

---

## **Chapter 8\* - Reservoirs**

---

*\*This chapter was prepared by J. Thornton, A. Steel and W. Rast*

### **8.1. Introduction**

Reservoirs are those water bodies formed or modified by human activity for specific purposes, in order to provide a reliable and controllable resource. Their main uses include:

- drinking and municipal water supply,
- industrial and cooling water supply,
- power generation,
- agricultural irrigation,
- river regulation and flood control,
- commercial and recreational fisheries,
- body contact recreation, boating, and other aesthetic recreational uses,
- navigation,
- canalisation, and
- waste disposal (in some situations).

Reservoirs are usually found in areas of water scarcity or excess, or where there are agricultural or technological reasons to have a controlled water facility. Where water is scarce, for example, reservoirs are mainly used to conserve available water for use during those periods in which it is most needed for irrigation or drinking water supply. When excess water may be the problem, then a reservoir can be used for flood control to prevent downstream areas from being inundated during periods of upstream rainfall or snow-melt. Particular activities such as power generation, fish-farming, paddy-field management or general wet-land formation, for example, are also met by constructing reservoirs. By implication, they are also water bodies which are potentially subject to significant human control, in addition to any other impact. Reservoirs are, nonetheless, a considerable, frequently undervalued, water resource: approximately 25 per cent of all waters flowing to the oceans have previously been impounded in reservoirs (UNEP, 1991).

Reservoirs range in size from pond-like to large lakes, but in relation to natural lakes the range of reservoir types and morphological variation is generally much greater. For example, the most regular, and the most irregular, water bodies are likely to be reservoirs. This variability in reservoirs, allied to management intervention, ensures that

their water quality and process behaviour is even more variable than may be characterised as limnologically normal. As reservoirs are so variable, it can often be misleading to make any general statements about them without significant qualification as to their type.

Reservoirs do, nevertheless, share a number of attributes with natural lakes and some are even riverine in their overall nature. Generally, all reservoirs are subject to water quality requirements in relation to a variety of human uses. The variation in design and operation of control structures in reservoirs can provide greater flexibility and potential for human intervention than in natural lakes (and, therefore, considerable scope for management and control) with the objective of achieving a desired water quality. However, the nature of the intervention or control can complicate the development and operation of water quality monitoring programmes, as well as the interpretation of resultant data (especially as the nature of these controls may vary over time, altering the responses of the system). For reservoirs, therefore, the assessment process must take full account of the direct management influences on the water body.

### **8.1.1 Definitions**

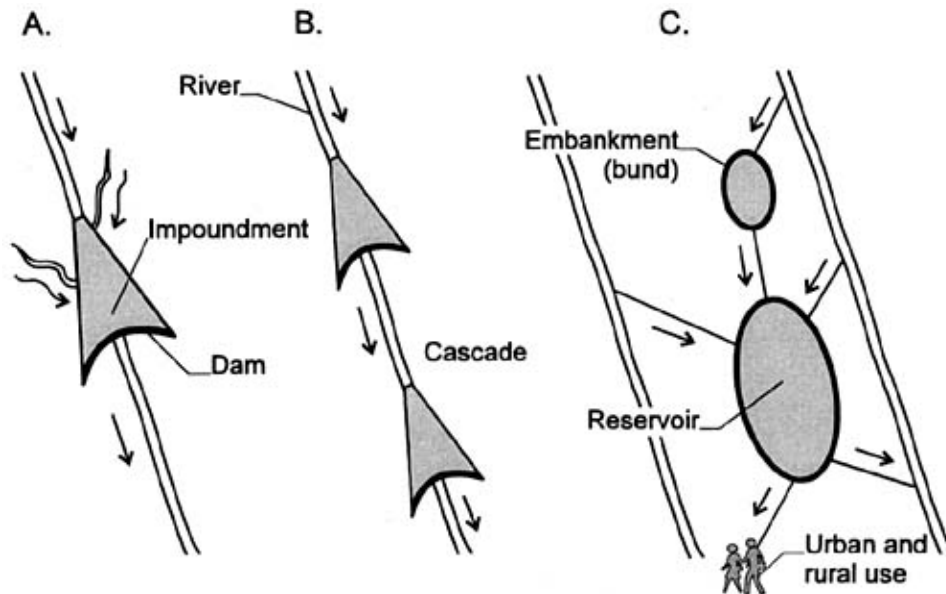
Unfortunately, descriptive nomenclature of artificially created water bodies is frequently confusing. The term “dam” is often applied to both the physical structure retaining the water, and the water so retained. For the purposes of this chapter, dam will be used solely to describe the physical structure, and the term reservoir will be used to denote the artificially created water body. A reservoir is therefore:

- a water body contained by embankments or a dam, and subsequently managed in response to specific community needs; or
- any natural waters modified or managed to provide water for developing human activities and demands.

Reservoirs formed by a dam across the course of a river, with subsequent inundation of the upstream land surface are often called impoundments. Water bodies not constructed within the course of the river and formed by partially or completely enclosed water-proof banks (and usually filled by diverted river flows or pipes) are often referred to as off-river, or banded, reservoirs. Reservoirs created by dams or weirs serially along a river course form a cascade (Figure 8.1).

Impoundments and off-river reservoirs, therefore, form the two main artificially created water body types in which differing amounts of human control are possible, and which are usually very different in their morphology. Impoundments tend to be larger, more sinuous and dendritic than off-river reservoirs, and the main control of their contained volume of water can usually only be exercised at an outlet (in other reservoirs both input and output are controllable). Off-river reservoirs are often virtually completely isolated from the local terrain by enclosing and water-proofed embankments, whereas impoundments are subject to considerable interaction with the flood plain within which they were formed.

**Figure 8.1 Various types of reservoirs: A. Reservoir created by damming a river; B. A cascade formed from a series of river impoundments (the upstream reservoir may be known as a pre-impoundment); C. Bunded or embanked reservoirs with controlled inflows and outflows to and from one or more rivers.**

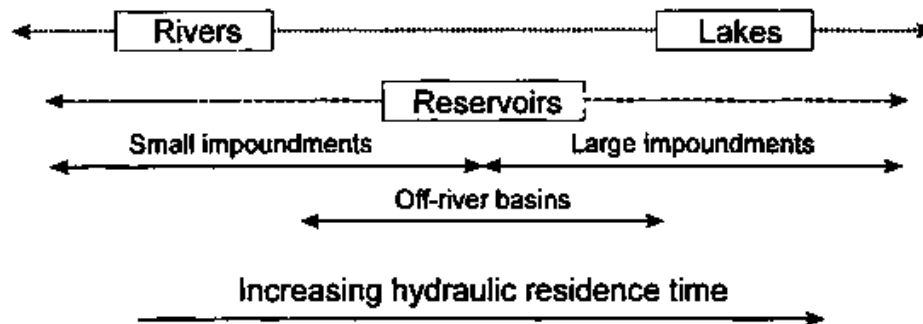


The wide variation in size and application of reservoirs results in them forming an intermediate type of water body between rivers and natural lakes (Figure 8.2; see also section 1.1), although the simple implications of this may often be subject to considerable behavioural distortion because of artificial management control effects.

## **8.2. Construction and uses**

Much of the variation in construction of reservoirs is the result of the original purposes for which they were constructed, although their principal uses can change over time. Other elements of variation in form are introduced as a result of regional geology and the availability of construction materials. For example, where clay deposits are plentiful, dam or embankment construction may be based on earthen structures with impervious clay cores, while in other areas dams may be constructed solely of massed concrete.

**Figure 8.2 The intermediate position of reservoirs between rivers and natural lakes is determined by their water residence time and degree of riverine influence  
(Based on Kimmel and Groeger, 1984)**



### 8.2.1 Typology

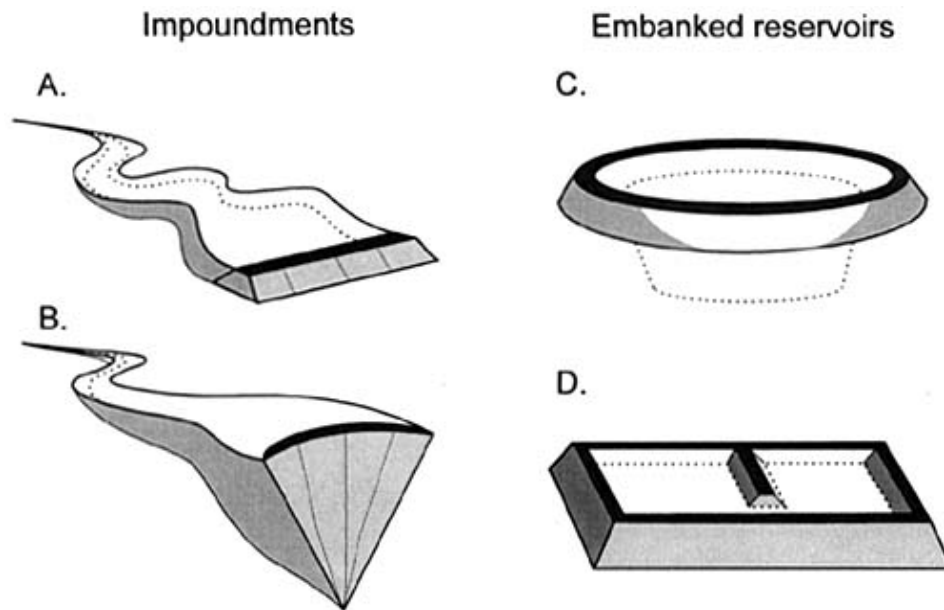
Figure 8.3 shows some generic reservoir forms. It is important to realise that such different forms, for similar volumes stored, can cause major differences in the physico-chemical and biological nature of the stored waters (see section 8.3).

#### *Impoundments*

Impoundments are formed from a variety of types of dam (Linsley and Franzini, 1972): earth-fill, gravity, arch, buttress and other, minor types. Earth-fill dams (e.g. Figure 8.3A) are the most common; about 85 per cent of dams in the 15 m to 60 m height range are of this type of construction (van der Leeden *et al.*, 1990). Arched dams are most commonly used in situations demanding extremely high walls, and account for about 40 to 50 per cent of the very large dams exceeding 150 m in height (Figure 8.3B). Small structures, of 3 m to 6 m in height, created to divert or impound water flow for various purposes can also be constructed by, for example, bolted timber structures. This form of dam typically has a life of only about 10 to 40 years. Novel technologies may also be used, such as inflatable dam structures which can be cheap to install and maintain, and may be collapsed in order to scour the dam bed.

