

*Chapter 6***MANAGEMENT OF RESERVOIRS**

Knowledge of the characteristics of reservoirs (man-made lakes, artificially constructed to address beneficial human needs) is important for the water quality manager, in order to properly apply management approaches to them. In the best case, ignoring the limnological and operational differences between reservoirs and natural lakes may cause some unexpected consequences; in the worst case, it can cause significant environmental and related problems. We know more about natural lakes than we do about reservoirs and a number of features of reservoirs do not differ significantly from lakes. Thus, this chapter stresses those characteristics that distinguish reservoirs from lakes. This is not an easy task, because the multitude of specific purposes of reservoirs and their connected features makes any generalization subject to numerous restrictions that determine whether a generalization is valid. Restrictions can be made in regard to some types of reservoirs, or to some of their geographic, hydrologic, morphometric and trophic characteristics. In each case, the particular features of the given waterbody must be taken into account, thus making the rules conditional. Thus, a theoretical basis for reservoir management is clearly needed (Tundisi et al., 1999b; Kennedy, 1999).

This chapter initially classifies reservoirs with respect to their water uses (Section 6.1.1), stressing the combinations of reservoir utilization within reservoir systems (Section 6.1.2). The purpose for which a particular reservoir was constructed determines its morphometric and other features, which is reflected in its water quality (Section 6.1.3).

Reservoir water quality and limnological typology is based on a range of geographical, geological, morphometrical, flow and trophic features (Section 6.2). Section 6.3 is devoted to discussing the effects of reservoirs on outflowing rivers and the management of reservoir outflows, primarily because the manager of a reservoir must not only pay attention to the waterbody itself, but also to its outflow. Specific methods for managing reservoirs which cannot be used to manage lakes, because of their different hydraulics, are discussed in Section 6.4.

Even though the level of reservoir construction is lower now than in the past, large reservoirs are still being constructed, particularly in developing countries. Thus, the last section of this chapter is devoted to water quality considerations during the construction of new reservoirs. Problems connected with reservoir construction, and the resulting need for environmental impacts assessments (EIAs), construction guidelines with respect to water quality, and the specific processes of newly-filled reservoirs and their aging, are discussed in Section 6.5.

6.1 DIFFERENCES BETWEEN RESERVOIRS AND NATURAL LAKES

In regard to their limnology and water quality, often little distinction is made between natural and man-made lakes (reservoirs). In fact, there are many similarities between these two types of waterbodies. Nevertheless, there also are differences in their limnology and water quality, as well as in the management possibilities, between the two types. Neglecting these differences may cause impacts related to not utilizing management options specific to reservoirs. Reservoirs, particularly larger, riverine reservoirs, behave differently from lakes with regard to several aspects of water quality. Thus, it is not wise to apply knowledge gained on natural lakes to reservoirs without consideration of the specific characteristics of the latter. This distinction also is important in regard to examining lakes and reservoirs separately or comparatively, and will increase the scientific insight into the properties and characteristics of both. It is stressed that this distinction holds true, particularly for larger, deeper reservoirs.

6.1.1 Reservoir Construction Types and Uses

This section discusses the most typical types of reservoir constructions and uses. However, because there are many possible variations between reservoir types, these differences primarily hold true primarily for those defined technically as large reservoirs according to the definition of the International Commission on Large Dams (ICOLD, 1994, 1998); namely, those with a dam height of at least 15 meters and any volume of water, or those with water volumes exceeding 1 million m³ and of any dam height. Shallow, and particularly smaller, pond-like artificial waterbodies like the thousands of ancient reservoirs of Sri-Lanka, are not much different from similarly-shaped natural lakes. An example of a transition between a natural lake and a reservoir is given by what are called *impounded lakes*. For some natural lakes, the water levels are artificially raised with the construction of a dam on the outlet tributary, in order to store more water in the lake for energy generation or irrigation.

Reservoirs can be built by constructing a dam across a river valley—these are called *river valley* or *dam reservoirs*. Dam reservoirs can be further classified into two categories, *main-stem* and *tributary*, on the basis of their location either on major rivers or just on small tributaries. Main-stem reservoirs are most often used for power generation, while water supply reservoirs are most often located on tributaries. Some ancient reservoirs were built in a period of primitive engineering capabilities and, thus, it was not possible to directly dam a river. In these cases, dams were built along the river, and the artificial depression was then filled with water from the river by means of a channel. These are the *off-river reservoirs*. They have variable uses, ranging from irrigation to fish production. Above ground reservoirs, like giant tanks, were built more recently and have similar uses. Well-documented examples of the latter are the system of reservoirs used as drinking water supplies for London (Duncan, 1990) and the Biesbosch system in The Netherlands (see Section 9.5). These are earth, stone and concrete above-ground structures to which water is

pumped from the river Thames or Meuse, respectively. In agreement with the designations described by Thornton and Rast (1996), they are called *embanked reservoirs* in this section, to distinguish them from dam reservoirs with very different water quality and management characteristics (Oskam, 1983; also see Section 9.5). The management options used more commonly for this specific type of reservoir are discussed in Section 4.3.2—*Epilimnetic Mixing* and Section 4.3.5—*Underwater Light Regime*.

The most basic physical force differentiating reservoirs from lakes, and from one another, is their theoretical water retention time, RT , where $RT = V/Q$. This is a theoretical property, different from the real time that an individual water parcel stays within a reservoir. Correlated with temperature stratification, some water layers may pass through a reservoir much more rapidly than others. Calculation of RT is usually based on the average inflow and average volume of water in a reservoir. It may vary considerably, however, between years and shorter-time intervals, due to the variability of flow rates and reservoir volumes. The use of the inflow rates for the calculation of RT is based on its use for construction considerations, particularly as the basis for the projected inflow water volumes. The use of inflows to calculate RT for existing reservoirs, and shorter time intervals, is based on the assumption that the volumes of water flowing into and out of a reservoir (or being withdrawn from the reservoir and/or being evaporated) are approximately identical. During periodic imbalances between the inflow and outflow of water, the RT value may be biased.

Table 6.1 lists the most common uses of reservoirs, and some reservoir features, which are to a certain degree connected with these uses. It is clear that throughflow reservoirs are not favorable as a drinking water supply. Their quality will not be improved, compared to its river inflows, which would be the case if the water retention time is long. For navigation purposes, the retention time is of no importance. On the other hand, a large accumulation capability (i.e., long RT) is important for flood protection.

Table 6.1. Features of reservoirs constructed for various purposes (Straškraba and Tundisi, 1999)

Primary use	Size	Depth	Retention time	Outflow depth
• Flood protection and flow regulation	Small to medium	Shallow	Regionally dependent	Surface
• Water storage	Small to medium	—	Extremely variable	Below surface
• Hydroelectricity	Medium to large	Deep	Variable	Near-bottom
• Drinking water supply	Small	Preferably deep	High	Intermediate to deep
• Fish cultivation	Small	Shallow	Low	Surface
• Pump storage	Small to medium	Deep	Extreme variable	Near-bottom
• Irrigation	Small	Shallow	Long	Surface
• Navigation	Large	Deep	Short	Whole profile
• Recreation	Small	Shallow	Long	Surface

Because of water scarcity in many regions and extensions of water usage, there is a strong tendency to add other water uses to the originally-intended purpose of a reservoir, so that multipurpose reservoir use is now common. Most recent reservoirs were constructed with a multipurpose use in mind. Nevertheless, the main use is usually the dominant consideration in the selection of a reservoir site, and correspondingly in its water quantity and morphometry characteristics.

6.1.2 Reservoir Systems

In many countries, particularly those with limited water reserves in relation to water demands (e.g., Spain, Brazil, Australia), complicated reservoir systems were constructed, often with some features of unified management. Reservoir systems management is first of all dictated by water quantity concerns. Water from several reservoirs is utilized in one place and/or water from one reservoir can be directed to different destinations and uses. The most elaborate system of this type is in the southern populated area of Australia. In this area, water for irrigation and urban water supply (including the 3 million people in Adelaide) is transported over distances of several thousand kilometers, and collected by a system of reservoirs on two sides of the highest mountainous range, the Australian Alps. The water is transported between watersheds belonging to two sea regions through tunnels which act like water siphons through peaks and across valleys.

Reservoir systems can be distinguished into reservoir cascades, reservoir multisystems and pumping schemes.

Reservoir cascades (paternoster lakes)

A reservoir cascade consists of a series of reservoirs located on the same river. The situation in Spain provides an example, where there are more than 1000 reservoirs in a territory of 500,000 km² (Margalef et al., 1976). The reason to build such reservoir cascades is either because of hydroelectricity production, enabling the maximum use of the river's hydropower potential, or, in the case of water deficits, the desire to keep water in the country as long as possible for its continuing use and reuse. Detailed limnological and water quality studies exist for such systems in Spain (e.g., Margalef et al., 1976), Brazil (e.g., Tundisi, 1986; Tundisi et al., 1990, 1991, 1995), the United States (Kennedy et al., 1985) and the Czech Republic (Hrbáček, 1966; Hrbáček and Straškraba, 1973; Straškraba, 1990).

From a water quality perspective, reservoir cascades are favorable. The reason is the retention of phosphorus, organic matter and other polluting elements and components in a given reservoir, so that the next reservoir in the cascade receives less pollution than the one upstream of it, and so on. However, this successional pollution decrease along a cascade will not occur, in spite of the large retention capacity of each reservoir, if the pollutant load from secondary tributaries and shoreline sources exceeds the water retention in the reservoirs. This is happening, for example, in the Barra Bonita Reservoir of the reservoir system on the Tiete River in Brazil, São Paulo State (Padisak et al., 2001; Barbosa et al., 1999—also see Section 9.8).

Reservoir multisystems

A reservoir multisystem comprises several reservoirs located in different watersheds (or sub-watersheds) that are operated jointly for water quantity and/or water quality purposes. Because water quantity is usually the primary concern, recent introduced attempts to also manage water quality are fairly difficult. The reason is that the chemical composition and water quality characteristics of the different reservoirs within the system may be markedly different, and the transfer of water between systems also can produce unwanted characteristics and changes within the reservoirs.

Pumping schemes

These reservoirs are used to augment hydroelectricity production during periods of peak needs. The water is either pumped into a reservoir built specifically for this purpose, into an upper-lying lake or into a cascade consisting of a large reservoir upstream and a smaller one immediately downstream. During periods of lower electricity demand, the excess energy is used for pumping the water upstream. During periods of high energy demand, the water is released through turbines to produce hydropower. A daily cycle of such operations is possible. On the other hand, using these reservoirs for additional purposes (e.g., drinking water supply), along with power production, is complicated because unwanted water quality deterioration can take place in the upper storage reservoir.

Pumping schemes can be divided into those constructed as a secondary storage in combination with conventional hydroelectric generators, and those which reversibly send water up and down the same turbines.

The effects of water pumping on fish and other organisms have been discussed (e.g., see Schindler et al., 1995). Several studies have demonstrated that there is only a small negative impact of pumping on fish and fisheries (Robins and Mathur, 1976).

6.1.3 Water Quality Differences between Natural Lakes and Reservoirs

With respect to water quality, reservoirs, particularly deep, stratified ones, differ from natural lakes in a number of limnological characteristics (Wetzel, 1983, 1990; Kennedy et al., 1985; Tundisi, 1986; Søballe et al., 1992; Thornton et al., 1996; Straškraba et al., 1993; Straškraba, 1999). Although shallow and small reservoirs are much more similar to natural lakes, some differences also have been recognized and summarized by Padisak et al. (1999). This section primarily discusses the characteristics of deep reservoirs, which have considerable consequences for water quality management. The essential differences are summarized in Figure 6.1.

Pollution of reservoirs. Pollutant loads to reservoirs are usually greater than for lakes located in drainage basins with similar land uses. This is due primarily to the fact that the drainage basins of reservoirs are generally larger than those of lakes. In a sample of lakes and reservoirs in the United States, the drainage basin to waterbody area ratio for reservoirs was on average 14 times higher than for lakes. This figure may be somewhat biased, however, since there are more reservoirs and fewer lakes in the southern, drier regions of

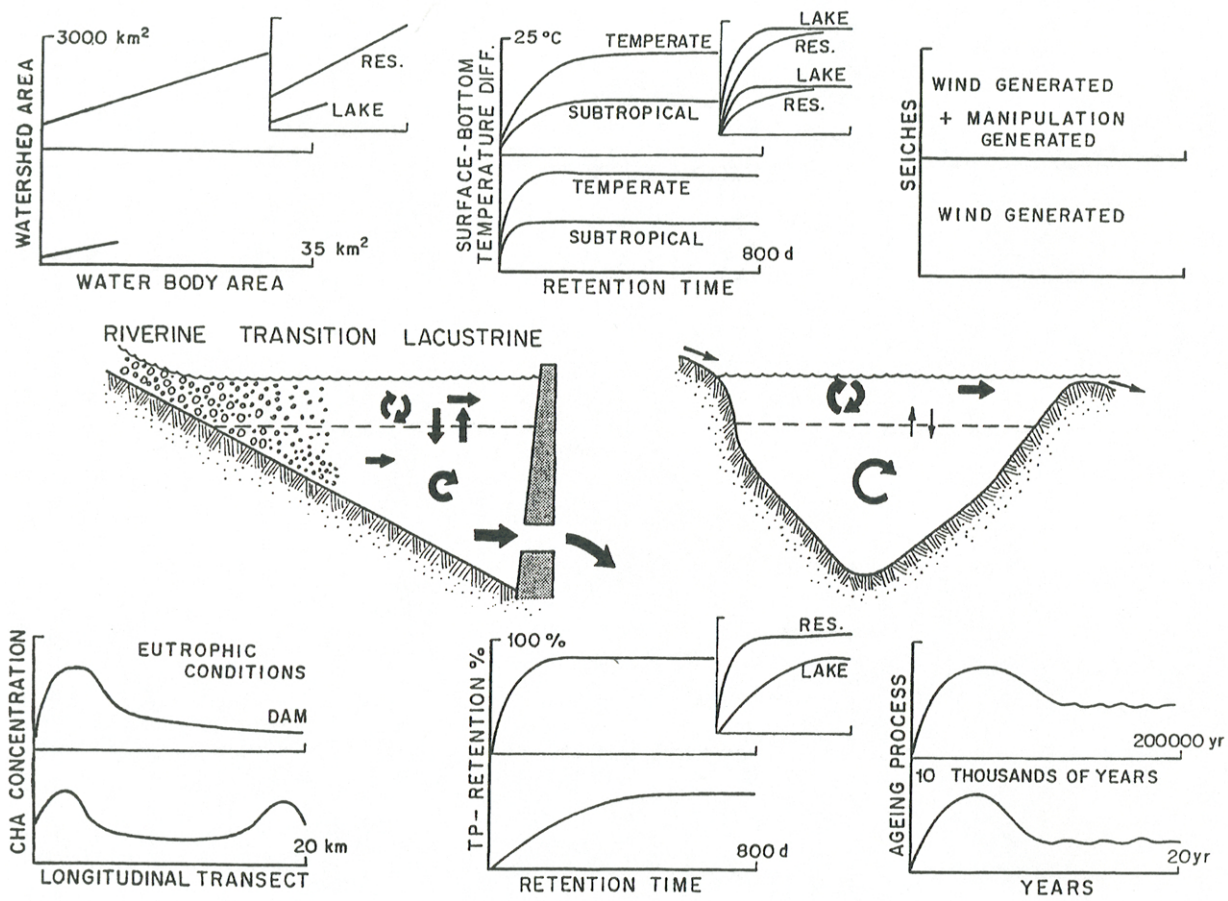


Fig. 6.1.

the United States, where larger watersheds are needed to provide water for dry periods. Nevertheless, the difference is still large. As diffuse (nonpoint) pollution enters waterbodies from each type of land use per unit land surface area, and point source pollution based on the number of inhabitants and mass-cultivated animals, and the quantities of various products made in factories, the drainage basin of a reservoir with similar land use and population densities generates more pollution because of its larger area. Thus, it would be expected that the eutrophication of a reservoir, at least of its inflowing part, should generally be higher than that of a lake. Chemical stratification also would be more pronounced in a reservoir, because the increasing sedimentation of organic matter entering it from the drainage basin or produced by phytoplankton within the reservoir due to its higher nutrient load, will be higher than for a lake. However, much depends on the land use, the pollution concentrations in the lake inflows, and the inflow rates. The consequence of increased organic matter sedimentation is increased decomposition and utilization of oxygen by microbial decomposers in the waterbody, leading to low hypolimnetic oxygen concentrations, or even the development of anoxic conditions in the waterbody. When the bottom water layer is deprived of oxygen, water treatment is typically more costly because of higher concentrations of manganese and iron, the increased occurrence of odors and smells, and the presence of hydrogen sulfide and methane. Further, phosphorus accumulated in the sediments is released at an elevated rate, causing increased algal productivity.

Stratification and mixing of reservoirs. In the same manner as for lakes, reservoir stratification is determined primarily by the reservoir's geographic location and morphometry (compare Section 1.3.2). For deep valley reservoirs, a characteristic feature is the strong dependence of limnological features like stratification and in-lake phosphorus retention on the theoretical water retention time, RT (Straškraba, 1998a, 1998b, 1999). Lakes also are affected by water flow rates; because of the generally higher inflows to reservoirs relative to their volumes, there are many more reservoirs than lakes with short water retention times, with their stratification being strongly affected by flows. Consequently, stratification conditions are much more variable in reservoirs than in lakes. Because of inter-annual variability in weather conditions, the same reservoir may only be weakly-stratified in a

Fig. 6.1. Schematic representation of the essential limnological differences between deep reservoirs and deep lakes. Reservoirs have uniformly deepening longitudinal transects with eccentric maximum depth and intensive longitudinal flows, while lakes have more central position of the maximum depth. Reservoirs also have larger watershed/waterbody areas and consequently higher throughflow (= shorter water retention times) than lakes. The degree of temperature stratification depends on geographical location and theoretical water retention time, as do the lakes. Due to the saturation character of relationship between stratification and RT shown in Figure 6.2, however, many lakes (with longer water retention times) are in the insensitive saturated region of the dependence, while reservoirs are in the sensitive region. Lakes usually have lower areal phosphorus loads and retain less phosphorus than reservoirs of similar retention times. Longitudinal transects of biologically-active variables (e.g., phosphorus, chlorophyll-a) are characterized by a peak near the inflow, while lakes have higher values along the shores (from Straškraba, 1998b).

