aquatic organisms and humans. As a result, only strictly-controlled chemicals and their brands can be used in developed countries. Particular care in their use is required in water supply watersheds. Water quality managers in developing countries must be careful to protect watersheds against the unfortunate habit of chemical producers providing developing countries with products not permitted in the developed world.

The rules of agrochemical application safe for water quality are the same as for fertilizers; namely, fluid forms are superior to powder forms, spreading during windy conditions and from airplanes, and in the close vicinity of streams and lakes, is to be avoided, and storage places are to be protected from leaking containers, particularly during rains.

Preventing pollution from reaching surface waters

Because the entry of some portion of applied fertilizers and other agrochemicals into groundwater cannot be completely avoided, management practices directed to reducing the entry of contaminated water into receiving waterbodies should be utilized. The practices consist first of all in utilizing the pollutant binding capacity of forests and meadows. Buffer zones along watercourses, particularly on the slopes of the river valleys, should consist only of forests or meadows for a minimum width of 50 meters (Haycock et al., 1997). Riparian mixed forests minimize the entry of fertilizers into watercourses, but also have other positive functions. Their hydrologic function is positive, causing water retention and retarding floods. Buffer zones are environments for organisms that consume pests, thus decreasing their spread. They also facilitate the survival and migrations of animals. The significant positive functions of marginal vegetation in decreasing nutrient concentrations is mentioned in Section 4.3.4.

If the highest nitrate concentration in receiving waters is close to 50 mg NO_3 l^{-1} (especially in high-flow periods), the following measures should be taken in the watershed, in cooperation with appropriate agricultural enterprises:

- Strictly conserving the second zone of public-health protection,
- Using nitrogen fertilizers in quantities not exceeding 100 kg ha^{-1} of farmland per year,
- Reducing the time during which fields are left without vegetation after harvest to the maximum extent (1–2 weeks at most), and to use catch crops,
- Avoiding the application of nitrogen fertilizers to frozen soil or onto fields in which no crops have been sown or planted.

Protective stretches of land surface formed by grasslands and forests prevent surface soil particles being washed down into streams and waterbodies. However, they may not reduce the leaching of dissolved pollutants (e.g., nitrates) from distant, elevated places.

Section 4.2.4 provides a discussion of the effective function of wetlands. Prevention of erosion, using methods discussed in Section 4.2.1, is necessary to stop the surface runoff of pollutants to streams.

Methods for preventing agricultural pollution can be summarized as follows:

- Agriculture is one of the greatest sources of diffuse pollution in many places around the world. Care should be taken to minimize diffuse pollution, which is only possible in cooperation with agricultural practitioners. It is to the benefit of agriculture not to allow expensive fertilizers to remain unutilized by crops.
- A general rule concerning agricultural techniques can be stated as follows: What is most efficient for plants is also most favorable for protecting water quality because it creates the least pollution. Only unutilized fertilizer causes water quality difficulties. Agricultural best management practices, therefore, also are the most useful water quality practices.
- The loss of fertile soils to agriculture is related to the greatest water pollution. Thus, it is in the interest of both agriculture and water quality to minimize erosion, using such methods as contour plowing, terracing, and not leaving soil bare without vegetation. The prevention of erosion is very important for reducing water pollution by phosphorus.
- Forests have generally positive water quality effects, and deforestation results in water quality deterioration. Rapidly growing introduced *Eucalyptus* plantations have negative effects and are exceptions to this rule. Forest fertilization also results in negative water quality impacts.
- The use of plant protection agents must be strictly controlled, particularly since some are highly toxic to aquatic life and humans.
- Buffer zone, riparian forests, stream marginal vegetation and wetlands are effective in reducing water pollution from nutrients, salts and some other chemical compounds.

The protection of water quality from agricultural activities is not just a technical issue, but also a topic of interest to farmers and farming organizations. Water quality specialists, however, must take the lead in this area. According to Fried (1991), the following actions are suggested within the European Union.

A. With respect to fertilizer use:
  - Creation or reinforcement of advisory agencies for farmers, and the establishment of codes of good agricultural practices,
  - Integrating environmental concerns in the training of farmers,
  - Reinforcement of information by all means,
  - Development of scientific research (mostly addressing the mechanical, physicochemical and biological phenomena of leaching).

B. With respect to intensive animal breeding:
  - Improvement of storage and transport, and creation of manure banks,
  - Improvement of spreading methods,

- Analysis and differentiation of manure types to achieve better environmental adaptation,
- Improvement of waste treatment,
- Improved conjunctive use of chemical and animal fertilizers,
- Improved training and information to farmers,
- More research on alternate uses of manure.

4.2.2 Cleaner Production

One important management method usually not under the direct control of agencies that manage water is summarized as *Cleaner Production* (Misra, 1996). It consists of making changes in the processes within a production plant, such that the emitted pollution is reduced. Major advantages inherent in this approach also can benefit the producer. Aside from reducing the expenses of fees for creating pollution, considerable savings of energy, water and various materials used in the production process also can be obtained. As an example, the introduction of the clean production approach in fifty galvanizing plants in The Netherlands resulted in a reduction in pollution to 55% of the original levels during the first year and, after gaining more experience, to 37% in the second year. In two large enterprises in the Czech Republic, primary savings attained by introducing clean production techniques totaled 50 million Czech Crowns. In focusing on this technology, the pollution reduction activity shifts to the production area. Interest in this method is primarily created by the ability to save considerable amounts of money by using it. But its value in helping solve environmental problems also plays a role. Agencies that manage water must teach industry leaders to use this approach and claim initiatives for pollution abatement.

An even wider approach analyzes the whole production process; namely, the life cycle analysis of a product. The production of a product is analyzed, with the goal of minimizing wastes over the entire production cycle, starting with the mining of raw materials through its use and finally to the disposal of the final product after use. This effort usually exceeds the capabilities of a given producer, demanding instead the synchronization of efforts by several enterprises. The environment has profited greatly in recent efforts of this kind, by wise and progressive industry leaders able to increase their competitive capabilities.

Industrial enterprises face increasing costs of raw materials, energy, water and pollution fees, and face increased pressure by environmental groups to reconsider their production methods and seek to retain competitiveness, while also demonstrating good will toward environmental protection. In addition to automation, this goal can be obtained by the recirculation of materials and water inside the production plants, by energy saving, by better space organization of the process, and by the minimization of transport. All these elements are important for protecting water quality, since the processes of material extraction, transportation and energy production can cause pollution, and the quantity and degree of the pollution of the water leaving the plant is decisive in regard to the water returned as effluent back to the plant. One scientifically rooted procedure with broad positive consequences for plant efficiency and competitiveness, as well as for water quality, that is favored by large international trusts is *the life cycle evaluation of products*, or *environmental life cycle assessment* (Curran, 1996).

The evaluation process in life cycle analysis consists of following a product throughout its entire life cycle, from its creation to its disposal. The production stages covered with this analysis include mining raw materials, processing for basic chemicals or metals, transportation, production of final materials needed for the product, production of the final product, packaging and distribution, the fate and environmental consequences of the product when it is used and, finally, the disposal of the remains or unused parts (e.g., the fate of packing materials, nonfunctioning parts or nonrepairable damaged products). Each step is evaluated in regard to the economy of the product, including the needs for materials, energy and water, and the environmental consequences of decisions at each step are estimated, as a means of identifying the cheapest, most efficient and least polluting option (Fig. 4.2). Many factories that have implemented this evaluation have found considerable savings and a resulting increase in competitiveness. This is typically accompanied by a considerable savings in water and energy resources, and a corresponding reduction in pollution. Thus, it is hoped that this procedure will become widely used and will benefit water quality. Because of increased water circulation within a factory, the quantity of the effluents also is reduced. Effective, specialized pre-treatment can be used, sometimes with the regeneration of some substances, which further reduces the pollutant load to the effluent or city wastewater treatment plant.

Considerable water quality improvement can also be obtained by citizens in their daily life on the basis of this approach, including the following:

- Water quality managers must stress the usefulness of clean production and product life cycle analysis, working to facilitate such evaluations. Local water management councils can be very helpful in this direction.
- Saving energy has positive consequences for water quality, as energy generation causes environmental degradation, including water pollution.
- Saving of water in households improves water quality, since existing wastewater treatment plants function better with less entering wastes, and there is less need for upgrading, renovation and new plant construction.

4.2.3 Wastewater Treatment

Wastewater discharges into lakes and reservoirs is a man-made forcing function of crucial importance for their water quality. However, it also is a controllable forcing function. It is possible in many situations to control it completely, either by water diversion or by wastewater treatment methods. Water diversion, however, results in another downstream waterbody having to cope with the pollutant load. Thus, treating the wastewater properly should be considered a generally more acceptable solution to the problem. This gives rise to two questions; namely (i) is it possible to solve all pertinent wastewater problems, and (ii) what is understood as a proper wastewater treatment?

The water pollution problems associated with municipal wastewaters includes their content of:

- Nutrients causing eutrophication,
- Biodegradable organic matter, causing oxygen depletion,

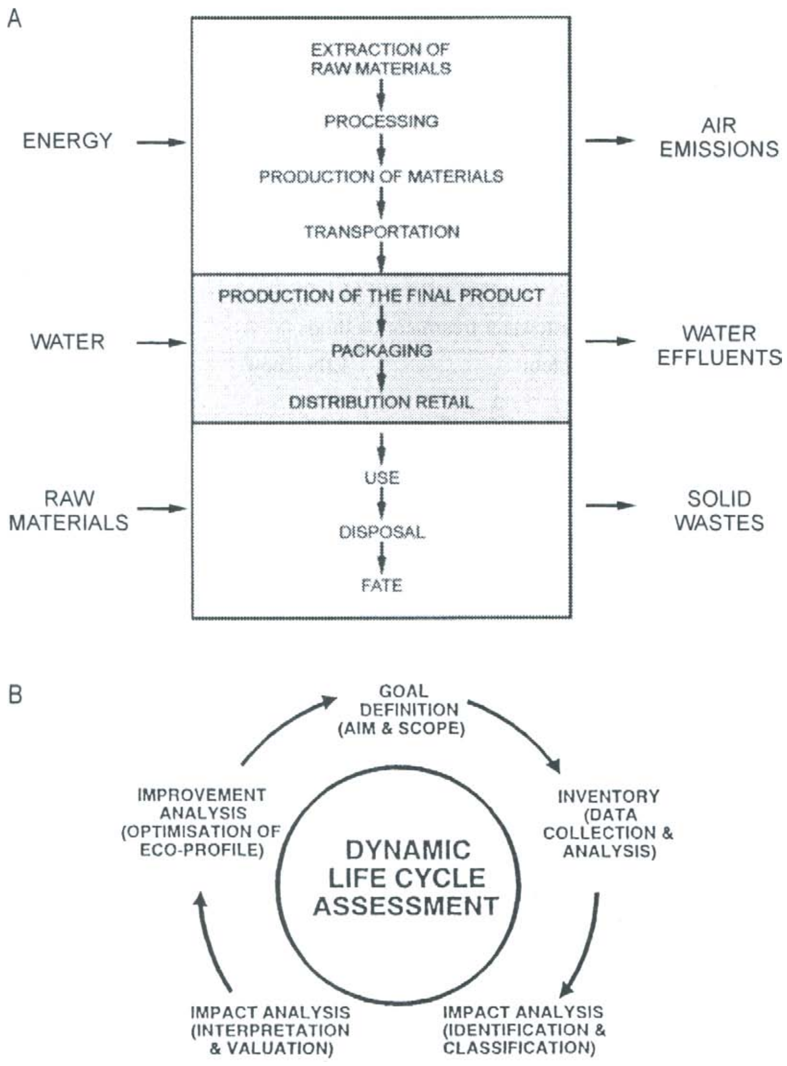


Fig. 4.2. Clean production and life cycle assessment of a product. A—The phases of the life cycle evaluation and the inputs and outputs taken into account (modified from Straškraba and Tundisi, 1999); B—Processes during the dynamic life cycle assessment (modified from Anonymous, 1994).

- Bacteria and virus affecting the sanitary quality of water, which is of particular importance when the water is used for bathing, swimming and drinking purposes,

- Heavy metals; namely, lead originating from petrol stations, zinc and cadmium from gutters, heavy metals from fungicides and other agricultural chemicals, and a wide range of other heavy metals in minor concentrations,
- Refractory organic matter, originating from industries, hospitals and the use of pesticides, and even from a wide spectrum of household articles.

Tables 4.2 and 4.3 provide an overview of a wide range of wastewater treatment methods. Clearly, there is a method available to address virtually any of the aforementioned problems.

Table 4.2. Survey of generally applied wastewater treatment methods

Method	Pollution problem	Efficiency	Costs (US \$/100 m^3)
• Mechanical treatment	Suspended matter removal	0.75–0.90	3–5
	BOD_5 reduction	0.20–0.35	
• Biological treatment	BOD_5 reduction	0.70–0.95	25–40
• Flocculation	Phosphorus removal	0.3–0.6	6–9
	BOD_5 reduction	0.4–0.6	
• Chemical precipitation ($Al_2(SO_4)_3$ or $FeCl_3$)	Phosphorus removal	0.65–0.95	10–15
	Reduction of heavy metals concentrations	0.40–0.80	
	BOD_5 reduction	0.50–0.65	
• Chemical precipitation ($Ca(OH)_2$)	Phosphorus removal	0.85–0.95	12–18
	Reduction of heavy metals concentrations	0.80–0.95	
	BOD_5 reduction	0.50–0.70	
• Chemical precipitation and flocculation	Phosphorus removal	0.9–0.98	12–18
	BOD_5 reduction	0.6–0.75	
• Ammonia stripping	Ammonia removal	0.70–0.95	25–40
• Nitrification	Ammonium is oxidized to nitrate	0.80–0.95	20–30
• Active carbon adsorption	COD removal (toxic substances)	0.40–0.95	60–90
	BOD_5 reduction	0.40–0.70	
• Denitrification after nitrification	Nitrogen removal	0.70–0.90	15–25
• Ion exchange	BOD_5 reduction (e.g., proteins)	0.20–0.40	40–60
	Phosphorus removal	0.80–0.95	70–100
	Nitrogen removal	0.80–0.95	45–60
	Reduction of concentrations	10–25	
• Chemical oxidation (e.g., with Cl_2)	Oxidation of toxic compounds	0.90–0.98	60–100
• Extraction	Heavy metals and other toxic compounds	0.50–0.95	80–120
• Reverse osmosis	Removes pollutants with high efficiency, but is expensive		100–200
• Disinfection methods	Reduction of microorganisms	High, can hardly be indicated	6–10

Table 4.3. Efficiency matrix relating pollution parameters and wastewater treatment methods

Method	Suspended matter	BOD_5	COD	Total		Ammonium nitrogen	Heavy metals	*E. coli*	Color	Turbidity
				Phosphorus	Nitrogen					
• Mechanical treatment	0.75–0.90	0.20–0.35	0.20–0.35	0.05–0.10	~0	0.10–0.25	0.20–0.40	—	0.80–0.98	
• Biological treatment*	0.75–0.95	0.65–0.90	0.10–0.20	0.05–0.10	~0	0.10–0.25	0.30–0.65	Fair	~0	—
• Chemical precipitation	0.80–0.95	0.50–0.75	0.50–0.75	0.80–0.95	~0	0.10–0.60	0.80–0.98	Good	0.30–0.70	0.80–0.98
• Ammonia stripping	~0	~0	~0	~0	0.70–0.96	0.60–0.90	~0	~0	~0	~0
• Nitrification	~0	~0	~0	~0	0.80–0.95	0.80–0.95	~0	Fair	~0	~0
• Active carbon adsorption*	—	0.40–0.70	0.40–0.95	~0.1	High**	High**	0.10–0.70	Good	0.70–0.90	0.60–0.90
• Denitrification after nitrification	~0	—	—	~0	—	0.70–0.90	~0	Good	~0	—
• Ion exchange	–0.40	0.20–0.50	0.20–0.95	0.80–0.95	0.80–0.95	0.80–0.95	0.80–0.95	Very good	0.60–0.90	0.70–0.90
• Chemical oxidation	—	Corresponding to oxidation	~0	~0	~0	~0	~0	~0	0.60–0.90	0.50–0.80
• Extraction	—	Corresponding to extraction of toxic compounds	~0	~0	~0	~0	0.50–0.95	~0	~0	~0
• Reverse osmosis*—see Table 4.2										
• Disinfection methods—essentially application of chlorine, ozone, etc.						Very high	0.50–0.90	0.30–0.60		

*Depends on the composition.

**As chloramines.

Industrial wastewater can cause the same water pollution problems as municipal wastewater. In addition, they also can contain toxic organic and/or inorganic compounds (particularly heavy metals and persistent organic pollutants). However, it is necessary to solve at the source the problems associated with industrial wastewater that cannot be solved with municipal wastewater treatment methods. The major portion of toxic substances must be removed by the industries, since they will be removed only partially, if at all, at municipal wastewater treatment plants, and/or will contaminate the sludge produced at municipal wastewater treatment plants, thereby eliminating the possibility of their use as a soil conditioner.

The removal of high concentrations of biodegradable organic matter at the source also is recommended, since it usually is much more cost-effective to remove these components, at least partially, when they are present in high concentrations.

The listed methods often are used in combinations of two or more steps to obtain the overall removal efficiency required by the most cost-moderate solution. Because wastewater treatment often is costly, it is recommended to examine all possible combinations of treatment options in the planning phase, in order to identify the most feasible and appropriate option.

Many existing municipal wastewater treatment plants were constructed years or decades ago, and may not meet today's higher standards. Nevertheless, upgrading existing wastewater treatment plants is possible, and may be more effective in some cases than building new ones (Novotny and Somlyódy, 1995; van Loosdrecht, 1998). Because the funding allocated to pollution abatement often is limited, the overall effect of upgrading wastewater treatment plants that can be upgraded with sufficient efficiency will be to the benefit of the environment. An attractive solution is often to introduce *tertiary treatment* by chemical precipitation and flocculation in an existing mechanical–biological treatment plant, with the addition of chemicals and flocculants before the primary sedimentation phase. The installation costs for this solution are minor, and the additional running costs are limited to the costs of chemicals. The result is a 85–95% removal of phosphorus at low cost. Similarly, nitrification and denitrification, ensuring a 80–85% removal of nitrogen, can be realized with the installation of additional capacity for biological treatment (the overall water retention time in the plant is increased by 4–12 hours, depending on the standards and composition of the wastewater), which is considerably less costly than construction of a completely new treatment plant. For details, see Hahn and Muller (1995).