Dammed rivers form the largest reservoirs; up to 150 km<sup>3</sup> in the case of the Aswan High Dam. Usually, their maximum depth is much greater than their mean depth (often nearly 3:1) and as a result a considerable proportion of their volume is derived from the quite shallow (i.e. littoral) areas which were created when the former riverine flood plain was permanently flooded. Impoundments tend to have higher watershed area to water surface area ratios than similar lakes. They also have a tendency to a sinuous form and a convoluted shoreline as a result of the artificial inundation of a terrain which would not otherwise contain a similar sized natural lake. This complex form and the tendency to have substantial shallows and deep sumps leads to horizontal and lateral heterogeneity in their physico-chemical and biological water quality variables (Figure 8.4) (see also section 8.3 and Figures 8.14 and 8.18). The differences mentioned above are highlighted by the comparison of reservoirs and natural lakes in North America given in Table 8.1.

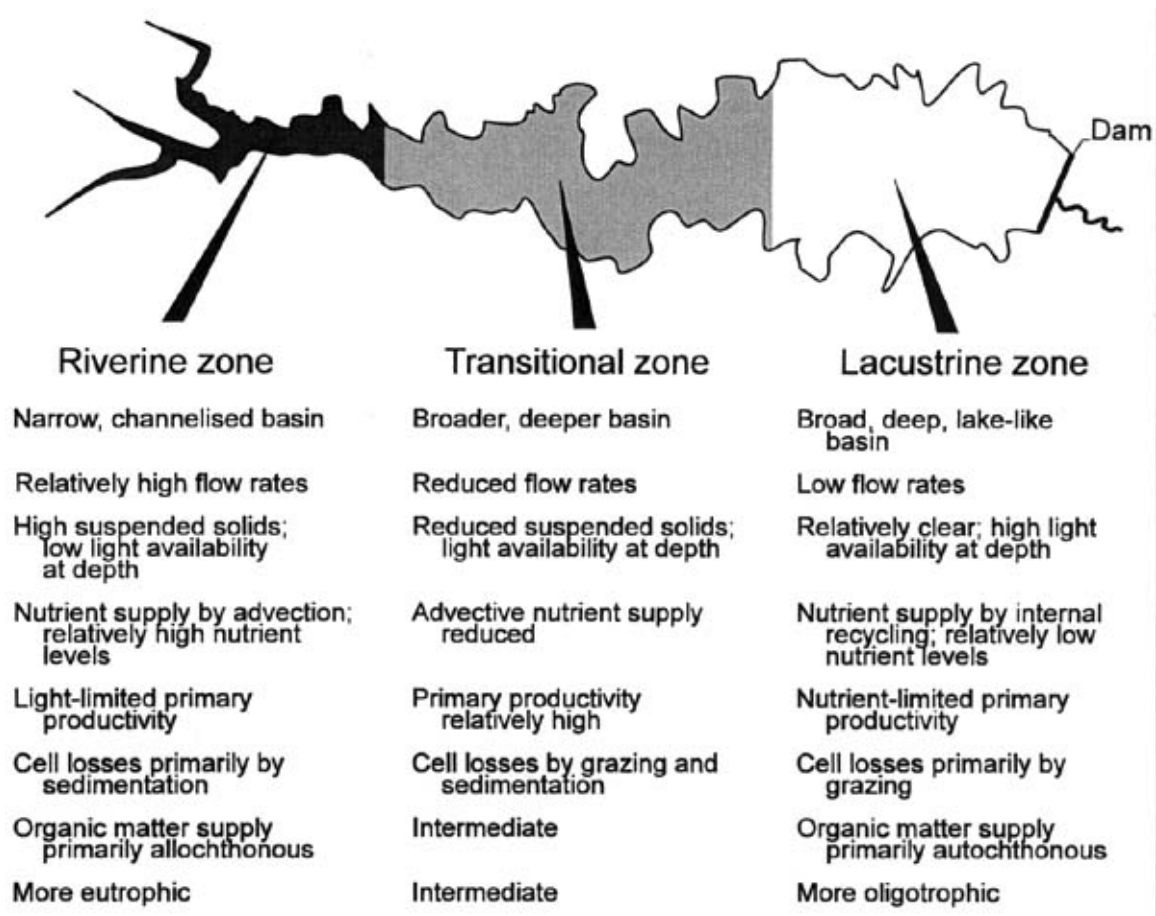
**Figure 8.3 Examples of the principal reservoir configurations: A. shallow, 'U' shaped; B. deep, 'V' shaped; C. deep, regular; D. shallow, regular**



#### *Other reservoirs*

Off-river reservoirs frequently have to be wholly constructed. This normally entails forming an embankment about the border of the reservoir site. Embankments are most often either concrete or clay-cored earth structures. Earth embankments are normally protected by stone or concrete on the water side. Further walling (baffles) may be placed within the reservoir site in order to cellularise the basin and control flow patterns. The reservoir volume is usually formed by excavation of the site, together with elevation of the embankment. As embankment slopes are normally in the order of 5:1, a high embankment would have a considerable ground-level footprint, and a compromise on embankment height is generally necessary in order to maximise the volume storage on any particular site.

**Figure 8.4 Longitudinal zonation of water quality conditions in reservoirs with complex shapes formed by damming rivers (Modified from Kimmel and Groeger, 1984)**



Embanked reservoirs are generally very simple in shape (from near-circular to rectangular) and virtually uniform in depth (Figure 8.3C, D). Generally, mean depths are greater than 80 per cent of the maximum depths and the volumes contained are less than  $100 \times 10^6 \text{ m}^3$  ( $0.1 \text{ km}^3$ ). Their tendency to great regularity in shape is indicated by shoreline development ratios ( $D_L$ ) of between 1 and 2, compared with values of 5 to 9 for impoundments (see Table 8.1 for an explanation of shoreline development). This regularity tends to reduce horizontal variability in physical, chemical and biological variables, particularly when associated with relatively short retention times. Apart from any management impacts, these morphological features influence the ecological behaviour of such reservoirs, and so must be taken into account fully during the planning of monitoring and assessment programmes (see sections 8.3 and 8.5).

**Table 8.1** A comparison of geometric mean values for some selected variables from natural lakes and reservoirs in North America

Variable	Natural lakes	Reservoirs	Probability that mean values are equal
Number of water bodies (n)	107	309	
<i>Morphometric variables</i>			
Surface area (km <sup>2</sup> )	5.6	34.5	0.0001
Watershed area (km <sup>2</sup> )	222.0	3,228.0	0.0001
Watershed: surface area ratio	33.1	93.1	0.0001
Maximum depth (m)	10.7	19.8	0.0001
Mean depth (m)	4.5	6.9	0.0001
Shoreline development ratio (D <sub>L</sub> ) <sup>1</sup>	2.9 (n = 179)	9.0 (n = 34)	0.001
Areal water load (m a <sup>-1</sup> )	6.5	19.0	0.0001
Water residence time (years)	0.74	0.37	0.0001
<i>Water quality variables</i>			
Total phosphorus (mg m <sup>-3</sup> )	54.0	39.0	0.02
Chlorophyll a (mg m <sup>-3</sup> )	14.0	8.9	0.0001
Areal phosphorus load (g m <sup>-2</sup> a <sup>-1</sup> )	0.87	1.7	0.0001
Areal nitrogen load (g m <sup>-2</sup> a <sup>-1</sup> )	18.0	28.0	0.0001

<sup>1</sup> Shoreline development, D<sub>L</sub> is a crude measure of surface complexity and is defined as the ratio of a water body's actual shoreline length to the circumference of a circle having the same area as that of the water body. D<sub>L</sub> is thus some measure of how nearly circular(= regular) is the plan form of a water body and typical values are:

Shape	D <sub>L</sub>
Circle	1
5:1 Rectangle or Ellipse	≈1.5
10:1 Triangle	≈2.5
Natural Lakes	2-5
Impoundments	3-9

Sources: Hutchinson, 1957; Leidy and Jenkins, 1977; Thornton *et al.*, 1982; Ryding and Rast, 1989

## 8.2.2 Uses

Reservoirs are generally used for water storage along a river course, for off-river water storage, or for inter-basin water transfer schemes. The latter usually require a variety of storage and transfer structures. An understanding of the natural and artificial influences common to these various uses helps in the interpretation or prediction of the physical, chemical and biological behaviour of the reservoir.

### *Impoundments and cascades*

Impoundments formed by dams are the most common form of large reservoirs (Veltrop, 1993) and can occur singly or in series on a water course as a cascade, where water passing through or released from one impounded section flows into a second, and so on. Examples include the Volga-Kama cascade in Russia (Znamenski, 1975) the Vlatava cascade in the Czech republic (Straskrabá and Straskrabová, 1975), the Tietê complex in Brazil (Tundisi, 1981) and the Highland Lakes of central Texas, USA (Rast, 1995). Depending on the topography of the land surrounding the river upstream of the dam wall, these impoundments can be dendritic to varying extents. In extreme cases, the impounded waters are riverine in appearance and with complex shorelines. In less extreme cases, the impoundment basins can mimic natural lakes, being more rounded and less riverine.

The creation of cascades can yield water quality benefits to the impounded sections downstream as a result of the retention of contaminants in the upstream impoundment. In such cases, the upstream impoundment has sometimes been referred to as a pre-impoundment. Many chemical and biological variables can be affected in lakes and reservoirs downstream of a major impoundment, as illustrated in Figure 8.5.