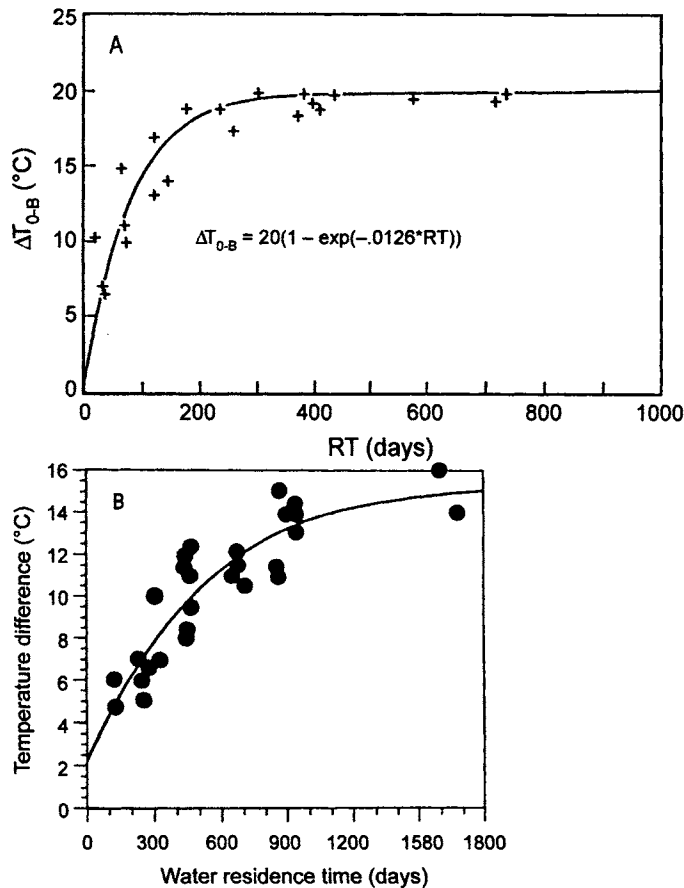


Fig. 6.2. Dependence of the degree of reservoir temperature stratification on theoretical water retention time (RT , days). The degree of stratification is expressed by a simple measure, temperature difference in the period of maximum temperatures between the surface and the hypolimnion (ΔT_{0-B} , °C). A—The relationship developed by Straškraba and Mauesberger (1988) for reservoirs in the Czech Republic and the Bavarian region in Germany; B—The same relationship for Texas Reservoirs by Groeger and Tietjen (1998).

wet year when the flows are high, and exhibit well-developed stratification in another year with drier conditions. This high sensitivity to weather conditions is another feature making reservoir management more difficult than for lakes. Thermal stratification affects a number of chemical and biological processes, and subsequently the water quality for such reservoirs. The relationship between the degree of stratification of deep reservoirs and the RT for the period of stratification is asymptotic. Reservoirs with an average RT of a few days are not stratified. The degree of stratification strongly increases with the prolongation of RT , slowly becoming independent of the retention time. Thus, there is no sharp boundary in

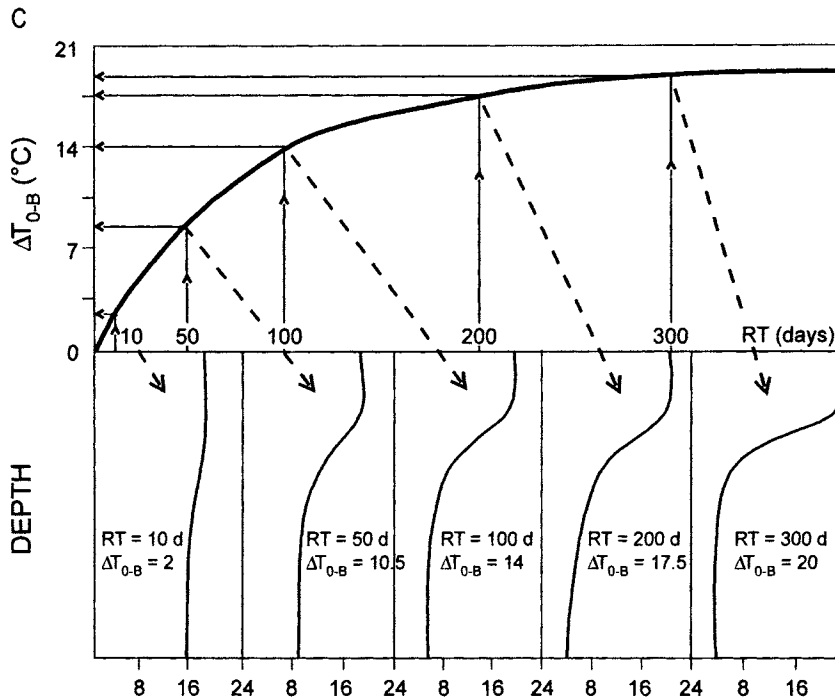


Fig. 6.2 (continued). C—The profiles at different ΔT_{0-B} ($^{\circ}\text{C}$) due to different retention times (RT) are shown.

a reservoir's RT above which no influence on stratification can be observed. Nevertheless, we can arbitrarily set the critical retention time, above which the stratification is only weakly affected by RT , at 200 days. Above this value, there is practically no effect at all, at $RT \approx 1$ year (see Fig. 6.2). Stratification of a reservoir with long-term average retention times highly exceeding the critical level of 200 days can still be conditioned by flow during extremely low water levels and high flows. On the other hand, deep, unstratified reservoirs with a retention time of only a few days may still become stratified during drought conditions, or during periods when the water throughflow is significantly reduced for flow operation. Because of variable water flows into and out of reservoirs, their temperature and chemical depth profiles are less smooth than for lakes.

A specific feature of some reservoirs is their *hydraulic stratification* (Tundisi, 1984), which is related to the separation of the deepest water layers within the waterbody, thereby not being part of the reservoir outflows and becoming more stagnant as a result. The separation of the water layers may be caused by the lower edge of the outlets, or by submerged structures such as walls build for protection of the construction site during the building phase. The influence of the outlet location is apparent in power generation reservoirs with large water throughflows (Fig. 6.3). Further, submerged weirs also can cause hydraulic stratification when the lower edge of the outlets is also deep, as is sometimes the case

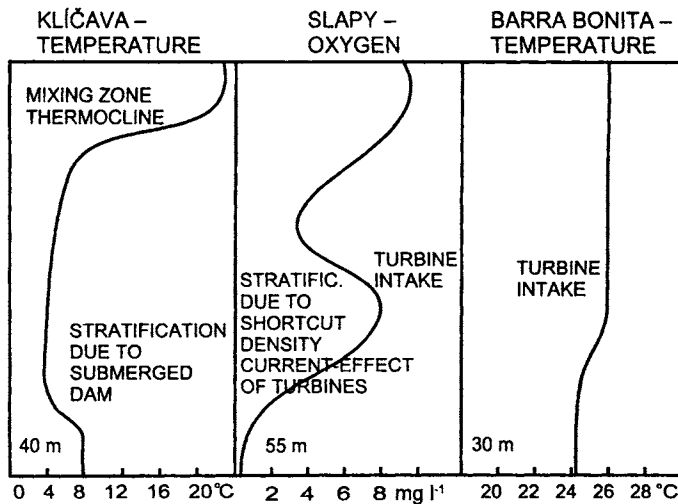


Fig. 6.3. Examples of hydraulic stratification caused by submerged weirs and location of the turbine intakes for different reservoirs.

for drinking water reservoirs. Thus, the submerged dams have to be destroyed, or at least opened sufficiently, to prevent the formation of a stagnant bottom layer of reduced water quality.

Another decisive variable for stratification, and a cause of differences between lakes and reservoirs, is the location of the water outlets. Water flows from a lake primarily from its surface water layers, whereas the outflow from reservoirs can be variable. Most reservoirs have deep outlets related to their intended beneficial use. For some reservoirs, surface outlets are constructed. During floods, the excess water can be discharged by overflows or by bottom outlets. The deep release of bottom water layers causes more admixing of surface water to deeper strata and, hence, decreased stratification.

Mixing within a reservoir depends on stratification, instantaneous water flow rates, and the shape of the reservoir. The water mixing is generally intensive, and extends over the whole depth when stratification is weak. When the temperature is high and, therefore, a density difference exists between the mixed layer and the hypolimnion, the water mixing is dominantly restricted to the upper water layer.

Longitudinal differentiation. Another typical feature of deep valley reservoirs is a longitudinal differentiation of water quality (Fig. 6.4). The main causes are changes in water flow rates and mixing along the length of the reservoir, with effects on associated physical and chemical processes. Although water moves on average down the length of a reservoir, considerable longitudinal and local biological and chemical inhomogeneities can exist (Groeger and Kimmel, 1984; Hejzlar and Straškraba, 1989; Ryding and Rast, 1989; Ground and Groeger, 1993). Locally, and at certain depths, water in the reservoir also can

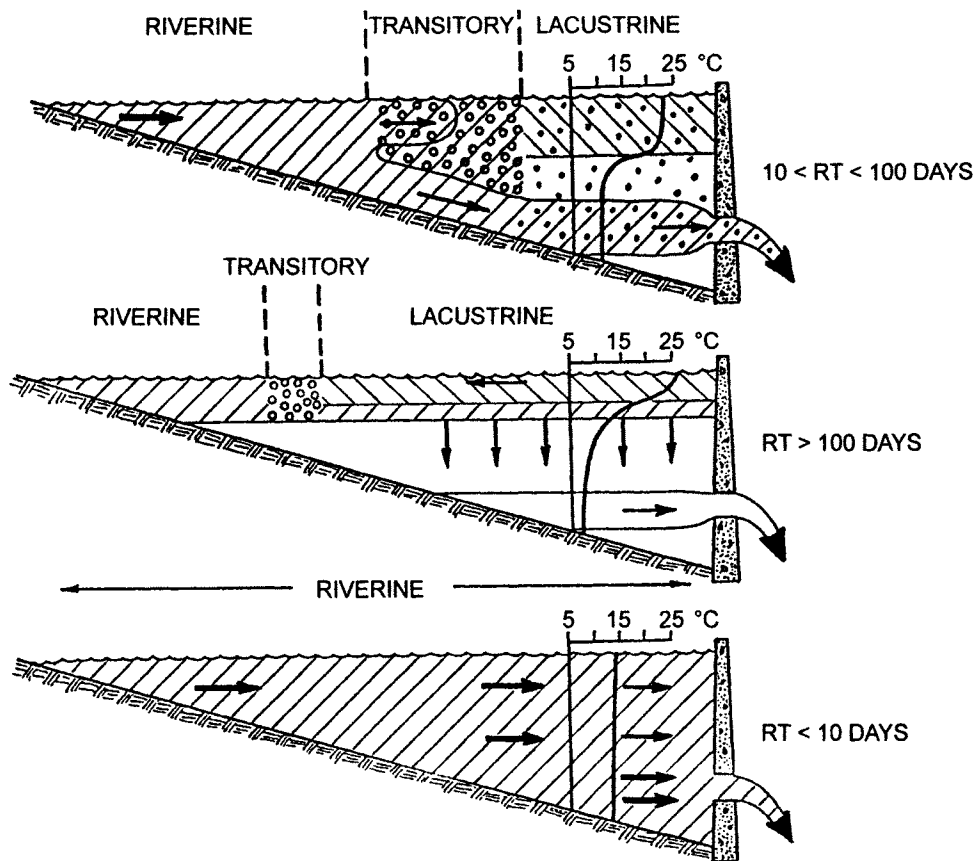


Fig. 6.4. Longitudinal differentiation of reservoirs with different theoretical water retention times. Different situations can be found not only in different reservoirs, but also in the same reservoir during different water levels and/or inflow rates. The typical three zones are the riverine inflow, the transitory zone and the lacustrine zone at the dam. The extent of the individual zones varies from domination of the riverine to domination of the lacustrine zone.

move upstream. Four major longitudinal regions of a deep valley reservoir usually can be distinguished, as follows:

- The inflow region,
- The transition region,
- The “lake-like” region,
- Coves (bays).

Such clear longitudinal differentiation, however, is only valid if a reservoir has one dominant inflow. Reservoirs receiving water from many smaller inflows may not possess such a characteristic, an example being the Tomhannock Reservoir (Melcher et al., 1997).

The inflow region is usually shallow and narrow, characterized by rapid, unidirectional water flow, with maxima near the center and close to the surface. The average length of this region is greater in reservoirs (or situations) with short average RT . The length of the region at a particular time depends on the actual flow rates and water level in the reservoir, as well as its degree of stratification. It is longer when flows are higher, water levels lower, and stratification less strongly developed.

The transition region is where the flowing river water enters the more stagnant reservoir water. It is characterized by major, and often sharp, differences in flow rates and stratification within the transition region. It is this region in which the river water, if colder than the reservoir water, plunges down to a depth of corresponding density. In its passage to a lower depth, its temperature slightly increases by mixing with the surrounding water masses. Depending on the density stratification within the reservoir, the plunged flow can continue as a bottom flow or an interflow. The sharp boundary between the two water masses also may be marked by differences in transparency: the river water may be turbid, with the reservoir water more transparent. If the density difference between the river and reservoir water is very small, or the inflow is warmer, the inflow will predominantly enter the surface layers of the reservoir.

Maximum concentrations of suspended sediments, nutrients and algae, as well as maximum sedimentation, occur in the transition zone. The sedimentation retention of reservoirs is very high, often more than 90% (Petts, 1984), and retention levels even up to 94% being observed. This characteristic limits the operational life time of reservoirs, with some of the shortest operational life times being observed for some Chinese reservoirs. As an example, the Heisong Reservoir lost 20% of its volume in 3 years, and the Sanmanxia Reservoirs 40% in 20 years. Classical estimates of the sediment filling of reservoirs were recently found in South America to be underestimates. The observed rates give up to 60 times the predicted value, with the major reason being human disturbance of soil by improper land practices (e.g., inadequate irrigation, line plantation, fires, increased flows).

The lake zone is more balanced and most stagnant, with wind effects also being stronger. Vertical stratification is most pronounced. *Coves* are typical where side streams enter a river. They may exhibit longitudinal differentiation similar to the main body of a reservoir, with modifications occurring because of density conditions and inflow composition. When water levels rise, water from the main body can enter the bays, being layered according to its instantaneous density situation and, simultaneously to a certain degree, to the mixing of inflowing and bay water.

Water level fluctuations. Water level fluctuations in many reservoirs are higher than for natural lakes. The extent of variability is related to the natural inflow variability and the purpose and operation of a reservoir. The highest variability is observed in dry regions with a high periodicity of river inflows. The water volume in summers of dry years may drop in such reservoirs to a small fraction of the full water storage volume. This property is typically known prior to the preparatory phase of reservoir construction. For each reservoir, reliable probabilistic estimates of long term changes in flow rates, utilization and release rates and corresponding water level fluctuations are made available. For deep reservoirs, high fluctuations can cause phytoplankton to become the dominant internal source of

organic matter production, which also corresponds to the conditions for reduced development of macrophytes. Water level fluctuations and associated development of macrophytes can have major impacts on the development of fish populations in reservoirs (Ploskey, 1983, 1986; Zalewski and Dobrowolski, 1994).

Phosphorus retention. From a water quality perspective, deep reservoirs have one positive feature compared to lakes; namely, they have a very high phosphorus retention capacity, R_P . They have a high phosphorus retention even with an average annual theoretical water retention time of about 10 days, with the R_P increasing to the theoretical water retention time RT of about 200–300 days (Schreiber and Rausch, 1979; Fiala and Vařata, 1982). Both the particulate and dissolved (both organic and inorganic) phosphorus is retained. Figure 6.5A illustrates the situation in Germany (based on data by Wilhelmus et al., 1978). When the RT was greater than 30 days, 70–90% of the reactive phosphorus was retained in the reservoir, whereas when the RT was less than 30 days, the total phosphorus retention dropped to less than 10%. For the shallow Lake Talquin, Turner et al. (1983) observed a decreased retention of both total phosphorus and silica during years with a low RT . A decrease in the RT from 44 to 22 days produced a drop of total phosphorus retention from 65% to only 25%.

Recent re-examination of the phosphorus retention capacity of reservoirs by Strařkraba et al. (1995), Kennedy (1999) and Strařkraba (1999) have shown that maximum retention capacity for both temperate and tropical reservoirs is on average around 80%, but can increase to above 90% in some situations. The phosphorus retention also depends highly on the areal phosphorus load, being maximum for reservoirs with very high phosphorus loads of more than about $15 \text{ g m}^{-2} \text{ yr}$. The high retention capacity is reached at relatively short retention times (Fig. 6.5). The phosphorus load of the river flowing out of a reservoir will be up to one-tenth of the load of the load in the inflowing river, unless there are also major phosphorus sources along the reservoir shoreline. The decreased phosphorus levels are considered a positive improvement of the trophic degree of the outflowing river. However, there also are instances in which the decrease was considered negative, due to its assumed effects on the decreased fish populations in the lower-lying lake (Kootenay Lake, British Columbia—according to Friedl and Wüest, in print).

In addition to phosphorus, reservoirs also can retain a fairly large quantity of organic matter and other components. Nitrogen is retained to a considerably smaller degree, much more in shallow than in deep reservoirs, and significantly only in tropical and subtropical regions. However, our knowledge of the optimal conditions for intensive nitrogen retention in different reservoirs is still limited. Silica also is retained in reservoirs, which is important for reservoirs dominated by diatoms. Armengol et al. (1999) have observed an exponential decline of many variables in Sau Reservoir in Spain, expressed as the rate of decrease of individual components along the length of this polluted reservoir in the following order: ammonia, soluble reactive phosphorus, turbidity, total phosphorus, total nitrogen, silica, alkalinity, chlorides, conductivity.

Degradation of organic substances by reservoirs. The retention of water in a reservoir causes a higher degradation of easily-decomposable organic substances, expressed as bio-

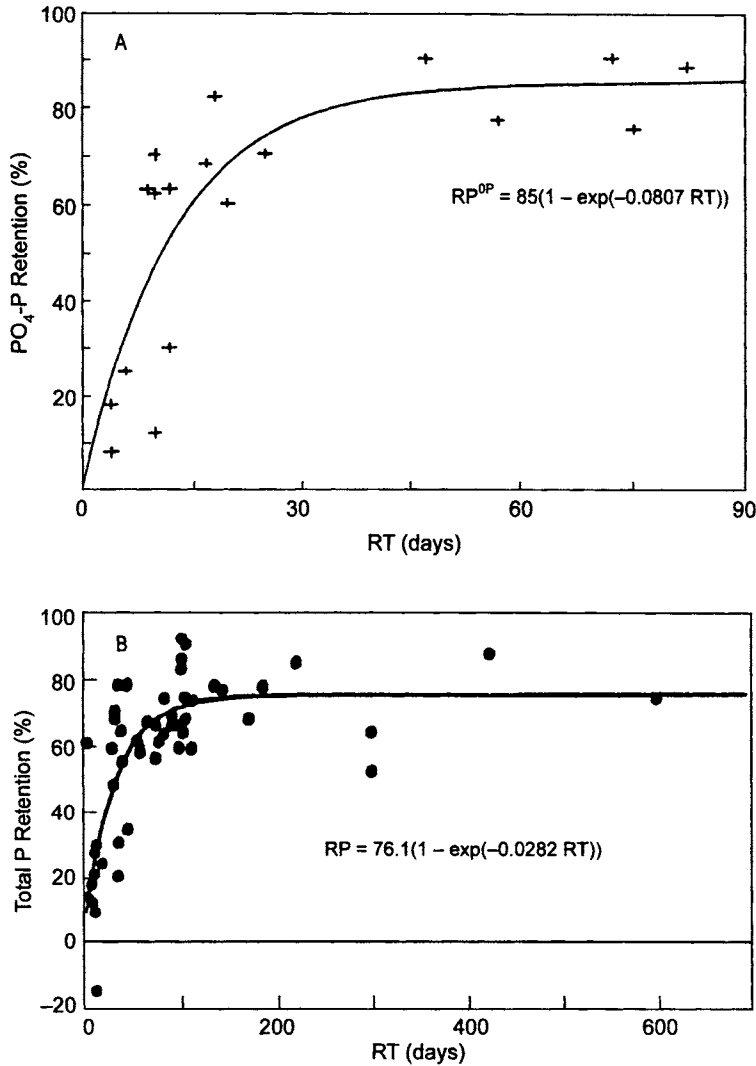


Fig. 6.5. Phosphorus retention by deep reservoirs. A—Phosphate phosphorus retention of German reservoirs; from data by Wilhelmus et al. (1978); B—Total phosphorus retention in the reservoirs of the Northern Hemisphere temperate region and dependence on the theoretical water retention time, RT (days). The reservoirs have mostly high areal loads.

chemical oxygen demand, BOD (self-purification), than in a comparable stretch of the original river. Quantitative relations of the water quality improvement from this reservoir characteristic in this direction were estimated by Straškrabová et al. (1993).

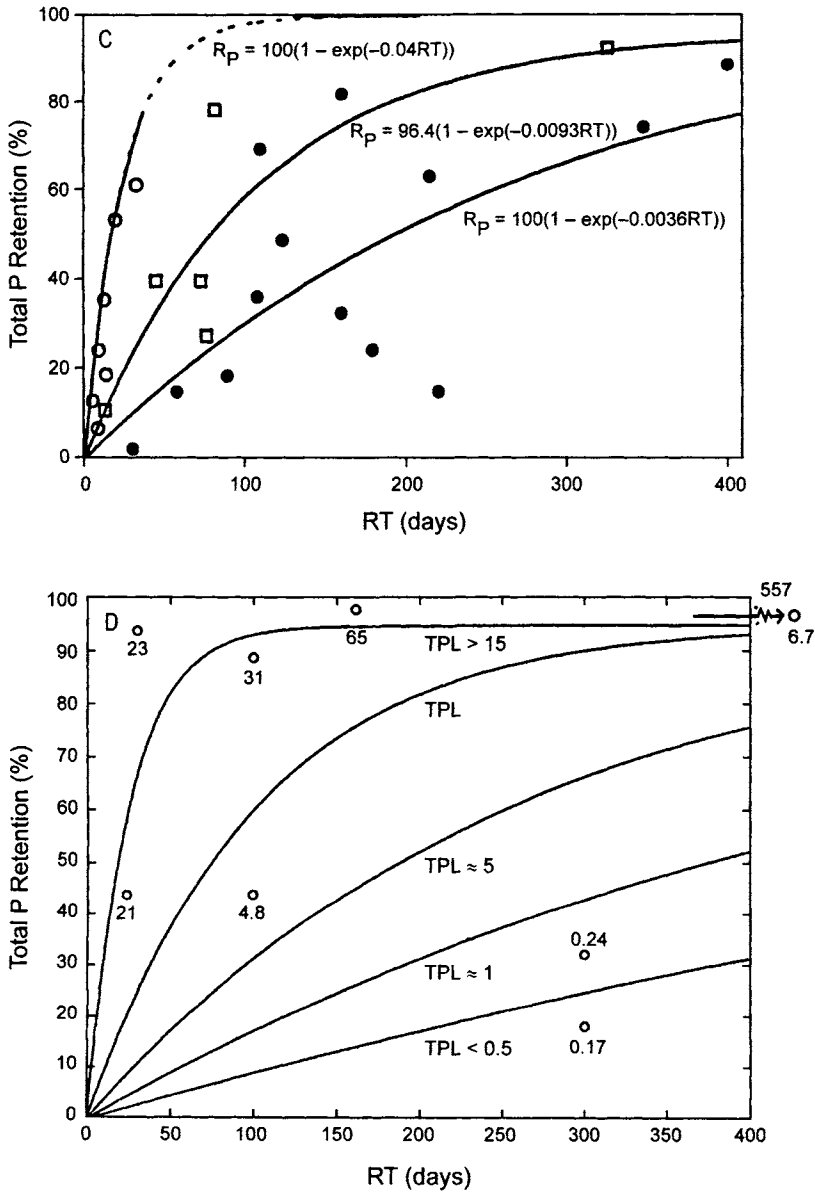


Fig. 6.5 (continued). C—Idealization of the phosphorus retention and dependence on RT and areal loads, based on data for reservoirs in the United States. The three curves are, from the highest, for areal load of 15, 10 and $5 \text{ g m}^{-2} \text{ yr}$, respectively (from Kennedy, 1999); D—Idealization for a range of areal loads and the position of data points for a few tropical Brazilian reservoirs. The tropical data suggest that, with respect to phosphorus retention, the tropical reservoirs behave in the same way as temperate ones (Straškraba, 1999).