The second question refers to the selection of the right standards for the treated wastewater. Any removal efficiency of any pertinent parameters (BOD_5, nutrients, bacteria, viruses, toxic organic chemicals, color, taste, heavy metals) is possible, using a suitable combination of the available treatment methods. However, what removal efficiencies are needed in the focal case? Because wastewater treatment is costly, the maximum allowable concentrations should not be set significantly lower than the lake or reservoir receiving the effluents can satisfactorily tolerate. The ban of phosphate detergents to decrease phosphorus concentrations in municipal wastewater treatment plant effluents is a point to consider. On the other hand, it might be even more expensive to install an insufficient treatment plant. Thus, the potential effects of a wide range of possible pollutant inputs on water quality and on the entire lake or reservoir should be assessed, as the basis for selecting an acceptable option. This will require a quantification of the impacts of various possible pollutant inputs, considering a wide range of solutions. All processes and components affected significantly by the impacts should be included in the quantification. It usually is very helpful to develop a water quality/ecosystem model, and use it properly to assist in the selection of specific environmental treatment methods (see Section 5.1). It is important to emphasize that a model has an uncertainty in all its predictions that must be considered in making a final decision. Thus, it is essential to use safety factors to the benefit of the environment, in order to ensure that the selected treatment methods will have the anticipated effects. If the uncertainty is not taken into account for the sake of economy, as is unfortunately often done, the investment may be essentially wasted because the foreseen restoration of the lake or reservoir will not be realized, as discussed in more detail in Chapter 5.

Application of the methods identified in Tables 4.2 and 4.3 gives only approximate results, which should be used with caution. More details always will be required in reality. However, first estimates, such as those shown in the tables, are useful for evaluating alternative solutions to wastewater pollution problems. The biological treatment may either be an activated sludge plant or a trickling filter.

The cost of treating 100 m^3 of wastewater is also based on approximate indications, because they can vary from place to place, and are highly dependent on the size of the wastewater treatment plant. The costs are calculated as the running costs (electricity, labor, chemicals and maintenance), plus 10% of the investment to cover interest and annual appreciation. The annual water consumption of one person in an industrialized country corresponds to approximately 100 m^3.

A problem in many developing countries is the relatively high cost of wastewater treatment. Although this cost might justify diversion of the wastewater, the application of "soft technology"—"ecotechnology"—also should be considered. Some corresponding methods will be touched on in the following sections, but proper planning at an early phase, and consideration of all predictable problems, offers the widest range of cost-effective possibilities, and may allow prevention of the pollution problems before they can occur.

Corrections at a later stage, when pollution has already degraded the water quality and associated ecosystems, are possible, but will always be more expensive than the costs of proper wastewater treatment at an early stage. This is due in part to the fact that the accumulation of pollutants in a lake over time will always cause additional problems and, therefore, result in additional costs. Thus, pollution prevention at an early stage is better than curing pollution at a later stage. Removal of phosphorus from wastewater at an early stage, for example, is always beneficial, since the surplus phosphorus will accumulate in the lake sediments to a large extent, allow its remobilization back into the water column under certain chemical conditions in the waterbody.

Model studies are able to reveal how long it may require to restore a lake, or how much higher phosphorus removal efficiency will be required to compensate for each year that implementation of an appropriate phosphorus removal technology is postponed. However, it is not unusual that implementation of a phosphorus removal technology a few years later than when it was first feasible may delay the restoration of a lake by one or more decades, due to the fact that the additional phosphorus accumulated in the sediments may significantly exceed the quantity of phosphorus in the water column.

Important pollution sources may be reduced if the liquid waste and sludge land disposal is avoided or minimized. For municipal areas, two options are used to decrease the hydraulic load of wastewater treatment plants, including (i) decreasing water use, thereby saving water and producing smaller volumes of polluted water, and (ii) separating storm water from municipal domestic waste, with a similar result. One result of these options is that the capacity of wastewater treatment plants can be kept smaller, achieving significant cost savings.

New approaches have emerged in regard to sustainable development. For instance, serious consideration is being given to separation toilets in some locations, which collect urine separately from faeces, thereby allowing utilization of the septic urine as fertilizer.

The selection of proper wastewater treatment methods for point sources of pollution is summarized in the following points:

- Develop models for the impacts of the wastewater on a lake or reservoir, considering the impacts on the water quality and the entire lake ecosystem.
- Apply the model to identify the maximum allowable pollutant concentration in the treated wastewater. Any uncertainty associated with the model predictions should be reflected in identifying the lower maximum allowable concentrations.
- Select the combination of available treatment methods able to meet the standards at the lowest costs without impacting the proper operation of the plant.
- If the investment needed for a proper solution to a problem cannot be provided, the application of cost-moderate technology that will reduce the accumulation of pollutants in the lake should be considered. Any measures taken at an early stage will likely reduce the costs at a later stage.

4.2.4 Natural and Constructed Wetlands

Natural wetlands

The ecotones between lakes and terrestrial ecosystems are crucial for protecting lakes against anthropogenic impacts (Haycock et al., 1997). These transition areas have the same function for a lake as a membrane does for a cell; namely, they prevent the input of undesirable components into a lake. Thus, it is crucial to preserve the shore ecotones around a lake and wetlands in the catchment area, independent of the management strategy being implemented. Further, man-made constructions should be prohibited in a zone 50–100 meters from the lake shoreline to keep the ecotone area intact.

In addition to preserving lakeshore ecotones, there are many other approaches for enhancing vegetation growth along and in rivers and their channels (Klapper, 1991), in order to increase the transformation and absorption of pollution (Fig. 4.3A). Efficient pollution removal can be obtained by maintaining natural vegetation in rivers entering reservoirs, particularly in tropical regions. An example of the significant reduction of nitrate nitrogen to almost complete exhaustion by vegetation along the stream banks within a distance of 1.5 km is shown in Figure 4.3B. Both rooted and submerged macrophytes, including

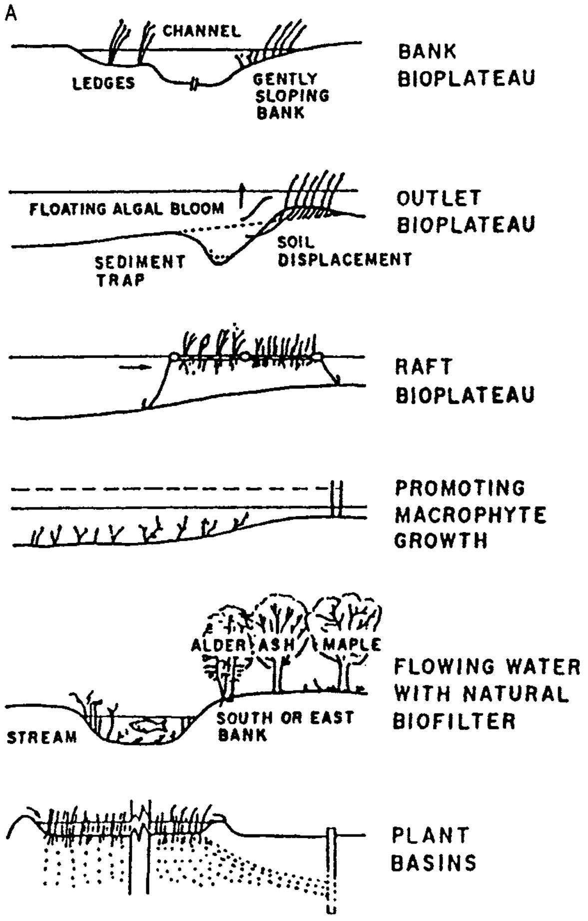


Fig. 4.3. Different forms of the application of vegetation for water quality protection and their efficiency. A—Approaches used (modified from Klapper, 1991).

the intensively-spreading tropical *Eichhornia crassipes* and *Pistia stratiotes*, are efficient removers. Artificial floating mats can be created when conditions for macrophytes are otherwise not adequate. These mats function as biofilters for pollution adsorption.

Although nonpoint or diffuse pollutants will inevitably flow toward a lake or reservoir, the land–lake transition zone can transform and/or adsorb the pollutants entirely or partially. Thus, it will significantly reduce the overall irreversible effects on the lake ecosystem. The most important processes can be summarized as follows:

- Nitrate is denitrified in the anaerobic conditions in the wetlands. Organic matter accumulated in the wetland converts nitrate to free nitrogen.
- Clay mineral is able to adsorb ammonium and metal ions.

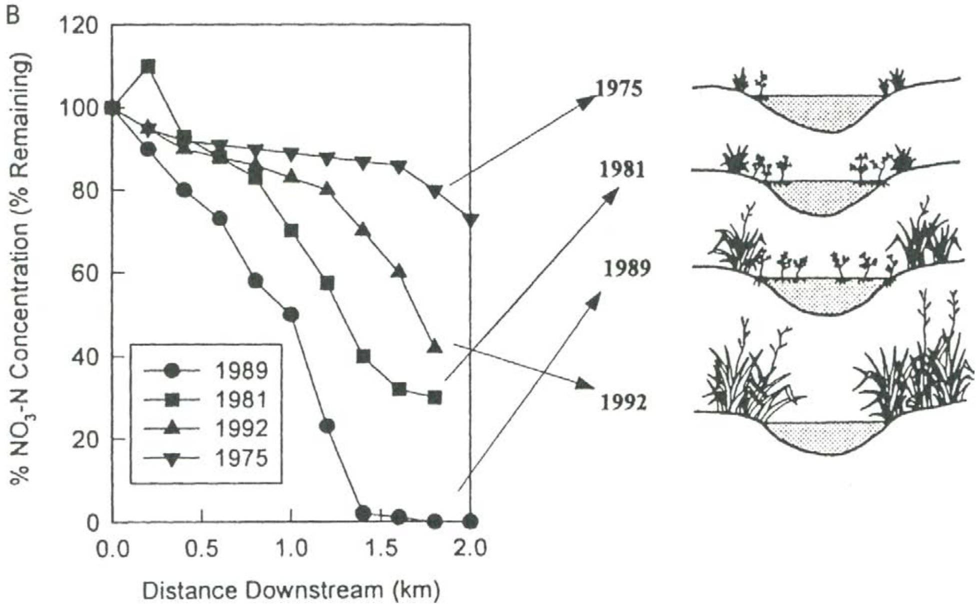


Fig. 4.3 (*continued*). B—Downstream changes in nitrate concentrations in the Whangamata stream shown with diagrammatic representation of changes in the streambank vegetation (from Downes et al., 1997).

- Organic matter is able to adsorb metal ions, pesticides and phosphorous compounds. Metal ions form complexes with humic acids and other polymer organics, which significantly reduce their toxicity.
- Biodegradable organic matter is decomposed aerobically or anaerobically by the microorganisms in the transition zone.
- Pathogens are out-competed by the natural microorganisms in the transition zone.
- Macrophytes are able to uptake heavy metals with a high efficiency and high specificity. Different plant species may take up different heavy metals, and this property can be utilized for removing heavy metals from contaminated land. Other toxic substances also may be removed by macrophytes, although it is difficult to provide any general rule for the removal efficiency.
- Toxic organic compounds will be decomposed by anaerobic processes in wetlands to a certain extent, depending on the biodegradability of the compounds and the water retention time in the wetland.

The denitrification potential of wetlands is often surprisingly high. As much as 2000–3000 kg of nitrate nitrogen can be denitrified annually per hectare of wetland area, depending on the hydraulic conditions (Jørgensen, 1994; Jørgensen et al., 1995). This is important for the protection of lakes, given that significant quantities of nitrate are released from agricultural areas. As much as 100 kg nitrate-N/ha may be found in drainage water from intensive agricultural activities. Because denitrification is accompanied by a stoichiometric oxidation of organic matter, significant quantities of organic matter also are removed in this process. However, the phosphorus bound as organic matter, or adsorbed to the organic matter, may be released by these processes. Thus, these processes should be examined carefully and quantitatively in each case, including consideration of whether the released phosphorus will flow toward a lake or groundwater aquifer, and these possibilities should be considered in developing lake management strategies.

Figure 4.4 illustrates the mass balances of nutrients in a natural wetland adjacent to a lake, applied for nitrogen removal. The experimental wetland was a 0.5 hectare freshwater marsh located in front of a shallow lake, and receiving a significant load nitrogen from nonpoint agricultural sources. As can be seen, the denitrification capacity is high, but the process is accompanied by a release of phosphorus. Thus, it is important to ensure the released phosphorus is not significantly reducing the effects of the nitrate removal. In this specific case, it was advantageous that the phosphorus was not flowing directly to the lake, but rather toward ground water.

The adsorption capacity of the transition zone offers significant protection against pollution by toxic substances, including heavy metals and toxic organic chemicals (primarily pesticides originating from agricultural activities). The ratio concentration of heavy metals or pesticides in organic matter to its concentration in water at equilibrium is strongly dependent on the composition of the organic matter and the presence of complex forming ligands. It is usually between 50 and 5000, indicating that the transition zone has an enormous binding capacity for these pollutants.

Ecotones serve as a buffer zone not only for pollutants, but also for biological species present in adjacent ecosystems. Thus, preservation of wetlands at the lakeshore may be crucial for maintenance of the biodiversity in lake ecosystems—a function that a manager should not overlook in developing an appropriate lake management strategy.

Table 4.4 provides an overview of the different types of wetlands found adjacent to lakes, including wet meadows, forested wetlands, marshes, bogs and shore wetlands. The table also identifies the characteristics of these seven types of wetlands, and their differing ability to cope with nonpoint pollution problems.

The importance of wetlands located adjacent to lake ecosystems have provoked such attention that drainage of wetlands has ceased in many countries, and previously drained wetlands are restored in some locations (Salánki and Herodek, 1989; Herodek, 1990; Salánki and Biró, 1994). In accordance with U.S. legislation, wetland areas cannot be drained for other uses, unless another wetland of the same size is developed elsewhere.

Constructed wetlands

Artificial wetlands also can be constructed to cope with diffuse pollution originating from agriculture, septic tanks and other sources (examples are given in Mitsch, 1994).

As an example of wetland pollutant removal efficiency, Jørgensen and Jørgensen (1988) have compared the efficiency of the methods used to abate eutrophication for a lake in Denmark, using a eutrophication model. The result of their case study has shown that the use of wetlands is a very effective pollution control method. While most of the other control

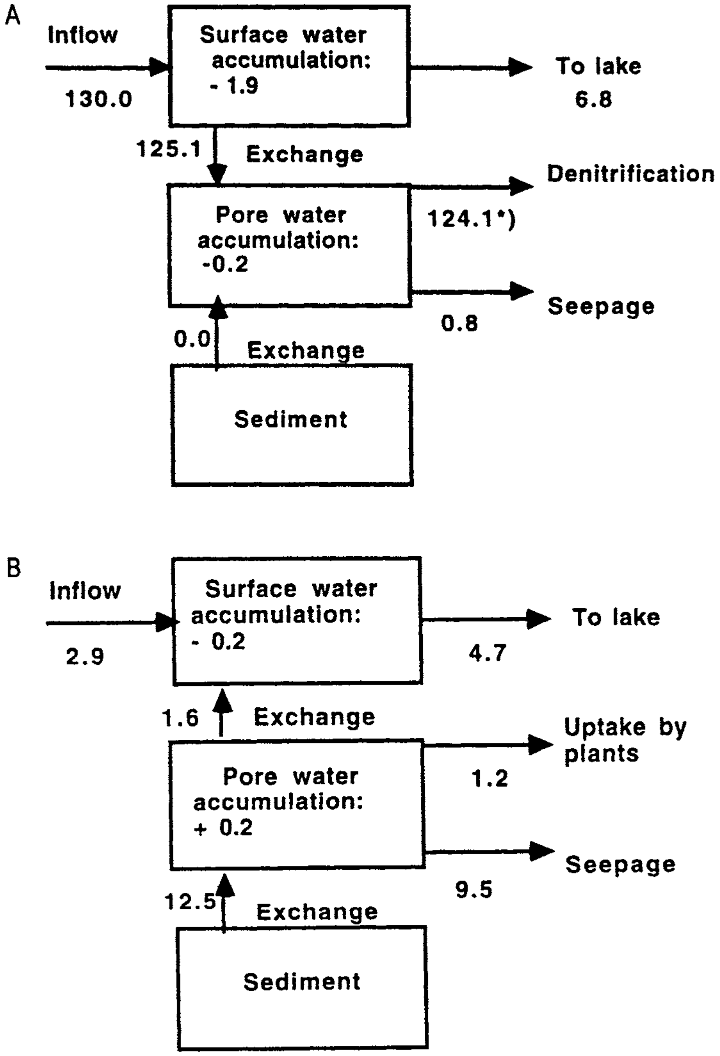


Fig. 4.4. Nitrogen and phosphorus budgets for a natural 5000 m^2 wetland adjacent to a Danish lake. A—Nitrogen budget in kg/day. Nitrite and nitrate nitrogen for period August 23–March 14. For denitrification, it is assumed that no nitrification takes place. If nitrification is considered, the value will correspond to 200 kg; B—Phosphorus budget in kg/day.

methods being considered did not reduce the phytoplankton concentrations and primary production more than 10%, constructing a wetland for nitrogen removal and partial phosphorus removal from the inflowing stream reduced the primary production and maximum

Table 4.4. Characteristics of wetlands adjacent to lakes (Patten, 1990)

Wetland type	Characteristics	Ability to retain nonpoint pollutants
Wet meadows	Grassland with water-logged soil; standing water for a part of the year	Denitrification only in the presence of standing water; removal of N and P possible by harvest
Freshwater marshes	Reed-grass dominated, often with peat accumulation	High potential for denitrification, which is limited by the hydraulic conductivity
Forested wetlands	Dominated by trees and shrubs; standing water not always for the entire year	High potential for denitrification and accumulation of pollutants, provided that standing water is present
Salt water marshes	Herbaceous vegetation usually with mineral soil substrate	Medium potential for denitrification Harvest possible
Bogs	A peat-accumulating wetland with minor flows	High potential for denitrification but limited by the small hydraulic conductivity
Shore wetlands	Littoral vegetation, often of great importance for the lake	High potential for denitrification and accumulation of pollutants, but area coverage variable

phytoplankton concentration by about 33%, thereby also increasing the water transparency from 0.6 m to 1.0 m.