### *Off-river storage*

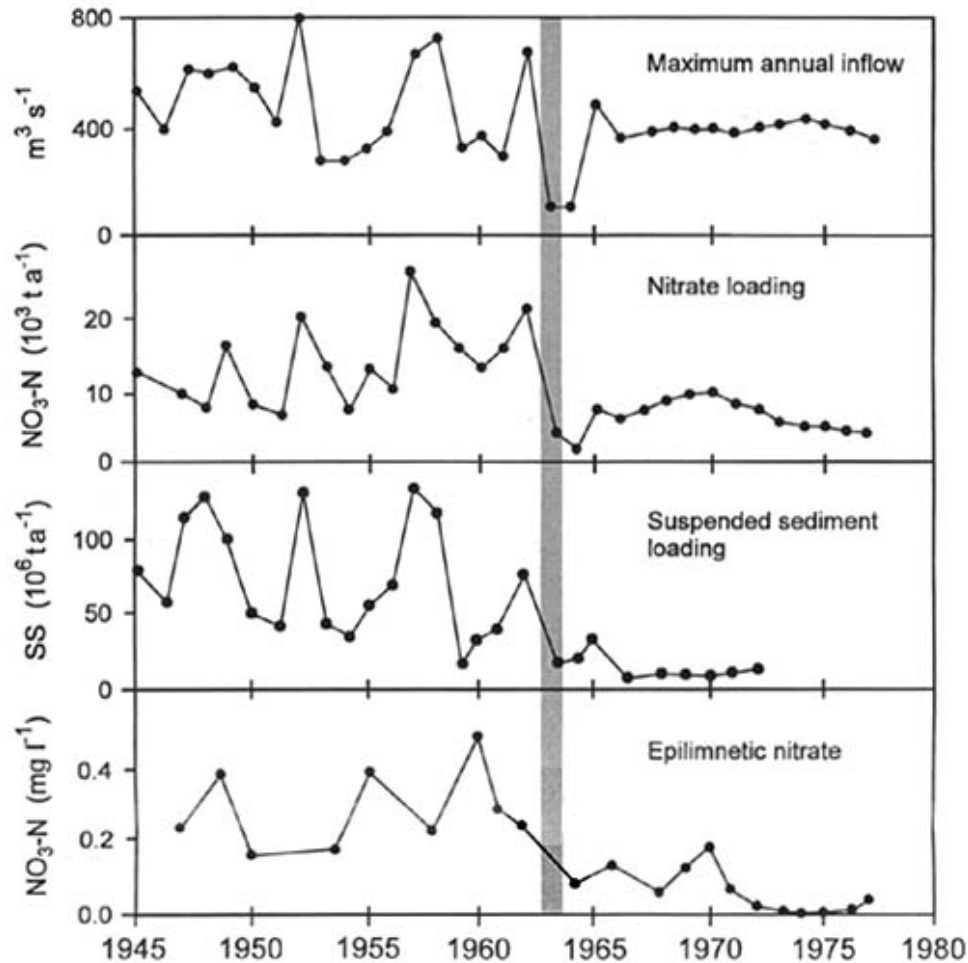
Off-river storage is usually achieved by constructing reservoirs (with embankments) off the main course of the river, although usually relatively close to it. They may be operated singly or in series. These reservoirs are frequently used for water supply purposes, acting as a means of controlling and modifying water quality and quantity transferred from the river to the treatment plant. They may also be used as a local resource for activities such as fish-farming or agricultural purposes (particularly rice cultivation) (Schiemer, 1984). Off-river storage reservoirs are generally filled and emptied by pumping, although some are designed to capture flood flows which enter the reservoir by gravity via a diversion channel or similar mechanism.

### *Inter-basin transfers*

Inter-basin transfer schemes are artificial hydrological systems which, because of their operation and potential impacts, require specific attention. Inter-basin transfer schemes often occur in water-poor regions, where water resources engineering efforts have been traditionally directed towards providing water from a variety of sources to centres of human settlement (Petitjean and Davies, 1988). This requires water to be drawn from watersheds outside of that in which the settlement was established, necessitating the transfer of water from one watershed to another. Transfers may be achieved in several ways, including pumping, but the most common involves creating a network of canals, balancing reservoirs and storages which make optimum use of gravity flows. While these integrated systems generally make use of natural water courses wherever possible to convey waters between catchments, they occasionally create balancing reservoirs that bear a greater resemblance to off-river storages than to the more traditional form of in-stream impoundment because the inflow and outflow are artificially created (i.e. the basin previously had no natural outlet and was internally drained).



**Figure 8.5 Effects of an upstream reservoir (Lake Powell) on some selected water quality characteristics of the downstream Lake Mead, USA. The shaded bar indicates the completion of the dam and the formation of the reservoir. (After Prentki and Paulson, 1983)**



Variants of such schemes include pumped-storage facilities where waters are alternately drained from, and returned to, reservoirs usually as a means of generating hydro-electricity during periods of peak demand (using power generated by other sources at other times to pump the water back up-gradient). This same technique has been used during drought periods in the Vaal River, South Africa, to reverse the river flow and augment water availability in upstream water supply reservoirs (DWA, 1986). Each of these operating regimes presents specific challenges for the monitoring and characterisation of water quality.

### 8.3. Special characteristics of reservoirs

The form and operation of reservoirs can have such an influence on their water quality characteristics that it is usually necessary to adopt some modifications to the more common strategies for assessment of water quality used in natural lakes. Reservoir

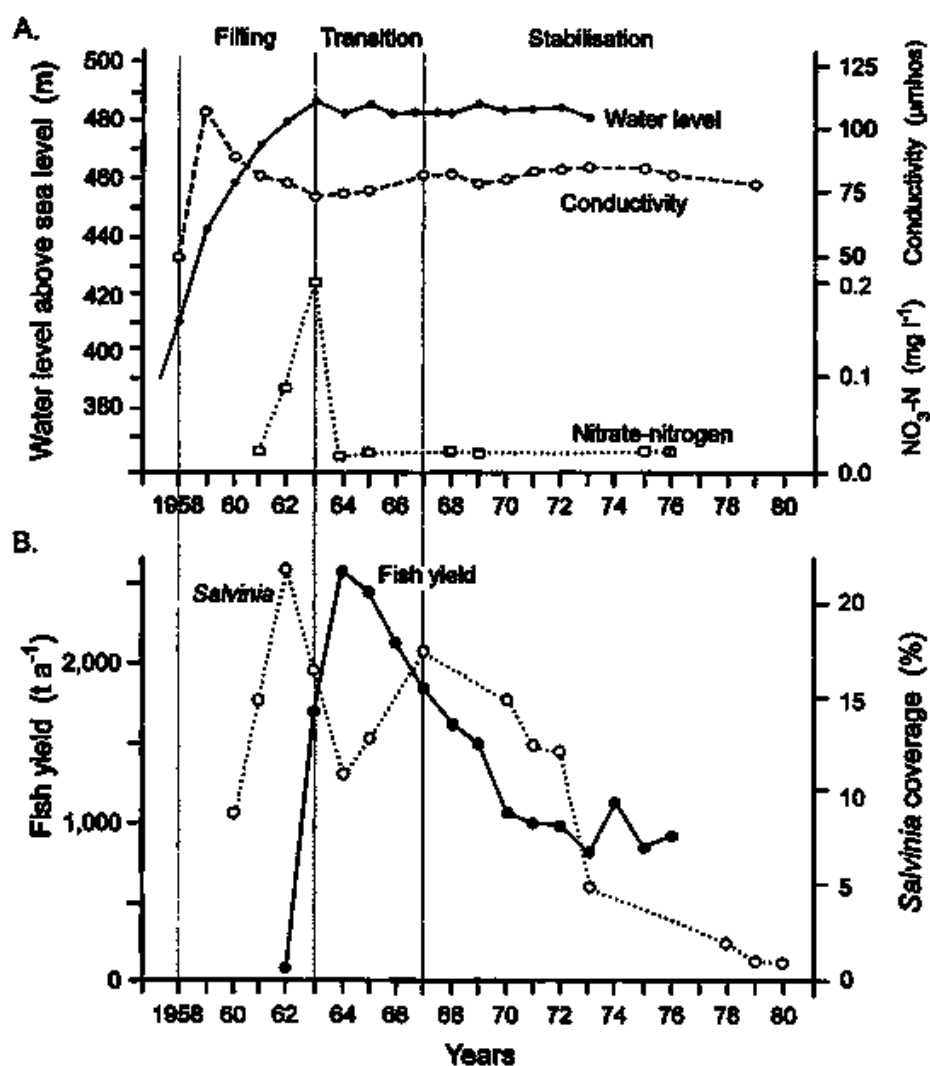
characteristics are, therefore, described in some detail in relation to their form and operation in the following sub-sections.

Reservoirs in densely populated or agricultural areas, and which receive little management control, have a tendency to be highly enriched although some also have a more rapid flushing regime than natural lakes which partly masks this enrichment effect (see section 8.4.1). There is, therefore, a potentially high dependency of productive capacity on management regime, source water qualities, and internal chemical and biological process rates.

Reservoirs show many of the same basic hydrodynamic, chemical and biological characteristics as the natural lakes described in Chapter 7. However, even when reservoirs are formed by the damming of a single river, creating water bodies which may look very much like natural lakes, the operating regime determined by the purpose for which the reservoirs were created (e.g. hydro-power generation, irrigation or domestic water supply) may significantly alter their physico-chemical character and biological responses. These responses may also be made more difficult to interpret as a result of the changing demands placed on such reservoirs over time (such as additional recreational uses). In most instances, the peculiar form of a reservoir, its mode of operation, and an unnatural location and shape may cause considerable, actual variation of the basic limnological behaviour (Straskrabá *et al.*, 1993).

Reservoirs formed by river impoundment undergo great changes in water quality during the early stages of their formation whilst a new ecological balance is becoming established. Balon and Coche (1974) were among the first to identify and document the sequence of eutrophication, recovery, and stabilisation following impoundment using data from Lake Kariba, Zimbabwe, the then-largest reservoir in the world (volume 160 km<sup>3</sup>; area 5,100 km<sup>2</sup>). Their work showed that the release of organically-bound elements from flooded vegetation, excreta and soils could result in an initial high level of biological production (sometimes called a trophic surge), suggesting a very different water quality than would actually be seen in the future. The duration of this increased productivity varies with the amounts of source material present within the flooded river basin, the nature of the soils and previous land uses, the elemental concentrations in the source waters and the degree of basin clearing prior to inundation (Figure 8.6). In these transient conditions, particularly careful assessment of the water quality is essential for the effective management of the reservoir. Some general effects of impounding running waters are summarised in Table 8.2.