Table 6.2. The effect of increasing water retention time on deep, stratified valley reservoirs

Variable	Reaction
Loading	Decreases
Stratification	Increases, then levels out
Surface temperature	Increases, then levels out
Bottom temperature	Decreases
Longitudinal differentiation	Increases, then decreases
Amount of sediments	Decreases
Nutrient retention	Increases, then levels out
Phytoplankton biomass	Increases, then decreases
Bottom fauna	Decreases
Trophic status	Increases, then decreases
Cyanobacteria	Increases
Hypolimnetic anoxia	Increases, then decreases
Zooplankton	Increases, then decreases
Fish biomass	Increases
Period of aging	Increases

The effects of water retention time on deep valley reservoirs, some of which were treated in more detail above, are summarized in Table 6.2. All the changes, except the decrease in load and the associated decrease in phytoplankton, are only valid below a critical *RT* of about one year. The phosphorus load decreases after this point, although at a slower rate, thereby also decreasing the phytoplankton levels in the reservoir.

6.2 DIFFERENT TYPES OF RESERVOIR WATER QUALITY

Management of reservoir water quality must take into account the specific characteristics of each waterbody, including its geographic location, water retention time, morphometry, geology and trophic and pollution status. This section points out management requirements and possibilities for reservoirs, based on these specifics. A classification of reservoirs is made, with the goal of facilitating appropriate management efforts. It must be kept in mind that, with respect to the all the variables discussed herein, there is a continuum of reservoirs, rather than a clear grouping of reservoirs into specific categories. The categorization is more or less arbitrary and transitions are common. Further, the same reservoir may belong to different categories in different years, depending on its condition.

6.2.1 Geographic Differences in Reservoir Water Quality

The geographic background for differences in reservoir water quality in different regions was described in Section 1.3.2. This section focuses on management possibilities and limitations for reservoirs in particular latitudinal and altitudinal positions. Most reservoir management methods have been developed in temperate regions. Their success in other

conditions, however, is not guaranteed, and it is necessary that we gain experience with their application in other regions.

Humid tropics

Reservoir construction is underway in many countries, and a pre-construction evaluation of the positive and negative environmental consequences with the use of environmental impact assessments (EIA, see Section 6.5.2) is very important for making correct management decisions. The water quality of tropical reservoirs (both in humid and more arid regions) is often much worse than that of temperate regions, with eutrophication far from being the only problem. Rapid economic growth can cause reservoir pollution from organic chemicals, eutrophication and toxicity to overlap, with their contribution to the total pollution being difficult to determine. Waterbodies in tropical regions are particularly prone to low oxygen conditions, with anoxic hypolimnia present in tropical regions at much lower nutrient loads than seen in temperate regions. One reason is the higher decomposition rates of organic matter in the elevated temperatures in the bottom waters. Another is the higher load of organic matter. The latter is related to the higher abiotic turbidity of many tropical rivers which, moreover, is composed of fine particles with high organic content. The character of tropical rains causes higher erosion rates for comparable precipitation levels. The consequence is that artificial mixing and oxygenation are often a more necessary and suitable management alternative, in spite of temperature differences of a degree or even less within the thermocline region. Such small temperature differences can be accompanied in tropical regions with layers of poor water quality (deoxygenation, hydrogen sulphide, methane, high ammonia, highly increased phosphorus concentrations, high quantities of iron and manganese, etc.). Thus, more elaborate mixing techniques (e.g., hypolimnetic mixing, oxygenation) are preferable.

Ecotechnological methods have a greater potential for reservoirs in tropical regions, not only because of the fewer resources available for water quality management and much lower labor costs, but also because of more active biological processes throughout the year. Suitable ecotechnological methods for reservoirs include the use of wetlands (Section 4.2.4), river shore vegetation preservation and management (Section 4.2.1), and pre-reservoirs and hydraulic regulation in reservoirs (Section 6.4.2). The application of biomanipulation (Section 4.3.1), very successful for temperate region, is still only in an experimental phase in the tropical regions, being more complicated because of more complex and local composition of fish fauna and the presence of omnivores.

One method for improving water quality in tropical reservoirs is the application of copper sulphate to kill phytoplankton blooms. Algae grow rapidly under the higher temperatures in the tropical regions, with a consequence being that the applications of copper sulphate have to be repeated several times during the year. The danger of an accumulation of toxic copper concentrations in the sediments of copper-treated waterbodies also increases significantly. Further, the rapid decay of the killed algal mass creates short-time, intensive difficulties by causing low oxygen concentrations and accompanying negative water quality changes. Finally, algae can adapt to increased copper levels, becoming progressively more insensitive to treatment. A more suitable method for preventing algal

blooms is phosphorus inactivation with in-lake alum or iron treatment. This method has not yet been widely used in tropical regions, however, so that verification of the rules for its successful application in temperate regions (Section 4.3.5) is not yet available.

Semi-arid and dry regions

Due to the character of soils and their weathering, and the character of water flow variability, a water quality problem more often encountered in reservoirs in semi-arid regions is turbidity (see Section 2.2.2—*Low Water Volume*).

The scarcity of natural lakes in semi-arid and dry regions, with evaporation exceeding precipitation, is addressed with the construction of numerous reservoirs. A negative aspect of this situation, however, is that water evaporation is increased by the formation of large areas of open water. The reservoirs in these regions are constructed so as to have large drainage basins and capacities to provide water reserves for dry periods. Large water level fluctuations create water quality difficulties, due to water quality deterioration during periods of decreased water levels. The combination of hot weather and concentrated nutrient levels provokes development of Cyanophycean water blooms with the production of toxins (Armengol et al., 1999—Spain; Naselli-Flores, 1999—Sicily).

Temperate regions

Construction of new reservoirs is becoming rare in temperate regions. Thus, problems of reservoir aging are not pressing. Wherever point source pollution is highly reduced, the dominant reservoir water quality problem is diffuse (nonpoint source) pollution. The extent of diffuse pollution can be very high, and also can be from such sources as air pollution, which is difficult to control. The overall environmental pollution is still high, and identification of its sources is difficult in many cases. Innovative, combined and integrated methods are sought and becoming successful (e.g., see the example of the Grosse Dhünn Reservoir). Wetland restoration and constructed wetlands (Section 4.2.4), pre-reservoirs, both with fixed construction or with the use of plastic curtains (Section 6.4.2—*Phosphorus Retention*), selective withdrawal, both with fixed structures and curtains (Section 6.4.2—*Selective Withdrawal*) and biomanipulation (Section 4.3.1) belong to the category of ecotechnological methods with least cost for application to the global environment. Properly-managed reservoir cascades also are capable of significantly improving water quality.

Subarctic and high mountain regions

Reservoirs are not very common in this region, although some large reservoir complexes exist in the subarctic region of northern Canada. There also are high-mountain reservoirs in the Alps and other mountain ranges. Because of the slow decomposition of organic matter and the low temperatures characteristic of these waterbodies, their oxygen levels are high. Some water quality problems may be related to elevated humic matter concentrations in tundra and forest regions. Further, faecal pollution can persist for prolonged periods in such waterbodies, even in pristine cold water.

6.2.2 Morphometric Differences

The differentiation of reservoirs into shallow and deep categories is based objectively on the effects of wind fetch (Section 3.2.1).

Hydrologically-shallow reservoirs. Reservoirs with maximum depths that do not exceed the water mixing depth are hydrologically shallow. Hydrologically-shallow reservoirs are different from deep, stratified reservoirs, being much more similar to hydrologically-shallow lakes than to deep reservoirs. Longitudinal differences are less pronounced, with wind-conditioned circulation and flows dominating if the theoretical water retention time, RT , exceeds 200 days. However, these differences are important for all shallow reservoirs. Macrophytic nearshore vegetation also is important, affected mainly by water level fluctuations. The same water level fluctuations in shallow reservoirs cause large areas of bottom sediment to be exposed. The same areal nutrient load results in higher trophic levels, the primary production being realized dominantly either as phytoplankton or macrophytes. Switching between phytoplankton and macrophyte stages depends on the water transparency and fish populations (see Section 3.2.1).

This categorization of *lake sizes* can only be arbitrary. The only objective differentiation might be waterbodies small enough that the geostrophic Coriolis force does not play a role, whereas it is important in large waterbodies. However, such delineation is difficult. Thus, a subjective categorization developed by Straškraba and Tundisi (1999) is used here (Table 6.3).

Small reservoirs are not favorable as a water supply because they are sensitive to local pollution. Successful biomanipulation is more easily achieved in small, shallow waterbodies, the main reason being that fish populations are more easily manipulated and maintained at certain levels in these types of waterbodies.

Similar to natural lakes, important water quality differences and management possibilities exist for hydrologically-shallow (unstratified) and hydrologically-deep (stratified) reservoirs (Section 3.2.1). Drinking water of good quality is more easily obtained from stratified reservoirs.

6.2.3 Classification of Deep Reservoirs on the Basis of Water Retention Time

The importance of the theoretical water retention time, RT , was delineated in Section 6.1.3. In accordance with the outlined relations, the categories of reservoirs given in Table 6.4 can be distinguished. It is stressed that the reservoirs of the first two categories are so different in their water quality conditions that the use of standard empirical relations for estimating their water quality conditions cannot be used, or have to be highly modified.

Reservoirs of the first type are often called *weirs*, and are used for navigation purposes and to enable water intake for industry. *Re-regulation reservoirs* used for nivelizing the river flow below energetic peaking operation reservoirs also belong to this type. The second group represents *main stem* reservoirs, and the last group *tributary* reservoirs (e.g., Søballe et al., 1992). It is to be remembered that, due to high flow variability, the same reservoir may belong to a different type under extreme flow or drought conditions.

Table 6.3. Size categories of lakes and reservoirs (Straškraba and Tundisi, 1999)

Category	Area (km ²)	Volume (m ³)
Large	10 ⁴ –10 ⁶	10 ¹⁰ –10 ¹¹
Medium	10 ² –10 ⁴	10 ⁸ –10 ¹⁰
Small	1–10 ²	10 ⁶ –10 ⁸
Very small	< 1	< 10 ⁶

Table 6.4. Categories of deep reservoirs, based on their long-term, average theoretical water retention time (*RT*)

Category	Retention time	Stratification
With very short retention time	$RT < 14$ days	Nonstratified
With short retention time	$15 < RT < 1$ yr	Strongly increasing with <i>RT</i>
With long retention time	$RT > 1$ yr	Fully developed, lake type, geographically conditioned

6.2.4 Classification into Hard-Water and Soft-Water Reservoirs

The distinction of hard-water and soft-water lakes and their management consequences are the same for reservoirs as for lakes (Section 3.2.2). Treatment of reservoir water containing humic materials for drinking water is difficult because bad tastes can be produced from the organic matter contained in them.

6.2.5 Oligotrophic and Eutrophic Reservoirs

Differences among reservoirs of different trophic states are the same as for natural lakes (see Section 2.2.2—*Eutrophication*, and Section 3.3.3).

Water throughflow also plays a significant role in reservoirs. When the water flow is very large (i.e., a short *RT*), full development of phytoplankton does not occur. Lakes and reservoirs with very short detention times also have lower phytoplankton biomass, as the biomass is continuously released from the reservoir in the outflowing water. The water quality of the reservoir is largely determined by the inflow, with the reservoir itself playing a dominant role in defining the quality of the outflowing water. Basic differences between the inflows, in-lake conditions and outflows of an oligotrophic and a eutrophic reservoir are summarized in Figure 6.6, along with corresponding management efforts necessary in the drainage basin, in the lake and at the outflow.

6.2.6 Degree of Pollution

The types of reservoir water pollution do not differ from that of lakes, as outlined in Section 2.2.2. The degree of pollution in reservoirs is often greater because of two reasons:

OLIGOTROPHIC			
MIXING ZONE	INFLOW P LOAD — LOW P CONC. — LOW N CONC. — LOW OM — LOW DO — LOW	RESERVOIR CHA — LOW SD — HIGH Algae — No blooms Turbid. — LOW Thermocline — DEEP Fish biomass — LOW, all kind	OUTFLOW DO — HIGH Pret. — LOW Gases — HIGH Fish biomass — LOW Use — Broad
HYPO-LIMNION		DO — HIGH H ₂ S, Mn, Fe — Sensitive fish + OM — LOW	
MANAGEMENT	CARE ON WATERSHED ACTIVITIES, WETLANDS, FOREST PRESERV., RESTRICTED AGRIC.	EXTENSIVE	NO PARTICULAR CARE NEEDED
EUTROPHIC			
MIXING ZONE	INFLOW P LOAD — HIGH P CONC. — HIGH N CONC. — HIGH OM — HIGH DO — LOW	RESERVOIR CHA — HIGH SD — LOW Algae — Blooms Turbid. — LOW Thermocline — SHALLOW Fish biomass — HIGH, non-sensitive	OUTFLOW DO — LOW Pret. — HIGH Gases — LOW Fish biomass — HIGH Use — Restricted
HYPO-LIMNION		DO — LOW H ₂ S, Mn, Fe + Sensitive fish — OM — HIGH	
MANAGEMENT	EXTREME CARE IN WATERSHED, WETLANDS, PRE-RESERVOIRS	INTENSIVE	OXYGENATION, MIXING AT DAM, DE-GASING

Fig. 6.6. Schematic water quality differences between a deep oligotrophic and deep eutrophic reservoir.

- For the same pollutant concentration in the inflowing water, the pollutant load of a reservoir is usually higher than for a lake, and is related to their relative retention times,
- The pollution concentration in the inflow to a reservoir is usually higher because of the typically larger pollutant-generating drainage basin area in relation to the area of the reservoir.

In rapidly developing tropical countries, some reservoirs simultaneously receive heavy organic pollutant and nutrient loads. Moreover, the pollution is often not only of domestic origin, but also of industrial origin, with toxic materials being produced in the latter. In this

case, the allochthonous organic matter is rapidly decomposed, resulting in poor water quality. Autochthonous organic production may be limited by toxic effects. Such waterbodies are simultaneously polluted with toxic materials and eutrophic. It is not easy, but is of great management importance, to distinguish between the two forms of pollution and their relative contributions to the water quality status of a waterbody. A sign of toxic pollution is the discrepancy between the high production potential corresponding to nutrient levels and the actual production and/or algal crops and significantly lower amounts of chlorophyll-a than expected on the basis of the potential trophic level (see Section 3.4.2).

6.3 THE EFFECTS OF RESERVOIRS ON RIVERS

A reservoir manager has a duty to take into consideration not only the reservoir itself, but also the reservoir outflows. People living downstream of a reservoir, fish populations in the downstream river and other biota should not be highly disturbed by the construction or operation of a reservoir. Two interconnected management aspects, one quantitative and one qualitative, must be considered.

In terms of river hydrology, different effects of a reservoir on the outflowing river can be distinguished, depending upon specific reservoir uses (see Table 6.5, upper part). In water supply and irrigation reservoirs, the withdrawn water is entirely lost to the downstream river reach. This results in severe water quality consequences and impacts on river biota, especially if the reduction in the river flows is great. As an example, a series of reservoirs on the Colorado River in the western United States reduced the flows in the river to such an extent that flows into Mexico are minimal and the quality of the water is poor. Flow regulation reservoirs ameliorate extreme flow regimes. Nevertheless, negative effects can occur, an example being the disastrous changes in the Nile Delta caused by the Aswan High Dam by the interruption in the continuity of sediments flows. The relation between water quantity and water quality are due to the fact that low outflows not only limit river water use, but also have negative consequences for water quality. Another important aspect is the depth from which water flows out of the reservoir. Water releases from the bottom layer of stratified reservoirs usually have the poorest water quality, compared to other water layers in the reservoir. In geographic regions with pronounced stratification, accompanied by low water temperatures, there are interferences with recreational activities along the river. The quality of the released water and its various uses also are affected by the extent of water level fluctuations. In an extreme case (e.g., the hydroelectric reservoir system with remote operation in the Snowy Mountains of the Australian Alps), it is dangerous to visit the outflowing stream when it only contains scattered puddles of water because people can be swept away without warning in a wave of released water. The physical impacts of a reservoir on the river depend on the flow reductions or increases (Table 6.5, lower part).

The limnological characteristics of reservoirs have strong influences on the degree of reservoir effects in the downstream river into which its water is released. Hydrology plays a major role, particularly in semi-arid and arid regions. The location of the reservoir on

Table 6.5. Impacts of four general uses of reservoirs on the discharges into the downstream river and details of the impacts of discharge modifications (modified from Crisp, 1994)

Reservoir type	Environmental impact				
	Modified amplitude of discharge regime	Modified seasonal pattern of discharge	Modified diel pattern of discharge	Decreased average flow	Increased average flow
Regulating	+	+	+		
Water supply	+	+		+	
Hydroelectric	+	+	+		
Water transfer	+	++	+	+	+
			+	(donor)	(recipient)
Discharge modification	Physical impact				
	Bed scour	Sediment deposition	Water velocity	Stream depth	Wetted area
Reduced flow	-	+	-	-	-
Increased flow	+	-	+	+	+
Modified flow pattern	+ or -	+ or -	+ or -	+ or -	+ or -

the river along its length determines the degree of the effects. Reservoirs on small head-water rivers have the most profound effects. Shallow, unstratified, wind-mixed reservoirs have a much less profound effect than deep, stratified reservoirs. Further, in hydrologically-shallow reservoirs, the outlet depth has little effect on downstream water quality, while that of stratified reservoirs has a significant effect. Reservoirs with water retention time of only a few days do not have much effect on the outflowing river, whereas the effect increases with increasing retention time up to some critical value, remaining constant above these critical values. Oligotrophic reservoirs have only a small effect, while eutrophic reservoirs have major effects. This multivariate character of reservoir ecosystems should be borne in mind. The listed effects following a change of one variable are only valid in comparable conditions. A deeper reservoir, for example, will have a greater effect on the outflowing river than a shallow reservoir only if it has the same water retention time. Physical, chemical and biological variables in the downstream river are affected by the reservoir in various ways. Factors listed in Table 6.6 represent gross generalizations that do not account for multivariate effects. Further details and many examples are provided by Petts (1984, 1989). The situation within a reservoir at the depth of its outflow is decisive for the quality of the water flowing into the downstream river. Mathematical models of reservoir water quality discussed in Chapter 6 can be used to attempt to predict the consequences of a reservoir on the outflowing river. Some mathematical models also enable reservoir operations that result in optimal effects on downstream aquatic resources. Additional changes can be caused by gas saturation in the dam spill gates (i.e., oxygen saturation and gaseous nitrogen supersaturation), and hydrological effects caused by instantaneous increases in the outflow volumes, such as those occurring below hydropower reservoirs.