Constructed wetlands may have either surface flow or sub-surface flows, with the latter sometimes called root zone plants.

Construction of artificial wetlands is an attractive, cost-moderate solution for nonpoint source pollution (Hammer, 1989; Cooper and Findlater, 1990; Moshiri, 1993; Vymazal et al., 1997). Although artificial wetlands are generally able to cope with nitrogen and heavy metal pollution from these sources, it is essential to properly plan where to locate them, since their efficiency is dependent on the hydrology and landscape patterns. They should remain covered by water most of the year, and have a sufficient water retention time to allow treatment of the pollution problems, thereby also protecting the most vulnerable ecosystems, which often are lakes and reservoirs. It also is important to ensure that the wetlands are not releasing other components (e.g., phosphorus; see the results from the experimental wetland, mentioned above).

It is noted that, in most cases, a wetland will reduce the water budget due to evapotranspiration. However, wetlands also reduce the wind speed at the water surface, thereby also perhaps reducing the evaporation rate. It is important to consider these factors during the planning phase for artificial wetlands. Finally, it should not be forgotten that full development of an artificial wetland may require 2–4 years, in order to obtain sufficient plant coverage and biodiversity to be fully operational. It is clear from past experiences that the application of models for wetlands encompassing all the processes reviewed above, as well

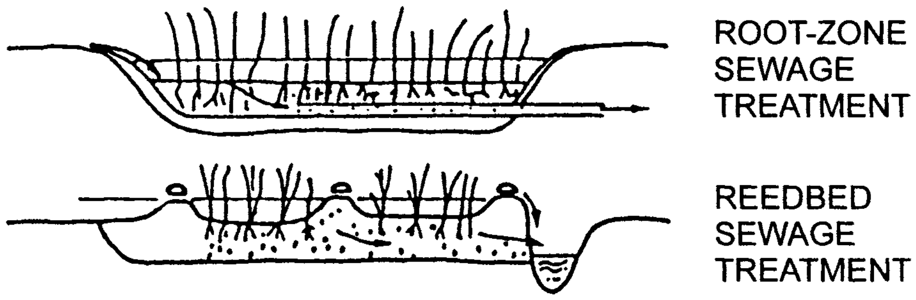


Fig. 4.5. Constructed wetlands can be distinguished into root-zone sewage treatment plants (sub-surface flow) and reedbed sewage treatment plants (surface flow) (modified from Klapper, 1991).

as for the lake, is compulsory if positive results are anticipated. Artificial wetlands are basically of two types; namely, root-zone plants (sub-surface flow) and reedbed plants (surface flow) (Fig. 4.5).

Wetlands encompassing the so-called root-zone plants also may be utilized as wastewater treatment facilities. This application of "soft technology" seems particularly advantageous for developing countries because of its moderate cost.

The self-purification ability of wetlands has found wide application as a wastewater treatment method in several developing countries (China, Philippines, Burma, India, Tanzania, Thailand).

Much attention also has been devoted to stocking fish cultivated in biological sewage stabilization ponds. These studies show that the nitrogen and phosphorus are retrieved from the sewage by fish, through the intermediate activities of bacteria, algae and other types of plankton. In order to mobilize the self-purification capability of a waterbody for sewage treatment, the main principle is to utilize the coordination between four types of primary components: producers, aquatic vegetation, consumers (including fish), decomposers (mainly bacteria) and abiotic factors (solar radiation, water exchange, etc.).

Bacteria decompose organic materials, including organophosphates, and purify water in a preliminary phase. Carbon dioxide, ammonia, phosphates are produced and utilized by algae and other aquatic vegetation. The oxygen released by photosynthesis is available to meet the needs of oxidizing organic matter by bacteria. A large quantity of algae and other types of plankton are utilized by rearing fries. The energy fixed by algae finally appears in the form of fish harvesting, with the water being further purified.

Waste stabilization ponds without fish cultures also are widely used, particularly in many African countries. This solution is cost moderate, being about US \$2–3/100 m^3 of water treated, including the operation costs, interest and appreciation. The typical system consists of three types of ponds working in series: anaerobic ponds, facultative ponds, and aerobic ponds. Unfortunately, many stabilization ponds are not operating properly due to pollutant overloading, inadequate maintenance, or use of incorrect design criteria. The systems often are designed by European or North American consulting engineering firms, which do not take the local socioeconomic and climatic conditions into account. The experience of DANIDA in East Africa has shown that application of ecological engineering approaches, in combination with an ecological model of the stabilization ponds, may yield a better design with a higher certainty of proper operation, provided that a proper maintenance scheme is applied. The produced plants may be used as fodder for domestic animals.

Wastewater treatment using water hyacinths (*Eichhornia crassipes*) has been applied as an alternative to waste stabilization ponds. The inorganic nitrogen and phosphorus from the sewage and the decomposition of organic pollutants by microorganisms are absorbed by the water hyacinths as a nutrient source. Experiments in China have shown that an average water hyacinth yield of about 10 kg m^{-2} may be obtained during the growing period (May–November). This level of production can absorb 1500 kg of nitrogen, 350 kg of phosphorus and 200 kg of sulfur per hectare. The water hyacinths, with the microorganisms and organic pollutants attached or coagulated on the root surfaces, are harvested as food for fish culture ponds, duck farms and pig farms. From May to November, the concentrations of chemical oxygen demand (COD), total nitrogen, ammonium, total phosphorus and orthophosphate were less than half the concentrations in the inlet. In contrast, when the water hyacinths were absent (December–April), the differences in COD, nitrogen and phosphorus concentrations between inlet and outlet were very small (Ma and Yan, 1989).

Many heavy metals are concentrated and accumulated in water hyacinths from very low concentrations in water. However, the heavy metal enrichment in this plant varies with the aquatic habitat. Water hyacinths with high residual amounts of heavy metals obviously cannot be used as fodder, limiting this ecological engineering approach for treatment of water polluted by organic pollutants (mainly municipal wastewater).

The root zone plant has found its application in treatment of small volumes of municipal wastewater in industrialized countries, particularly where construction of a sewage system to an adjacent wastewater treatment plant would be prohibitively expensive. The decomposition of organic matter and denitrification usually does not cause any problems, provided the plant has 5–10 m^2/person equivalent, dependent on the climatic conditions. Phosphorus removal is only about 10–20% by a root zone plant, although the addition of iron chloride may increase the efficiency to 80% or more, due to precipitation of iron phosphate. The application of this method seems attractive for recreational areas, where the population density is low, but the wastewater loading has a significant impact.

The recommended management of natural or artificial wetlands and of lakeshore ecotones may be summarized as follows:

- Maintenance and preservation of the transition zone between the terrestrial ecosystems and the lake ecosystem should be compulsory. The ecotone between the two types of ecosystems functions as a buffer zone for preservation of species diversity in both ecosystems.
- The different types of wetlands forming the transition zone have a high adsorption capacity for many pollutants, such as heavy metals and toxic organic compounds.
- The different types of wetlands forming the transition zone are able to denitrify up to several tons of nitrate nitrogen per hectare annually.

- Recovery and construction of artificial wetlands are crucial abatement methods for treating diffuse pollutants originating from agricultural activities.
- Application of artificial wetlands, including waste stabilization ponds and root zone plants, may be attractive wastewater treatment methods for developing countries, for recreational areas adjacent to a lake ecosystems, and generally for areas with low population densities.

The application of a quantitatively-based management scheme of all the identified wetland types, including development of models for these ecosystems, is recommended.

4.3 IN-LAKE METHODS

The approaches that can be used to manage water quality within a lake include mechanical, chemical and biological methods. The useful methods are those that are comparatively inexpensive, and that produce the smaller impacts on the total lake environment. These include mainly methods based on ecological knowledge, such as regulating fish populations by using biomanipulation, etc. Further, using a combination of methods is probably the best overall approach, utilizing the partial capabilities of the individual methods for the greatest overall success.

4.3.1 Biomanipulation

Biomanipulation is a term coined by Shapiro et al. (1975) for various lake water quality management methods based on biological interventions. This term is usually restricted to one particular method, based on manipulating the fish populations in a lake so as to change algal biomass. The theoretical basis of this method was established during the 1950s and 1960s by Hrbácek et al. (1961, 1986), Hrbácek (1962), Brooks and Dodson (1965) and Hall et al. (1970). Hrbácek demonstrated that fish stock levels in ponds influenced the level of primary production and nutrient cycling via the herbivorous grazing by zooplankton. He demonstrated that when overpopulated planktivorous fish are eradicated, the waterbody changed from having high algal concentrations and low transparency to a condition with less algae and increased transparency. Brooks and Dodson (1965) demonstrated a change in the zoo- and phytoplankton composition, and an increase of phytoplankton density, when a herring-type zooplankton feeding fish was introduced into a lake in the United States (Fig. 4.6).

Shapiro et al. (1975) and Shapiro (1978, 1995) elaborated the idea by manipulating piscivorous fish in food webs to produce a desirable pelagic community structure within the ecosystem, favoring low algal levels. Comparative studies on several reservoirs in the Czech Republic (Hrbácek et al., 1986) and in England (Duncan, 1990; Duncan et al., 1991; also see Section 9.6) have shown that, for the same nutrient level, the algal crops can be reduced by up to by 50% with this method. Reviews of all aspects of biomanipulation are provided by Hosper (1989), Gulati et al. (1990), Reynolds (1994), DeBernardi and

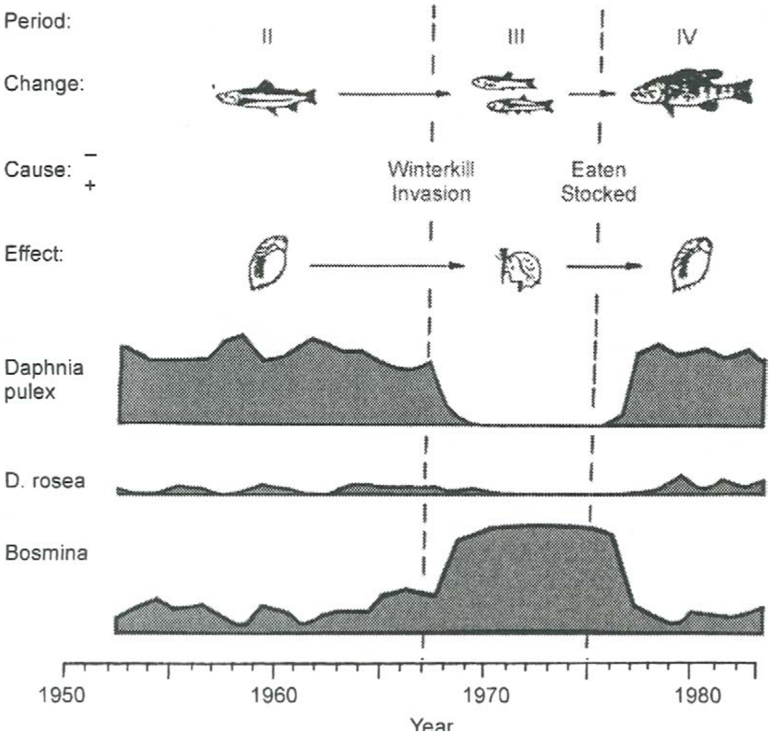


Fig. 4.6. Results of biomanipulation experiment in a natural lake. After winter kill of predators and invasion of the zooplankton feeding *Alosa,* the zooplankton population changed from larger *Daphnia* species to small *Bosmina*; after introduction of invasive predator, the large species capable of controlling phytoplankton were rapidly reestablished (modified from Brooks and Dodson, 1965).

Giussani (1995) and Shapiro (1995). The use of biomanipulation in shallow lakes is discussed by Perrow et al. (1997). The reviews generally show that if the method is to be successful, specific conditions have to be fulfilled.

Biomanipulation is based on what is called in contemporary limnology *top down control* (Fig. 4.7). The primary control is the natural, internal control within the ecosystem, based on mutual interactions between the abiotic variables and different organisms within an aquatic ecosystem. The type of control discussed in classical limnology was a *bottom-up control,* based on the idea that abiotic variables such as light, temperature and nutrients affect the most elemental steps in the aquatic production process; namely, the algae and aquatic macrophytes. The control then moves from the lower to increasingly higher levels of trophic organization, from the phytoplankton to the organisms that feed on it; namely, the zooplankton. The zooplankton is the decisive element for the growth of zooplankton-feeding fish, which are in turn preyed upon by predatory fish. The importance of the top

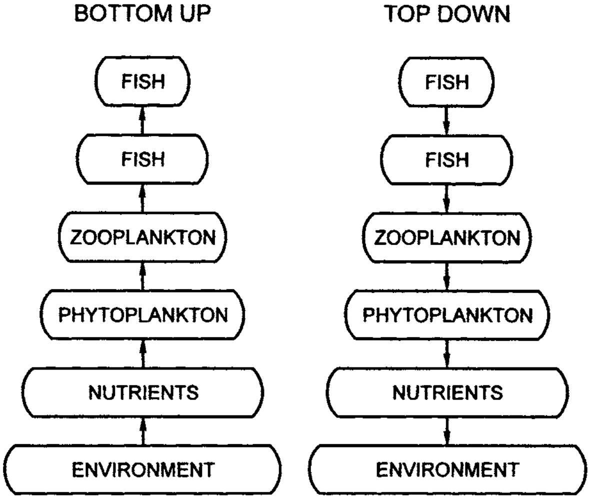


Fig. 4.7. Schema of bottom-up and top-down control in aquatic ecosystems. Both controls are realized simultaneously, with the effect of each one prevailing under certain conditions. (Orig.)

down control (i.e., the effects that predators have on the development of zooplankton and the zooplankton control of phytoplankton development) was only recognized more recently. It is now known that both types of control are simultaneous, and that there are feedback relations between the abiotic environment and its various biotic components.

The top down component of the natural, internal control of an aquatic ecosystem is so strong that some typically physical variables, including temperature, have been determined to be controlled by the biota. The effect in this case is due to adsorption of sunlight radiation by microscopic algae in the upper water layers. When dense algal populations exist in a waterbody, heat is adsorbed in its surface layers, warming the water. In contrast, less heat penetrates to the deeper water layers, making them colder than if the waterbody had less concentrated algal populations.

The principle of biomanipulation rests in food chain manipulation, by reducing the feeding pressure of fish on zooplankton. As a result, large species of zooplankton predominate, which are capable of keeping the phytoplankton levels down. The two typical states existing before and after biomanipulation are shown in Figure 4.8.

The feeding pressure of fish on zooplankton is high when the number of zooplankton-feeding fish is high. This situation is common in lakes and reservoirs with stunted fish populations (i.e., overcrowded fish populations which only grow slowly). Because of their numbers and small size (small fish have relatively greater food requirements), however, they decimate larger zooplankton species, and the smaller zooplankton are unable to control algae populations. The distribution of energy and dominant flow pathways in these two situations is very different.

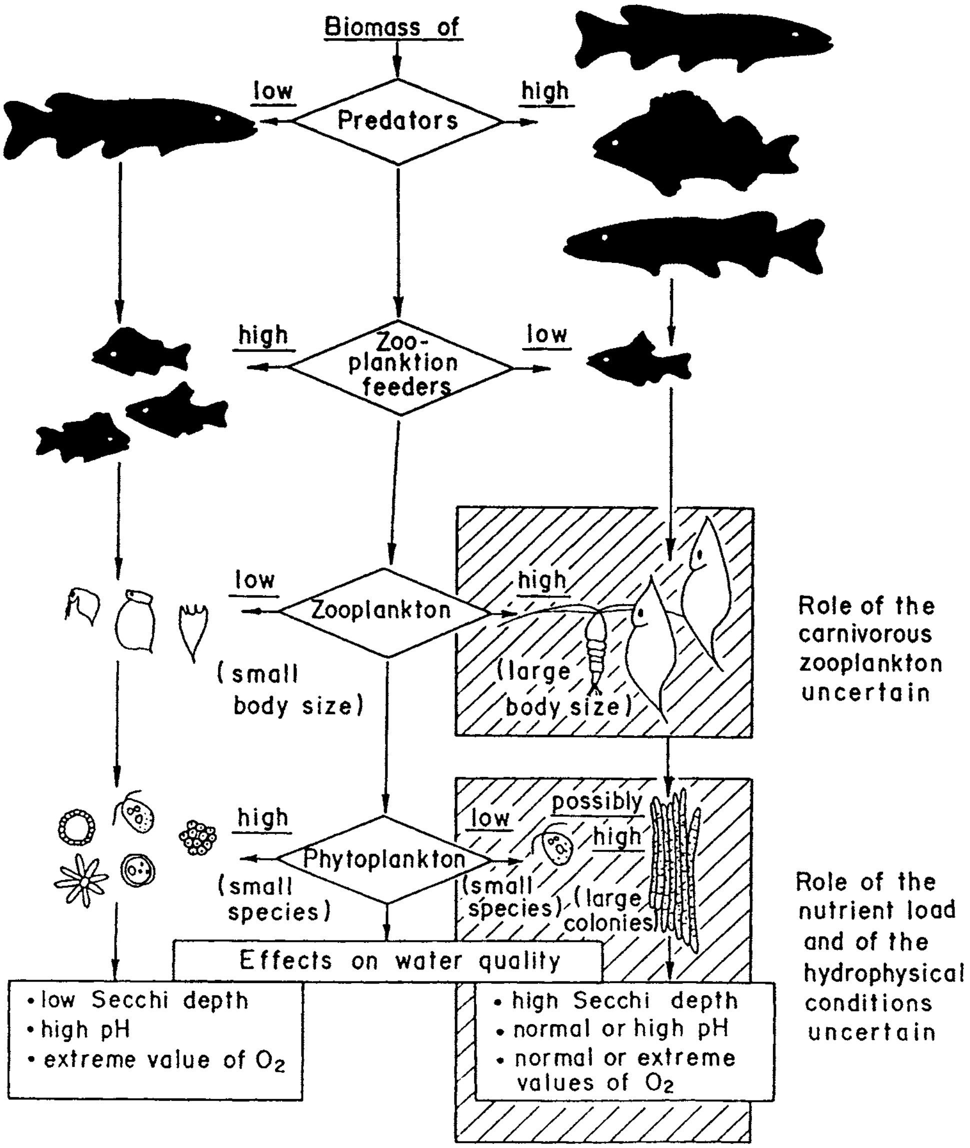


Fig. 4.8. Schematic representation of two situations in European lakes/reservoirs, with (i) domination of planktivorous fish when small zooplankton are unable to control phytoplankton development and with (ii) domination of predatory fish which reduce zooplanktivorous fish and, therefore, enhance large zooplankton capable of significantly reducing phytoplankton population. At high phosphorus concentrations, however, a switch to large phytoplankton inedible by zooplankton or to macrophytes is possible (modified from Benndorf et al., 1994).