Figure 8.6 The changes occurring after the filling of Lake Kariba, Zimbabwe, showing the transition to stabilised conditions. A. Variations in water level, salinity and nitrate-nitrogen. B. Coverage by the aquatic plant *Salvinia molesta* and total yields from the inshore fishery on the Zimbabwean side of the reservoir. (Based on Marshall and Junor, 1981 and Marshall *et al.*, 1982)



**Table 8.2** Changes in water quality characteristics arising in water bodies created by impoundment compared with the characteristics of a river prior to impoundment

Characteristics of river stretch	Not impounded	Minor impoundment	Major impoundment/chain of impoundments
Flow velocity at mean low water discharge	20 cm s <sup>-1</sup>	5-10 cm s <sup>-1</sup>	5 cm s <sup>-1</sup>
Residence time in the area of impoundment	na	1-5 days	> 5 days
Mean depth of water	1.5 m	2-5 m	5 m
Physical O <sub>2</sub> input per unit of volume	xxx	xx	x
Day/night fluctuations of O <sub>2</sub> concentration; tendency to O <sub>2</sub> supersaturation	x	xx	xxx
Self-purification of organic pollution <sup>1</sup>	x	xx	xxx
Ammonia oxidation	xxx	xx	xx
Fine sediment deposition at low discharges	-	x	xxx
Resuspension of fine sediment at high discharges	xxx	xx	x
O <sub>2</sub> depletion in sediment	-	x	xxx
Turbidity due to suspended sediment	xxx	xx	x
Secondary pollution, algal growth and turbidity due to algae	x	xx	xxx
Development of higher aquatic plants	x	xx	xxx

x to xxx Minor to significant effect

- Negligible or no effect

na Not applicable

<sup>1</sup> Resulting from biological activity

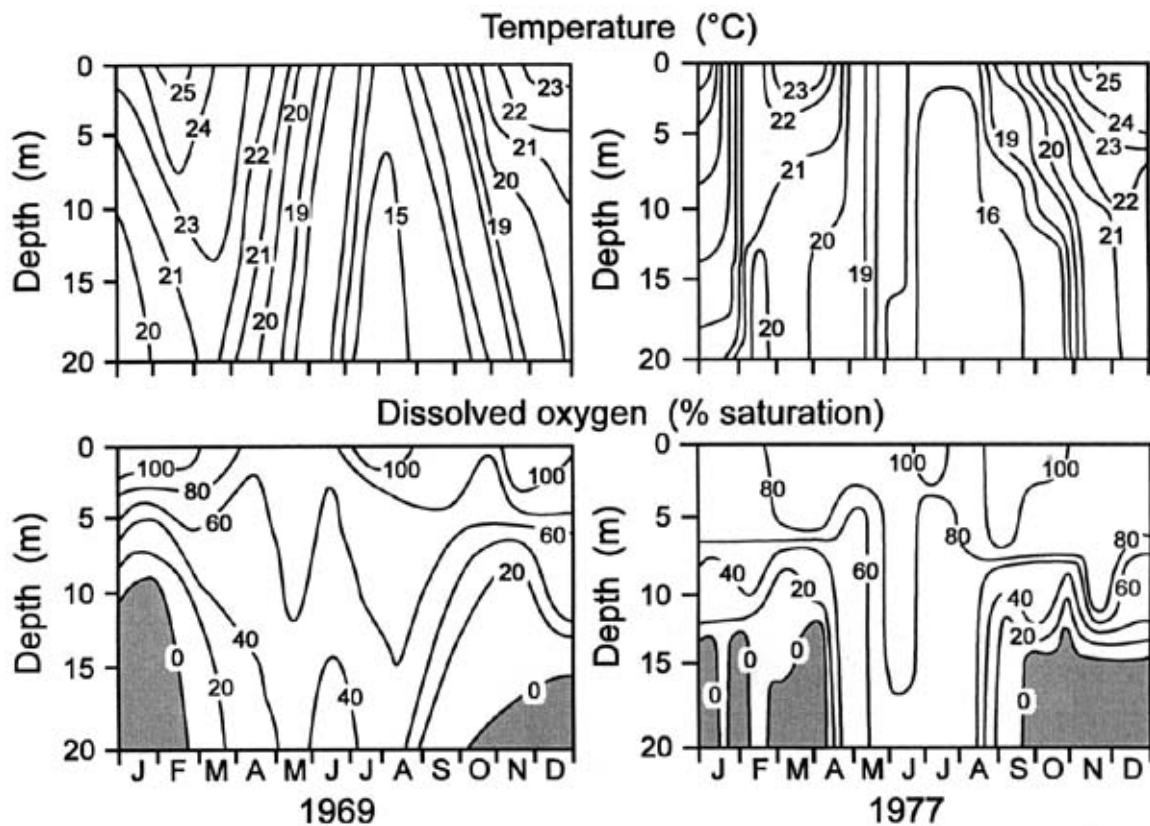
The following sub-sections give some examples of ways in which the water quality characteristics of reservoirs are influenced by reservoir type and operation to an extent that significantly different monitoring and assessment strategies may be required from those recommended for natural lakes.

### 8.3.1 Thermal characteristics

Most reservoirs experience the same thermal structure development as lakes. If sufficiently deep they become dimictic in temperate areas, or monomictic in polar and

tropical areas, during their annual cycle. Many reservoirs are, however, polymictic due to their relatively shallow depths or the effects of enhanced flow induced turbulence. In part, their tendency towards thermal stratification is determined by the geography of their basins. Reservoirs constructed on broad flood plains are generally less deep and more susceptible to multiple mixing that those constructed in confined river channels, canyons or ravines. A particular problem associated with thermal stratification is the potentially large variations in water quality that may be induced by internal waves (seiches) at fixed-level off-takes at the reservoir shores. These seiches can have a range sufficiently great to present epilimnetic water (warm, oxygenated and with a high algal density) and hypolimnetic water (cold, anoxic, concentrated  $\text{Fe}^{3+}$ ,  $\text{Mn}^{3+}$ ,  $\text{H}_2\text{S}$ , etc.) alternately to the outlet. This can create particular problems for water users requiring a constant water quality. Similar events may occur transiently under periods of sustained wind-stress.

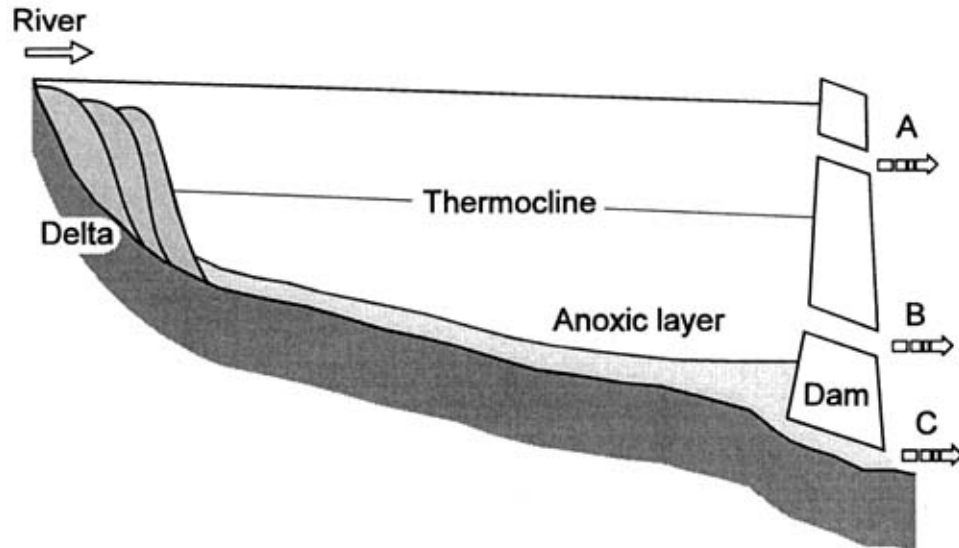
**Figure 8.7 Variation in the seasonal temperature and dissolved oxygen profiles of Lake Chivero, Zimbabwe 1969 and 1977 (Modified from Thornton, 1982)**



In tropical reservoirs, as with lakes, the onset of stratification occurs over a smaller temperature range as a result of the higher ambient temperatures in these systems (Serruya and Pollinger, 1983). Figure 8.7 shows summarised data for oxygen and temperature for Lake Chivero, Zimbabwe (volume  $250 \times 10^6 \text{ m}^3$ ; area  $26 \text{ km}^2$ ) (Thornton, 1982). The isopleths illustrate the monomictic condition typical of many warm water lakes, but also show the same reservoir undergoing multiple annual mixings in 1977 (a rare event in this reservoir). Reservoirs can exhibit greater intra-annual variability than natural lakes and their annual variation can be affected by changes in operational

protocols and water usage. These characteristics must be considered when drawing possible conclusions about time-based trends in water quality within reservoirs.

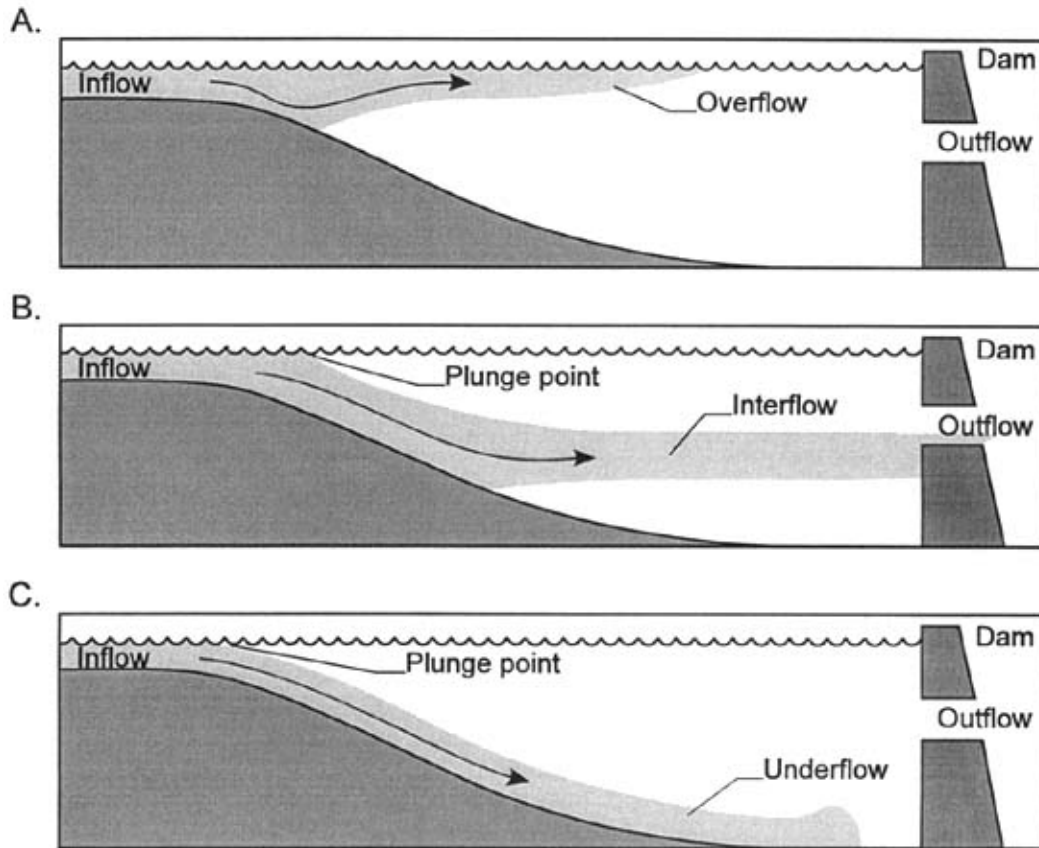
**Figure 8.8 The quality of water withdrawn from a reservoir determined by the depth and location of water withdrawal points (A, B, C) in relation to the thermocline: A Oxygenated epilimnetic water; B Anoxic hypolimnetic water; C Anoxic, sediment-laden water (After Cole and Hannan, 1990)**