Significant differences in the quantities of most variables mentioned in Table 6.6 exist between surface and bottom water discharges. Discharges from either level are either

Table 6.6. Downstream water quality effects (modified from Straškraba et al., 1993)

Variable	Changes in downstream water quality
<i>Physical variables</i>	
River channel structure	River channels located below dams can be substantially damaged by decreased, increased, and particularly erratic water flow rates
Hydrology	Decreased average water flow rates result when the usage of reservoir water is high (e.g., irrigation reservoirs) or when water evaporation rates are high. Periodic short-time flow variability increases and unnatural pulses are produced, with increased variability and disruption of natural hydrological cycles occurring, particularly below hydropower reservoirs. The timing of annual maxima is shifted
Thermics	A decrease in average temperature occurs. The degree of temperature decrease escalates with greater water retention time and outlet depth. Geographical distinctions: in temperate regions, temperatures below reservoirs are higher than in unaltered river systems in winter, but are lower in summer; in tropical regions, the temperatures are increased in both winter and summer. The annual temperature range is increased in surface outflow reservoirs, but decreased in deep-water outflow reservoirs. Vernal temperature rises are delayed in surface outlet reservoirs, and even further delayed in deep-water outflow reservoirs
Silt content (= turbidity)	Decreased silt loading occurs, which may cause a decrease in floodplain soil fertility, with corresponding consequences on agricultural, wetland and forest productivity
Detritus	The composition of particles changes from abiotic to biotic, and particle size decreases
Light	Light penetration is increased
<i>Chemical variables</i>	
Oxygen	If the reservoir is eutrophic, and the outlet depth is below the thermocline, the dissolved oxygen concentrations in the outflow water may drop to near-zero values
Hydrogen sulfide (H ₂ S) and carbon dioxide (CO ₂)	Concentrations increase, especially in eutrophic, stratified reservoirs with long water retention times
pH	Values decrease, except when the inflow pH is very low (e.g., in blackwater reservoirs in the Amazon drainage basin)
Nitrogen	The gaseous nitrogen content increases in aerated reservoirs to supersaturation levels that cause fish kills. This is not due to high gaseous nitrogen in the outflow depth of the reservoir, but rather related to processes that occur during aeration at the spill gates
Organic matter	Organic matter concentrations decrease downstream when there are no sources of in-lake organic production. Phytoplankton production can result in overwhelming in-lake organic matter production in highly eutrophic reservoirs receiving low organic matter input

Table 6.6 (continued)

Variable	Changes in downstream water quality
<i>Chemical variables (continued)</i>	
Phosphorus	The phosphorus concentrations decrease, and the degree of the decrease is higher when the water retention time and trophic degree are greater. An exception occurs when bottom waters are released from eutrophic reservoirs with anoxic hypolimnia. Reduced phosphorus levels result in decreased biological productivity in the outflow river
Nitrates	Nitrate concentrations are usually nearly unchanged, but sometimes may increase slightly. When strong reducing conditions exist in the reservoir, the concentration of nitrates downstream is decreased
Nitrites	Concentrations of nitrites are usually increased, particularly during deep-water releases from reservoirs of higher trophic degree
Total solids	Total solid concentrations remain nearly unchanged
Seston	The energetic value of seston is higher in reservoir outflows
<i>Biological variables</i>	
Plankton	Plankton abundance generally increases downstream
Phytoplankton composition	The phytoplankton composition changes downstream. In small rivers, there is a transition from riverine (periphytic) species to pelagic species. In large rivers, the number of lacustrine species increases below a reservoir
Phytoplankton production	Specific phytoplankton production (per unit mass of phytoplankton) can be extremely high if hypolimnetic phytoplankton enriched with chlorophyll-a are released to the river and reach high light conditions
Phytoplankton biomass and chlorophyll-a	The quantities depend on the location of the outflow: Surface outflows deliver more phytoplankton, whereas hypolimnetic releases reduce the transport of phytoplankton biomass. Phytoplankton from the hypolimnion have higher chlorophyll-a content
Zooplankton	A small river below a reservoir is highly enriched in zooplankton. In a large river below a reservoir, a transition from potamoplanktonic composition to pelagic composition takes place. Zooplankton biomass usually increases in the outflow, compared to the inflow due to flushing from the lake
Benthos	Increases below slightly eutrophic reservoirs, and usually decreases below highly eutrophic reservoirs in relation to anoxia. Composition is usually highly changed. Detrimental effects of short-term water level fluctuations on benthos are high
Fish	Reservoirs represent a barrier to fish migration, and the spawning waters often cannot be reached. Feeding habits are often reduced. Fish abundance below reservoirs vary greatly, based on the specific conditions. Changes can include fish kills due to gaseous nitrogen supersaturation, declines in fisheries, and improved oxygen and feeding conditions in some situations

constant for each reservoir, or variable according to the hydrologic conditions and reservoir operation. Examples of differences between surface and bottom outlets are given in Table 6.7. As can be seen, on the average and for similar sets of variables, the epilimnetic releases result mostly in reduced concentrations, compared to the hypolimnetic releases from the same reservoir. The hypolimnetic releases lead to an increase of concentrations, compared to epilimnetic releases, particularly in eutrophic reservoirs. Such increases are greater in reservoirs with longer retention times. An exception is represented by algae, with their outflow to the downstream river being higher during epilimnetic releases.

Chemical changes in the downstream river below a reservoir are highly affected by the process of reservoir aging. Phosphorus can leave a reservoir for a number of years after its filling, instead of exhibiting decreased concentrations (Section 6.1.3—*Phosphorus Retention*). As an example, Grimard and Jones (1982) estimated an increase of phosphorus concentration from 5 to 22 $\mu\text{g l}^{-1}$ in LaGrande-2 Reservoir. Inorganic nitrogen also was reported to increase by more than 50% during the aging period of a few shallow large Volga reservoirs (Pirozhnikov, 1984).

The biological consequences of large reservoirs in affecting the nature of downstream rivers are great. If the reservoir causes a reduction in the maximal flows and scouring effects, increased macrophyte growth can occur downstream. Below the reservoir, complete disruption of the river ecosystem is often observed, and can result in fish kills and impoverishment of fish populations. Deterioration of the drinking water supply and loss of high value recreational sites also can occur. However, there also can be positive effects, such as when the outflow from deep reservoirs improves water quality in a polluted river to such an extent that trout or similar sensitive fish species are able to survive. Because reservoirs

Table 6.7. Chemical changes below an epilimnetic release reservoir (Cow Green Reservoir on River Tees, United Kingdom) and from two bottom release reservoirs with different average theoretical water retention times (Vir Reservoir, Czech Republic, $RT = 100$ days; Slapy Reservoir, $RT = 38$ days). The inflow value in concentration in mg l^{-1} and the outflow value in percent of the inflow. Data from Petts (1986) according to Holmes and Whiton (Cow Green), according to Penáz et al. (1968) (Vir), and data from Hrbáček and Straškraba (1973) (Slapy Reservoir)

	Epilimnetic release		Hypolimnetic release			
	River Tees		Slapy Reservoir		Vir Reservoir	
	Inflow	Outflow	Inflow	Outflow	Inflow	Outflow
Sodium	3.6	72			6.4	178
Potassium	1.01	51			3.7	168
Magnesium	2.03	37	4.4	100	1.8	233
Calcium	36.3	24	16.4	95	12.3	162
Sulfate—S	5.2	78			19.4	160
Nitrate—N	0.13	154	0.83	111	5.5	127
Ammonia—N	0.02	200	136	163	0.3	100
Phosphate—P	0.025	121	0.052	81	0.18	78
<i>Average (except for phosphorus)</i>		98		137		171

function as settling and biological oxidation basins and phosphorus traps (Section 6.1.3), a significant improvement in outflow water quality typically occurs.

The extent of the river length affected by the reservoir, and the point at which conditions in the river return to normal for an undamped river, is defined by the *reset distance* (Ward et al., 1984). This distance can vary considerably, and is determined by the reservoir position in the drainage basin, the geography of the area and other variables. Inflows that enter the river below a reservoir also are important. For example, below Balbina Reservoir (Brazil), deoxygenated waters persist in the downstream river for as far as 20 km from the reservoir outflow. The Eildon Dam outflow modifies conditions in its downstream river for 138 km, and the temperature effect below Hume Reservoir (both in Australia) ceases only after 200 km in the downstream river. The effect of large reservoirs can extend as far as river deltas, and result in the loss of estuary ecosystems, reduction of fishery habitats, and saltwater intrusion into delta farmlands.

Fish kills take place below reservoirs when anoxic hypolimnetic water is released. Reservoirs also often hinder natural fish migration, leading to serious impoverishment of fish fauna. The construction of fish passes in dams is a delicate issue, and many fish ladders constructed for this purpose do not function properly. Further, in many cases, fish passes were not constructed at all.

6.4 MANAGEMENT OF RESERVOIR WATER QUALITY

The dual goal of reservoir management is to ensure sufficient quantities of water of acceptable quality. Good water quality is of prime importance for drinking water supply reservoirs, but human life requires good quality water in most instances. In fact, water from most reservoirs is used for many purposes, both directly and indirectly.

The following four basic options for managing water quality in a reservoir and/or its outflowing or withdrawn water are currently in use, with some being common for both natural and man-made lakes:

- Management of the water quality in the reservoir drainage basin,
- Management options applied in the reservoir itself,
- Use of selective offtakes to withdraw water of the best possible quality,
- Use of additional means to improve the gas conditions of outflow water.

The decision regarding which option to use in a given situation requires consideration of the feasibility of the options, estimation of the probable effects, and estimates of the costs and needed manpower. Some recent mathematical models belonging to the category of specific reservoir models (e.g., Davis et al., 1987a, or Fontane et al., 1981, for selecting best layers, or Grimard and Jones, 1982, for estimating the reservoir aging process), multiparameter optimization models (e.g., Kalceva et al., 1982) or to the category of decision support systems, *DSS* (e.g., Davis et al., 1987b; Davis et al., 1991) can be helpful. Further details are provided in Chapter 5.

6.4.1 Management of Water Quality within the Reservoir and Its Drainage Basin

Simultaneous management of the water quality of both an entire reservoir drainage basin and the reservoir itself is the best option for achieving high quality in a reservoir and its outflowing water. General methods for achieving this goal were provided in Chapter 4.

6.4.2 Management Approaches Specific to Reservoirs

In addition to the common methods of water quality management, previously discussed in Chapter 4, there also are a number of methods specific to reservoirs. These methods include the possibility of manipulating the hydrological conditions of a reservoir by selective water withdrawal, the Wahnbach method of phosphorus precipitation at the reservoir entrance, the use of pre-impoundments, methods of managing reservoir outflows, and methods utilizing reservoir systems.

Selective withdrawal (hydraulic regulation)

Use of selective offtakes. Selective water offtakes use an outflow depth or depths that allow utilization of the water of the best quality in a reservoir. This is particularly important in offtakes for drinking water treatment plants, but also important for river outflow considerations. The use of selective offtakes in reservoir water quality management has important consequences for reservoir outflows. However, it must be noted that any change of the outflow depth has consequences for the quality of the water at that depth. The outflowing water is replaced by water from surrounding strata, and usually results in differing water quality. Thus, the dynamic nature of water quality must be acknowledged and respected. The use of reservoir water quality models that address hydrodynamic conditions (Chapter 5) offers considerable help in attaining this goal.

The use of selective offtakes is a fairly recent practice since water quality and environmental problems were not considered during the construction of most existing reservoirs. McMahon and Findlayson (1995) pointed out the high costs incurred when selective offtakes must be constructed in existing reservoirs for environmental reasons. For example, they estimated that the cost of one recently-constructed new outlet in the Upper Yarra Dam in Australia was US \$10 million. However, the method outlined below, using plastic curtains, offers a less expensive substitute. Reports of successful uses of selective offtakes for water quality management (Christenson et al., 1996), and for problems with downstream water quality (Yogo et al., 1997) suggest that the use of mathematical models for optimal performance is useful (Fontane et al., 1981; Edelshtein and Puklakov, 1996).

Hydraulic regulation that selects the best time and depth of the water outflow is the cheapest option for improving water quality. This is a good method, provided the limnological situation of the reservoir is known beforehand. A simple, but rarely adopted, precaution is to ensure at the planning stage that the reservoir possesses a multiple outlet structure with the outlets spaced vertically at about 5 meter intervals. A minimum provision would be a surface and a bottom possibility of water discharge. A better control is afforded by reservoirs with multiple offtake horizons, so that water of good quality can always be

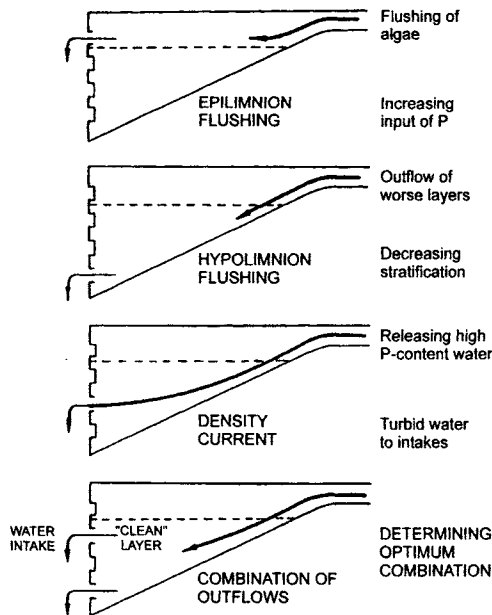


Fig. 6.7. The use of selective offtakes for managing reservoir water quality by hydraulic regulation. In each case, some positive (upper row) and some negative effects take place. The management must be directed to domination of the positive effects. A hydrodynamic model may help to decide the best conditions for improving the situation.

withdrawn by selecting the appropriate outlet depth in relation to thermal stratification (Fig. 6.7).

The following options are possible with the use of multiple offtakes:

- Removal of excess algae by using near-surface outlets,
- Removal of near-bottom water layers with deteriorated quality by using deep outlets,
- Using short-cut currents (undercurrents) for rapid passage of the inflow water peaks with the worst water quality,
- Selecting the layer of best quality water for intakes to the drinking water treatment plant.

Any of these options has both positive and negative effects on water quality. Using the *near-surface outlets* (the first bullet above), the excess algae can be flushed out, as demonstrated for Slapy Reservoir (Javornický and Komárková, 1973). However, the phosphorus input is increased by directing all inflow water to the surface layers, thereby increasing the algal production rate. The retention time of the surface layers must be less than 10 days to allow significant flushing of algae. The flushing rate has to more than compensate for the increased algal growth rate.

When attempting to dilute or remove the worse hypolimnetic water layers by a *near-bottom outlet*, a negative impact is produced by decreasing the stratification. Higher flow rates of deep water layers can create shear stress, causing more water mixing with the

upper layers. In addition to releasing anoxic waters, another positive effect is to increase the oxygen content, which will decrease sulfide accumulation (and toxicity effects), raise the redox potential and enhance microbial processes.

In creating short-cut currents, the rapid passage of the inflowing water through the reservoir can be used to get rid of pollution spikes. The spring floods often represent the dominant phosphorus input, and the probability of high summer algal crops and hypolimnetic anoxia decreases if these floodwaters pass rapidly through the reservoir without being extensively mixed with other water strata. In a similar manner, an accidental spill of toxic, radioactive or other water degrading substance can pass rapidly through a reservoir without much interference or in-reservoir mixing. However, this also does not necessarily occur without a negative side effect. Turbid water reaching the layer used for drinking water offtake during the phosphorus flushing, for example, increases the need for chemicals at the water treatment plant. Thus, it is necessary to determine in each particular situation whether the positive or negative consequences will prevail. The best means available to help in this decision is a good hydrodynamic model (Chapter 5). Hypolimnetic releases in reservoirs must be tested before they are done, by calculating the nutrient budget prior to and after possible releases. The numerical model SELECT (Davis et al., 1987a) is capable of simulating the withdrawal limits of the various proposed applications of the withdrawal approach. It is possible to determine the maximum possible flow rate under a given stratification, in order to minimize the release of epilimnetic water.

For the selection of the best water layer, automation of monitoring water quality parameters (depth profiles of temperature, dissolved oxygen and water transparency) is provided by the "clear layer" equipment of Pařízek (1984). The procedure is based on the observation that the most transparent water layer typically contains the best quality water, with the lowest concentrations of organic substances. Automatic determination of the most transparent layer drives the selection of the best layer for a drinking water treatment plant. Nevertheless, it is best to determine whether or not the assumption that the most transparent water layer contains the lower content of organic substances holds true. A considerable saving on chemicals used for drinking water treatment can be achieved in this way.

The *advantage* of the method is its *cost*, which is nearly zero. There are some *limitations*, including the need for good knowledge of the inflow water quality and its depth distribution within the reservoir. Moreover, the knowledge of changes in water quality under the effects of changing the outlet or offtake depth is helpful. Possible strong *negative impacts* on the downstream users also must be considered.

Curtains. When multiple outlets structures are not available, it is still possible in some instances to use plastic curtains. The use of plastic curtains was recently shown to be a successful method for modifying the outflow depth (e.g., Asaeda et al., 1996). However, the depth selection is more limited than with multiple outlets. Creation of a near-surface and near-bottom outlet can be realized by a curtain of a corresponding height anchored at the bottom and lifted by floats. Another way is to anchor a curtain at a certain height above the bottom and float it up to the surface (Fig. 6.8). Outlets from intermediate depths need more elaborate arrangement. Considerable leaking around the edges and bottom must be taken

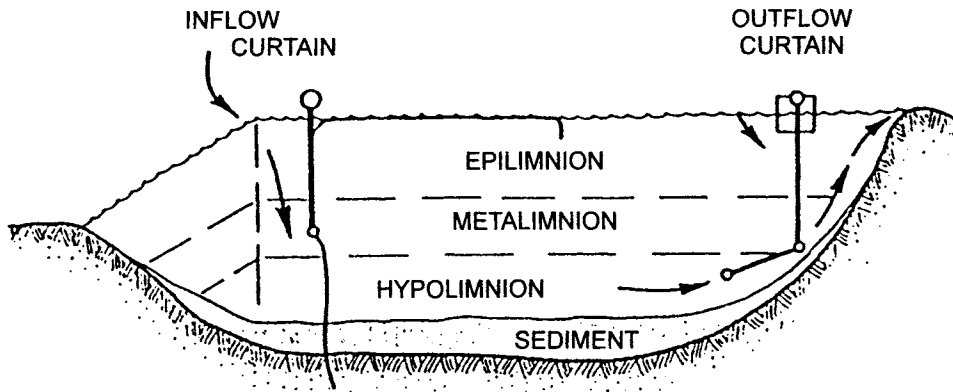


Fig. 6.8. The use of plastic curtains as a partial substitute for water quality management by hydraulic regulation (from Aseada et al., 1996).

into account. Because the pressure exerted on the curtains from internal water movements is enormous, the curtain material must be of high quality and strong enough to endure it.

Curtains also have been used in a few instances at the inflow to direct the water flow to the hypolimnion or epilimnion, respectively. Considerable mixing with the reservoir water is created as the water passing through the curtain submerges or rises according to the density differences.

Phosphorus retention by pre-impoundments

As shown above, reservoirs can trap both total and orthophosphate phosphorus efficiently through particle sedimentation, and algal uptake of the dissolved nutrient followed by algal sedimentation. This phosphorus retention capacity can play an important role when using this feature of reservoirs to decrease the phosphorus concentrations with the use of small reservoirs (called pre-impoundments) located at the inflows of the main reservoir. The design of a pre-impoundment is illustrated in Figure 6.9. The reservoir must be deep enough to enable intensive sedimentation of the inflow particles as well as the algae produced in it. In the optimal design, a sill enables the sedimentation of inflow particles to be concentrated in the narrow inflow part, with a baffle helping to the steady water flow through it.

This feature was recognized by a group of limnologists from Dresden, Germany (Uhlmann et al., 1971; Uhlmann and Benndorf, 1980; Benndorf, 1973; Benndorf et al., 1975; Pütz, 1995; Pütz and Benndorf, 1998), who developed a calculation method for sizing such pre-reservoirs for the maximum retention capability. The calculation method is outlined in Figure 6.10. The phosphorus removal rate increases with the average water retention time, as seen in Figure 6.11 for reactive phosphorus (OP) and total phosphorus (TP). The figure also indicates a good agreement between phosphorus removal predictions and observations for 11 pre-impoundments in Germany. In temperate regions, there is a *seasonal* trend in the elimination rate due to changing phytoplankton development, and this

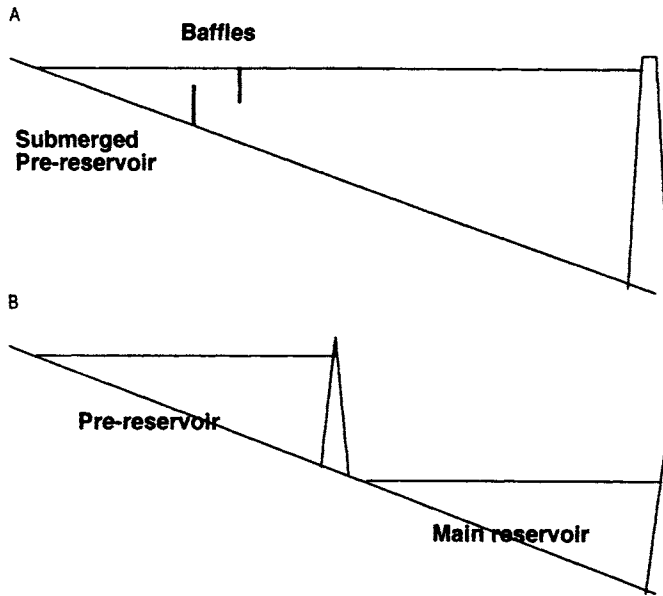


Fig. 6.9. Design of pre-impoundments (= pre-reservoirs). A—Submerged pre-impoundment with baffle. During the low water stage in the reservoir, the pre-reservoir functions as in B; B—Standard pre-impoundment build on inflowing streams.

trend is also well described by the calculation model. Long-term observations of phosphorus removal efficiency for another German reservoir are presented in Figure 6.12.