Procedures used in temperate Northern Hemisphere lakes

Deep lakes. A low feeding pressure of fish on zooplankton is obtained when a "healthy" composition of fish stock is present. A healthy fish stock means well-developed predator populations and reduced numbers of well growing noncarnivorous fish.

The composition of fish populations that result in the control of phytoplankton by zooplankton can be achieved in two ways:

- Temporarily, by eradication of stunted fish populations with rotenone poisoning and predator stocking (rotenone is not toxic to invertebrates and phytoplankton; Stenson, 1972).
- Continuously, by introducing predatory fish and net harvesting of nonpredatory fish. A collaboration with the local sport fishery and the use of commercial fishery methods is needed. Drawdown of the reservoir water level during the reproduction period of undesirable fish species laying eggs on shore vegetation is a possibility to reduce the abundance of zooplanctivorous fish.

Winter fish kills in some freezing reservoirs can also be a good starting point for modifying species composition. The methods used for fish removal in England for purposes of biomanipulation are identified in Table 4.5.

Most effective examples of biomanipulation apply to relatively small waterbodies (Leventer, 1979) because of the greater difficulty of continuously manipulating fish populations in large ones. There are not many published examples for larger waterbodies such as reservoirs (Benndorf, 1987, 1988; Benndorf et al., 1988; Hrbácek et al., 1986; Seda et al., 1989; Duncan, 1990; Zalewski et al., 1990; Zalewski, 1994), and the results are usually not as convincing as those from smaller, but deep waterbodies. However, the results from the

Table 4.5. Removal techniques used in fish removal in shallow lakes in England (modified from Moss et al., 1996)

Systematic electrofishing—This has been done from a rowboat, with a rower and operator

Electrofishing for isolated large fish or small shoals of such fish—The fish are chased in calm, clear water with a powered boat, with the cathode tied across the bottom of the boat and the anode applied to the bow

Seine netting—Nets from 50 to 120 m have been used for encircling concentrations of fish. A floating mobile pontoon is used

Isolating nets—Light weight 60 m monofilament nets were used, paid out from the back of a rowboat to surround shoals and concentrate fish for removal by electrofishing

Passive fish traps (fyke nets)—The nets used conventionally by eel fisherman are set for periods of 12–24 hours to catch large fish which have evaded other methods

Scare lines and fish traps—Ropes onto which brightly colored scraps of cloth are towed through the water by boats. This herds fish to traps made from stop nets, from which the fish are removed by seining

Prevention of successful spawning—Bream, roach and tench, and perhaps other fish, will readily spawn onto netting if this is placed in traditional spawning areas. The netting can then be removed to dry highly eutrophic London reservoirs (Duncan, 1990; Duncan et al., 1991) are very convincing, with the fish biomass being very low (5–37 kg/hectare) for about 20 years or more, with grazer control of algal populations being dominant throughout the summer, clearing the water and reducing subsequent treatment costs.

Shallow lakes. Willemsen (1980) observed two states in shallow waterbodies in The Netherlands: one with clear water and macrophytes, and the fish fauna dominated by pike, and one with turbid water, no macrophytes present and fish fauna dominated by bream. A mathematical model constructed to clarify the conditions needed to switch between the two states is discussed in Chapter 5. The model shows the importance of the critical nutrient level for successful biomanipulation, measured as a substantial decrease of phytoplankton and increased transparency.

The principal objective of biomanipulation in shallow lakes is to generate a sufficiently-long period of clear water to allow macrophytes to become established. To achieve this goal, and for other technical reasons, biomanipulation is best undertaken in the winter and early spring, in order to generate clear water as early as possible in the season. The biomanipulation activity may have to be repeated if macrophytes do not colonize effectively within the first season. Understanding the nature of the factors and mechanisms responsible for turbid water preventing macrophytes growth is critical if biomanipulation of shallow lake is to be successful. If sufficient information is available, particular components of the fish community may be targeted and precise figures for exceeding critical threshold values may be set. In the absence of this information, a safe strategy is to remove at least 75% of the fish. Stocking with piscivores is a useful additional measure of fish removal (Perrow et al., 1997). A practical decision tree for biomanipulation of shallow flood-plain lakes in England was elaborated by Moss et al. (1996).

Advantages and drawbacks. One of the most extensive data set demonstrating the positive effect of balanced fish populations on low algal biomass is from Quiros (1995), who investigated the effect of fish assemblage composition on lake water quality in 110 lakes in Argentina (between 25–55.8°S latitude). He demonstrated that, at comparable total phosphorus concentrations, lakes with planktivores, but without piscivores, had the highest phytoplankton biomass and lowest water clarity. The average chlorophyll-a concentration was 40.6 mg m^{-3} for these lakes, while the chlorophyll-a concentration of lakes with both planktivores and planktivores was only 26.3 mg m^{-3}, a 65% reduction. A thorough evaluation of the biomanipulation experiments published through 1992 by Kasprzak (1995) and Jørgensen and de Bernardi (1998), comprising 22 whole lake experiments and 10 enclosure experiments are summarized below. With one exception, all were performed in temperate regions, mostly in stratified lakes:

- A success, measured as noted above, was achieved in two-thirds of the 25 observations; in 28%, the result can be described as ambiguous, while a disappointing result was obtained in only two cases.
- The disappointing results are due to too-high initial total phosphorus concentrations in the waterbody. It can be shown that the two possible structures (domination by phytoplankton and planktivorous fish, and domination by zooplankton and top-carnivorous

fish) are both stable at a total phosphorus concentration between about 60–125 $\mu g\ l^{-1}$. Thus, any improvement with biomanipulation at total phosphorus concentration above 120 $\mu g\ l^{-1}$ will only be temporary. The domination by phytoplankton and planktivorous fish will eventually occur at total phosphorus concentrations above 125 $\mu g\ l^{-1}$ (also see structurally-dynamic modelling discussion in Chapter 5).

- Poor results were observed with very high phosphorus concentrations. In very eutrophic waterbodies, therefore, it is necessary to combine biomanipulation with nutrient reduction by other methods.
- Biomanipulation success is generally more pronounced in smaller, shallow waterbodies, particularly because the control of fish populations is easier under such conditions.
- A shallow waterbody, or shallower areas of deeper ones, may switch to a macrophyte dominated state, thereby dictating the consequences for the respective use of the waterbody.
- The creation and stabilization of a strong population of piscivorous, predatory fish populations is difficult and time consuming, unless achieved by commercial net fishery. The use of rotenone poisoning is often the only shock sufficiently strong to trigger the conversion.
- The extent to which planktivorous fish must be removed depends largely on the species and size composition of the fish community.
- Due to very different turnover times of the organisms, a new, stable equilibrium may require several years to develop. However, this is also true for other eutrophication processes, such as nutrient input reduction when the high internal loading is capable of extending the duration of the eutrophic state for a number of years.
- The biomanipulation procedure cannot be considered a routine method, since it depends on a number of circumstances and can be performed only with the participation of skilled limnologists.
- Local and waterbody-type specific criteria for successful application of biomanipulation must be used.

As stressed above, the present experience is based on temperate conditions. However, it focuses primarily on the northern part of the temperate region, with relatively uniform species composition of fish and zooplankton fauna.

Application of biomanipulation in subtropical and tropical regions. Lazzaro et al. (1992) provide a discussion of the application of biomanipulation in the southern part of the United States. The fish at the top of the food chain in this situation is the omnivorous gizzard shad (*Dorosoma vittatus*), which is able to switch its food source from zooplankton to bottom detritus, thereby not exerting efficient control of zooplankton. Further, high fecundity and development in early years allows it to successfully out-compete other predatory and zooplankton-feeding species.

Some studies on the application of biomanipulation in subtropical and tropical regions do exist. Straškraba et al. (1969) reported on the results of a rotenone poisoning experiment in a small Cuban lake. Although the lake was only observed for 4 months, the phytoplankton decreased and the transparency increased. Arcifa et al. (1986) and Starling et al. (1998) made short term, enclosure experiments in the Paranoa Reservoir in Brazil, a very eutrophic reservoir located at a latitude of 15°S in Brasilia, the capital of Brazil. The total phosphorus concentration was about 190 mg m^{-3} at the time of the experiment. The addition of different numbers of planktivores (*Hypophthalmichthys molitrix*, silver carp) to the enclosures resulted in changes to the zooplankton and phytoplankton composition. Although the experiments in the Broa Reservoir (22°S, elevation 800 meters) by Roche et al. (1993) show conditions more complicated than those seen in the North, the trends were generally similar. Magadza (1995) and McQueen (1997) discuss other applications of this technique under subtropical and tropical conditions.

Successful applications and experiments, using the silver carp (*Hypophthalmichthys molitrix*) have been reported for lakes in Israel and Brazil (Leventer, 1979; Leventer and Teltsch, 1990). The food web effect is different from that seen in Figures 4.7 and 4.8, due to the feeding of grass carp directly on large colonies of phytoplankton and macrophytes. However, as in all other cases of fish introductions, caution must be used in introducing foreign species into a new waterbody. In fact, in Israel, the introduction of silver carp also affected the populations of other species (Gophen, 1995).

Applications in subtropical and tropical regions are more complicated because of high fish diversity, changing species composition from place to place, the presence of omnivorous fish and more complicated food chains (Arcifa and Northcote, 1997; Lazarro et al., 1992; Lazarro, 1997). More knowledge of the food webs in such systems is needed. The more diversified fish fauna and its trophic relations must be known for each lake situation. The higher reproduction rates of fish, zooplankton and phytoplankton will need greater control efforts to keep the structure of these populations optimal from the perspective of phytoplankton reduction. More knowledge on the zooplankton feeding of tropical zooplankton also is needed. On the other hand, a positive feature might be the greater interest in fish as a food source, and the existing skill of fisherman to use the net fishery. In temperate climates, the sport fishery concentrates on selective elimination of piscivores. However, from the perspective of biomanipulation, the presence of piscivores should be facilitated.

The *advantage* of biomanipulation is that it is completely natural in its components, with no chemicals or machinery needed. It only requires manpower to implement. Further, it also can combine both the need to protect water quality and maintain fisheries. Education of fisherman is often needed to convince them not to remove predators, and not to stock a lake with nonpredatory species. The *drawback* is the need of continuous control of fish populations, which tend to return to the stunted population state not because of natural processes, but rather because of recreation sport fisheries concerned with predatory, rather than zooplankton-feeding fish. Biomanipulation is one method with no significant potential *negative impacts* if performed without rotenone poisoning. Rotenone poisoning is not desirable in drinking water reservoirs and may result in the killing of rare and endangered species. The *cost* depends on the way in which the method is performed. It is relatively low, particularly if done in combination with organized fishery, but will increase in cost when these elements are not combined. Further, the cost of rotenone is quite high.

4.3.2 Mixing and Oxygenation

Methods discussed in this section are some of the most commonly used for lakes and reservoirs. Some belong to the category of preventive means, while others are used in a curative way to get rid of the water quality problems that have reached a critical stage.

Artificial mixing is used either to oxygenate a deoxygenated hypolimnion, or to inhibit phytoplankton growth. As shown below, seven mixing methods exist, with the four most common ones presented schematically in Figure 4.9:

- Destratification by total mixing of the water column,
- Mixing and re-aeration of the hypolimnion,

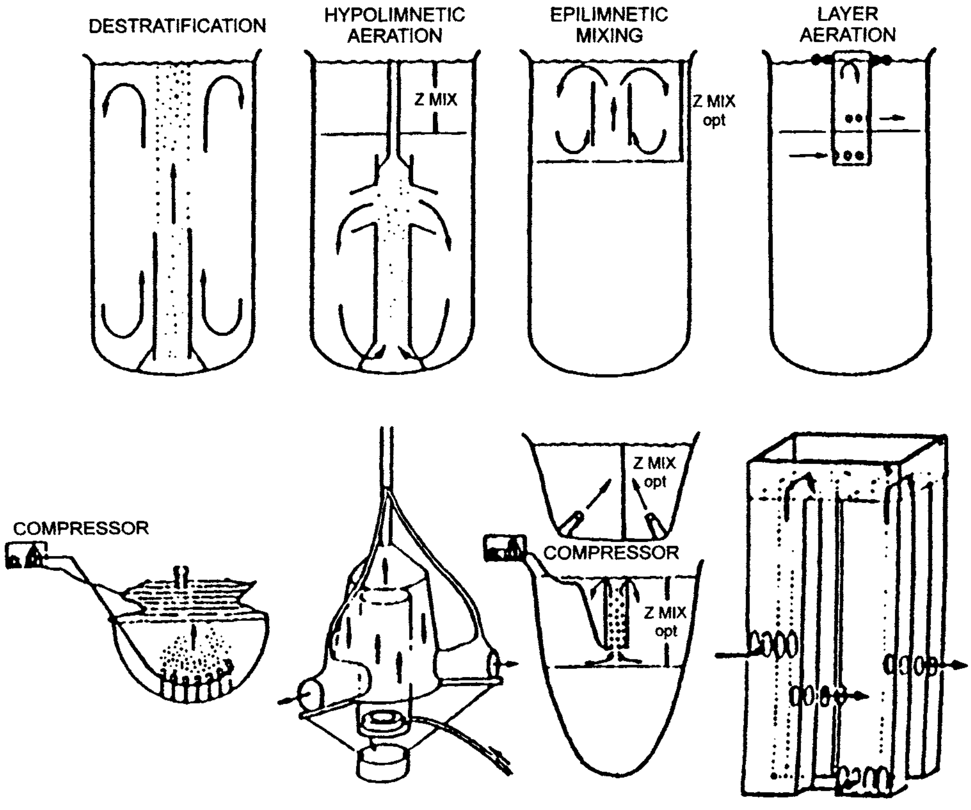


Fig. 4.9. Schematic representation of the four most common mixing types. The top row shows the mixing, the bottom row the actual arrangement. From left to right: destratification with compressed air with an aerator or with tubing laid on the bottom, hypolimnetic aeration (the partial air-lift hypolimnetic aerator LIMNO of the firm Aqua Techniques), epilimnetic mixing in two versions—in an embankment reservoir and a deep lake or valley reservoir, and the layer aerator of Kortmann (modified from Straškraba and Tundisi, 1999).

- Epilimnetic mixing,
- Layer aeration,
- Hypolimnetic oxygen aeration,
- Metalimnetic mixing,
- Propeller mixing.

The use of these different approaches depends on the type of problem encountered and on the treatment possibilities. Destratification is the simplest method, being used with varying success. As will be shown, unsuccessful use of this method may have two reasons, including inadequate mixing and its use under conditions that do not consider the limits of the application of this method. Hypolimnetic mixing and re-aeration is the most commonly used approach, avoiding some of the negative effects and limitations of destratification. In contrast to the previous methods, epilimnetic mixing is curative in nature. Curative methods are advantageous from the ecotechnology perspective and, therefore, highly recommended. Metalimnetic mixing is the newest method, designed for conditions when a lake has developed specific layers of low water quality. The Speece cone used for hypolimnetic oxygenation is a technically elaborate and expensive method. Only limited information exists regarding the newest approach of using surface propellers.

Destratification–artificial circulation–aeration

The name of this procedure highlights its purpose. Lake stratification is destroyed and lake circulation is restored. The theory is explained in Kortmann et al. (1994). In shallower, smaller lakes, it is done by injection of compressed air from a diffuser to the water at the lake bottom (Fig. 4.10). When aeration is the main goal, this simple bubble plume diffuser was found to be the simplest, most efficient arrangement, even for a deep lake (McGinnis et al., 1998). In larger, deeper waterbodies, the stream of bubbles must be directed by a broad tube of 2–3 meters in diameter to create in-lake circulation. The lake bottom water is enriched by oxygen, algae are mixed to greater depths with a subsequent decrease in their net production, the pH of bottom water is increased, and that of the surface layers decreased. Three goals are simultaneously being sought:

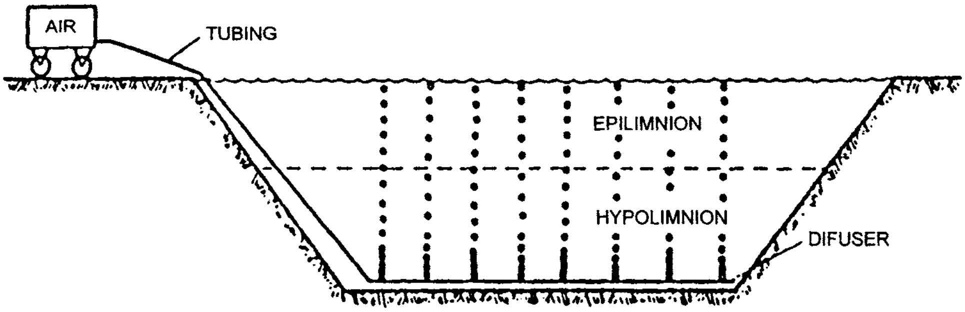


Fig. 4.10. Typical arrangements for lake mixing in smaller lakes (modified from Straškraba and Tundisi, 1999).

- The goal of destratification is to prevent algae from remaining in the light-illuminated water layer, with a resultant decrease in phytoplankton biomass formation.
- The goal of circulation is to decrease the pH, and cause a shift from blue-green algae to less noxious green algae.
- The goal of aeration is to oxidize the hypolimnion, with the consequence of preventing the release of phosphorus, iron and manganese.

There may be an environmental price to pay, however, because the process of lifting the hypolimnetic water to the lake surface may also result in higher phosphorus concentrations and increased algal growth. Lorenzen and Mitchel (1973) determined the circumstances under which the desirable effects of destratification were to be expected. Earlier examples of the practical use of this technique, made without regard to the Lorenzen and Mitchel rules, are summarized by Pastorok et al. (1980). Based on 40 attempts, they claim a significant change in algal biomass in 65% and a decrease in 70%, and an increase accompanied by changes in species composition in 30%. Raman (1988) provides practical examples for twelve lakes in Illinois. A good example of the successful use of destratification in tropical Malaysia is provided by Kassim et al. (1997).