Impoundments can also exhibit a range of thermal patterns at varying times of the year because of fluctuating water levels caused by their operating regimes. They may be deep enough to stratify while at full supply level (or maximum capacity) but shallow enough to mix repeatedly or constantly at lower stage levels. This depth variation may also cause atypical behaviour, such as in the hydroelectric dams in northern Sweden where winter draw-down (spring filling) prevents the ice covered waters from exhibiting the amictic characteristics of their natural relatives. Similarly, few reservoirs would be expected to be meromictic; although the solar ponds of the Sinai, Israel, are possibly an exception to this generalisation.

The use of multi-level off-takes and particularly valves which scour water from the bottom of the reservoir (Figure 8.8) can significantly modify the thermal structure and chemical gradients of reservoirs by selectively removing either surface, mid-depth or bottom waters. Not only do the resulting discharges modify the downstream flow regimes and have potential downstream impacts (Davies, 1979), but they can also selectively remove cold, anaerobic waters (the hypolimnion) from the reservoir, leaving an apparently unstratified water body behind. Similarly, the hydraulic influences of these off-takes can create some unique "short-circuit" effects within the water body which, when combined with the volumes of water generated by the large watershed to surface area ratio, encourage an underflow of denser water that can modify the impact of riverine inflows on the reservoir water quality (Figure 8.9).

**Figure 8.9 Density flows in reservoirs: A. Overflow of warm incoming waters. B. Interflow. C. Underflow (After Moore and Thornton, 1988)**



In some reservoirs, facilities are specifically provided to modify substantially, or even to eliminate completely, thermal stratification. If thermal stratification is eliminated in a deep reservoir (e.g. mean depth 20 m), the sediments experience abnormal conditions of temperature and oxygenation within what would otherwise be the summer stagnation period. Thus, relative to a natural lake, a completely atypical thermal and hydrodynamic regime can be established. Stratification control facilities can also greatly enhance the natural turbulence in reservoirs, causing considerable modification of the vertical and horizontal distributions of chemical variables, together with biological organisms and their production dynamics. This type of control may be exercised by harnessing input energy when pumping water into the reservoir (e.g. by jetting the input water), or by a separate system of air- or water-pumping.

### **8.3.2 Chemical characteristics**

Chemical events which occur in reservoirs are not unique compared with lakes, although their timing and intensity may be unusual. Inflow-outflow velocities and water body morphometry can also dramatically affect the within-lake characteristics of the reservoir itself (Figure 8.10). In reservoirs subject to thermal stratification (as in similar lakes), the suppression of vertical transport processes at the thermocline normally allows an oxygen gradient to occur which can cause anoxic conditions to develop in the hypolimnion. The rich sediments of most reservoirs would then almost certainly ensure the movement of

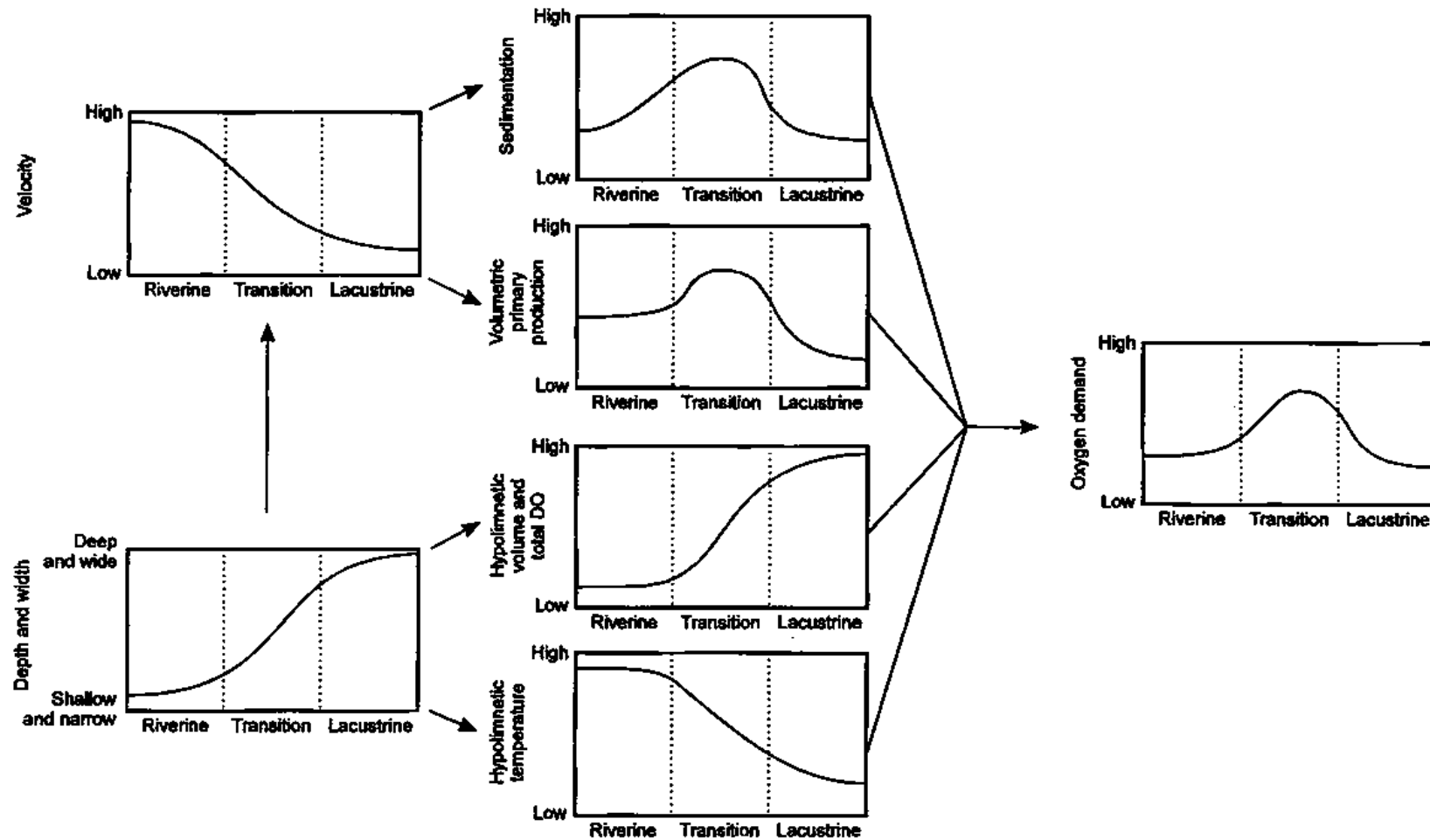
copious quantities of iron and manganese back into the water column, with the possible eventual formation of large quantities of hydrogen sulphide. As mentioned before, these events can significantly affect the users of the reservoir if water is withdrawn from the hypolimnion. Hypolimnetic deoxygenation is more common in tropical and sub-tropical reservoirs because of the higher rates of decomposition occurring at the ambient temperatures of those reservoirs. De-oxygenation is a particular problem at the first inundation of tropical impoundments. This is due to the oxygen demand of the decaying, submerged carbonaceous materials exceeding the available oxygen supply until a more stable aquatic regime is established.

When assessing the distributions of chemical variables in reservoirs, and their associated process rates, it is always necessary to bear in mind the potential effects of substantial draw-offs. These can directly affect the depth distributions of water quality variables and result in quite unusual chemical and biological profiles. This is illustrated by metalimnetic oxygen minima created by selective withdrawal of waters at that depth (Figure 8.11).

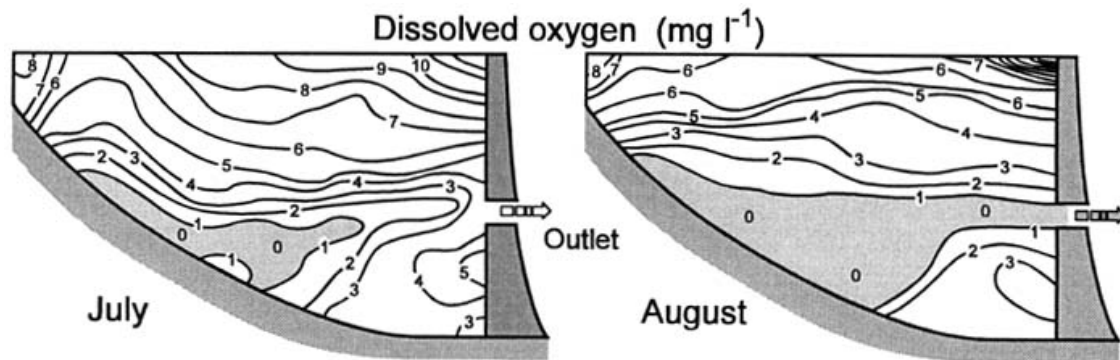
In some reservoirs, denitrification can result in a substantial reduction in the inorganic nitrate-nitrogen concentrations compared with the concentrations of the source waters (see example in Figure 8.17). This is usually associated with a greater instability in the water column due to the enhanced internal turbulence in the reservoir, its relative shallowness, long water retention time (e.g. > 6 months) and reduced dissolved oxygen content of the water. If the dissolved oxygen at the sediment surface is maintained at about 10 per cent saturation combined with a slow circulation in the remainder of the water column, considerable quantities of nitrogen gas can be released from the sediment into the overlying water. In areas where source waters are contaminated by agricultural run-off, the combined effects of storage (acting as a buffer or barrier between source water and supply to consumers) and de-nitrification can provide enormous benefits to water supplies by reducing the exposure of consumers to surface water derived nitrates (see Figure 8.17). In deeper, more oxygenated reservoirs, denitrification is a less effective process particularly if the sediments have been exposed and dry out, as may occur in drought years (Whitehead, 1992).