Paul et al. (1998) increased the phosphorus retention of the Saidenbach Reservoir in Germany with a submerged, overflow flexible curtain across the mouth of the inflow. The curtain was a cost-effective substitute for conventional pre-impoundments, causing a 30–40% increase in the soluble phosphorus retention.

Water level operation

Due to reservoir outflows that can be manipulated, water level operations, with positive effects on reducing macrophyte vegetation and decreasing organic matter in the drying shore sediments (Section 4.3.3), are more easily performed in reservoirs than in lakes. Further, the manipulation of fish reproduction by a decline in the water level at the time of laying eggs among shore vegetation is possible.

However, negative effects also can be created by the water level drawdown. As the newly-exposed sediments release water, air bubbles can escape from the supersaturated pore water and the sediment may become unstable and cause slumps. The larger the water drawdown, and the steeper the reservoir sides, the more frequent slumps may occur. Slumps have comparable effects in regard to extreme flood events, in that they can cause relocation of sediments into deeper water strata, cause turbid water layers unsuitable for treatment, and cover bottom-living organisms, destroying some of them.

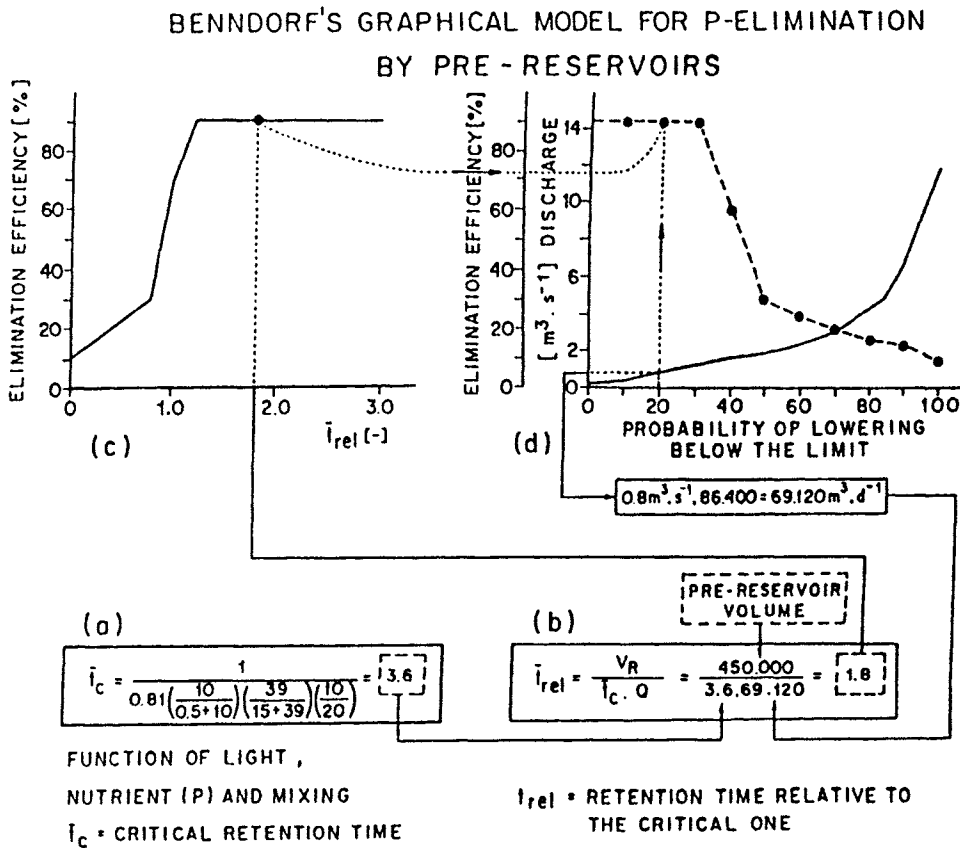


Fig. 6.10. Graphical model for the calculation of pre-reservoir efficiency. The model can be used for sizing the pre-reservoir at a stream with a given flow, for the given size of the pre-reservoir, or for estimating pre-reservoir functioning during different flow, phosphorus concentration and solar radiation conditions. For the calculation of the critical retention time (at which maximum efficiency is retained), the first bracket is for the effect of the phosphorus concentration, the second for the effect of radiation, and the last for the effect of the depth relative to the optimum depth (z_{max}) of 10 meters. In the expression for phosphorus, the two higher values represent the measured phosphorus concentrations, and the low value the half saturation constant of phytoplankton growth for phosphorus. The middle term gives average values of solar radiation during the period of calculation and the corresponding half saturation constant for phytoplankton growth (from Benndorf, 1973).

6.4.3 Management of Reservoir Outflows

The goal of management of reservoir outflows is to maintain sufficient water quantity and quality conditions for downstream use and aquatic life.

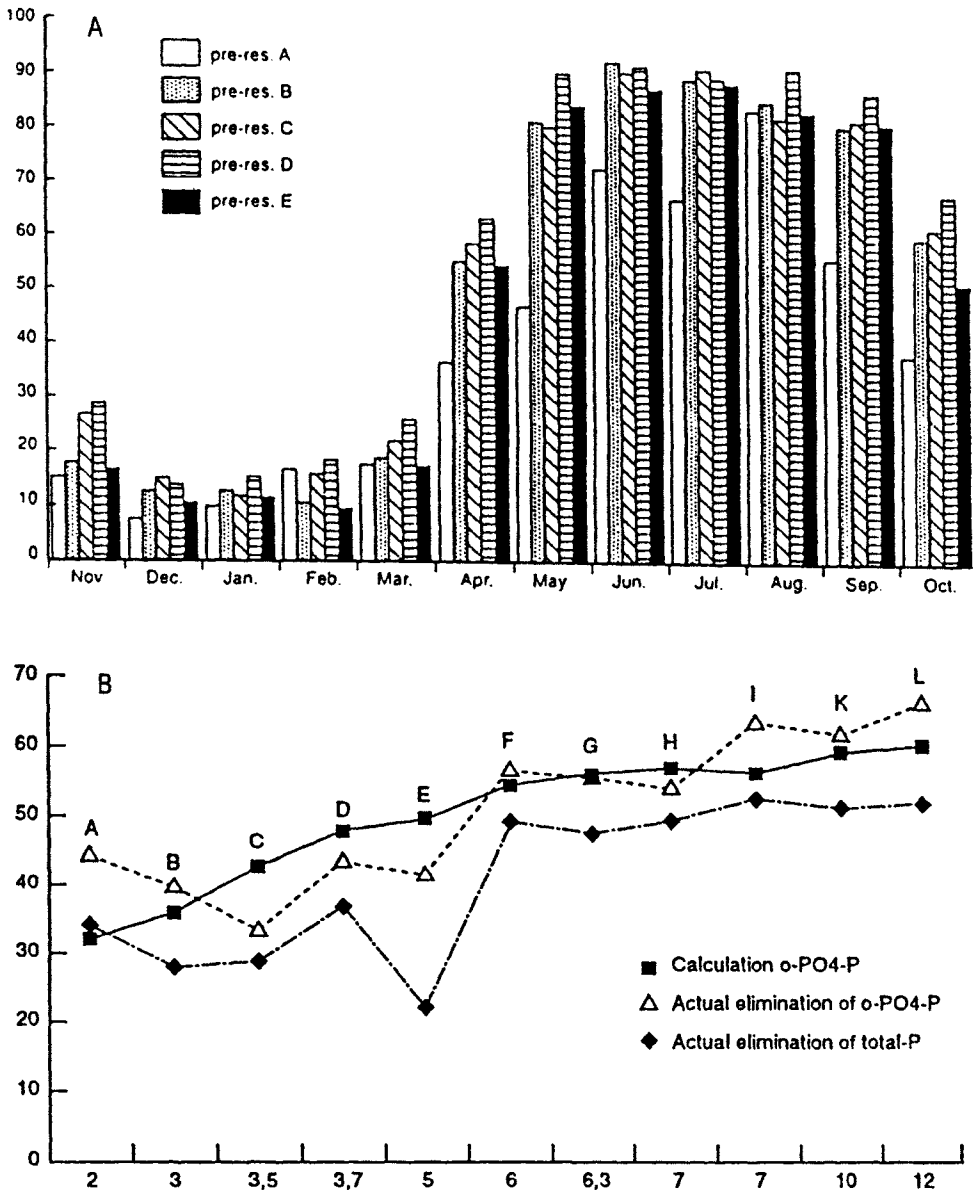


Fig. 6.11. Comparison of the calculated and observed pre-reservoir efficiencies for a number of pre-reservoirs in Germany. A—Seasonal changes in 5 different pre-reservoirs; B—Comparison for 11 pre-reservoirs with different retention times, showing a very good agreement and lower efficiency achieved for total-P than for orthophosphate (labile inorganic) phosphorus (from Pütz, 1995).

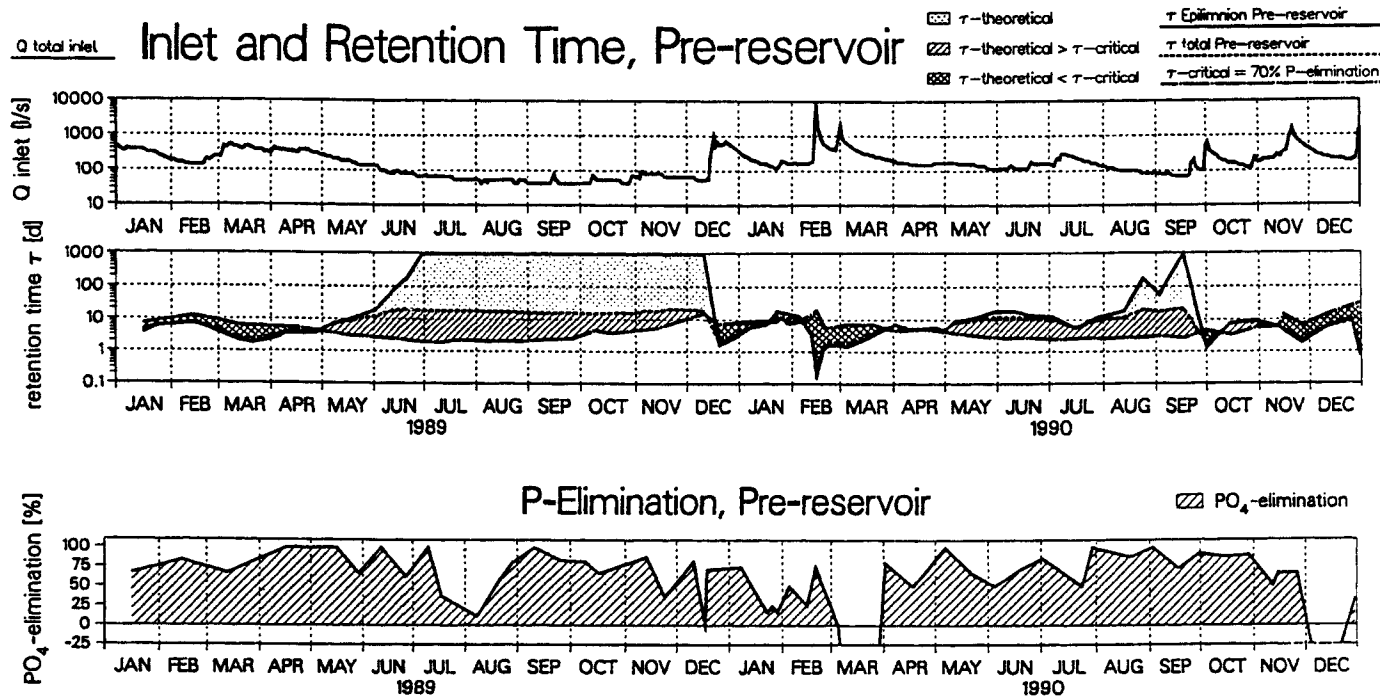


Fig. 6.12. Regular observations of the retention efficiency of a pre-reservoir in Germany and comparison with values calculated according to Benndorf's model. The inflow rate, theoretical water retention time of the total pre-reservoir, its epilimnion, and comparison with the critical retention time for achieving 70% phosphate—phosphorus elimination according to the model of Benndorf.

The quantitative aspect, maintenance of adequate water flow, is usually an obligation for the manager prescribed in the form of minimum permissible flows. Additional requirements may be defined in the form of maximum flows and rates of change in flow (Morehardt, 1986). Quantitative methods for determining minimum flows are not yet well developed, and local conditions of downstream users must be taken into account. Some methods used in the United States and the United Kingdom are based on conditions for downstream fish life (Binns and Eiserman, 1979; Orth and Leonard, 1990). The input variables for calculating these flows are relatively simple ones, including depth, discharge or velocity, basin area or distance from one stream shore to the other along the bottom. A hydrologic model is used to estimate the consequences of flow variations. The determination of habitat suitability for locally-important stream fish species is necessary.

The task of determining minimum permissible flows simultaneously from the quantitative and qualitative aspects can be difficult. Although higher water discharges are generally considered more favorable than low flows, a simple augmentation of water quantity does not solve water quality problems below reservoirs polluted by urban and industrial effluents or by irrigation return flows. Methodologies along these lines have been formulated (Gore and Judy, 1981; Richter et al., 1997). Moog (1993) formulated management strategies to minimize the impacts of peaking operations on stream fauna, and Cada (1998) reviewed the efforts to reduce the impacts of power supply reservoirs on reservoir fisheries. Mathematical models used to help minimize the environmental impacts of hydroelectric reservoirs are discussed by Dionne and Thérien (1997). The operation of a temperature control device for management of the in-reservoir and outflow temperatures was modelled by Hanna (1998).

Possibilities for improving water quality at the location of the dam consist mainly of modifications of the gas regime of the outflow. Table 6.8 lists alternative techniques used to manage outflows. Rather than discussing the details of each procedure, a significant reference is provided for each method.

Several approaches regarding aeration/oxygenation that were previously discussed in Section 4.3.2 can be included in managing hydropower outlets. The use of destratification in the vicinity of the dam is shown in Figure 6.13A. Figure 6.13B illustrates the use of a combination of oxygenation from the bottom, and mixing by a propeller or a water

Table 6.8. Techniques for management of reservoir outflows. The references are either to the inventor, to a thorough summary of the usage, or both (modified from Sraškraha et al., 1993)

Technique	Reference
Selective withdrawal	Gaillard, 1984; Parizek, 1984; Filho et al., 1990
Aeration/oxygenation at hydropower outlet works	Cassidy, 1989
Vacuum-breaker venting system	Price and Meyer, 1992
Spill-water re-aeration	Cassidy, 1989
Czech method of oxygenation	Haindl, 1973
Epilimnetic pumps	Quintero and Garton, 1973; Mobley and Harshbarger, 1987

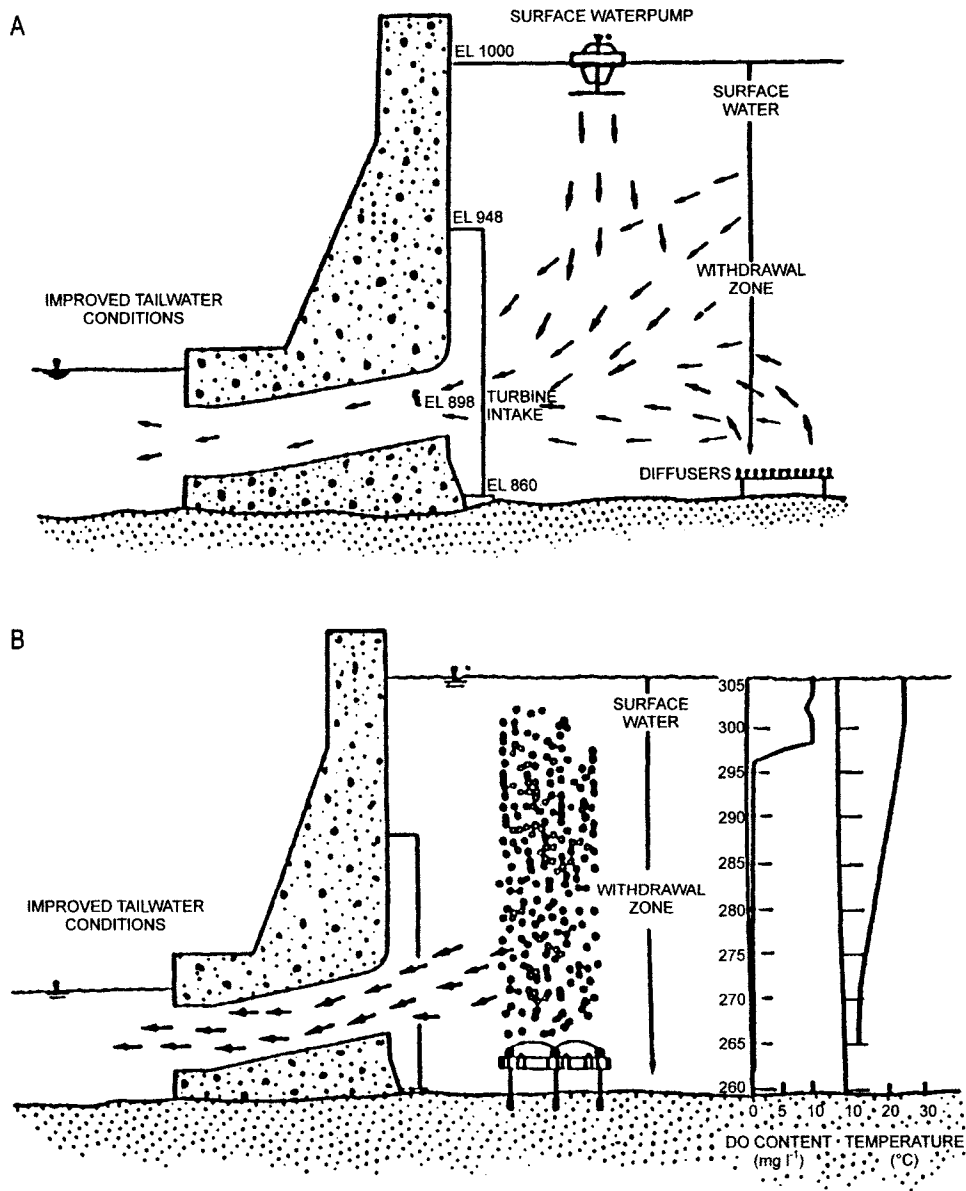


Fig. 6.13. Increasing oxygen concentrations in the reservoir outflow by mixing and aeration. A—Using propeller mixing and oxygenation by a diffuser in the close vicinity of the dam. B—Destratification close to the dam. The profiles of temperature and oxygen before the mixing started is shown (from Mobley, undated).

pump from the surface (Mobley, undated). An improvement is achieved in cases of de-oxygenated water at the turbine intake levels. The outflow oxygen concentration can be increased to levels suitable for fish and other aquatic life, and devoid of smells, by using such approaches. Further, outflow temperatures can be increased, in comparison to unmanaged situations, and structures also are better protected against corrosion.

Problems may arise when the water comes from the hypolimnion of an eutrophic reservoir. This is because the water is deoxygenated, contains large concentrations of organic compounds, iron and manganese, and has a high phosphorus content. The consequences may include large-scale fish kills and eutrophication of the river, accompanied by taste and odor problems that make its treatment difficult for a drinking water supply.

For reservoirs, there also is a possibility to improve water quality downstream during the release of water from the reservoir into the outflowing river. Many technical components were invented to increase the oxygenation of the water being released from a reservoir via turbines or overflow, examples being spill water aeration (Cassidy, 1989), vacuum breaker venting systems (Price and Meyer, 1992), infuser weirs and high-performance weirs (Hauser and Brock, 1996; Hauser and Morris, 1995), and auto-venting and re-aerating turbines (Hopping et al., 1997, 1999; March et al., 1992).