Model studies by Schladow (1992), Wüest et al. (1992), Schladow and Fisher (1995) and McGinnis et al. (1998) showed the realistic shape of the rising plumes of compressed air, allowing it to calculate the necessary forces to efficiently circulate the whole water column. Schladow's results indicated that some of the earlier attempts were insufficiently designed to adequately mix the entire water column. Thus, it is necessary to stick to the rules of Lorenzen and Mitchel (1973) and Schladow (1993) for successful application of this technique. Model studies by Imtaez and Aseada (2000) indicated that water quality improvement can be obtained by using the appropriate gas flow rate and number of bubble ports, and applying it at an appropriate period of the year.

In addition to the review by Pastorok et al. (1980), Burns and Powling (1981) and Burns (1990) also reported examples from Australia with *negative impacts*. It is not possible to estimate how much of the negative effects were due either to insufficient mixing, or to the increasing surface concentrations of phosphorus resulting from the mixing (i.e., lifting the phosphorus from deeper water layers to the surface). In a case described by Fast and Hulquist (1982), compressed air used to destratify a lake caused supersaturation of the water with dissolved nitrogen and causing downstream fish kills. In smaller remote lakes in Australia with no electricity supply, Burns (1998) has used solar batteries to run the air compressor. The *cost* of this procedure is low, equaling the price of the compressor and the installation of the pipe and diffuser. If applied following the conditions given by Lorenzen and Mitchel (1973), and the criteria by Schladow (1993), the method has the following *advantages*:

- Hypolimnetic oxygen increases,
- No increased phosphorus release from the sediments,
- The quantities of iron and manganese remain low or absent,
- A decreasing quantity of algae.

New types of aeration systems for efficient mixing and aeration of shallower waters are produced by various firms; namely, a system with hollow fiber membranes (Weiss et al., 1996), the NOPOL aeration system (Anonymous, 1997). Aeration may be also done by propellers with air injections, as shown below in the discussion on propeller mixing.

A method based on particular knowledge of limnology and algae was theoretically developed by Reynolds et al. (1984) and applied practically in a German lake by Steinberg and Zimmermann (1988). The water column is intermittently destratified in a way so as to minimize the growth and maximize the losses of different algae. Cyanobacteria and algae were highly reduced with the application of this method, with the instantaneous development of different species in the lake.

Hypolimnetic aeration

There are aerators which can oxidize the hypolimnion without breaking down the thermocline (e.g., Bernhardt and Hotter, 1967; Fast et al., 1975; Anonymous, 1985; McQueen and Lean, 1986; Bernhardt, 1987; Prien and Bernhardt, 1989; Anonymous, 1989; Little, 1995; McGinnis and Little, 1999; McGinnis et al., 1998). The study by Burris and Little (1998), using a mathematical model, showed that for one of the devices, it is possible to double the oxygen transfer to water in hypolimnetic aerators when the initial bubble diameter is reduced from the more standard 5 mm to just 2.5 mm. More generalized results to predict efficient bubble diameters for different devices and conditions are underway (Little and Del Vecchio, 1999).

The principle is evident in Figure 4.11, which shows one of the aerator types. The air bubbles rising from the diffusers at the lake bottom are allowed to reach the surface in a narrow aeration tube, while water is pumped to be released at a predestined depth. This corrective technique is used in instances of high hypolimnetic oxygen deficits, taste and odor problems, and increased concentrations of manganese and iron (e.g., Prepas and Burke, 1997). It is not applicable in shallow lakes without well-developed hypolimnia. It is difficult to mix a narrow water stratum near the bottom water layer. For successful application of this technique, the total oxygen demand of the lake must be correctly estimated, checked for possible metalimnetic oxygen minima, and the phosphorus-binding capacity of the bottom sediments considered. When sediments are rich in sulphate, a decoupling of the iron and phosphorus cycles takes place, and no positive effect is achieved (Hupfer and Zippel, 1998). The procedure has the *advantage* that the high concentrations of elements in the hypolimnion are not transferred to the epilimnion, and do not enhance algae growth. The improved oxygen conditions in the hypolimnion improve water quality by decreasing the iron, manganese, tastes and odor problems for drinking water supply, decreasing the damage to turbines and other structures by corrosion, and improving the downstream water quality. Cultivation of sensitive fish also is facilitated. Possible *negative environmental impacts* may occur in lakes and reservoirs in pristine areas by the transportation and installation of the fairly large equipment, and the installation and use of electricity. The investment *cost* is much higher than for destratification, due to the needed equipment. The operating costs depend on the hypolimnion area, the rate of oxygen consumption in the lake and the degree of thermal stratification, and can be calculated with a procedure given by Cooke et al. (1986). A combination of hypolimnetic mixing, with the injection

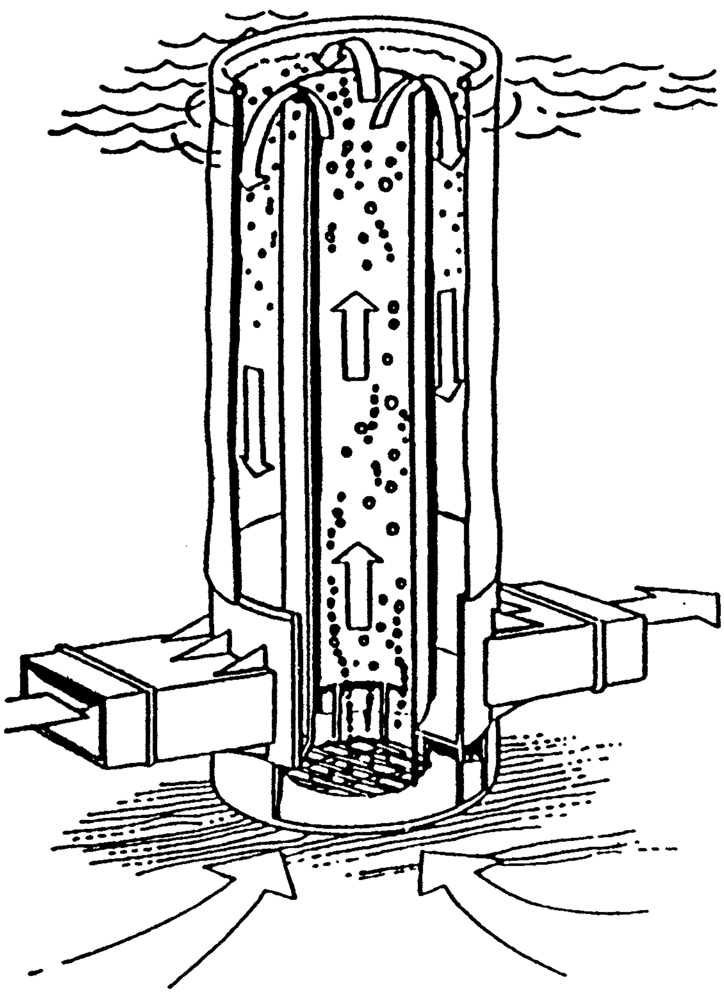


Fig. 4.11. A hypolimnetic aerator in operation (modified from Anonymous, 1989).

of hypolimnetic calcium hydroxide [$Ca(OH)_2$] was used in Germany (Anonymous, 1994) (Fig. 4.12).

Hypolimnetic oxygenation

Pure oxygen generated at the lakeshore is used to increase the oxygen concentrations at the lake bottom without extensive mixing (Fast et al., 1975; Gemza, 1997). The oxygen is injected into the device, with the movement of water from the hypolimnion and back created with a propeller. Oxygen-enriched water was injected at a rate of 0.2 $m^3 s^{-1}$, with concentrations between 8–11 mg l^{-1}. The fine bubbles released from the device that do not

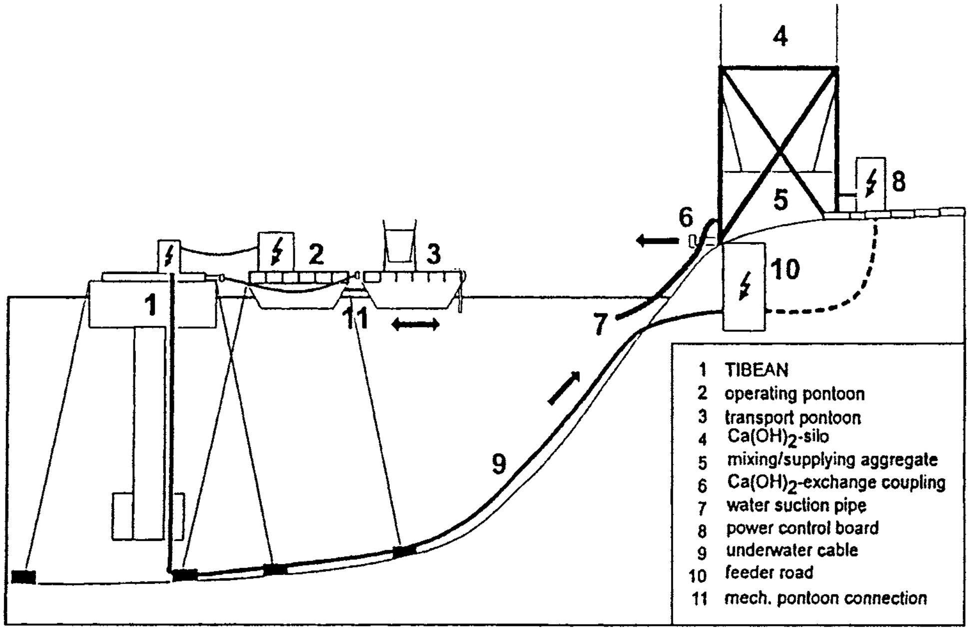
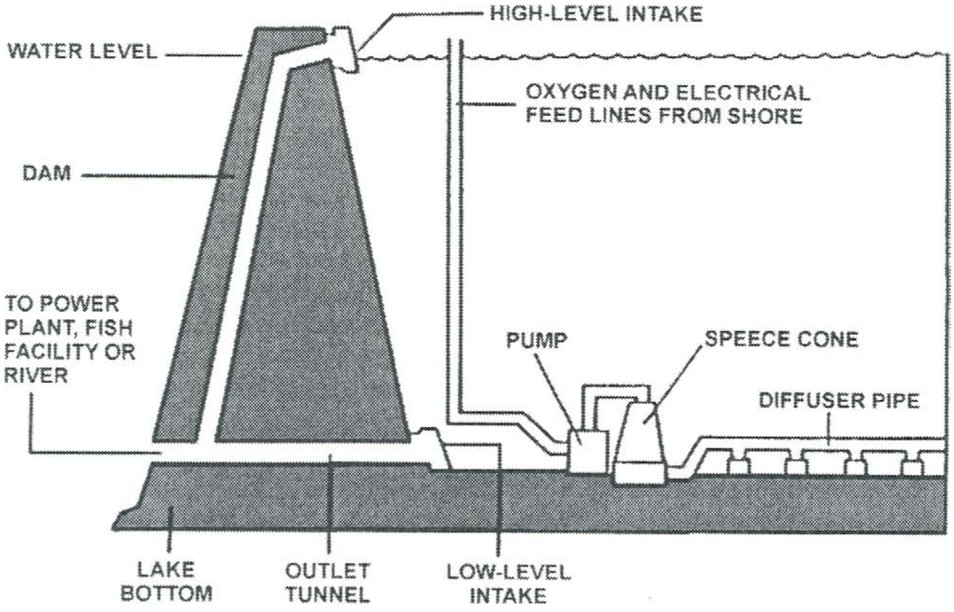


Fig. 4.12. Schematics of the pilot project on combination of hypolimnetic aeration and hypolimnetic $Ca(OH)_2$ addition, with the use of the hypolimnetic aerator type TIBEAN, as used in Germany. From Koschel et al. (1998).

dissolve in the water are trapped by a bubble collection hood, so that little mixing takes part while the water is being enriched with oxygen. The number of operations using this method has been low to the present time. Thus, it is difficult to highlight its *advantages* relative to hypolimnetic aeration. In present applications, however, the improvement in water quality was significant. Because the device used is simpler than the one used for aeration, the *costs* can be less.

Speece et al. (1982) and Speece (1994) used a special device (i.e., *Speece cone*) to supersaturate a certain amount of water up to 50–150 mg O_2 l^{-1} in a special underwater conical chamber. The water is then horizontally diffused into the hypolimnion at a low speed, without breaking the thermal stratification. Detailed studies of the bubble dynamics and oxygen transfer in the Speece cone were made using a mathematical model by McGinnis and Little (1998). Practical experience with the water quality improvement resulting from the hypolimnetic oxygenation, in comparison to the widely-used hypolimnetic aeration, shows higher hypolimnetic dissolved oxygen levels, lower levels of induced oxygen demand, and maintenance of more stable thermal stratification (Beutel and Horne, 1999). The procedure is illustrated in Figure 4.13. Kennedy et al. (1995) reported the investment cost for a large reservoir (a volume of 1.29 billion m^3) to correspond to US $5 million, with the operating costs being about US $800,000 per year.



Epilimnetic mixing
Straškraba (1986) named this technique, suggesting its use in deep waters. However, it has generally only been used in situations in which the whole waterbody, not just the epilimnion, is mixed. Two possible arrangements are evident in Figure 4.9. The method is highly recommended, as it is the only mixing method aimed at prevention, rather than correction. The main goal is to reduce phytoplankton growth, irrespective of high phosphorus concentrations. This is achieved by decreasing the light available to the phytoplankton population, by mixing it to deep, dark strata. The surface water layers are mixed to a predestined depth conducive for minimal net phytoplankton production. This is achieved when the mixing depth ($z_{\mathrm{mix}}opt$) is equivalent to the depth at which net photosynthesis is reduced to zero (i.e., water column respiration equals water column photosynthesis). More detailed explanation of this approach is given in Section 4.3.8—*Manipulation of the Underwater Light Regime*. Such mixing systems were originally developed for stratified impoundments in England. A mixing system destroys or prevents thermal stratification. Some systems use compressed units which discharge air bubbles through bottom diffusers (Symons et al., 1965, 1967), while others physically transport water with pumps (Ridley et al., 1966).

Cooley and Harris (1954) designed the mixing system of Φ-angled inlet jets installed in the London drinking supply reservoirs. Summer thermal stratification was prevented, or an established thermocline in these reservoirs, about 17 meters deep, was destroyed. Wind energy applied to the longest axis of the reservoirs helped mixing. In practice, the degree of achieved horizontal and vertical mixing resulted in isotherms throughout the summer, and the mixing of algae to dark strata. Ridley and Steel (1975) proposed changing the optical properties of the reservoir water, by using the Φ-angled jet to re-suspend bottom sediment material. It appeared that this option could increase water treatment costs.

Several *advantages* of epilimnetic mixing of London reservoirs are reported:

- Deoxygenation and the release of nutrients from the sediments is prevented by the absence of a mid-summer hypolimnion,
- Mixing operations reduced algal crops in these highly eutrophic conditions,
- Transformation of a stratified waterbody with a warm epilimnion and deoxygenated hypolimnion into a cooler, well-mixed and well-oxygenated one improved trout fishery.

A result of treating raw, eutrophic riverine water was that the overall *costs* of producing a satisfactory drinking water were much reduced. The mixing system originally designed to double the supply of potable water by oxidizing the deoxygenated hypolimnion (Cooley and Harris, 1954) proved to be a major cost-effective tool for the limnological management of eutrophic impoundments that previously had large blue-green blooms that did not respond to algaecide treatment (Steel, 1972, 1978a, 1978b; Duncan, 1990).

In deep waterbodies it is suggested the principle of epilimnetic mixing by the standard diffuser installed on the bottom of a tube of 2–3 meters in diameter be used, locating the lower end to the depth $z_{\text{mix}}opt$. In this way, only the upper layers of the waterbody are mixed, and the hypolimnetic conditions are not directly tackled. Anoxia does not occur, however, since the primary algal production is minimized.

Metalimnetic aeration

Metalimnetic aeration oxygenates the water in the metalimnion without destructing either the hypolimnion or the epilimnion (Stefan et al., 1987). The purpose is to produce an oxygenated refuge in the metalimnion for *Daphnia*. A fully submerged bag-type device is used.

Layer aeration

Kortmann et al. (1982, 1988) and Kortmann (1994) used a detailed knowledge of stratification and heat conditions in lakes and reservoirs for the redistribution of available heat and oxygen in a stratified lake or reservoir. By means of specific devices (Fig. 4.14), discrete layers of lakes or reservoirs are created and aerated, establishing several thermocline-type barriers to vertical diffusion, and reducing the volume and areal extent of the hypolimnion. Methods for calculating the size of the system are given by Kortmann et al. (1994). *Advantages* of the method include that manipulation of the thermal structure creates desirable physical/chemical conditions, as well as an oxygen supply. Because it is possible to act selectively, the negative side effects of mixing which often accompany destratification (e.g., nitrogen supersaturation, increased diffusion transport to the epilimnion, metalimnetic anoxia) are avoided. Oxygenation is very efficient; in one case, only 3.2 $m^3\ d^{-1}km^{-2}$ were needed, compared to 41 $m^3\ d^{-1}km^{-2}$ for hypolimnetic aeration (average of 15 applications, Cooke et al., 1986). The *cost* is about one-fifth that of hypolimnetic aeration.