Figure 8.10 Relationship of morphometry, retention time and longitudinal variation in water quality process rates to oxygen demand along the length of a reservoir (see also Figure 8.4) (After Cole and Hannan, 1990) Reproduced by permission of John Wiley & Sons, Inc.



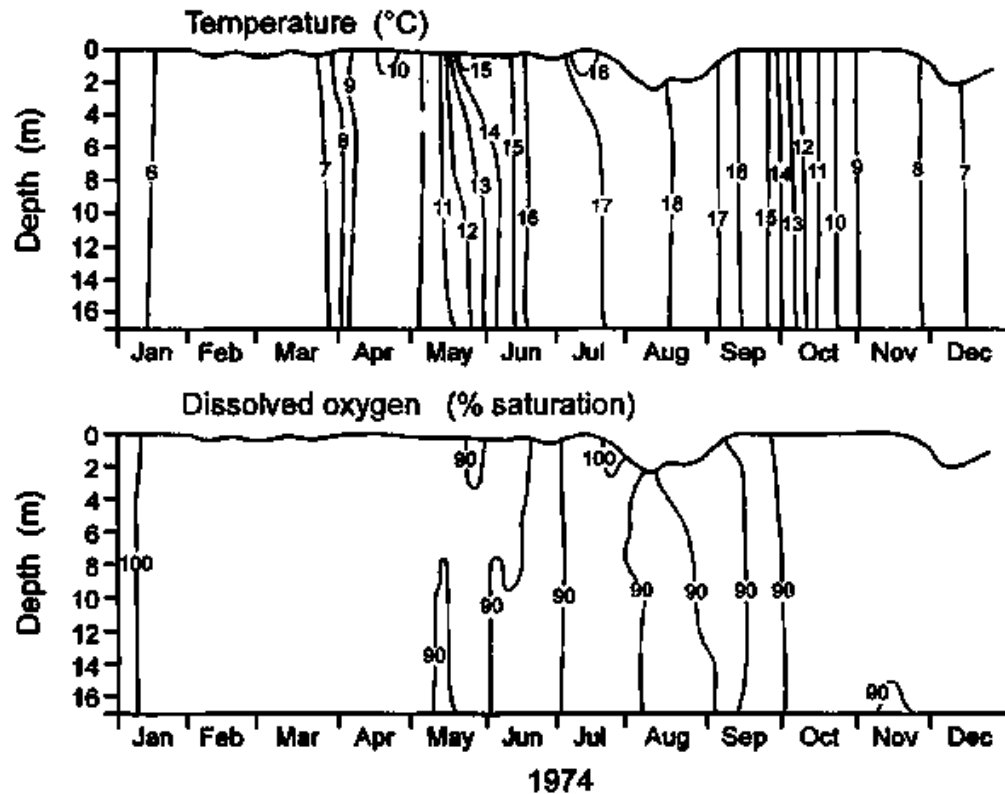
**Figure 8.11** An example of modifications in the depth distribution of dissolved oxygen by currents caused by mid-depth water withdrawal (Based on Ebel and Koski, 1968)



One aim of thermal stratification control in reservoirs (or any other managed water body) is often to eliminate the chemical problems associated with stratification, rather than just to alter the thermal structure of the water mass. Complete destratification can ensure substantial dissolved oxygen concentrations from surface to sediments, as illustrated in Figure 8.12 for a deep reservoir, i.e. mean depth  $> 15$  m (volume  $19.6 \times 10^6$ ; area  $1.3 \text{ km}^2$ ) (compare with the natural stratification illustrated in Figures 7.9, 7.22 and 8.7). Maintenance of an oxidised microzone at the sediment surface is also quite possible. This prevents the interchange of many noxious or undesirable substances between water and sediments, either directly or because they remain bound to the iron complexes formed in aerobic conditions. The sediment biota also experience warm, oxygenated conditions. Fully aerobic sediments are less effective at denitrification, although some nitrate loss can still occur by nitrification, especially if the sediments are rich in carbonaceous materials (O'Neill and Holding, 1975). An alternative approach to destratification is to re-aerate the hypolimnetic waters, by direct supply of oxygen without disrupting the thermal profile (Bernhardt, 1978). By this means, the cool hypolimnetic water is maintained as a water supply or fisheries resource even through the warm months of the year. Such management actions (usually in the pursuit of adequate drinking water quality) completely alter the chemical characteristics of a reservoir from its more natural conditions.

In addition to control of thermal stratification, a variety of other interventions such as pre-impoundments, chemical modification of water quality within smaller reservoirs (e.g. addition of a coagulant such as alum or an inhibitor such as copper sulphate) and sediment manipulation, can all significantly alter the chemical characteristics of a reservoir. Similarly, the transfer of water between basins can result in a reservoir having a very different ionic composition to that which would occur naturally in the receiving basin. Petitjean and Davies (1988) document such effects from a variety of inter-basin transfer schemes throughout the world.

Figure 8.12 Uniformity in annual temperature and dissolved oxygen depth distributions in Queen Elizabeth II reservoir, UK achieved by jet-mixing in the water column. Compare with an unmanaged situation in a similar reservoir in Figure 8.18.



### 8.3.3 Biological characteristics

As with chemical properties, biological characteristics of reservoirs are fundamentally the same as for natural lakes, but the peculiar physico-chemical conditions which may occur in managed reservoirs can also result in biological production and ecological successions quite different in degree and timing from an equivalent natural lake. The biology of reservoirs is particularly influenced by:

- the effects of greater flow-through and turbulence,
- the nutrient loading they normally receive,
- the plankton populations of the inflows relative to those in the reservoir itself, and
- the management controls applied and their effects.

An understanding of the biological characteristics of reservoirs, in addition to their physical and chemical features, is important to their management. Biological assessment techniques are commonly included in reservoir assessments because some uses of reservoir water (e.g. drinking water supply, fisheries, recreation) are particularly subject to the effects of biological communities (especially algal populations) and their interactions (e.g. between fish and plankton groups).

Enhanced turbulence, such as produced by artificial destratification measures, can maintain phytoplankton in suspension when they would otherwise sink to the sediments, or can affect productivity by carrying them into deeper waters with insufficient light penetration to support photosynthetic production (Horn and Paul, 1984). The increased turbulence can also maintain greater amounts of organic material in suspension, sustaining filter-feeding zooplankton when food resources might otherwise be much lower and limiting to their growth (Steel, 1978a; Horn, 1981).

The extreme water level fluctuations of some reservoirs also pose biological problems for the establishment of rooting macrophytes and spawning areas for fish. When highly managed, the unusual vertical profiles of temperature and chemical variables present abnormal conditions for benthic organisms.

A major problem for reservoirs (as for lakes), and a driving force behind much of their management, is the biological outcome of eutrophication (see section 8.4.1), particularly as manifest in the enhanced phytoplankton growth. The resultant phytoplankton population densities cause problems for recreational users, for treatment processes in drinking water supply and directly to consumers. Users may be merely reluctant to use the water because of its taste and odour but, at worst, they may experience a toxic effect. Bunded reservoirs used for water supply are particularly prone to benthic mats of *Oscillatoria* (a filamentous blue-green alga) which imparts considerable earthy or musty tastes and odours to the water (van Breeman *et al.*, 1992). Many strains of cyanobacteria (blue-green algae) can produce an active intra-cellular toxin, particularly when the phytoplankton are senescent and decaying. Toxin production may occur naturally or as a result of management attempts to control large phytoplankton populations, for example, by the application of copper sulphate. The toxins released may then have a direct effect on water consumers (livestock and humans). Cyanobacterial toxins are becoming an increasing source of concern for water managers where eutrophic reservoirs are used for recreation, aquaculture or potable supplies (Lawton and Codd, 1991).

Warm water reservoirs (tropical/sub-tropical) may have a particular problem with floating plants, such as *Salvinia molesta* in Lake Kariba and *Eichhornia crassipes* in Lake Brokopondo, South America (Van der Heide, 1982). Such exceptional macrophyte growths can significantly reduce dissolved oxygen concentrations in the water as they decompose, interfering with fishing and restricting potable and industrial use.