The quality of water flowing out of a reservoir is directly related to the horizontal and vertical distribution of the water within the reservoir (and the quality of the water), as well as the flexibility of the operation of the multiple outlets (Cassidy and Dunn, 1987; Ashby et al., 1995). There is a strong relationship between water quality and the quantity of water flowing out of a reservoir. When the outflow quantity is low (in relation to the reservoir volume), only a thin layer is taken to the outlet. With large water releases, the water quality can significantly change as broad layers of water are taken to the outlet, and as more inflowing water enters different layers to replace the outflowing water.

Selective withdrawal was previously discussed as a means for managing water quality within a reservoir. Several management options for re-oxygenation are available, including spill water oxygenation and the use of hydraulic skis.

6.4.4 Management of Reservoir Systems

Reservoir systems are managed in respect to both water quantity and quality. The quantitative management is typically solved with detailed mathematical optimization methods. The problem is how to best manipulate the water outflow, uptake and pumping from individual reservoirs to achieve the maximum water use, while keeping the constraints of slow and low water level declines, minimum releases and others.

When water quality considerations are included, the task becomes much more complicated because the number of variables and constraints to be considered increases. Nonlinear interrelations between water quantity and quantity must also be considered.

The simplest consideration is the quantity operation of reservoir cascades. The structure of the system is simple: Water flows unidirectionally from the uppermost to the lowermost reservoir. Each reservoir improves water quality by natural processes of sedimentation, production, etc., occurring within the reservoir. Suspended solids, organic matter and phos-

phorus, as well as other polluting substances, are decreased by the passage of the river through the reservoirs. Because the decrease is in percentage (but also strongly depends on retention time), the uppermost reservoir usually decreases the pollution most intensively if its retention time is not very short. The cheapest and very efficient water quality management approach is hydraulic regulation. By selecting the proper depth levels for the water uptake and outflow, considerable water quality improvement can be achieved.

Operation of pumping schemes is usually not combined with water quality problems, either because the quantity of water being pumped is low, or because the reservoirs of the pumping scheme are used solely for hydropower generation.

A specific method using reservoir systems is *storage sequencing* and *reservoir bleaching*. If reservoirs in a system have different water quality, it is possible to optimize water quality for the supply by properly scheduling their use (Kortmann, 1989). The rule is to use the most eutrophic reservoir early in the growing season, whereas less eutrophic reservoirs are used later in the growing season and during fall overturn. Moreover, if one reservoir in the system is devoted to water distribution to users, it is possible to use selected offtakes to obtain the best possible quality.

6.5 CONSIDERATIONS FOR NEW RESERVOIRS

Although the period of intensive reservoir construction around the world appears to be over, reservoir construction nevertheless continues in many developing countries. The problems associated with various water quality and nontechnical aspects during the construction of reservoirs fall into the following categories:

- Consideration of positive and negative aspects of a given reservoir and its site selection,
- Evaluation of environmental consequences of reservoir construction and its alternatives,
- Determination of optimal reservoir features, from a water quality perspective.

6.5.1 Issues in New Reservoir Construction

Reservoir aging. Poor water quality is a feature of newly-constructed reservoirs during the period ranging from a few to up to 10 years after they begin to fill. This process is termed reservoir aging or “trophic upsurge”. The length of this period depends on several variables. It is shorter when the average water retention time of the reservoir is short, with the reverse being true when reservoir filling takes several years. It also is longer when the nutrient and organic matter input from soil and drowned vegetation is high, whereas increased temperatures make it shorter under otherwise comparable conditions. Reservoir aging is marked by deteriorated oxygen conditions in deeper reservoir water strata, increased manganese and iron concentrations in the reservoir, and more complicated and expensive drinking water treatment. The name “trophic upsurge” is based on the increased productivity levels during the first few years of the reservoir’s existence. It is also observed in the form of high fish yields several years after filling is complete. Fishery biologists in

the former Soviet Union predicted high fish yields from the huge reservoirs in the country. These high yields, however, were not observed after the period of trophic upsurge passed (for more details, see Section 6.5.4).

Before the planning for any reservoir construction begins, it is both wise and prudent to consider its potential positive and negative consequences from a broad perspective (Goldsmith and Hildyard, 1984; Cernea, 1988; UNEP/UNESCO, 1990; Straškraba and Tundisi, 1999). Alternatives to reservoir construction (energy- and water-saving programs, utilization of other water sources, location of the use for which the reservoir was built being directed elsewhere, etc.) should be evaluated. The reason for this approach is that many reservoirs constructed in the past appeared not to fulfill the expectations and/or have a number of negative impacts. Table 6.9 lists possible positive and negative consequences of reservoir construction to be considered. Some might be irrelevant for a specific reservoir, but it is nevertheless useful to consider all possible aspects. The fact that the list of negative effects is longer than the positive effects should not create the impression that negative effects dominate. It only expresses the need to consider more items from a water quality perspective, as discussed below in more detail.

An example of the extent of positive and negative effects is provided by the Aswan High Dam in Egypt and Sudan. The reservoir produces 7000 million kWh of electricity annually, enables cultivation of 3655 km² of land, and has increased the national income of Egypt by US \$500 million annually. The negative consequences also are rather extensive, but are not yet expressed well in economic terms. The infection rate of bilharzia increased from 0 to 80% because of the dam and irrigation ditches, the catch of sardines in the eastern Mediterranean Sea decreased 95%, and the recreation industry in the Nile Delta, particularly around Alexandria, is threatened because the dam prevented beach replenishment. Moreover, the annual silt enrichment of the Nile floodplain has been eliminated by the dam.

Social problems. The primary socioeconomic consequence of reservoir construction is the need to relocate people. In the recently-realized gigantic Chinese project of the Three Gorges Reservoir, it is expected that more than one million people will be relocated. To the present time, the greatest relocation of people was related to the construction of the Aswan High Dam (i.e., Lake Nasser), with 120,000 people being relocated. This is followed by Lake Volta with 70,000 people, and Lake Kariba and Lake Kanji with 50,000 people relocated. The Cabora Bassa Reservoir in Mozambique required the resettlement of 25,000 people to new villages, which was done with due respect for family and tribal groupings. The relocation of people away from their traditional scattered communities nevertheless led to many social problems.

Population displacements are often accompanied by the loss of jobs and other adverse socioeconomic consequences. The World Bank (1993) stated: "Involuntary resettlement gives rise to a great extent different from, and usually more severe than those encountered in voluntary resettlement. A feeling of powerlessness and alienation is often engendered in those who are relocated, especially when entire communities are uprooted from familiar surroundings. Therefore, whenever possible involuntary resettlement must be avoided or minimized, and alternative development solutions must be explored".

Table 6.9. Possible positive and negative effects of reservoirs (from Straškraba and Tundisi, 1999)

Positive effects:

- Production of hydropower energy
- Creation of low-energy water purifiers
- Retention of water in the area
- Creation of drinking water and water supply sources
- Representative reserves of biological diversity
- Increased economic possibilities for portions of the local populations
- Creation of recreation possibilities
- Protection of downstream areas from flooding
- Increased fishery possibilities
- Water storage for low-flow periods
- Enhanced navigation
- Increased irrigation potential

Negative effects:

- Displaced local populations
- Deteriorated conditions for original population
- Health problems created by spread of waterborne diseases
- Loss of edible native riverine fish species
- Loss of agricultural land and valuable timber resources
- Loss of wetlands and land/water ecotones—useful natural structures; loss of the natural floodplain and conversion of wildlife habitat
- Loss of biodiversity (unique species); displaced wildlife populations
- Loss of mature agricultural land, well-cared for generations (e.g., rice paddy)
- Excessive human immigration to the reservoir region, and increases in many associated social, economic and health problems
- Need for adequate compensation for loss of agriculture, fisheries grounds and housing, as well as compensation for loss of fishing, recreational and subsistence activities
- Degradation of local water quality
- Decreased flow rates below the reservoir and increased flow variability
- Decreased downstream temperature and silt/nutrient transport
- Decreased dissolved oxygen at the bottom and the outflow of the reservoir
- Decreased pH and organic matter content in the outflow water
- Increased hydrogen sulphide (H₂S) and carbon dioxide (CO₂) at the bottom and outflow of the reservoir
- Barrier to fish migration
- Loss of valuable historic or cultural resources (e.g., loss of countless Native American burial grounds and other sacred sites in Oregon, resulting in the loss of cultural identity for some tribes)
- Decreased aesthetic values

Secondary social impacts may include:

- Internal anthropogenic pressures on labor resources, such as the end of the nomad era and the necessary re-training of nomadic shepherds into settled farmers, urbanization and industrialization of the territory, economic development connected with new access roads and electricity, increased recreation pressure, etc.,

- Effects of changed environment on the health and productivity of humans and domestic animals, namely with regard to new waterborne diseases,
- Potential danger of disasters resulting from dam breaking.

Health problems. Large reservoirs in warmer climates are associated with the spreading of infectious diseases (hepatitis, poliomyelitis, typhoid, dysentery, cholera, etc.) and with mass reproduction of parasites. The greatest threat is associated with irrigation projects, which creates good conditions for the proliferation of parasites. Mosquitos, blackflies and other animals are vectors of malaria, virus infections and intermediates for bilharzia and onchocerciasis. In the Amazon River drainage basin, people living around Tucuruí Reservoir suffered from a large attack by blackflies, which caused several hundred cases of encephalitis. The health effects of some major reservoir projects are summarized in Table 6.10.

Weed problems. After Lake Kariba was flooded, a large infestation of the floating fern *Salvinia molesta* appeared and covered large areas of the lake surface (Magadza, 1988, 1997). A very inefficient strategy was used; many specialists were engaged to solve the problem, which finally disappeared by itself. The reason for the disappearance was the exhaustion of nutrients entering the lake as a result of the floods. If a nutrient budget calculation had been made before the reservoir construction, and the aging process (Section 6.5.4) taken into account, these unnecessary negative impacts might have been avoided. (See Chapter 9.)

Rapid filling with sediments. The length of the operational life of a reservoir is much shorter than that of a natural lake, due primarily to its more rapid filling with sediments. The primary reason is the larger drainage basin : waterbody ratio of a reservoir, as compared to a natural lake. The consequences are major water quality changes in the inflow part of the reservoir, due to the influence of the accumulated sediments, which usually contain significant quantities of easily-decomposable organic matter (soil particles). As a result, bacterial decomposition of the organic matter consumes the oxygen in the waterbody. Anoxic conditions are caused by the remobilization of phosphorus and other polluting substances

Table 6.10. Major health problems connected with reservoir construction (from data by WHO, with supplement from Gleick, 1999)

Project	Year of completion	Health effect	Degree of impact
Vo Ha Dam (Ghana)	1966	Schistosomiasis	70%
Sugar estate irrigation (Tanzania)	1968	Schistosomiasis	85%
Kainji Dam (Nigeria)	1969	Schistosomiasis	30–70%
Aswan High Dam (Egypt, Sudan)	1969	Schistosomiasis	100%
Ubolratana Dam (Thailand)	1970	Helminths	52–90%
Malumfashi irrigation (Nigeria)	1978	Schistosomiasis	65%
Srinagarind Dam (India)	1978	Malaria	25%
Gezira irrigation project (Sudan)	1979	Schistosomiasis	70%
Diana Dam (Senegal)		Schistosomiasis	100%

(manganese, iron, heavy metals, etc.) from the sediments into the water column. The water layers deprived of oxygen, and enriched by pollutants in the inflow zone, may extend along the reservoir, reaching the offtakes or outflow. The degree of organic enrichment of sediments might be sufficiently high to lead to the evolution of gases like methane and/or hydrogen sulphide, whose smell may be obnoxious. During periods of decreased water levels, the accumulated sediments may produce smells and/or may be rapidly overgrown by plants, which can then decay after being submerged.

Downstream problems. During the reservoir aging process, the quality of the outflow water will typically be worse than in following years. The degree of this water quality deterioration depends on the state of the reservoir, and on the hydrodynamic conditions that are decisive for which water layers reach the outflow. Multiple outlets can help improve the downstream water quality during this period, particularly when severe anoxia occur in deeper strata.

6.5.2 Environmental Impact Assessment

The method recommended for proper evaluation of the environmental consequences of reservoir construction is the use of Environmental Impact Assessments (EIA) (Canter, 1977). This procedure is now obligatory for all projects supported by the World Bank (World Bank, 1993), and is even subject to law in some countries. The goal of the assessment is to specify all possible negative consequences of the reservoir construction, with respect to the social, physical and biological environment. Different alternatives must be specified and evaluated in order to determine the alternative with the minimum negative impacts. Public involvement based on the availability of relevant information also is typically requested. The immediate effects connected with different aspects of construction, as well as long-term effects, must be analyzed. These effects are not limited only to the immediate reservoir basin, but also its downstream effects and socioeconomic impacts. The list of items to be covered (Table 6.11) is based on experience gained during the construction of huge reservoirs in Africa and Brazil. An example of EIA evaluation for a reservoir, in the form of a questionnaire matrix, is shown in Figure 6.14.

After reservoir completion, post-construction monitoring should continue at least several years. The goal is to ascertain whether or not the results expected on the basis of predictions have actually been achieved.

6.5.3 Guidelines for Construction of Reservoirs

The water quality aspects of reservoir construction depend on the planned primary use of the reservoir, which is related to the restrictions for its size, theoretical water retention time, depth and other features, as well as the local possibilities. However, it usually happens that the primary purpose is exceeded beyond the initially-designated primary use and, therefore, the water quality of any constructed reservoir should be optimized. The hydrological and technical issues of reservoir construction and its costs are not discussed here.

Table 6.11. Items to be considered in environmental impact assessments (EIA) associated with reservoir construction (from Straškraba et al., 1993)

-
- A relocation program for the local displaced population
 - Health problems arising out of the reservoir construction (e.g., dispersal of waterborne diseases) and excessively dense population at the construction site
 - Loss of edible native species of fish, some of which may be indigenous and unique
 - Loss of native terrestrial communities of fauna and flora, especially threatened species
 - Loss of local aquatic and terrestrial biodiversity
 - Loss of valuable timber resources
 - Loss of mature agricultural land, well-cared for generations (e.g., rice paddies)
 - Loss of natural wetlands, wetland species and unique land/water ecotones
 - Loss of recreational potential
 - Loss of cultural heritage
 - Loss of water to evaporation
 - Excessive human immigration to the reservoir region, with many attendant social, economic and health problems
 - Provision of an adequate compensation for loss of agricultural lands and fisheries grounds, as well as compensation for loss of fishing, recreational and subsistence agricultural activities
 - The effect of the presence of the reservoir itself upon the local ecology, economy and society
 - Degradation of local water quality
 - Spread of waterborne diseases and pests
 - River bed and coastal erosion
 - Damage to the downstream river by the loss of water, loss of fertilizing silt downstream, fish kills, changed temperature regimes and general water quality deterioration (also see Section 6.3)
-

Rather, only the features of future reservoirs that are optimal from the perspective of drinking water supply are discussed. The strictest criteria are used here, which evidently cannot be applied everywhere. Further, there are uses which cannot easily be combined, and optimization from one perspective cannot simultaneously represent optimal conditions with respect to another usage. Compromise solutions will certainly be necessary. Nevertheless, the overriding goal should be to approach as much as possible the features listed below for any reservoir being constructed.

The reservoir features optimal from a drinking water supply perspective can be summarized as follows:

- Geographical latitudes between 20–35 degrees are mostly characterized by evaporation exceeding precipitation and, therefore, by large water losses. These are typically regions with few natural lakes and a greater demand for reservoir construction. Nevertheless, alternative solutions should be sought.
- In addition to its present state, take into consideration probable future development of the drainage basin. Drainage basin aspects are as important as the site for the reservoir construction itself. Present and future land use is of vital importance.
- Select the least inhabited and industrialized drainage basin possible. The pollution important from a water quality perspective does not include only domestic, organic and toxic pollution, but also the nutrient concentrations, particularly phosphorus, in the river.

	RESERVOIR					HEADWORKS				PRIMARY CONDUIT						RIVER DOWNSTREAM											
	-Sedimentation	-Shoreline protection	-Slope stability	-Preparation/cleaning	-Water quality	-Secondary reservoir uses	-Dam or diversion weir & intake	-River diversion for const'n	-Fill/borrow cores	-Spillway or flood protection works	-Fishpass facilities	-River traffic facilities	-Canal	-Pipeline	-Utilization facilities	power station	irrigation	pumped storage	intermediate storage	-Process stations	pump/treatment	power station	Flow regime	-Channel regime	-Water quality	-Flow passing/energy	-Dissipation facilities
SOCIAL ENVIRONMENT																											
Public participation																											
Employment																											
Settlement																											
Land value																											
Existing land uses																											
Risks and anxieties																											
Personal and social values																											
Historical/cultural																											
Landscape/visual																											
Recreation																											
PHYSICAL ENVIRONMENT																											
River regime																											
Erosion/land stability																											
Sedimentation																											
Surface water																											
Ground water																											
Agricultural soil																											
Foundation materials																											
Climate/atmosphere																											
Nuisance (noise, dust, smell)																											
Landform																											
BIOLOGICAL ENVIRONMENT																											
Forest																											
Shrubland																											
Grassland																											
Herbfield (alpine)																											
Sand/Shingle/Rock																											
Cropland																											
Urban land																											
Lakes																											
Rivers																											
Estuaries																											
Lateral-tidal																											
Marine																											
Wetlands																											

Fig. 6.14. Example of a matrix of variables to be taken into consideration for an EIA concerning construction of a new reservoir.

- Thus, minimization of agricultural nonpoint source pollution, and efficient purification, including treatment for phosphorus reduction, must be considered. Future development in the drainage basin should be controlled with respect to its water quality consequences.
- In the planning phase, consider restrictions on further increases in pollution and the decrease of existing pollution. The processes of “clean production” (Section 4.2.2) should be considered where appropriate.
 - Choose localities at higher elevations if possible. Higher elevations are often less inhabited, less intensively industrial, and utilized less for agriculture. The colder climate is also favorable for enhancing good water quality, since autochthonous-related eutrophi-

cation is less developed. In terms of water quality, several smaller reservoirs located at high elevations are preferable to one large lowland reservoir.

- Forested areas and meadows are preferred over agricultural areas. This is because the fertilization of fields is usually more intensive than the fertilization of forests and meadows, so that the probability of increased eutrophication is diminished (Section 4.2.1).
- If site selection can be made between sites with point and diffuse pollution sources, the former are preferred. Construction of purification facilities for point source pollution purification can be made part of the reservoir construction plan, while reducing pollution from diffuse sources is typically more difficult.
- Select the maximum depth available, avoiding shallow sites. The depth of a reservoir decides on the ratio between the volume of the layers where autochthonous organic matter is produced (trophogenic zone) and where it is reduced (decomposed, mineralized-tropholytic zone). A higher relative volume of the tropholytic zone results in less negative consequences from in-lake decomposition.
- Localities more open to wind effects are preferred. Higher winds cause deeper mixing of the surface water strata. Thus, phytoplankton are more or less homogeneously distributed over the whole water mixing depth. Phytoplankton get less light (i.e., decreased energy) if mixed to deeper depths, and autochthonous organic production is minimized. In tropical regions, a fully-mixed reservoir might be advantageous in preventing the formation of hypolimnetic anoxia.
- Larger lake surface areas are preferable to smaller ones. The wind speed increases over the water surface and larger distances of wind travel on the surface, creating deeper water mixing. Particularly important are the distances in the direction of the most common winds.
- Multiple outlets enable flexible operation and selective hydraulic regulation.
- A very short theoretical water retention time is not favorable. An optimal average theoretical retention time is about 100 days. Reservoirs with short theoretical retention time are subject to large variations in water quality, due to flow-dependent changes in the inflowing river. Reservoirs with long retention times are more susceptible to hypolimnetic anoxia. The higher water supply of reservoirs with average retention times facilitates the efficient utilization of hydraulic regulation methods.
- Locating the multiple offtakes in the lake-like region of a reservoir, but not directly in the dam, allows a more flexible selection of the depths from which raw water is taken, which is useful during periods of reservoir stratification.
- Fisheries management is preferable, but intensive fish cage cultivation will degrade water quality. The relationships between fish composition and water quality (Section 4.3.1) show that balanced fish populations, with predators controlling zooplankton-feeding fish, can significantly decrease the quantities of algae in a reservoir. The possible consequences of sport fisheries that concentrate on predatory fish for the mass reproduction of zooplankton-feeding fish have to be checked.
- Construction of turbine outlets and spillways in a way that maximizes oxygenation of water, which is important for downstream water quality, should be planned.