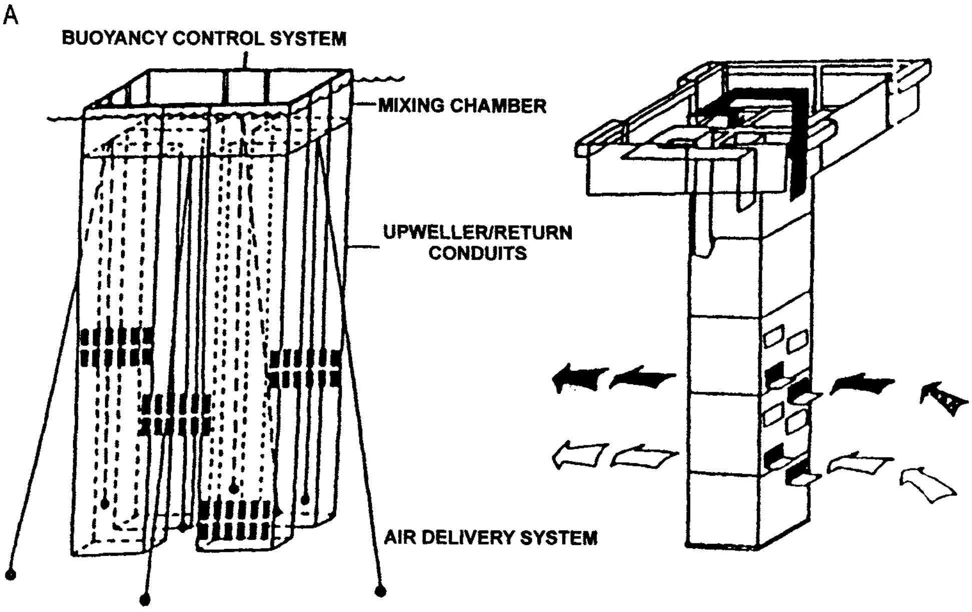


Fig. 4.14. Principle of layer aeration and devices used for layer aeration. Modified from Straškraba and Tundisi (1999). A—Schematic representation of difference between layer aeration, hypolimnetic aeration and artificial circulation (from Kortmann, 1994).

Propeller mixing and oxygenation

Propeller mixing and oxygenation is a system differing from all previously-discussed methods in the manner in which mixing is accomplished. The others are based on mixing accomplished by rising air bubbles from lower layers in a waterbody. This method entails mixing from above by the use of a propeller. The propeller is attached to the bottom of a pontoon, and can be used in many different applications. It is combined with a compressor that jets bubbles into the propeller region so that the surface layer becomes oxygenated. Technical specifications are given in Fay (1994). A device called the Stratification Breaking Propeller, with the propeller located at the bottom of a brad pipe similar to standard aerators for deep waters, reverts the operation of bubbler-based mixing devices by sucking water from the waterbody surface and releasing it near the bottom. A flexible "accordion-like" pipe for this propeller is described by Zoran and Milstein (1999).

Comparison of different oxygen transfer devices

The efficiency and cost of three different oxygen transfer devices (hypolimnetic aerator, bubble plume and Speece cone) were compared by McGinnis et al. (1998). A combination of direct measurements performed on the reservoir in different years, and a mathematical model representing a modification of the model by Wüest et al. (1992), was used. The results have shown that, in a 70 meter deep drinking water supply reservoir, the bubble

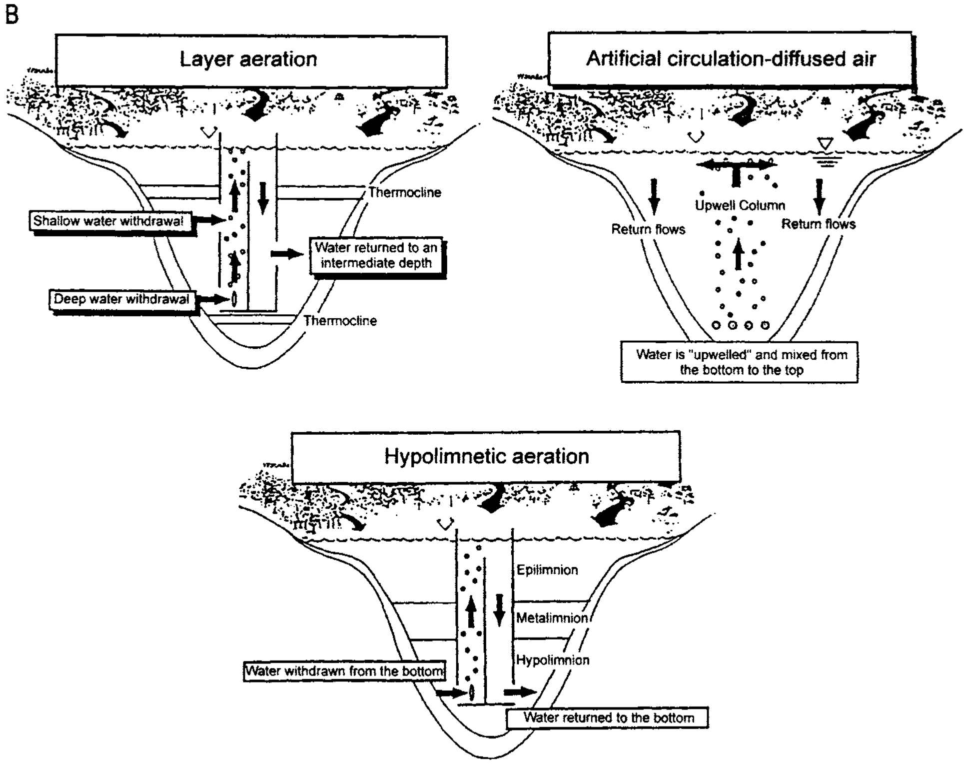


Fig. 4.14 (*continued*). B—Two devices for layer aeration (modified from Straškraba and Tundisi, 1999).

plume oxygenator (with a length of 2500 meters and initial bubble diameter of 2.5 mm) were very efficient in oxygenating the hypolimnion. The initial bubble diameter proved to be a very sensitive parameter. However, the consequences for other components of the system, and the water quality in general, were not investigated.

4.3.3 *Hydraulic Regulation*

Hydraulics and hydrodynamics play an important role in defining the water quality of standing waters. The possibilities for modifying the natural flow conditions in lakes are limited. The situation is different for reservoirs, however, for which the location of the outlet, intensity of inflow and outflow can be manipulated to a different degree. Proper location of the reservoir and the positions of the outlet elevations (multiple outlets) play an important role in water quality optimization. From a water quality perspective, one important variable is the retention time of water in the reservoir, both the theoretical retention time and the actual currents in the reservoir. Determination of the theoretical water retention time during the planning stage represents an inexpensive and feasible management strategy for water quality improvement.

The following options are distinguished:

- Hydraulic regulation (also called selective withdrawal),
- Diversion of inflow water,
- Extraction of hypolimnetic water; hypolimnetic siphoning.

Dilution

Welch and Patmont (1980) applied the method of dilution in Moses Lake in Washington, obtaining a significant reduction in algal blooms by decreasing the water retention time of the lake from 10 to 5 days. The limitations of the approach are great. It is applicable only when sufficient water of low phosphorus and algae content is available. Because of the high demands on water quantity and quality, it is rarely possible to dilute an entire lake or reservoir.

Lake level manipulation

During decreased lake levels, the shallow sediments can desiccate, getting 20–50% compacted and consolidated. During sufficient aeration of the sediments, the organic matter is oxidized and the content of organic matter decreased.

Macrophytes are reduced with decreased lake levels. Three studies have shown a reduction of 50–90%, due to freezing and drying of roots. The decrease in the winter time was more effective than that during summer. The decrease was drastic for *Elodea densa* (by 84% in one case), but the stand regenerated rapidly the following year.

Diversion of inflow waters

The best known example of the successful diversion of polluted waters from a lake is that of Lake Washington (Edmondson, 1972, 1991). Lake Washington is an urban lake, being surrounded by a population of 500,000 inhabitants, and used for drinking water supply of Seattle, as well as for the recreation of its drainage basin inhabitants. This successful story was the result of concentrated scientific and political activities of W.T. Edmondson, who convinced the local politicians and managers about the usefulness and need to divert the pollution from the lake in order to save its water quality. A collector of domestic sewage was constructed along the lake to divert the treated wastes to Puget sound.

In this way, the wastes were diluted with a much higher water amount, producing little apparent harm to Puget sound, and leading to successful restoration of water quality in Lake Washington. The use of this approach is possible, however, only when a much larger volume water body is available for diluting the pollution, which is relatively rare.

The *advantages* of the method include the costs, which are less than if all the effluent sources have to be treated separately, including tertiary treatment. The *limitation* consists of the need for a sufficiently large waterbody capable of assimilating the effluents.

Hypolimnetic withdrawal by the Olszewski method

This method consists of sucking hypolimnetic waters of low oxygen and high iron, manganese and phosphate contents, from a lake. It is a method proposed by Ruttner (1931) and used very early in the history of lake restoration (Olszewski, 1961, 1967). The principle is shown in Figure 4.15. It is based on the presumption that a place can be found around a lake which is considerably below the lake's surface level, so that with some sucking a siphoning effect can be created to produce a free flow of water through a tube. Some minimal harm utilization of the water sucked out of the lake hypolimnion also must be guaranteed, either to fields as a source of fertilization, or to a larger river where the pollution will be sufficiently diluted.

Nurnberg (1987) provided a summary of the procedure used in 17 eutrophic or hypertrophic lakes with phosphorus inputs drastically reduced, before its application in Europe and the United States. Limited beneficial effects resulting from the reduction was observed, because of substantial phosphorus releases from the anoxic sediments. Both the depth of anoxic water and the total phosphorus concentrations decreased after hypolimnetic withdrawal was begun. However, no decrease of the duration of the anoxic period was observed in larger lakes. Significant decreases of epilimnetic total phosphorus concentrations were observed after 2–3 years of operation (or earlier in smaller lakes), and appeared more distinct as the water withdrawal has continued. The average annual decrease was 11%, with highly eutrophic lakes experiencing a slightly larger percentage decrease than lakes with lower initial total phosphorus concentrations. The decrease of the epilimnetic total phosphorus concentration was significantly correlated with total phosphorus export via hypolimnetic withdrawal.

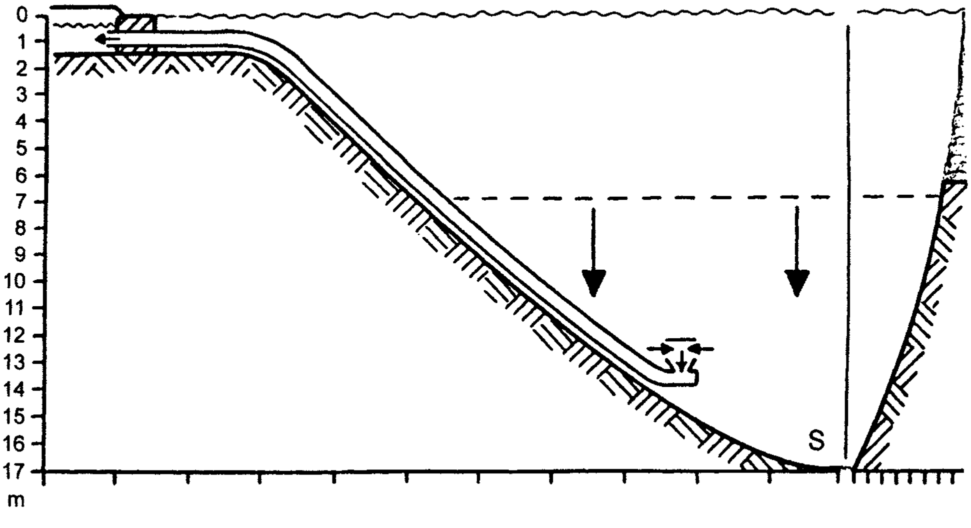


Fig. 4.15. The principle of the hypolimnion siphoning method of Olszewski (1961, 1967). (Orig.)

Advantages of the method consist of its very low labor needs and its continuous effects. Once installed, it can run unattended. A *limitation* is that the condition decreases the phosphorus load before the application starts. The method is directed to shortening the period of internal phosphorus loading effects. The needed location of the tube outlet below the level of the tube inlet is not feasible in a flat territory. The best results are achieved when the tube inlet is placed into the depth of maximum phosphorus concentrations, but does not touch the sediments. The *cost* is very low for both installation and operation.

4.3.4 Biomass Removal

The removal of biomass from a lake focuses primarily on removing aquatic plants. It implies that a corresponding quantity of the elements (phosphorus and nitrogen being of most interest from the context of eutrophication) that constitute biomass also will be removed. The composition of the littoral and benthic vegetation reflects the composition of the environment, (i.e., the sediment and the water). Macrophytes, for example, can take up not only nutrients, but also pesticides and heavy metals.

The methods of biomass removal fall into three categories:

- Biomass harvesting,
- Use of plant-eating aquatic animals,
- Other methods.

Mechanical plant harvesting

Biomass may be removed from a lake or reservoir by harvesting the macrophytes (e.g., Moss, 1995). In addition to eradicating obstructions to transport, clogging of structures, and organic decay problems, this method may result in a nutrient and toxic substance reduction of major significance for an aquatic ecosystem and should be considered as a supplement to other management possibilities.

There are many different types of harvesters, depending on the type of vegetation to be harvested (submergent, emergent, floating), the size of the waterbody, the quantity of plants to be harvested, and the depths to be reached. They range from relatively simple arrangements on small paddle boats, to strong barges of several meters length with elaborate mechanics for harvesting. Many firms in several lake-rich industrial countries sell diversified arsenals of such boats.

Macrophyte harvest is applied to many Chinese lakes to provide pig, duck and cattle feed. Mass balance calculations show that the nutrient removal by this process may be important for the entire lake's nutrient budget. Depending of the magnitude of the external nutrient load, the potential removal of phosphorus through weed harvest has been estimated to range from 20% (Wile, 1975), 37% (Carpenter and Adams, 1977) and 60% (Welch et al., 1979). A hypothesis to explain the relations between macrophytes and internal phosphorus loading was presented by Welch and Kelly (1990).

The time of harvest is often important. *Phragmites* have their peak nutrient concentrations in western Europe in the late summer (August/September), and harvesting them at that time will often double or triple the quantity of nutrients removed, compared with harvesting them 1–2 months later.

As indicated above, removal of heavy metals and pesticides is possible with the use of macrophytes. The use of plants for removal of toxic substances has been practiced for purifying contaminated soil, with good results (see Jørgensen, 1993). The plants are able to attain concentrations of heavy metals 50–1000 times the concentration in soil water. The concentrations are slightly smaller for pesticides (in the order of 10–200 times). If these results are considered in a lake management context, it should be possible to remove a significant amount heavy metals over a period of 3–4 years by harvesting 2000–3000 kg ha^{-1} each year.

If rooted vegetation is harvested, however, the diffusion from the lake water to the interstitial water in the sediment may cause a slower removal rate. In fact, large-scale experiments of the application of vegetation for removal of heavy metals and pesticides from lake and reservoir water have still not been carried out.

A theoretical problem is associated with the application of weed harvesting to lower the phosphorus concentration in a lake and, hence, the algal concentrations. If rooted macrophytes obtain most of their nutrients from sediments, then weed harvesting would actually be reducing an internal nutrient source, rather than removing a portion of the annual phosphorus inflow. If the internal phosphorus supply is relatively large, a reduction of lake phosphorus could result from harvesting and interrupting the transport of phosphorus from sediment to water via rooted plants (Welch and Kelly, 1990; Welch et al., 1994). There may be other problems, however, because increased excretion of phosphorus, and thereby of algal blooms, have been observed following weed harvesting in some cases (Nichols, 1974). In addition, the harvestable biomass may be depleted with each successive year of harvest. If the external phosphorus load is relatively large, the phosphorus content of the lake generally cannot be reduced, even though large masses of weeds can be removed.

Thus, each individual case must be examined carefully before this management tool is applied in practice. The examination should always include in-lake experiments, and the use of quantification assessments either by mass balance calculations or models (see Chapter 5). The role of submerged vegetation for fish spawning, however, should always be considered before implementing a biomass harvest plan.

Use of aquatic animals for plant removal

Because aquatic plant harvesting methods are relatively expensive, and chemical treatment methods have negative consequences, there is a recent trend toward the use of biological organisms, such as vertebrates (manatees), and insects (beetles, sandhoppers). Different groups of aquatic animals can be helpful in macrophytes removal. The order of their extent of use is as follows:

- Fish,
- Aquatic vertebrates,
- Invertebrates.

Fish

Table 4.6 gives the characteristics of the fish species generally used for biomass removal. Grass carp are particularly attractive for this purpose, as they use aquatic vegetation as their only food source. It is possible to remove plant biomass equivalent to 1–5 times the weight of the grass carp on an annual basis (wet-weight basis). Heavily-eutrophic ponds typically contain in the order of 10,000 kilograms or more of plant biomass (wet-weight basis) per hectare, and a complete removal of this biomass would imply the removal of about 50 kilograms of nitrogen and 10 kilograms of phosphorus per hectare, a significant quantity of nutrient removal. If a depth of 5 meters is considered, it will correspond to the reduction of the nitrogen and phosphorus concentrations, respectively, of 1 and 0.2 g m^{-3}. This removal, consistent with the above-noted removal capacity of 1 kg/carp, requires a standing stock of about 3000–10,000 kilograms of grass carp. Experience shows that such a high density is very difficult to maintain in a waterbody unless artificial oxygenation is used. A more realistic, but still relatively high, density would be in the order of 1000 kilogram of grass carp per hectare, which would yield a removal capacity of 1000–3000 kilograms of biomass, corresponding to a removal of 5–15 kilograms of nitrogen and 1–3 kilograms of phosphorus. For a pond with a depth of 5 meters, this would correspond to a reduction of the nitrogen concentration by 0.1–0.3 g m^{-3}, and the phosphorus concentration by 0.02–0.06 g m^{-3}. The need for a continuing harvest of a sufficient fraction of the grass carp also should be emphasized. In many cases, the effect of fish release is hardly measurable without a significant harvest of this fish, which obviously will mean a reduction of the phosphorus and nitrogen corresponding to the content of these elements in the harvested biomass.

It can be seen from these calculations that a significant biomass removal by the use of grass carp is only feasible for relatively small lakes (probably up to about 10 hectares in area) and ponds. However, this does not imply that fish release should not be used for the removal of macrophytes for larger lakes and reservoirs. It is necessary in each case to establish management goals, and compare different strategies to achieve these goals, in order to make a proper selection of the environmental management plan for a lake or reservoir. If macrophyte removal is desirable for a larger lake, one of the test scenarios should be to use fish release for removal of macrophytes. The evaluation of the text scenarios, however, should encompasses all quantitative aspects of the problem, to ensure that the expected results will be achieved.

This method is not recommended for a lake or the reservoir contaminated by toxic substances, since the fish will biomagnify the toxic substance, rendering the fish useless for human consumption.

A new, but already widely-spread nuisance is the invasion of aquatic macrophytes into areas in which they were previously not established. Two management approaches are applicable in this case; namely, a protectionist and an interventionist strategy. The former group attempts to prevent invasions, usually on the basis of legislation. However, this often does not work, since the invasions are caused only indirectly by human activities, and are not intended. The interventionist strategies remove or suppress the invaders by these discussed methods.