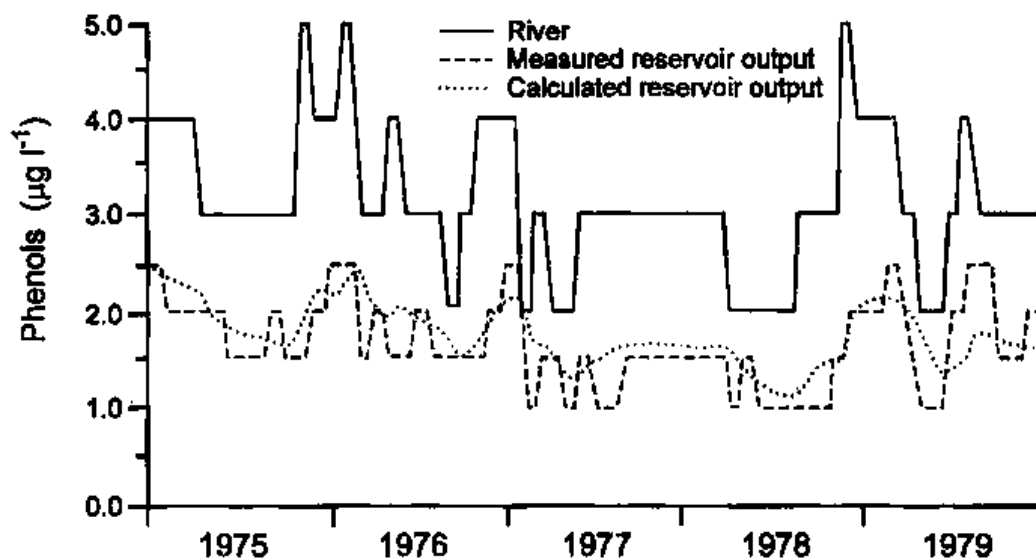
Standard approaches to biological assessment and management of reservoirs are complicated by the extreme variety, location and uses of many reservoirs. As in natural lakes, trophic relations in reservoirs vary from simple food chains to highly complex food webs; the latter often being characteristic of the conditions in reservoirs created by flooding river valleys. In reservoirs with simple morphometry, the possible absence of littoral zones and macrophyte refuges for herbivorous zooplankton can increase the zooplankton's exposure to predation by fish. Large fish stocks can deplete herbivorous zooplankton populations to levels which enable phytoplankton populations to grow unrestrained by any grazing by zooplankton (i.e. to the limits of nutrient or energy availability). Factors which reduce fish stocks (and consequently their predation on zooplankton) can enable zooplankton populations to reach levels which can potentially deplete phytoplankton populations through grazing effects, even when phosphate (required for algal growth) is in excess. In reservoirs with a varied morphology (different

shoreline habitats as well as sheltered and exposed and deep and shallow areas), many other inter-trophic effects may also take place because the niche diversity is sufficiently high to allow the coexistence of much more varied biological communities (Benndorf *et al.*, 1988). A particularly clear understanding of the interactions of such factors is necessary for a valid assessment of the biological nature of these types of water body.

### *Microbiology*

The typical microbiological characteristics of reservoirs appear to be the same as for lakes (Straskrabová and Komárková, 1979). The main source of energy for bacterioplankton is decomposable organic material. With short retention times, this material is mainly derived from the inflows into the reservoir. As the retention time increases in larger reservoirs relative to the outflow rates, the main source of energy becomes the primary productivity within the reservoir. Seasonal changes in bacterial populations relate mostly to seasonal variations in source water conditions and the primary productivity in the reservoir.

**Figure 8.13** Calculated and measured phenol concentrations in water withdrawn from the Honderd en Dertig reservoir, The Netherlands, compared with the incoming river water. The reduction in phenol concentrations in the reservoir water is achieved by microbiological decomposition during water storage. (After Oskam, 1983)



Microbiological activity is important in the degradation of organic compounds of industrial origin which are frequently present in the source waters of lakes and reservoirs in highly populated and industrialised areas (Oskam, 1983). Together with dilution and the elimination of the source of the organic contaminants, microbial breakdown is a major factor in maintaining a satisfactory drinking water quality in some reservoirs, e.g. Honderd en Dertig, the Netherlands (volume  $32 \times 10^6 \text{ m}^3$ ; area  $2.2 \text{ km}^2$ ) (Figure 8.13). This process can be further enhanced by the serial operation of reservoirs, if available.

Many reservoir source waters are subject to gross viral and bacterial pollution because of effluent disposal and run-off. Reservoirs can form a barrier to the survival of

pathogenic micro-organisms; water storage for 20 days or more normally reduces river water coliform concentrations to about 1 per cent of their initial value, due to the relatively alien reservoir temperature, exposure to ultra-violet radiation, and ionic conditions. This effect appears to be maintained even when reservoirs are subject to substantial mixing for thermal and chemical control purposes.

#### **8.3.4 Trophic classification**

Reservoirs exhibit a range of trophic states in a manner similar to the natural lakes described in Chapter 7. Individually, however, they can also do so over their length and can exhibit considerable spatial heterogeneity (Figures 8.4 and 8.15). Providing a trophic state description of a confined, riverine reservoir is very difficult and debate has taken place concerning the relevance of such classifications in such reservoirs (e.g. Lind, 1986). Their trophic states may range from nutrient rich (eutrophic) in their upper reaches to nutrient poor (oligotrophic) closer to the dam wall (see Figure 8.4). This tendency is enhanced when they consist of several basins with discrete morphologies and distinct characteristics, such as embayments or human settlements, influencing their responses to external stimuli (Kimmel and Groeger, 1984; Kennedy and Gaugush, 1988; Thornton *et al.*, 1990). Classifying whole reservoirs as oligotrophic on the basis of sampling stations located over the “deep hole” adjacent to the dam wall can, therefore, be misleading if more nutrient rich water is generally characteristic of the major part of the reservoir system.

While some investigators have attempted to create volume-weighted or area-weighted characterisations, it appears that most investigators continue to base trophic classifications on a single sampling site (Straskrabá *et al.*, 1993). Some justification for this can be derived from the fact that water withdrawals are more common at the dam end of reservoirs than elsewhere. In an attempt to provide an appropriate comparative framework for classification of impoundments, several workers have devoted considerable effort towards defining trophic concepts across climatic regions (Ryding and Rast, 1989; Thornton and Rast, 1993). Although trophic classifications can often be ascribed to lakes and reservoirs in the temperate zone on the basis of single indicators, such as hypolimnetic oxygen regime, such simple classifications are less applicable in other latitudes, requiring the more refined approaches described by these workers. At a minimum, it may be necessary to segment a reservoir into multiple regions of distinct water quality and trophic character as described below.

### **8.4. Water quality issues**

Despite the complexity of environmental and social issues surrounding reservoirs, particularly large impoundments (Petr, 1978; UNESCO/UNEP 1990; Thornton *et al.*, 1992), large numbers presently exist and others continue to be built. In order to manage these systems in an environmentally-sound manner, and to minimise the occurrence of conditions that interfere with the beneficial uses of their waters, regular collection and analysis of data is required. In this respect, reservoirs are not different from natural lakes. However, reservoirs present specific challenges that are rarely present in natural lakes. Thus, whilst the water quality issues of concern in reservoirs parallel and overlap those of natural lakes, certain differences and specific conditions also exist. A summary of the major issues and assessment implications relevant to lakes and reservoirs is given in

Table 7.5. Further information on assessment strategies and selection of appropriate monitoring variables is available in Chapters 2 and 3.

The following sub-sections highlight some issues of particular relevance to reservoirs and the assessment of their water quality. Some issues of major concern in lakes are less of a general problem in reservoirs. For example, reservoirs are less susceptible to acidification than are natural lakes. The influence of the source water can be so dominant in the overall chemistry of some reservoirs, as a result of high flow-through, that gradual water quality modifications are more a function of the source rivers and streams than of the characteristics of the reservoir itself.

#### **8.4.1 Eutrophication**

Reservoirs, like natural lakes, are affected by the process of eutrophication. Some reservoirs undergo the full process of gradual ageing that ultimately converts lakes to wetlands and to terrestrial biomes (Rast and Lee, 1978). Unlike natural lakes, however, most reservoirs have a design life (typically estimated to be greater than 30 years) which reflects the period over which the structure is capitalised as well as the on-going demand for the water that the reservoir must supply. Exceptions to this generalisation do exist, for example, in the eastern Cape Province of South Africa where several reservoirs have been constructed (primarily as salinisation and sediment control structures) with significantly shorter life expectancies (DWA, 1986). These reservoirs tend to exhibit the symptoms of eutrophication (reduction in depth, excessive plant growth, etc.) much more rapidly than natural lakes or reservoirs constructed elsewhere. Despite such exceptions, many reservoirs do mimic natural lakes in their transition from an aquatic environment to a terrestrial environment over time. That time period, however, is generally much shorter than the geological time scale associated with most natural lakes.

Reservoirs are also susceptible to cultural eutrophication or an increased rate of ageing caused by human settlement and activities in the watershed. Some impoundments may be more productive than their natural counterparts because of their generally larger watershed areas and terminal location. For any given unit area load of pollutant generated from a specific type of land usage, the larger watershed area results in a greater load being delivered to the water body. To some extent, however, this greater load is often moderated by a generally higher flushing rate (or shorter water residence time) than typical for a similarly-sized natural lake (e.g. Table 8.1). This higher flushing rate is principally related to the greater watershed area delivering the water load to the reservoir.

As described above, considerable artificial control of the normal responses associated with increasing eutrophication is possible in reservoirs. In some situations, thermal stratification and any associated chemical deterioration can be controlled. Appreciable depression of primary production can be achieved by artificially circulating phytoplankton into waters below the euphotic zone (zone of phytoplankton production), resulting in a decrease in population photosynthesis and production relative to respiration and sedimentation (Steel, 1975). Thus a reduction in the efficiency of primary production can take place even in the presence of what might otherwise be overwhelming quantities of phosphorus and nitrogen. Alternative forms of biomanipulation are also possible in some reservoirs by exploiting the effects of controlling fish stocks (see section 8.3.3); either directly or by controlling water level at critical spawning times.