- The possibility of combining several reservoirs into one system, and selecting the most suitable water quality among them, should be considered. Because a reservoir has a high self-purification capacity (Section 6.4.2), the second or third reservoir in a cascade will likely have better water quality (if not subject to high pollution load from its shores and secondary tributaries). However, a water resource system only provides advantages if the water quality is the dominant, or at least subdominant, aspect.
- Agricultural activities located close to reservoir shores may have more negative effects than when they are located more distant from a reservoir.
- The preservation of forests and wetlands is of primary importance.
- The use of mathematical models enables estimation of future water quality, evaluation of different management options possible and evaluation of construction and site alternatives from a water quality perspective (Chapter 5).

6.5.4 Reservoir Aging

The water quality of every new reservoir is worse during the filling phase, and in the first years of its existence, than during the following period. A particular characteristic is the anoxia of deeper layers. In instances of heavy organic and nutrient load from the submerged territory and inflow, the anoxia conditions may even reach nearly up to the water surface. This is due to the process called reservoir aging, which describes the rapid changes and deteriorated water quality that occurs during this period. The period of aging is also called “trophic upsurge”, because higher biological production takes place during this period. Much slower limnological changes following the period of aging, which may last for decades or centuries, are referred to as reservoir evolution.

A reservoir manager should not be surprised that the predicted water quality for a reservoir is not realized in the first years. These predictions typically are based on stable conditions, in contrast to the unstable conditions that prevail in the first years of a reservoir's existence. Aging takes place in all reservoirs, but to a different degree and with different speed, depending on the quantity of organic matter and nutrients liberated from the inundated soils and/or brought into the reservoir in its inflows. The water quality consequences of aging will be particularly severe when the organic and nutrient load from the flooded territory is high. For a reservoir with such a heavy external pollutant load that the water quality can be expected to be low even after the aging period, the manager must already expect water quality difficulties. The greatest water quality differences between the aging and post-aging periods are encountered in relatively pristine areas, where water quality predictions for stable (post-aging) conditions are very favorable, but water quality during the aging period can be very low.

Reservoir aging has two primary causes:

- External, physical–chemical,
- Internal, biological.

The *external, physical–chemical causes* are due to the high input of organic matter and nutrients from soil disturbed during construction, and from the decay of flooded terrestrial

vegetation, including trees, shrubs and grasses. The felling of trees, destroying of constructions, building of roads in the river valley to be submerged, construction of roads and bridges along and across the reservoir, rock and soil extraction for the dam construction in the vicinity of the site, and the construction activities of the dam and associated buildings and other structures, are environmental disturbances that lead to the enrichment of the water accumulating in the reservoir. The particular water quality difficulties connected with these activities raise the question of whether or not to clear out all the vegetation on the land surface to be inundated, and to what a degree (summarized in Ploskey, 1983, 1986). The felling of trees in the inundated territory is a common practice for small- and medium-size reservoirs constructed in populated territories. However, it is impossible in the case of large reservoirs in less-inhabited countries. The importance of trees will depend on the reservoir morphology. Trees prevent fisheries in the productive nearshore areas, and endanger the use of nets reaching to greater depths. Thus, at least partial clearing of selected shoreline stretches is recommended when fisheries are of importance. On the other hand, submerged trees represent nursery, feeding, and protection grounds for many species of fish, so that fish density is generally higher among such vegetation. The food supply in such overgrown regions is high, because the associated bacteria and algae with invertebrates feeding on them represent favorable food supplies for certain fish species. The decomposition of wood in the reservoir is very slow, and it takes decades before trees disappear. Moreover, trunks floating on the surface endanger boat traffic. The felling of trees may have negative water quality consequences when done by heavy machinery with the consequent destruction of the soil. During the initial period, more organic materials and nutrients are released into the water from the disturbed soil than from decaying needles or leaves from trees. Shrub clearing is done less frequently, but may be more costly if done carefully without destruction of the soil layers, while drastic grass eradication will only lead to soil disturbance.

The *internal, biological causes* are related to the reconstruction of the biological associations from those present in the rivers to those more suited to the newly-created lake-like conditions (Straškraba et al., 1987). The management consequence is that, in the initial period phytoplankton growth is more intensive not only because of higher nutrient releases, but also because of the absence of proper control of the phytoplankton by invertebrates that feed on it. The reason is the differing rates of reproduction of the small organisms (algae) and larger organisms (zooplankton). It takes a longer time before the more slowly-developing zooplankton reach population densities sufficient to be able to control phytoplankton to levels normal for mature waterbodies. Fish have the slowest development rates, requiring several years to reach maturity. Development of fish populations in a reservoir, starting from a few individuals living in the river, takes more time than the period when the first newborn generation reaches maturity. The first generation is still diluted, and more generations must develop before the new lake is saturated with fish. Further, in temperate regions, fish reproduce only once a year, while the reproduction of smaller zooplankton and phytoplankton is more or less continuous. Strong interrelations between fish, zooplankton, and phytoplankton, and also among different fish species, exist in the aquatic-free water environment. This is due primarily to the trophic feeding relations: Predatory fish feed on

nonpredatory fish species, nonpredatory fish species feed on zooplankton (a few species also on detritus macrophytes and phytoplankton), zooplankton consume phytoplankton. Feeding by all organism groups is selective, with the selection based on the size and taste of the prey organisms. The effect is a top-down control; that is, control by predatory fish, which is propagated by zooplankton-feeding fish and filtering zooplankton down to the phytoplankton. The composition of the pelagic associations of organisms, including the species composition of phytoplankton, depends on the composition of the fish populations. A balanced fish population, consisting of predators controlling the density of nonpredatory fish, is preferred for good water quality, since it leads to the persistence of zooplankton species capable of keeping phytoplankton populations low. When predatory fish are either absent, low or consist only of littoral or benthic species, the nonpredatory fish populations become dominant, eliminating the larger zooplankton species. Larger zooplankton are then substituted for smaller species, being less efficient filterers, and the phytoplankton control does not work. Up to twice much phytoplankton is present when the small zooplankton are numerous and the large zooplankton filterers are rare. The absolute concentrations of phytoplankton depend on the concentrations of available nutrients, light and temperature.

Water quality problems that commonly occur during reservoir aging, and their respective causes, are given in Table 6.12.

Table 6.12. Water quality events and problems that can occur during reservoir aging, and their underlying causes

Problem	Causes
<ul style="list-style-type: none"> ● Increased concentrations of organic matter 	Leaching of organic matter from soil; decomposition of drowned vegetation
<ul style="list-style-type: none"> ● Increased color 	Color indicates resistant organic matter; color changes occur very slowly, and increased values are lasting signs of aging
<ul style="list-style-type: none"> ● Low oxygen concentrations (particularly in hypolimnion) 	Oxygen is consumed during the decomposition of dissolved and particulate organic matter that enters through the inflows and is released from disturbed soil and decaying vegetation
<ul style="list-style-type: none"> ● High nutrient concentrations 	Nutrients are leached from disturbed soil
<ul style="list-style-type: none"> ● Excessive growth of vegetation (particularly floating aquatics) 	New tropical reservoirs are particularly susceptible to this problem
<ul style="list-style-type: none"> ● Increased phytoplankton production 	Algae grow rapidly as the result of increased nutrient concentrations
<ul style="list-style-type: none"> ● Increased fish production 	Some species of fish are able to reproduce rapidly in response to the high food supply; nevertheless, some years must pass before the fish population is well established
<ul style="list-style-type: none"> ● Increased manganese and iron, remobilization of mercury, emissions of carbon dioxide and methane 	While the increase of manganese and iron is common in anoxic hypolimnia, a significant increase of mercury by remobilization from soil is observed rarely; carbon dioxide and methane emissions have mainly been observed in tropical reservoirs

The duration of the reservoir aging period differs between reservoirs. The average span, however, is between four to more than ten years. In Amazonian reservoirs, stabilization takes a minimum of 10 years, depending upon the rate at which the submerged tropical humic forests decompose. The length and shape of the physical–chemical process of reservoir aging is controlled by the latitude, reservoir volume, water retention time, quantity of organic matter accumulated during filling, activities in the drainage basin, and the quantity of input of suspended materials. With respect to biological processes, the most important element is the rate and degree of the development of fish populations, and the control these organisms exert over the rest of the reservoir ecosystem. The aging process is shorter in reservoirs with rapid water throughflow than in those with slower throughflow. The geographical location (more rapid aging in tropics) and time required for filling (slow and intermittent filling prolongs the aging period) are decisive factors in the aging process. The sequence of events that normally take place during reservoir aging is shown in Figure 6.15.

Most reservoirs stabilize after a few years. Following the aging process, the limnological evolution of the reservoir occurs, and is largely driven by the impact of human activities (e.g., intensification of land use activities and industrial activities).

Management during aging

Reservoir aging will usually not create many difficulties in reservoirs for which water quality conditions are not crucial for their functioning (e.g., hydropower generation, flood protection). However, the water quality conditions in the outflowing river may become critical for downstream users and aquatic life, particularly for fishes dependent on reservoir use. The manager of a drinking water reservoir is in a particularly difficult situation, and must cope with this feature to the maximum extent. The manager has essentially three possibilities for reacting to the expected period of water quality deterioration, as follows:

- Start using the reservoir for a drinking water supply only after at least one or two years (depending on the expected deterioration).
- Make provisions for treating water of worse quality during this period than that expected after this period.
- Use appropriate in-lake management options (e.g., mixing of different options).

Knowledge of the aging process, and consideration of its causes as outlined above, will enable a reservoir manager to apply at least some of the following countermeasures, which also will have positive effects on water quality at a later period:

- Any measures decreasing pollution of the major inflows must be done before the filling of the reservoir begins.
- Minimizing soil cover disturbance in the future submerged bottom areas. The disturbance associated with the reservoir construction, including building roads, should as much as possible be located on the downstream side of the dam.
- The vegetation cover of the future reservoir bottom is best left intact, except for at least partial felling of trees and shrubs. The use of heavy machinery that disturbs the soil will significantly increase nutrient leaching from soils.

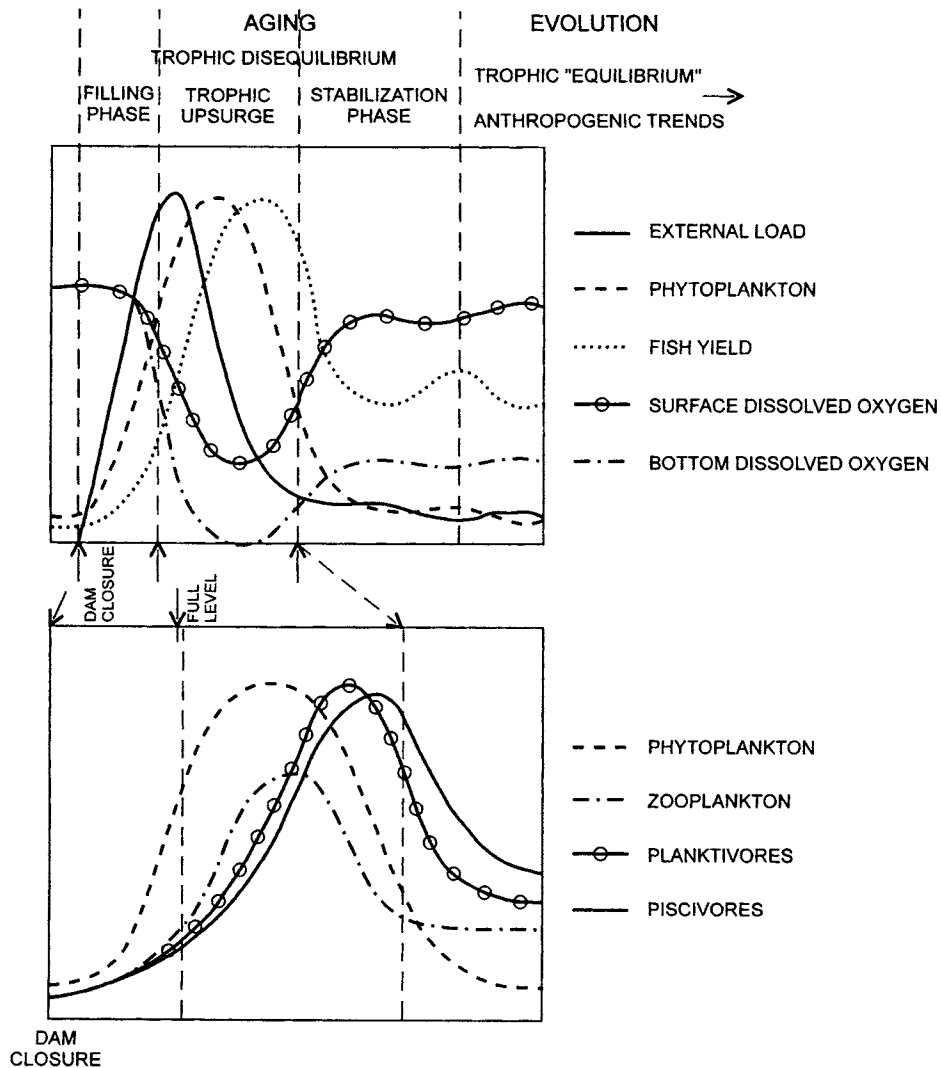


Fig. 6.15. Schematic representation of several observations on reservoir aging (x-axis). The succession of peaks of different organisms is shown in a more extended form in the lower part.

- Agricultural activities on the future reservoir bed, and around the future lake perimeter, should be avoided, or the fertilizer and pesticide use minimized, particularly those in the form of powder. No plowing should be done before these areas become submerged.
- Preservation of wetlands and/or simple support of vegetation, particularly marshy ones, along the future perimeter of the reservoir enhances pollution retention.

- Pre-reservoirs, both those to be submerged in the future and those higher on the inflows, constructed before filling begins will help decrease water pollution, particularly the future phosphorus load to the reservoir.
- The introduction of suitable predatory and prey fish during the filling period accelerates the development of balanced fish populations, and shortens the trophic upsurge.

REFERENCES

- Armengol, J., Garcia, J.C., Comerna, M., Romero, M., Dolz, J., Roura, M., Han, B.H., Vidal, A. and Šimek K., 1999. Longitudinal processes in canyon type reservoirs: The case of Sau (N.E. Spain). In: J.G. Tundisi and M. Straškraba (Eds), *Theoretical Reservoir Ecology and Its Applications*. International Institute of Ecology, Brazilian Academy of Sciences and Backhuys Publishers, Leyden, pp. 313–346.
- Asaeda, T., Priyantha, D.G.N., Saitoh, S. and Gotoh, K., 1996. A new technique for controlling algal blooms in the withdrawal zone of reservoirs using vertical curtains. *Ecol. Engineering*, 7: 95–104.
- Ashby, S.L., Kennedy, R.H. and Jabour, W., 1995. Water quality dynamics in the discharge of a south-eastern hydropower reservoir. *Lake Reserv. Manage.*, 11(3): 209–215.
- Baltz, D.M., Moyle, B.B. and Knight, A.N., 1934. Competitive interactions between benthic stream fishes, riffle sculpin, *Cottus gulosus*, and speckled dace, *Rhinichthys osculus*. *Can. J. Fish. Aquat. Sci.*, 39: 1502–1511.
- Barbosa, F.A.R., Padisak, J., Espindola, E.L.G., Borics, G. and Rocha, O., 1999. The cascading reservoir continuum concept (CRCC) and its application to the River Tiete-Basin, Sao Paulo State, Brazil. In: J.G. Tundisi and M. Straškraba (Eds), *Theoretical Reservoir Ecology and Its Applications*. International Institute of Ecology, Brazilian Academy of Sciences and Backhuys Publishers, Leyden, pp. 425–437.
- Benndorf, J., 1973. Prognose des Stoffhaushaltes von Staugewässern mit Hilfe kontinuierlicher und semikontinuierlicher biologischer Modelle. *Intern. Rev. Ges. Hydrobiol.*, 58: 1–18.
- Benndorf, J., Zesch, M. and Wiesner, E.M., 1975. Prognose der Phytoplankton-entwicklung in geplanten Talsperren durch Kombination von Wachstumskinetischen Modellvorstellungen und Analogiebetrachtungen zu bestehenden Talsperren. *Intern. Rev. Ges. Hydrobiol.*, 60: 737–758.
- Binns, N.A. and Eiserman, F.M., 1979. Quantification of fluvial trout habitats in Wyoming. *Trans. Amer. Fish. Soc.*, 108: 215–228.
- Biswas, A.K. and Agarwal, S.B.C. (Eds), 1992. *Environmental Impact Assessment for Developing Countries*. Butterworths–Heinemann Ltd, Oxford, 196 pp.
- Biswas, A.K. and Geping, Q., 1987. *Environmental Assessment for Developing Countries*. United Nations University, Tycooly Internat.
- Čada, G.F., 1998. Efforts to reduce the impacts of hydroelectric power production on reservoir fisheries in the United States. *Internat. Review Hydrobiol.*, 83(Special Issue): 43–50.
- Canter, L.W., 1977. *Environmental Impact Assessment*. McGraw-Hill, New York, NY.
- Cassidy, R.A., 1989. Water temperature, dissolved oxygen, and turbidity control in reservoir releases. In: J.A. Gore and G.E. Petts (Eds), *Alternatives in Regulated River Management*. CRC Press, Boca Raton, FL.
- Cassidy, R.A. and Dunn, P.E., 1987. Water temperature control and areal oxygen consumption rates at a new reservoir and the effects of the release waters. In: J.E. Craig and J.B. Kamper (Eds), *Regulated Stream: Advances in Ecology*. Plenum Press, New York, NY, pp. 339–351.

- Cernea, M.M., 1988. Involuntary Resettlement in Development Projects. World Bank Technical Paper No. 80.
- Christeason, D.Y., Sound, R.L. and Marotz, B.L., 1996. Hungary Horse dam's successful selective withdrawal system. *Hydro Review*, 15(3): 10–15.
- Crisp, D.T., 1994. Reproductive investment of female brown trout, *Salmo trutta* L., in a stream and reservoir system in northern England. *J. Fish Biology*, 44: 343–349.
- Davis, J.R., Holland, J.P., Schneider, M.L. and Wilhelms, S.G., 1987a. SELECT: A numerical, one-dimensional model for selective withdrawal. Instrumentation Report E-87-2. U.S. Army Eng. Waterways Sta., Vicksburg, MS.
- Davis, J.R., Nanninga, P.M., Hoare, J.R.L. and Press, A.J., 1987b. Transferring scientific knowledge to natural resource managers using artificial intelligence concepts. *Ecol. Model.*, 46: 73–89.
- Davis, J.R., Nanninga, P.M., Biggins, J. and Laut, P., 1991. Prototype decision support system for analyzing impact of catchment policies. *ASCE J. Water Resour. Plng Manage.*, 117: 399–414.
- Dionne, D. and Thérien, N., 1997. Minimizing environmental impacts of hydroelectric reservoirs through operational control: A generic approach to reservoirs in northern Quebec. *Ecol. Model.*, 105: 41–63.
- Duarte, C.M. and Kalff, J., 1987. Latitudinal influences on the depth of maximum colonization and maximum biomass of submerged angiosperms in lakes. *Can. J. Fish. Aquat. Sci.*, 44: 1759–1764.
- Duarte, C.M. and Kalff, J., 1990. Patterns in the submerged macrophyte biomass of lakes and the importance of the scale of analysis in the interpretations. *Can. J. Fish. Aquat. Sci.*, 47: 357–363.
- Duncan, A., 1990. A review: Limnological management and biomanipulation in the London reservoirs. *Hydrobiol.*, 200/201: 541–548.
- Edelshtein, K.K. and Puklakov, V.V., 1996. Water quality control in a stratified reservoir: Assessment with the use of mathematical modelling. *Water Res.*, 23(4): 457–467.
- Fiala, L. and Vařata, P., 1982. Phosphorus reduction in a man-made lake by means of a small reservoir on the inflow. *Arch. Hydrobiol.*, 94: 24–37.
- Filho, M.C.A., De Jesus, J.A.O., Branski, J.M. and Hernandez, J.A.M., 1990. Mathematical modelling for reservoir water-quality management through hydraulic structure: A case study. *Ecol. Model.*, 52: 73–85.
- Fontane, D.G., Labadie, J.W. and Loftis, B., 1981. Optimal control for reservoir discharge quality through selective withdrawal. *Water Resour. Res.*, 17: 1594–1604.
- Gaillard, J., 1984. Multilevel withdrawal and water quality. *Proc. ASCE, J. Environ. Engng Div.*, 110: 123.
- Gilpin, A., 1995. *Environmental Impact Assessment*. Cambridge Univ. Press, Cambridge.
- Gleick, P.H., 1999. *The World's Water 1998–1999*. Island Press, Washington, DC.
- Goldsmith, E. and Hildyard, N. (Eds), 1984. *The Social and Environmental Effects of Large Dams*. Rep. Europ. Ecol. Action Group (ECOROPA), Quintrell & Co. Ltd, Wadebridge, Cornwall.
- Gore, J.A. and Judy, R.D., 1981. Predictive models of benthic macroinvertebrate density for use in instream flow studies and regulated flow management. *Can. J. Fish. Aquat. Sci.*, 38: 1363–1370.
- Grimard, Y. and Jones, H.G., 1982. Trophic upsurge in new reservoirs: A model for total phosphorus concentrations. *Can. J. Fish. Aquat. Sci.*, 39: 1473–1483.
- Groeger, A.G. and Kimmel, B.L., 1984. *Organic Matter Supply and Processing in Lakes and Reservoirs*. EPA.
- Groeger, A.V. and Tietjen, T.E., 1998. Hydrological and thermal regime in a subtropical reservoir. *Intern. Review Hydrobiol.*, 83(Special Issue): 83–91.