Table 4.6. Characteristics of fish species used for biomass removal

Characteristics	Silver carp	Grass carp	Wuchang fish
• Largest body weight	20 kg	35 kg	3 kg
• Typical mature weight	5 kg	5 kg	0.5 kg
• Feeding habits	Filter	Herbivorous	Herbivorous
• Main food (adult)	Phytoplankton algae, detritus	Aquatic macrophytes	Zooplankton with aquatic vegetation
• Water quality	Eutrophic	Clear water	Clear water
• Highest tolerated BOD_5 ($mg\ l^{-1}$)	30	15	30
• Spawning temperature	18–30°C	22–28°C	20–28°C
• Dissolved oxygen at high feeding intensity	$> 4–5\ mg\ l^{-1}$	$> 4–5\ mg\ l^{-1}$	$> 4–5\ mg\ l^{-1}$
• Dissolved oxygen at appetite loss	$1\ mg\ l^{-1}$	$1\ mg\ l^{-1}$	$1\ mg\ l^{-1}$

Aquatic vertebrates

Recent support of the proliferation of the water cow, manatee (*Halicore dugong*), in Florida is used to increase consumption of aquatic macrophytes and thus decrease the blockage of waterways. Grazing by domestic cattle also can be an efficient means of controlling macrophytes in the lake shallows. Although other aquatic vertebrates, such as water buffalo and hippopotamus also can feed intensively on aquatic vegetation, their numbers in a given location are usually not sufficient to promote and maintain significant plant destruction.

Invertebrate

Among the beetles, the most intensively studied are weevils, belonging to the family of Curculionidae. In the tropics, *Neochetina eichhorniae* and *N. brucei* are used to control floating vegetation, limiting reproduction of these plants. The weevil *Eurhynchiopsis lecontei* is native to North America and is used to control the densities of an invasive species to this region, the European milfoil, *Myriophyllum spicatum* (Creed, 1998). The application of weevils to control aquatic vegetation is reaching a commercial level in the United States. The alligator flea beetle (*Agasicles hydrophila*) also is considered a potential agent. Some naturally-reproduced Brazilian grasshoppers have been observed to destroy floating vegetation in newly-flooded reservoirs.

Other methods

Methods for chemical eradication of macrophytes and blue-green algae (see Section 4.3.8) are still fairly widely used, although their negative consequences are widely known. Many of the chemicals accumulate in the waterbodies, and are incorporated into different biotic and abiotic components of the environment (particularly predatory fish and higher vertebrates). They are potentially dangerous from the human health perspective, particularly when the water is used for drinking water supply. Some of the newer products have not yet been sufficiently tested to guarantee the proclaimed specificity in regard to their potential impacts of the health of humans and other higher organisms.

One new method for local protection of selected shoreslines, like lake beaches, against macrophyte growth is the use of new generations of highly-resistant, stable screens.

Of course, aquatic vegetation does not only have negative consequences and, therefore, its control must be considered. In small impoundments in the United States, for example, fishermen have observed a decline of predatory fish harvest due to previous overeradication of aquatic vegetation. In such cases, efforts have been made to re-introduce vegetation into such waters (Fischer et al., 1999). Motor-boating is also a cause of macrophyte vegetation disturbance, with no-wake zones being discussed as a means of vegetation protection (Asplund and Cook, 1999). Conflicts between different users groups, therefore, may be created in such situations.

4.3.5 Sediment Treatment Methods

Lake bottom sediments accumulate phosphorus over long time periods and, therefore, the phosphorus concentrations in the upper few millimeters of the sediments can be much higher than the phosphorus content of the overlying water column. This large phosphorus source is, to some degree, exchanged with the upperlying water, the net direction of the exchange depending on such things as the differences in concentrations at the water–sediment boundary. When the phosphorus concentration in the water column decreases (e.g., by decreasing the phosphorus load to a reservoir), the direction of phosphorus movement is from the sediment to the water. Because of this chemical reality, an individual waterbody may exhibit eutrophic conditions for several years after the external phosphorus load was reduced. Further, this exchange is enhanced as much as a factor of 10 when the bottom of the lake exhibits anoxic conditions in the water column. Thus, various procedures are used to decrease this exchange, including increasing the near-bottom oxygen concentration and/or by removing the upper layers of sediment and using mechanical barriers for the exchange.

Sediment removal

This method consists of removing the upper layers of the lake bottom sediments that are rich in phosphorus. Peterson (1982) reviewed different methods of sediment removal and their cost-effectiveness. Several types of dredging equipment are typically used for such purposes. The sediment has to be transported as a slurry, with an 80–90% water content, to a disposal area for dewatering. After drying and some chemical treatment, the sediment can be used as fertilizer (if it contains little or no heavy metals) or for other purposes (Fig. 4.16).

The *advantages* of the method include its relatively long-lasting effect. In Lake Trummen in Sweden, for example, the phosphorus concentration in the water dropped from a peak level as high as 900 $\mu g\ l^{-1}$ to less than 10 $\mu g\ l^{-1}$ and remained at that low level for the entire observation period extending over 9 years.[1] The *negative impacts* of the procedure

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[1] In this example, the stormwater overflow from impermeable surfaces was not managed, and the problem began to reappear after a longer period of time.

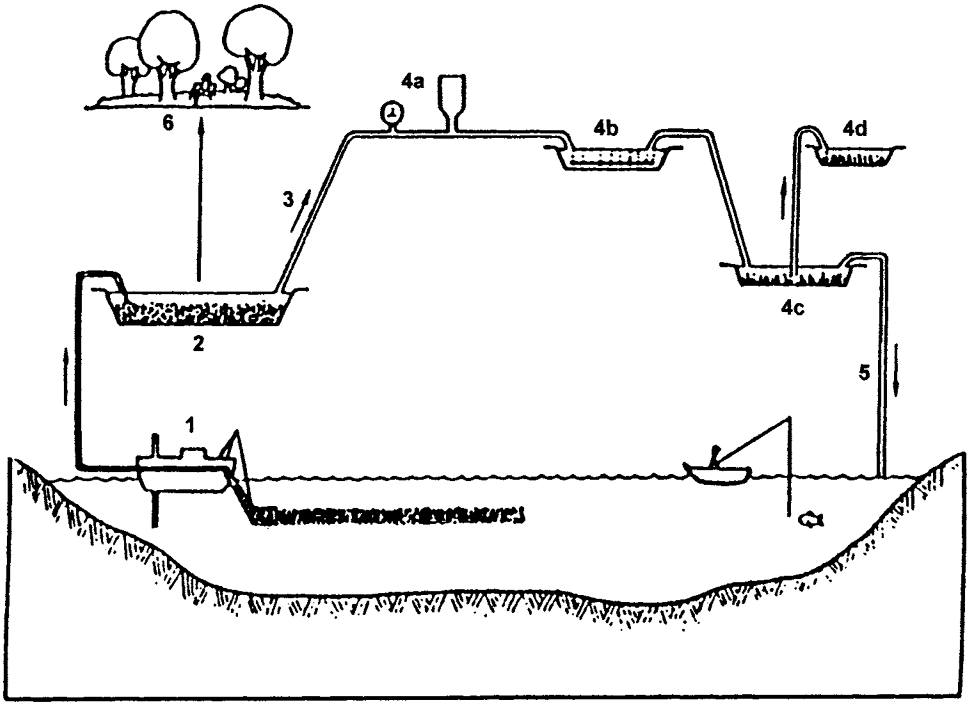

Fig. 4.16. Dredging a shallow lake for sediment removal. 1—The bottom mud suction dredger. 2—Settling pond for sediment drying. The dried material can be used for construction purposes. 3—Runoff water taken to the aluminum sulfate automatic dosing instrument 4a and its aeration basin 4b. The overlying water is returned to the lake through tube 5 (redrawn from Eiseltová, 1994).

are significant, as an extensive area is needed to store the dredged slurry before it dries out and can be used as field fertilizer. The *cost* of dredging is high, the figure given by Peterson (1981) for dredging alone amounting to between US \$0.23–15.00/m^2, and does not include disposal and transport costs. Using a mathematical model, Stefan et al. (1980) provided a means of predicting the dredging depth that will minimize internal nutrient recycling in shallow lakes.

Sediment aeration and oxidation

The *RIPLOX method* of sediment aeration and oxidation has been widely used in Scandinavia and Germany (Ripl, 1994) and focuses on decreasing phosphorus release from sediments. Ferric chloride is applied to the sediments low in iron to decrease phosphorus release. A very low pH is created in the sediment (pH = 3). Lime is then added in a quantity so as to create a pH optimal for denitrification (usually between 7.0–7.5). Calcium nitrate is subsequently injected into the top 30 cm of sediments to oxidize and break down organic matter and denitrify the sediments (Ripl, 1976, 1980, 1983) (Fig. 4.17). The

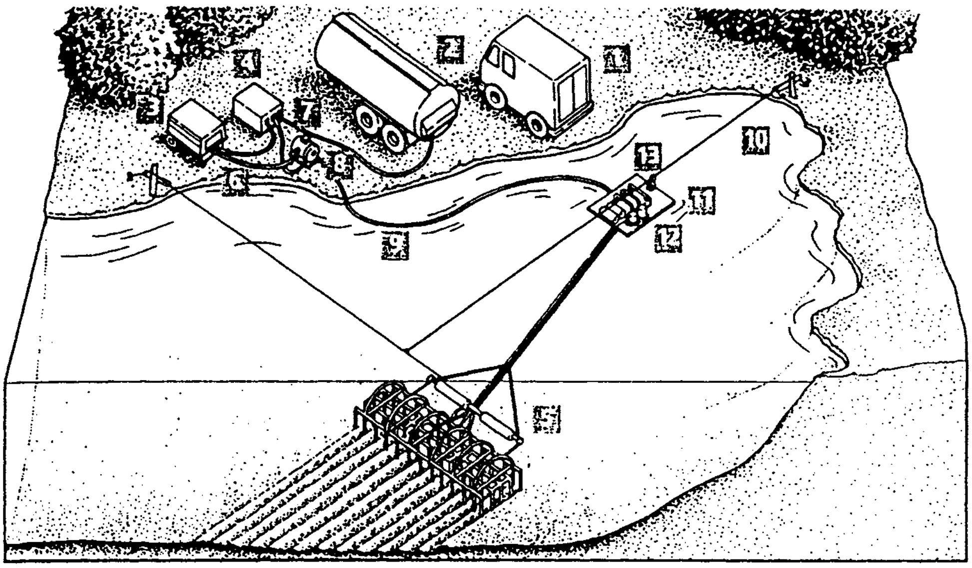

Fig. 4.17. The Ripl's RIPLOX procedure for sediment dosing with iron chloride to reduce the rate of phosphorus release. 1—Field laboratory. 2—Chemical supply tank. 3—Portable compressor for bubbling air into the chemical mixing tank. 4—Chemical mixing tank for the chemicals (calcium nitrate, ferric chloride). 5—Harrow-like device to loosen sediment with compressed air and inject chemicals. 6 and 7—Air feed lines to mixing tank and to drive pumps. 8—Air-driven pump. 9—supply line for chemicals. 10—Guide line for pulling the harrow across lake bottom. 11—Air driven dilution pump for mixing chemical with water and injecting mixture into sediment. 12—Dilution water intake. 13—Pneumatic winch (redrawn from Eiseltová, 1994).

first application of this method in Sweden was made in Lake Lillesjö, which was used for many years as a sewage recipient. As a consequence, fish kills often were observed, the lake being covered by *Lemna minor* in early spring. The oxygen concentration was close to zero for most of the year. When the sewage was diverted from the lake, the lake was treated with the RIPLOX method and the macrophytes also were harvested. After the treatment, the oxygen levels were high, the Secchi disk transparency increased, and the phosphorus concentrations decreased drastically. Recent application in an urban river arm in Vienna resulted in a significant reduction in nutrient and chlorophyll levels, a shift from Cyanobacteria to diatoms and green algae, and an increase in Secchi depth. Simultaneously, macrophyte growth became apparent (Donabaum et al., 1999). The *advantage* of this method is that the treatment is very intensive and has an immediate effect. Thus, it can be used for very degraded, shallow urban lakes of relatively small size. No large space is required, as with the previous method, and the same piece of equipment can be used in different lakes. The major *limitation* is the fact that the injection requires special equipment, which can only be used on flat and shallow bottoms. The *cost* of the first application in a small, shallow lake (e.g., area = 42,000 m^2, of which only 12,000 m^2 of bottom were treated, mean depth ~ 2 m, and a maximum depth of 4.2 m) was US $112,000 (1995 dollars), spent mostly for the development of the equipment. Not linked to any specific mixing device, the equipment can be used in most applications, thus considerably decreasing the cost. The chemicals used with this method totaled about 13,000 kg of iron-III-chloride ($FeCl_3$) (= 10,800 kg ha^{-1} treated and 3100 kg ha^{-1} of the whole lake) applied over 6 days, 4200 kg ha^{-1} of $Ca(OH)_2$ which was treated applied to the lake for 1 week, and 10,000 kg ha^{-1} of $Ca(NO_3)_2$, with a total cost of ~US $3500/ha (1995 dollars).

The Froth Tailing System is a means of extracting organic matter from sediments. It is still in the experimental phase, giving promising results, but has not yet applied under natural conditions. The technology uses micro air bubbles and lime for washing out organic matter.

Sediment capping

An alternative and cheaper technique for the goal of reducing nutrient remobilization is to cover the lake bottom sediments with foil, clay, sand or crushed bricks, or other inert materials. A review of the properties, costs and effectiveness of alternative materials is given by Cooke and Kennedy (1988). Palermo (1998) presents design considerations for capping contaminated sediments. Capping the sediment with calcite was performed in Lake Arendsee in Germany (Rönicke et al., 1998). *Cyanobacteria* blooms disappeared from the previously heavily-infected lake, periods with phosphorus concentrations below 10 mg m^{-3} were prolonged, and the mean Secchi disc transparency doubled.

4.3.6 In situ Nutrient Inactivation

Inactivation of phosphorus

This procedure consists of spreading alum (aluminum sulfate, $AlSO_4$, at present no longer recommended), sodium aluminate ($Na_2Al_2O_4$), or ferrous chloride into a lake. This forms flocculates that bind phosphorus and coagulate algal cells, which then settle to the lake bottom sediments, also sealing them from further release of phosphorus. The dense population of a mixture of dominantly green algae sedimented significantly during the first two days after the addition of alum to the water. Over a 30-day period, a sealing layer of the flocculate on the bottom was completed (Piedrahita, 1998). Experience in some countries has shown that the chemical coagulation of phosphorus in lakes is highly effective for prolonged periods up to 20 years (Cooke et al., 1993a, 1993b; Welch and Cooke, 1998). Based on comparisons of 21 applications in both polymictic and dimictic lakes by Welch and Cooke (1998), the average period of reduction ranged up to 10 years. Interference with this process occurs in shallow lakes overgrown by macrophytes, and when the external loading exceeds the phosphorus binding capacity of the flocculate. Evaluating the effects of the phosphorus reduction on overall water quality, Holz and Hoagland (1998) concluded that alum was extremely effective in controlling sediment phosphorus release rates, improving water clarity, reducing phytoplankton biomass, shifting phytoplankton species composition from Cyanobacteria dominance toward bacillariophytes and chlorophytes, increasing daphnid biomass, and increasing usable fish habitat. Keeping the water pH between a range of 6–8 is necessary to enable the formation of sedimentable flocculate and to prevent an increase in the formation of potentially toxic dissolved aluminum. Thus, the dosage and effects will depend on the initial alkalinity and pH, and this techniques does not function well in eutrophic waters with very high pH values (Francko and Heath, 1981). Although no special equipment was used in most instances (Cooke et al., 1986; Welch et al., 1988; Conover, 1988; Welch and Cooke, 1995), Quaak et al. (1993) developed a technology using heavy machinery. Recent use of this technique involves applying alum and sodium aluminate separately. The aluminium dose is maximized to create a seal preventing the release of phosphorus from the sediment, and to control aluminum toxicity by maintaining a pH range between 6–8. The total lake area can be treated or, alternatively, just the areas exhibiting hypolimnetic oxygen depletion. Kortmann et al. (1994) have withdrawn water from the hypolimnion and, after adding chemicals, returned it to the metalimnetic–hypolimnetic interface. In large reservoirs, the application may be restricted to places with the greatest phosphorus release (Barko et al., 1990; Smeltzer, 1990). For small reservoirs, the addition of the chemicals to the inflowing water proportional to flow rates proved a feasible method (Bannink and van der Vlugt, 1978).

Lake treatment with iron (Fe) or calcium (Ca), which can be considered substitutes for aluminium, did not exhibit such long-term positive effects, although shorter-term positive effect were achieved. Walker et al. (1989) increased the efficiency of iron precipitation by releasing it by means of an hypolimnetic aerator. Deppe and Benndorf (1998) reported on successful remediation of a Cyanobacteria bloom in a reservoir, using a combination of bivalent iron application for phosphate precipitation, with the simultaneous transport of hypolimnetic water rich in free carbon dioxide into the upper layers. Randall et al. (1999) experimentally observed some effects of ferric sulphate on zooplankton feeding, due to its presence as particles interfering with *Daphnia* filtration, as well as indication of some toxic effects causing a reduction of reproduction and increased mortality rates. The safe level of iron (Fe) was estimated in this case as 1.7 mg l^{-1}.

Positive results also were achieved with calcium in hard-water lakes (see next subsection on calcite precipitation).

Calculation models by Kennedy and Cooke (1982), Kennedy et al. (1987) and Rydin and Welch (1998) can be used to determine the dose of alum necessary for a given lake's pH and alkalinity values.

Advantages of this technique are becoming increasingly appreciated, particularly since the addition of chemicals, particularly iron, does not cause any side effects. No special equipment is needed. Alum treatment is long lasting, observations showing at least three years, but typically longer, positive effects (average expectation of 10 years). A corresponding decrease in chlorophyll concentrations is not always observed after one chemical application (explicable on the basis of the nonlinear relationship between phosphorus and chlorophyll; see Section 2.2.2—*Eutrophication*). No similar evaluations of the length of effects are known for iron treatment, although the effect is definitely not as long lasting as for alum. *Drawbacks* of alum application include intensive labor needs, a decrease in the water pH due to alum, and the possible appearance of toxic dissolved aluminum from an overdose and decreased pH. Aluminum in drinking water is considered a health risk

(Reiber et al., 1995), and if the application conditions are not carefully followed, negative consequences may occur.