- Ground, T.D. and Groeger, A.W., 1993. Longitudinal Gradients of Water Quality in Texas Reservoirs. In: *Lake Management & Diversity, Competing Values, Needs, and Goals—13th Intern. Symp. of the North American Management Society.*
- Haindl, K., 1973. Suitable Solution of Bottom Outlets of Dams and Oxidation Outlets for the Improvement of Water Quality in Rivers. *Proceedings IAHR, Istanbul.*
- Hanna, R.B., 1998. Results of simulated temperature control device operations on in-reservoir and discharge water temperatures using CE-QUAL-W2. *Lake Reserv. Manage.*, 15(2): 87–102.
- Hart, R.C. and Allanson, B.R. (Eds), 1984. *Limnological Criteria for Management of Water Quality in the Southern Hemisphere. Inland Water Ecosystem Programmes Report No 93. Pretoria.*
- Hauser, G.E. and Brock, W.G., 1996. Using an infuser weir to aerate water releases from hydro plants. *Hydro Review*, 15(1): 1–4.
- Hauser, G.E. and Morris, D.L., 1995. High performance aerating weirs for dissolved oxygen improvement. In: *Proceedings WaterPower 95, San Francisco, CA, July.*
- Hejzlar, J. and Straškraba, M., 1989. On the horizontal distribution of limnological variables in Římov and other stratified Czechoslovak reservoirs. In: B. Henderson-Sellers and V. Straškrabová (Eds), *Proceedings of the International Conference of Reservoir Limnology and Water Quality, Vol. 1. Physical Limnology, Mathematical Models and Microbial Decomposition.* (also see, *Arch. Hydrobiol. Beih. Ergebn. Limnol.*, 33, 41–55.)
- Hopping, P.N., March, P.A., Brice, T.A. and Cybularz, J.M., 1996. Plans for testing and evaluating the new autoventing turbines at TVA's Norris Hydro Project. In: *Proceedings, North American Water and Environment Congress. ASCE.*
- Hopping, P.N., March, P.A., Brice, T.A. and Cybularz, J.M., 1997. Update on development of autoventing turbine technology. In: *Proceedings Waterpower '97. ASCE.*
- Hopping, P.N., March, P.A. and Wolff, P.J., 1999. Justifying, specifying, and verifying performance of aerating turbines. In: *Proceedings Waterpower'99. ASCE.*
- Hrbáček, J. (Ed.), 1966. *Hydrobiological Studies, Vol. 1. Academia, Praha.*
- Hrbáček, J. and Straškraba, M., 1973. *Hydrobiological Studies, Vol. 2. Academia, Praha.*
- ICOLD, 1994, 1998. *World Register of Dams. International Commission on Large Dams, Paris.*
- Javornický, P. and Komárková, J., 1973. The changes of several parameters of plankton primary productivity in Slapy Reservoir 1960–1967, their mutual correlations and correlations with the main ecological factors. In: J. Hrbáček and M. Straškraba (Eds), *Hydrobiological Studies, Vol. 3. Academia, Praha, pp. 155–211.*
- Kalceva, R., Outrata, J., Schindler, Z. and Straškraba, M., 1982. An optimization model for the economic control of reservoir eutrophication. *Ecol. Model.*, 17: 121–128.
- Kennedy, R.H., 1999. Reservoir design and operation: Limnological implications and management opportunities. In: J.G. Tundisi and M. Straškraba (Eds), *Theoretical Reservoir Ecology and Its Applications. International Institute of Ecology. Brazilian Academy of Sciences and Backhuys Publishers, Sao Carlos, Brazil, pp. 1–28.*
- Kennedy, R.H., Thornton, K.W. and Ford, D.E., 1985. *Characterization of the Reservoir Ecosystem. Microbial Processes in Reservoirs. Developments in Hydrobiology, 27. Junk, The Hague.*
- Kessler, D.H. and Vershuur, G.L., 1996. Hypolimnetic oxygen deficit and anoxic factors in Garner Lake, a West Tennessee reservoir. *Lake Reserv. Manage.*, 12(4): 462–467.
- Kortmann, R.W., 1989. Raw water quality control: An overview of reservoir management techniques. *J. NEWWA*, 197–220.
- Magadza, C.H.D., 1988. *The Status of Lake Kariba. Expert Group Management on River/Lake Basin Approach to Environmentally Sound Management of Water Resources. ILEC, UNEP, UNCED, Otsu and Nagoya, Japan.*

- Magadza, C.H.D., 1997. Some aspects of shared waters management in Africa. In: LACAR'97, 7th International Conference on Lakes Conservation and Management. 26–31 October, 1997, San Martin de las Andes, Argentina.
- March, P.A., Brice, Th.A., Mobley, M.H. and Cybularz, J.M., 1992. Turbines for solving the DO dilemma. *Hydro Review*, 11(1).
- Margalef, R., Planas, D., Armengol, J., Vidal-Celma, A., Prat, N., Guiset, A., Toja, J. and Estrada, M., 1976. *Limnología de los embalses españolas*. Direccion General de Obras Hidraulicas. Ministerio de Obras Publicas, Madrid.
- McMahon, T.A. and Findlayson, B.L., 1995. Reservoir system management and environmental flows. *Lakes Reserv. Manage.*, 1: 69–76.
- Melcher, J., Soracco, R.J. and Boylen, Ch.W., 1997. Spatial delineation of biotic and abiotic gradients in a rural New York reservoir. *J. Amer. Water Resour. Assoc.*, 3(1): 35–45.
- Mobley, M. (undated). Forebay Oxygen Diffuser System to Improve Reservoir Releases at TWA's Douglas Dam. Manuscript.
- Mobley, M.H. and Harshbarger, E.D., 1987. Epilimnetic pumps to improve reservoir releases. Miscellaneous Paper E-87-3. In: Proceedings CE Workshop on Reservoir Releases. U.S. Army Eng. Waterways Sta, Vicksburg, MS, pp. 133–135.
- Mobley, M.H., 1997. TVA Reservoir Aeration Diffuser System. TVA Technical Paper 97-3, ASCE WATERPOWER'97, Atlanta, GA, August 5–8, 1997.
- Moog, O., 1993. Quantification of daily peak hydropower effects on aquatic fauna and management to minimize environmental impacts. *Regul. Rivers Res. Mang.*, 8: 5–14.
- Morehardt, J.E., 1986. *Instream Flow Methodologies*. EPRI/EA, Palo Alto, CA.
- Naselli-Flores, L., 1999. Limnological aspects of Sicilian reservoirs: A comparative, ecosystemic approach. In: J.G. Tundisi and M. Straškraba (Eds), *Theoretical Reservoir Ecology and Its Applications*. International Institute of Ecology, Brazilian Academy of Sciences and Backhuys Publishers, Leyden, pp. 283–311.
- Orth, D.J. and Leonard, P.M., 1990. Comparison of discharge methods and habitat optimization for recommending instream flows to protect fish habitat. *Regulated Rivers Res. Manage.*, 5: 129–138.
- Oskam, G., 1983. Quality aspects of the Biesbosch reservoirs. *Aqua*, 6, 1156: 497–504.
- Padisak, J., Kohle, J. and Hoe, S., 1999. Limnological differences between a shallow pre-reservoir and a shallow lake—a case study of the Upper Kis-Balaton and Lake Balaton. In: J.G. Tundisi and M. Straškraba (Eds), *Theoretical Reservoir Ecology and Its Applications*. International Institute of Ecology, Brazilian Academy of Sciences and Backhuys Publishers, Leyden, pp. 347–383.
- Padisak, J., Barbosa, F.A.R., Borbely, G., Borics, G., Chorus, G., Espindola, E.L.G., Rocha, O., Torokne, A.L. and Vasas, G., 2001. Phytoplankton composition, biodiversity and a pilot survey of toxic cyanoprocarotes in a large cascading reservoir system (Tiete basin, São Paulo State, Brazil). In: *Proc. Internat. Association of Theoretical and Applied Limnology*, Vol. 27, Part 5, pp. 2734–2742.
- Pařízek, J., 1984. Využití efektu čisté vrstvy (Utilization of the “clean layer” effect—in Czech). In: M. Straškraba, Z. Brandl and P. Porcalová (Eds), *Hydrobiologie a kvalita vody údolních nádrží*. CSVTS, České Budějovice, pp. 72–83.
- Paul, L., Schrüter, K. and Labahn, J., 1998. Phosphorus elimination by longitudinal subdivision of reservoirs and lakes. *Water Sci. Technol.*, 37(2): 235–244.
- Peňáz, M., Kubíček, F., Marvan, P. and Zelinka, M., 1968. Influence of the Vir River Valley Reservoir on the hydrobiological and ichthyological conditions in the River Svratka. *Acta Scientiarum Naturalium Academiae Scientiarum Bohemoslovacae*, Brno, 2: 1–60.
- Petts, G.E., 1984. *Impounded Rivers*. John Wiley and Sons, Chichester.

- Petts, G.E., 1986. Water quality characteristics of regulated rivers. *Progress in Physical Geography*, 10: 492–512.
- Petts, G.E., 1989. Perspectives for ecological management of regulated rivers. In: J.A. Gore and G.E. Petts (Eds), *Alternatives in Regulated River Management*. CRC Press, Boca Raton, FL, pp. 3–24.
- Pirozhnikov, P.L., 1984. The bioproductional effect of the impoundment of large rivers and its importance for fishery economy. *Verh. Int. Verein. Limnol.*, 18: 822–832.
- Ploskey, G.R., 1983. A review of the effects of water-level changes on reservoir fisheries and recommendations for improved management. Technical Report E-83-3. U.S. Army Eng. Waterways Sta., Vicksburg, MS.
- Ploskey, G.R., 1986. Effects of water level changes on reservoir ecosystems with implications for fisheries management. In: G.E. Hall and M.J. Van Den Avyle (Eds), *Reservoir Fisheries Management: Strategies for the 80s*. Reservoir Committee, Southern Division American Fisheries Society, Bethesda, MD, pp. 86–97.
- Price, R.E. and Meyer, E.B., 1992. *Water Quality Management for Reservoirs and Tailwaters*. (Report 2) Operational and Structural Water Quality Enhancement Techniques. Technical Report E-89-1. U.S. Army Eng. Waterways Sta., Vicksburg, MS.
- Pütz, K., 1995. The importance of pre-reservoirs for the water-quality management of reservoirs. *J. Water SRT-Aqua*, 44: 50–55.
- Pütz, K. and Benndorf, J., 1998. The importance of pre-reservoirs for the control of eutrophication of reservoirs. *Water Sci. Technol.*, 37(2): 317–324.
- Quintero, J.E. and Garton, J.E., 1973. A low energy lake destratifier. *Trans. Amer. Soc. Agricultural Engineers*, 16: 973–978.
- Richter, B.D., Baumgartner, J.V., Wigington, R. and Braun, D.P., 1997. How much water does a river need? *Freshw. Biol.*, 37: 321–249.
- Robbins, T.W. and Marthur, D., 1976. The muddy run pumped storage project: A case history. *Trans. Amer. Fish. Soc.*, 1: 165–172.
- Ryding, S.-O. and Rast, W., 1989. *The Control of Eutrophication of Lakes and Reservoirs*. Man and the Biosphere Programme, Vol. 1. Parthenon Press, UK, 311 pp.
- Scheffer, M., 1998. *Ecology of Shallow Lake*. Chapman and Hall, Chichester.
- Schindler, J.E., Speziale, B.J., Mellichamp, S.P., Robertson, E.E. and Hains, J.J., 1995. The effect of pump storage power generation on water column optical features and plankton dynamics in the forebay of Richard B. Russel Reservoir. *Lake Reserv. Manage.*, 11(3): 245–253.
- Schreiber, J.D. and Rausch, D.L., 1979. Suspended sediment–phosphorus relationships for the inflow and outflow of a flood detention reservoir. *J. Environ. Qual.*, 8: 510–514.
- Søballe, D.M., Kimmel, B.L., Kennedy, R.H. and Gaugush, R.F., 1992. *Reservoirs. Biodiversity of the Southeastern United States: Aquatic Communities*. John Wiley and Sons, London, pp. 421–474.
- Straškraba, M., 1990. Limnological particularities of multiple reservoirs. *Arch. Hydrobiol. Beih. Ergebn. Limnol.*, 33: 677–678.
- Straškraba, M., 1998a. Coupling of hydrobiology and hydrodynamics: Lakes and reservoirs. In: J. Imberger (Ed.), *Physical Limnology. Coastal and Estuarine Studies*, Vol. 54. American Geophysical Union, Washington, pp. 623–644.
- Straškraba, M., 1998b. Limnological differences between deep valley reservoirs and deep lakes. *Int. Review Hydrobiol.*, 83(Special Issue): 1–12.

- Straškraba, M., 1999. Retention time as a key variable of reservoir limnology. In: J.G. Tundisi and M. Straškraba (Eds), *Theoretical Reservoir Ecology and Its Applications*. International Institute of Ecology, Brazilian Academy of Sciences and Backhuys Publishers, Leyden, pp. 385–410.
- Straškraba, M. and Mauersberger, P., 1988. Some simulation models for water quality management of shallow lakes and reservoirs and a contribution to ecosystem theory. In: W.J. Mitsch, M. Straškraba and S.E. Jørgensen (Eds), *Wetland Modelling*. Elsevier, Amsterdam, pp. 153–176.
- Straškraba, M. and Tundisi, J.G., 1999. *Reservoir Water Quality Management. Guidelines of Lake Management, Vol. 9*. International Lake Environment Committee, Kusatsu, Japan.
- Straškraba, M., Tundisi, J.G. and Duncan, A., 1993. *Comparative Reservoir Limnology and Water Quality Management*. Kluwer Acad. Publishers, Dordrecht.
- Straškraba, M., Blažka, P., Brandl, Z., Desortová, J., Komárková, J., Kubečka, J., Procházková, L. and Sed'a, J., 1987. A hypothesis on reservoir aging. *Arch. Hydrobiol. Beih. Ergebn. Limnol.*, 33: 803.
- Straškraba, M., Dostálková, I., Hejzlar, J. and Vyhánek, V., 1995. The effect of reservoirs on phosphorus concentration. *Int. Rev. Ges. Hydrobiol.*, 80: 403–413.
- Straškrabová, V., Komárková, J. and Vyhánek, V., 1993. Degradation of organic substances in reservoirs. *Water Sci. Technol.*, 28(6): 95–104.
- Thornton, J.A., Rast, W., and Steele, W., 1996. Reservoirs. In: D. Chapman (Ed.), *Water Quality Assessments*, E&FN Spon, Routledge Publishers, UK, pp. 369–412.
- Thornton, J.A., Rast, W., Holland, M.M., Jolankai, G. and Ryding, S.-O., 1999. *Assessment and Control of Nonpoint Source Pollution of Aquatic Ecosystems. A Practical Approach*. Man and Biosphere Series, Vol. 23. Parthenon Publishing Group, Paris.
- Tundisi, J.G., 1984. Estratificação hidráulica em reservatórios e suas consequências ecológicas. *Cienc. Cult.*, 36: 1498–1504.
- Tundisi, J.G., 1986. Limnologia de represas artificiais. *Bol. Hidraul. Sameam*, 11: 1–46.
- Tundisi, J.G., 1993. Theoretical basis for reservoir management. *Verh. Int. Verein. Limnol.*, 25: 1153–1156.
- Tundisi, J.G., Carlos, S. and Matsumura-Tundisi, T., 1990. Limnology and eutrophication of Barra Bonita reservoir, S. Paulo State, Southern Brazil. *Arch. Hydrobiol. Beih. Ergebn. Limnol.*, 33: 661–676.
- Tundisi, J.G., Matsumura-Tundisi, T., Calijuri, M.C. and Novo, E.M.L., 1991. Comparative limnology of five reservoirs in the middle Tiete River, S. Paulo State. *Verh. Int. Verein. Limnol.*, 24: 1489–1498.
- Tundisi, J.G., Bicudo, C.E.M. and Matsumura-Tundisi, T. (Eds), 1995. *Limnology in Brazil*. Brazilian Acad. Sciences, Brazilian Limnological Society, Brazil.
- Tundisi, J.G., Matsumura-Tundisi, T. and Rocha, O., 1999a. Ecossistemas de águas interiores. In: A.C. da Reboças, B. Braga and J.G. Tundisi (Eds), *Águas Doces no Brasil*. São Paulo, Escrituras Editora, pp. 153–192.
- Tundisi, J.G., Matsumura-Tundisi, T. and Rocha, O., 1999b. Theoretical basis for reservoir management. In: J.G. Tundisi and M. Straškraba (Eds), *Theoretical Reservoir Ecology and Its Applications*. International Institute of Ecology, Brazilian Academy of Sciences and Backhuys Publishers, Leiden, pp. 505–528.
- Turner, R.R., Laws, E.A. and Harris, R.C., 1983. Nutrient retention and transformation in relation to hydraulic flushing rate in a small impoundment. *Freshw. Biol.*, 13: 113–127.
- Uhlmann, D. and Benndorf, J., 1980. The use of primary reservoirs to control eutrophication caused by nutrient inflows from non-point sources. In: N. Duncan (Ed.), *Proceedings: Land Use Impact on Lake and Reservoirs Ecosystems*, May 26–June 2, 1978, Warsaw.

- Uhlmann, D., Benndorf, J. and Albert, W., 1971. Prognose des Stoffhaushaltes von Staugewässern mit Hilfe kontinuierlicher oder semikontinuierlicher Modelle. I. Grundlagen. *Intern. Rev. Ges. Hydrobiol.*, 56: 513–539.
- UNEP/UNESCO (United Nations Environment Programme and United Nations Education, Scientific and Cultural Organization), 1990. *The Impact of Large Water Projects on the Environment. Proceedings of an international symposium. Paris, 1986.* The Unesco Press, Paris, 316 pp.
- Ward, J.V., Davies, B.R., Breen, C.M., Cambray, J.A., Chutter, F.M., Day, J.A., de Moor, F.C., Heeg, J., O’Keeffe, J.H. and Walker, K.F., 1984. Stream regulation. In: R.C. Hart and B.R. Allanson (Eds), *Limnological Criteria for Management of Water Quality in the Southern Hemisphere.* South African National Scientific Programmes Report no 93, pp. 32–63.
- Wetzel, R.G., 1983. *Limnology* (2nd edn). Saunders College Publ., New York, NY, 767 pp.
- Wetzel, R.G., 1990. Reservoir ecosystems: Conclusions and speculations. In: K.W. Thornton, B.L. Kimmel and F.E. Payne (Eds), *Reservoir Limnology: Ecological Perspectives.* John Wiley and Sons, New York, NY, pp. 227–238.
- Wilhelmus, B., Bernhardt, H. and Neumann, D., 1978. Vergleichende Untersuchungen über die Phosphoreliminierung von Vorsperren—Verminderung der Algenentwicklung in Speicherbecken und Talsperren. *DVGW Schriftenreihe Wasser*, 16: 140–176.
- World Bank, 1993. *Water Resources Management. A World Bank Policy Study.* World Bank, Washington, DC.
- Yogo, N., Inoue, S., Haga, M. and Ioriya, T., 1997. Effects of selective intake management on the environment of a reservoir. In: P. Dolejš and N. Kalousková (Eds), *Reservoir Management and Water Supply—An Integrated System, Vol. 2.* W&ET Team, Czech Republic, pp. 25–32.
- Zalewski, M. and Dobrowolski, A., 1994. Manipulation and monitoring of water level in a reservoir as a tool for improvement of water quality by control of biotic mechanisms. *Commission Internationale Des Grands Barrages, Durban*, pp. 135–142.