Limitations of this procedure include its inefficiency for lakes and reservoirs with retention times under one year, and its ineffectiveness in shallow lakes overgrown by plants. For example, the effects of the application of iron chloride to a shallow Dutch lake with a water retention time of 35 days lasted only for three months (Boers et al., 1992). The method also works better in deeper lakes, due to the absence of the re-suspension and dispersion that takes place in shallower lakes. However, one lake with an average depth of 2 meters was also successfully treated. Shallow lakes overgrown with submerged vegetation do not enable the sedimentation of flocculates and the sealing of the lake bottom. The magnitude of the sulfate loading during an alum treatment may adversely interact with the iron cycle through anaerobic respiration and, therefore, decrease the phosphorus binding capacity of the sediment. Kortmann et al. (1994) suggested that the use of aluminum nitrate may retain the beneficial properties of alum, while avoiding the negative impacts of sulfate loading. The *negative impacts* of this method are minimal, although there is some uncertainty about the possible long-term accumulation of aluminium in the sediments, and its possible release in toxic form at low pH (e.g., as a consequence of acidification). For these reasons, the addition of ferrous chloride is preferred in Europe, while alum application is widespread in the United States. The *costs* are relatively low, corresponding in Sweden to about US $3000–10,000 per hectare (1994 dollars).

Schulze-Rettmer (1991) has used a method potentially applicable in waterbodies for the simultaneous chemical precipitation of ammonium and phosphate in the form of magnesium–ammonium–phosphate.

Calcite precipitation

Co-precipitation of phosphorus with calcium carbonate is known to significantly reduce the productivity of hard-water lakes (Wetzel, 1975; Rossknecht, 1980; Avnimelech, 1983; Koschel et al., 1983, 1987; Murphy and Prepas, 1990). This observation led to attempts to enhance this process by adding calcium carbonate and calcium hydroxide to waterbodies (Murphy et al., 1983, 1990; Koschel, 1990, 1997; Babin et al., 1994; Dittrich et al., 1997).

Long-term investigations of calcite precipitation in four German and Austrian hard-water lakes indicated that the trophic state affects the dynamics, quantity, deposition, co-reactions and structures of calcite in the pelagic zone of the lakes. The highest average calcite precipitation in stratified hard-water lakes were found in eutrophic lakes. Calcite precipitation increased during the eutrophication process in lakes with trophic states ranging from oligotrophic to slightly eutrophic, decreasing again in the more polluted lakes. The highest efficiency of self-purification (rise of turbidity, co-precipitation of phosphate, rise in sedimentation and deposition) was reached with an increase of calcite precipitation and a change of calcite forms (Koschel, 1997). Applications in Germany in Lake Schmaler Luzin were directed to dosing $Ca(OH)_2$ into the hypolimnion, with simultaneous hypolimnetic aeration (Koschel et al., 1998). The result was a continuous decrease of the hypolimnetic phosphorus concentration, a more than doubling of phosphorus sedimentation, and a three-quarters decrease in the mobilization of phosphorus from the sediments.

In hard-water Frisken Lake, British Columbia, which receives high phosphorus loads from the natural weathering of apatite, the addition of 0.8 tons of $Ca(OH)_2$ per hectare resulted in the removal of 80% of the chlorophyll-a and 97% of the soluble reactive phosphorus from the lake. The addition of 0.8 tons/hectare of $Ca(OH)_2$ and 0.24 tons/hectare of $CaCO_3$ to hypereutrophic hard-water Halfmoon Lake in Alberta resulted in a decrease of total phosphorus and chlorophyll-a in two successive years of 53% and 63% of the pre-treatment values, respectively (Babin et al., 1994). The sediment release in the summer during both years was 50% lower. Because of trends of increasing loading, as observed in increased total phosphorus and chlorophyll-a concentrations in nearby lakes, the authors estimated that, after correcting for this trend, the chlorophyll-a concentration decreased to 24%, and the total phosphorus concentration decreased to 54%, of the pre-treatment values. Higher winter oxygen concentrations also resulted from the treatment.

In situ nitrate elimination
Preliminary attempts to eliminate nitrate were made in reservoirs in former East Germany. This was attempted by means of (i) a lattice of straw, and (ii) the addition of natrium thiosulfate to the lake hypolimnion. Both methods were used for Zeulenroda Reservoir. The methods resulted in bacterial decomposition of nitrate to elemental nitrogen (denitrification). The maximum obtained efficiency was a reduction of the hypolimnetic nitrate concentration of 90%. Economically, the straw lattice method was advantageous, as the cost corresponded to about 40% of the cost of the natrium thiosulfate method. However, the application of natrium thiosulfate to a lake was easier. The danger of the increased liberation of phosphorus and heavy metals was noted. The use of straw also was investigated in other places (Soares and Abeliowich, 1998).

4.3.7 Methods for Correcting Acidified Lakes

Only two options are considered to be useful for correcting acidified lakes, namely liming and organic matter addition.

Liming of acidified lakes
In northern Europe, extensive liming was used to decrease the symptoms of acidification of streams and lakes. The symptoms include not only the disappearance of fish, but also toxicity to humans due to dissolution of aluminium. More details about the magnitude of this problem and methods for its solution can be obtained from Section 6.3. Liming is recommended only as an emergency method, and will not fundamentally solve the problem. Its ultimate solution lies in preventing acidification by reducing or eliminating NO_2 and NO_x atmospheric emissions at their sources.

Adding organic matter to acidified lakes
It was recently recognized that some addition of organic wastes to an acidified lake improves its condition by raising its pH, and promoting some growth of algae which represents an additional buffer (Davison et al., 1991). The degree of wastes and their desirable composition has to be estimated for each case on the basis of a simple balance calculation.

4.3.8 Other Methods

This section discusses methods that do not belong to any of the previously-defined groups. The first technique focuses on the effects of light on phytoplankton photosynthesis, and was previously mentioned briefly in connection with epilimnetic mixing. The second technique is poisoning of algae by chemicals, discussed here to provide a complete picture of alternative methods, but recommended to be avoided whenever possible.

Manipulation of the underwater light regime

The most effective preventive technique is to create conditions that do not allow algal biomass to grow. The net algal growth in a lake or reservoir is a result of two simultaneous processes, although occurring with variable intensity during the day and night. On the one hand, algal photosynthesis takes place during the day, during which organic matter is produced. On the other hand, respiration degrades the organic matter back to its mineral components. While photosynthesis depends on light, therefore occurring only in the uppermost sunlight-illuminated water layers during the day, respiration takes place in all depths and over the full 24 hours of a day. The illuminated zone discussed here is defined approximately as the depth in the waterbody to which at least 1% of the surface light penetrates, and is labeled z_{eu} (Fig. 4.18). No photosynthesis of algae is assumed to take place below z_{eu}. If the algae are mixed to depths greater than z_{eu}, they obtain less light on average because they are only within the illuminated zone for a part of the day. During the other part, they are located deeper in the waterbody, and do not photosynthesize in the dark, but only respire. The mixing depth within which the algae are intensively mixed can be calculated, for which the photosynthesis in the whole mixed water column equals respiration and there is no net growth of algal biomass. This depth is termed $z_{\mathrm{mix}}opt$.

The depth of light penetration depends on the extinction coefficient of the water, which defines which proportion of light is adsorbed in one meter of the water column. The extinction coefficient depends on the mineral and biotic particles, and the content of refractory colored organic matter, in the water. Thus, it is a unique characteristic of each waterbody (and possibly each period of time). In determining the extinction coefficient for the purposes of this discussion, the biotic particles (mainly algae, producing the so-called self-shading effect, termed ε_q) are not considered. In addition to light, algal photosynthesis also depends on temperature and the concentration and supply of nutrients. When nutrients are in abundant supply, algae will photosynthesize vigorously. It is fortunate that the minimal net algal growth described above can also be achieved in waterbodies with high nutrients. The temperature effect can be taken into account with the detailed calculation of $z_{\mathrm{mix}}opt$, by means of a mathematical model of the integral photosynthesis (integrated over mixing depth and over 24 hours). As a rough preliminary approximation for temperate summer conditions, $z_{\mathrm{mix}}opt$ can be considered to be equal to the condition of $z_{\mathrm{eu}} < z_{\mathrm{mix}}$ which is given by $z_{\mathrm{eu}}\varepsilon_q = 3.7$ (Steel, 1972). An additional manipulation might be possible by increasing the background light attenuation coefficient (ε_q), as has been suggested by Ridley and Steel (1975).

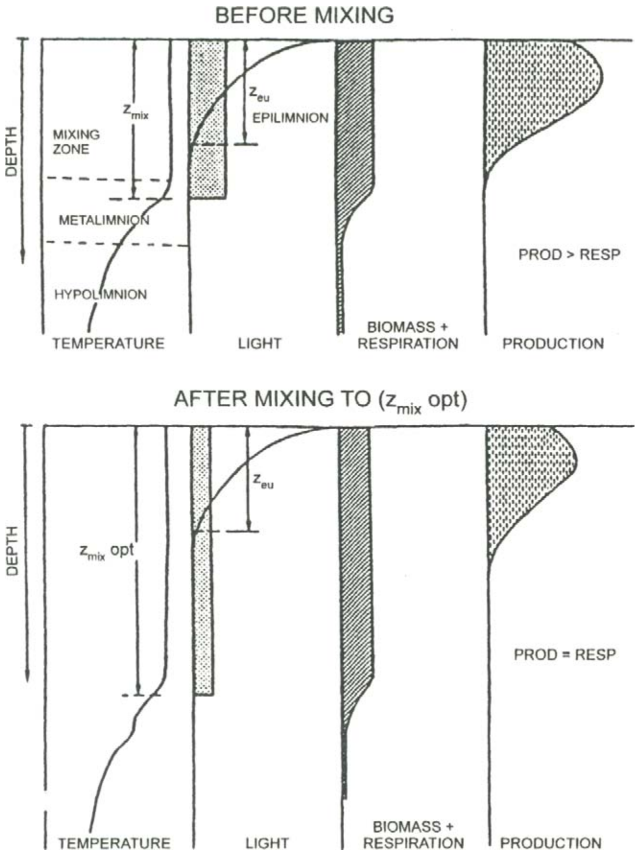

Fig. 4.18. Explanation of the functioning of epilimnetic mixing. (Orig.)

Algicid use, particularly copper poisoning

The use of algaecides is to be discouraged. The addition of algaecides (e.g., simazine, copper sulfate) has long been used as an emergency measure to control excessive algal growths, usually when they are already well advanced. The copper sulfate ($CuSO_4$) dosage varies as a function of the depth of the algal layer, with a concentration of 1–2 mg l^{-1} being desirable. The primary *advantage* of the method is that it works rapidly. The *limitations* are its high toxicity of the accumulating copper, and the short duration of its effects. In waters with an alkalinity above 150 mg l^{-1} calcium carbonate ($CaCO_3$), or with high contents of organic matter, a chelated copper form must be used or copper will be rapidly lost from solution. McGuire et al. (1984) improved this method by focusing the application early in the bloom cycle, using granular copper sulfate. Kortmann et al. (1988) increased the effectiveness and achieved cost reductions by depth-discrete application.

Laboratory investigations of six methods of chemical control of Cyanobacteria blooms producing hepatotoxic microcystin showed lime and alum treatment did not produce cell lysis and subsequent release of toxins into water, but caused cell coagulation and sedimentation without any (lime) or little (alum) increase in the toxin concentrations in the water (Lam et al., 1995). Lime, and to a lesser degree alum, appear more suitable than either algaecides or chlorine for controlling microcystin-containing Cyanobacteria blooms in drinking water.

This method is not advisable because of its *negative impacts* on the environment. Even at doses below regulatory limits, copper is toxic to fish and zooplankton. In some instances, zooplankton kills caused by algaecides result in peaks of phytoplankton after detoxification, because the algae recover faster than zooplankton. Algae in regularly treated lakes also can get adapted to copper, necessitating a continuous increase in the copper dosage. This is particularly the case in tropical conditions, where regrowth is rapid and frequent reapplication is necessary. Demayo et al. (1982) observed that some algae develop resistance to copper. Thus, its application can favor some nuisance species. The decay of dead algal or weed biomass can cause oxygen loss and nutrient regeneration, resulting in fish kills and algal blooms following chemical treatment. Its use also leads to long-term accumulation of copper in sediments, or the addition of a toxic chemical to drinking water. The side effects of 58 years of copper sulfate treatment of Fairmont Lake (Minnesota) are described by Hanson and Stefan (1984). The associated *costs* depend on the needed dosage.

4.4 INNOVATIVE AND COMBINED METHODS

This section identifies some combinations of methods that have been considered and/or used for solving water quality problems for particular lakes and reservoirs, as well as some suggested innovative experimental approaches. The general principles of the integrated water management are discussed in Chapter 7.

4.4.1 Innovative Methods

There is a number of innovative methods, particular from densely-populated countries (e.g., China, Japan), usually related to complex ecological considerations of water quality treatment.

As an example, Pu et al. (1998) have experimented with a hypertrophic, macrophyte-covered shallow bay of Taihu Lake in China, using what they call a physico-ecological engineering method. It is based on the in-lake creation of stable artificial ecosystems, in this case specifically developed water-isolated materials and filters constructed from bamboo stakes. The filters represent a physical–biological membrane, improving the water quality passing into the system from the surrounding lake to replace the water taken for drinking water supply. Filtration through two such membranes also is an option. In spite of decreased nutrient concentrations and turbidity inside the areas, certain kinds of snails appear to be efficient in further decreasing the turbidity. The low turbidity enables dense growths of submerged vegetation, which also were harvested for use. Difficulties related to plant overgrowth by filamentous algae were solved by presenting artificial substrates for growth, which were then periodically taken out. There is no indication whether or not fish also were used to control water quality inside the system.

Niwa et al. (1995) reported on four complexes of innovative measures from Japan, including fallen leaf control system, current control system, pumice filtration system, and artificial suspended reef. The current control system is intended for riverine reservoirs, and represents an elaboration of the selective discharge facility as described in Chapter 6 with artificial mixing. Pumice with an automated cleaning method is used to remove phytoplankton. The suspended "reef" is constructed to provide suitable habitat for zooplankton, fish and snails to multiply and prey on Cyanobacteria and algae before they become abundant.

A mobile plant to withdraw the high nutrient content from the hypolimnion of lakes, called PELICON (from Phosphorus ELImination CONtainer), was developed by Keil and Meyer-Jenin (1995). Hypolimnetic water is pumped into the plant, consisting of one or more floating phosphate separators supported by a containerized shore base, supplying the coagulant to form sludge that is pumped into a sludge collector.

4.4.2 Combined Methods

Because the efficiency of the management methods given in this chapter varies in different situations, there is good reason to combine different approaches. A typical, and necessary, combination is always to use both watershed and in-lake methods. The probability of getting water of good quality from very polluted lakes is extremely low, and the primary task should always be to decrease the pollution within the watershed. A combination of watershed and in-lake methods gives the best results. As an example, Wehrli and Wüest reported very successful reduction of the total phosphorus in Lakes Baldeggersee and Sempachersee in Switzerland, by combining the reduction of phosphorus loads from municipal wastewater and artificial in-lake mixing. In Baldeggersee, the reduction was from the peak annual averages of over 500 $\mu g\ l^{-1}$ in 1975 to below 100 $\mu g\ l^{-1}$ in 1994, and in Sempachersee from a maximum annual average of about 170 $\mu g\ l^{-1}$ in 1983–1985 to only 60 $\mu g\ l^{-1}$ in 1995.

Nevertheless, the success of the different in-lake methods given in Section 4.3 also depends on a number of circumstances, and good knowledge of the specific water quality situation is always necessary. Major differences exist particularly between the possibilities for shallow versus deep lakes, as outlined in Table 4.7. Thus, successful attempts also exist to combine different in-lake methods.

Stanley Lake, a drinking water reservoir near Denver, Colorado, had water quality problems arising from nutrients in local runoff, in discharges from upstream treatment plants, and within the reservoir itself. McGinnis et al. (1998) evaluated five general control strategies, including oxygenation, alum treatment, shoreline stabilization, an inflow sedimentation pond, and inflow wetland treatment. A technical and economic analysis showed that oxygenation was the most effective control strategy.

Table 4.7. Different possibilities for in-lake techniques in deep and shallow lakes (Orig.)

Management technique	Deep lakes	Shallow lakes
• Epilimnetic mixing	Useful–prevention	Conditional use
• Destratification	Conditionally useful	Use only if periodic stratification
• Hypolimnetic mixing	Useful	No use
• Layer aeration	Possible	No use
• Biomanipulation	Difficult	Successful
• Phosphorus precipitation	Expensive	Efficient
• Sediment capping	Difficult	Feasible
• Sediment dredging	Difficult	Feasible
• Selective off-takes + curtains	Useful	
• Hypolimnion siphoning	Feasible	

Lake Alte Donau, a shallow lake in Vienna, was restored by a combination of internal and external measures (Donabaum et al., 1999). Watershed measures concentrated on minimizing the nutrient load from contaminated groundwater, from stormwater, and from a large number of waterfowl. The in-lake methods used included enhanced water exchange, chemical flocculation, and nitrate oxidation of the sediments with macrophyte re-colonization and stocking with fish predators for biomanipulation. Zalewski (1999) restored shallow Polish lakes using rehabilitation of buffer zones, naturalization of river channel morphology, regulation of the flow regime of the incoming river to decrease the nutrient supply, creating wetland systems and applying a variety of biomanipulation techniques.

In addition to the selection of appropriate methods, consideration also should be given to the possibilities of zoning their application within a waterbody. As an example, recreation should be located far away from water abstraction sites, in-lake methods should be concentrated on the smaller volume of water taken for drinking water treatment, etc. One such "zoning" brought to an extreme, as developed in China, was given above in the section on innovative approaches.

The conclusion to be emphasized is that these examples should not just be followed, but should also lead to an analysis of the particular situation, taking into considerations a multitude of methods. Considerations of sustainability give clear preference to pollution prevention methods, rather than correction approaches. Mastering methods and considering the range of their possible applications has typically led to the selection of the most suitable combination of approaches, in contrast to continuing to use one or a few "well proved" methods.

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