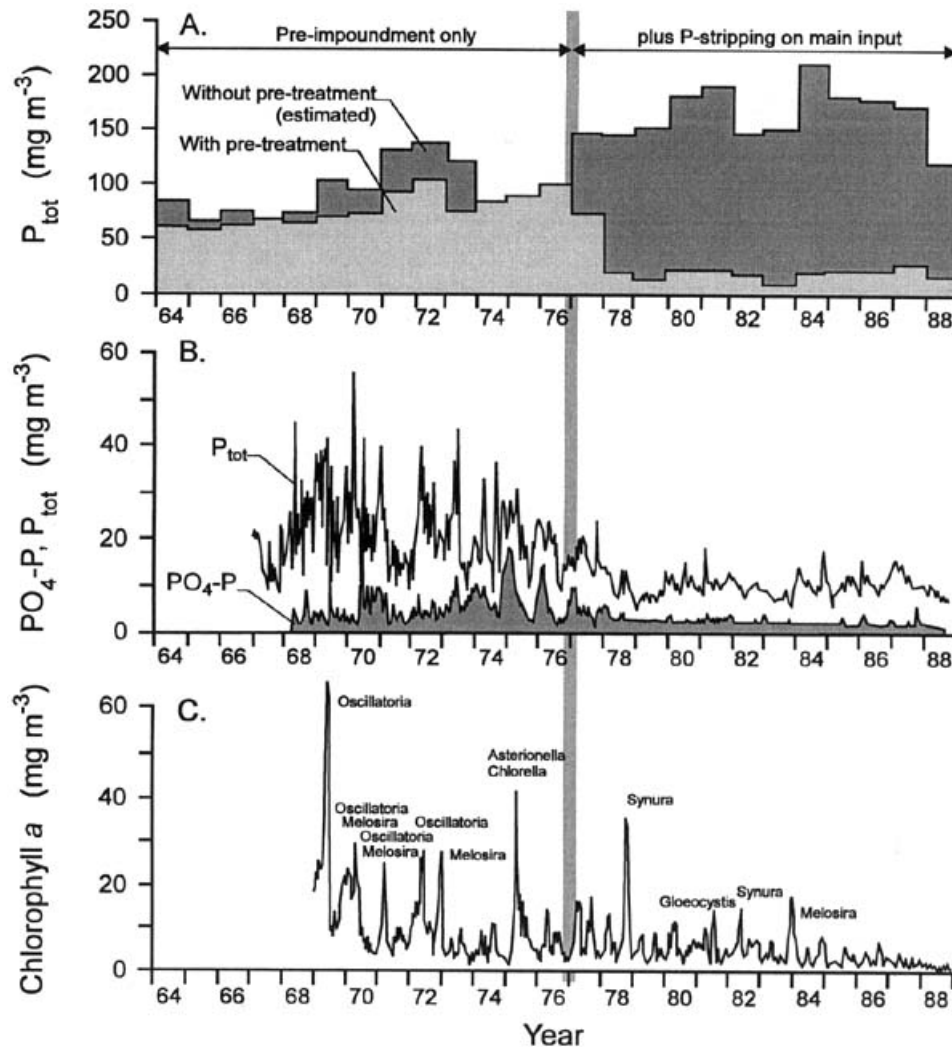
Other measures to reduce nutrient concentrations within reservoirs include the use of flow by-passes, pre-impoundments, scour valves discharging nutrient-rich hypolimnetic (bottom) water, and modifications to the operating regime which can alter the effects of water and nutrient loads within the reservoir. The inlet to Delavan Lake, Wisconsin (volume  $54.8 \times 10^6 \text{ m}^3$ ; area  $7.2 \text{ km}^2$ ), for example, has been modified so that nutrient-rich high flows will be passed through the dam without entering the main body of the lake (University of Wisconsin-Madison, 1986). This example is a purposely designed short-circuit effect created by the proximity of the inlet and outlet and enhanced by the construction of a diversion structure to accentuate the flow of water towards and over the dam during flood events. In contrast, the modified inlet permits river waters to mingle gradually with the waters of the main lake basin during lower flows.

In many circumstances greater water quality control is often achieved by a combination of approaches to control eutrophication. For example, the operational water quality management of the Wahnbach impoundment in Germany (volume  $40.9 \times 10^6 \text{ m}^3$ ; area  $1.99 \text{ km}^2$ ) (LAWA, 1990), developed over a number of years, uses a combination of phosphorus elimination by treatment of inputs, pre-impoundment and hypolimnetic re-aeration to produce high quality drinking water (Figure 8.14). Many other procedures (such as sediment removal, flocculation and flow control) have also been shown to be potential modifiers of the response of a reservoir to eutrophication (Jorgensen and Vollenweider, 1989; Ryding and Rast, 1989).

Operational manipulations may not always result in beneficial effects, even within the basins of eutrophic reservoirs. Drawdown caused by the withdrawal of aerobic surface waters for drinking water or irrigation supply purposes can make a reservoir more susceptible to overturn. This can introduce nutrient-rich bottom waters to the euphotic zone, enhancing algal growth and creating an intensified oxygen demand throughout the water column. An extreme example of such an impact is reported by Robarts *et al.* (1982) from Hartbeespoort Dam, South Africa. Passing anaerobic waters through turbines or similar precision machinery can also cause severe damage to the equipment. The initial eutrophication of Lake Kariba (see section 8.3) resulted in the (unintentional) passage of anaerobic waters through the hydroelectric turbines, damaging them so badly that they had to be replaced (Balon and Coche, 1974). McKendrick (1982) described similar disruptive impacts from withdrawal of anaerobic water for drinking water treatment at Lake Mcllwaine (now Lake Chivero), Zimbabwe. Neither of these latter cases resulted in any visible water quality change within the reservoir basins. Similarly, release of anoxic, hypolimnetic water from the eutrophic Iniscarra reservoir, Ireland, caused fish mortalities in the downstream waters of the River Lee (Bryan, 1964).



**Figure 8.14 Monitoring to determine the effectiveness of measures taken to prevent the Wahnbach reservoir, Germany from becoming eutrophic. The measures consisted of a combination of pre-impoundment, phosphorus elimination in some source waters, and hypolimnetic aeration. A. Reductions achieved in the phosphorus inputs to the reservoir between 1964 and 1988 compared with the estimated concentrations if phosphorus reduction measures had not been applied. B. Total phosphorus and phosphate concentrations in the reservoir water over the same period. C. Associated chlorophyll a concentrations in the reservoir and the principal algal species present. (Modified from LAWA, 1990)**



#### 8.4.2 Public health impacts and contaminants

In addition to the range of potential health impacts arising from water-borne diseases and water-related disease vectors described in Chapter 7, the construction of a reservoir can provide an avenue for transmittal of diseases and their occurrence in areas where such diseases, and natural immunities, did not previously exist. This is especially true in the tropics, where the construction of reservoirs has been implicated in the epidemic

spread of river blindness (onchocerciasis), bilharzia (schistosomiasis), and guinea worm disease (dracunculiasis). Volta Lake, Ghana, is an extreme and well-documented example of a reservoir where the spread of these diseases almost decimated the local and migrant populations attracted to the reservoir, necessitating an extensive and on-going international control programme (Thanh and Biswas, 1990). Similar, but less extreme, examples have been reported from other large-scale water resources development programmes in Africa, Asia and South America (Thanh and Biswas, 1990; Bloom *et al.*, 1991).

Industries and urban settlements adjacent to, or in the drainage basin of, reservoirs can further compound human health problems through the release of contaminants, and through the discharge of wastewaters to these water bodies or their source waters (as in lakes; see Chapter 7). In many cases, the presence of a reservoir can attract development that could not otherwise be sustained due to a lack of process and drinking water. Contaminants of particular concern in reservoirs with respect to human and animal health are:

- synthetic organic compounds,
- nitrates,
- pathogenic bacteria,
- viruses, and
- cyanobacterial toxins.

Section 8.3 has already provided some detail of the particular impacts of these contaminants in reservoirs, and of how the conditions within a reservoir can affect them, as well as how management techniques may reduce their impacts on water quality and water use (see also section 8.6). Toxic metals may be a problem in some areas, although the normal processes of adsorption to particulate material and subsequent deposition in the more quiescent regions of a reservoir or pre-impoundment are generally the only effective means of containment in such cases (see also Chapter 7). Sediment oxygenation, as may be achieved in managed reservoirs (see section 8.3.2), is also a possible means of ensuring retention of contaminants within the basin.

### **8.4.3 Salinisation**

Many reservoirs are situated in arid and semi-arid areas where surface water is naturally scarce and for these reservoirs the problem of salinisation (also referred to as salination or mineralisation) can be severe. Irrigation of these areas can lead to leaching of salts from the soils, and their transport in return flows to the reservoirs. This can be aggravated by the highly seasonal rainfall of these areas increasing the evaporative concentration of the ambient salinities in the water bodies during the dry season. In the reservoirs of the eastern Cape Province of South Africa, for example, salinities can exceed a median value of 1,000 mg l<sup>-1</sup> measured as total dissolved solids (TDS) (DWA, 1986). The South African Department of Water Affairs (DWA, 1986) gives a range of median TDS concentrations, for 13 major reservoirs throughout the country, of between 137 mg l<sup>-1</sup> and 955 mg l<sup>-1</sup>. The extreme values of TDS measured in these reservoirs ranged from 99 mg l<sup>-1</sup> to 2,220 mg l<sup>-1</sup>. Salinities in this range limit the possible uses of the waters because all but a few salt-tolerant crops, and most industrial and consumptive uses, of the water are seriously affected by high salinities (see Chapter 3).

## 8.5. Sampling strategies

As with natural lakes, sampling strategies for reservoirs must be based upon the objectives of the assessment programme as set out in Chapter 2. The modifying influences of off-take locations, selective-level withdrawals, dendricity, and linear gradations of water quality along the main lengths of impoundments, are complicating factors that must be considered in developing an appropriate reservoir sampling regime. The principal purpose(s) for which the reservoir was created should also be considered. For multi-purpose reservoirs, the use requiring the highest water quality should generally be used as the basis for determining an appropriate quality objective, and for guiding water quality management programmes. Some possible monitoring strategies in relation to principal water uses are given in Table 8.3.

**Table 8.3** Suggested monitoring strategies for some major uses of reservoir waters

Principal water use	Main sample site location	Sampling frequency <sup>1</sup>	Hydrodynamic considerations	Physical and chemical measurements	Biological methods
Potable water supply	At outlet to supply	Continuous, daily to weekly	Thermal stratification, short-circuit flows	Temperature, diss. oxygen, colour, turbidity, suspended solids, odour, pH, organic compounds, metals, nitrate	Coliforms, pathogens, phytoplankton species, chlorophyll a
Industrial water supply <sup>2</sup>	At outlet to supply	Continuous, daily to weekly	Thermal stratification	Temperature, pH, hardness, dissolved and suspended solids, major ions	Pathogens <sup>2</sup>
Power generation	Close to outlet	Daily to weekly	Thermal stratification, internal water currents	Conductivity, dissolved and suspended solids, major ions, dissolved oxygen	
Irrigation supply	Representative open water site(s) and/or outlet(s)	Weekly to monthly		pH, total dissolved solids, sodium, chloride, magnesium	Faecal conforms
Fisheries and recreation	Representative open water site(s) <sup>3</sup>	Weekly to monthly	Thermal stratification	Suspended solids, dissolved oxygen, BOD, ammonia	Phytoplankton species, chlorophyll a, fish biomass
Aquaculture	At inlet and open water site(s)	Daily to weekly	Thermal stratification	Temperature, suspended solids, dissolved oxygen, ammonia, pesticides	Chlorophyll a
Flood control	Inflow(s) and outflow(s)	Monthly to annual		Suspended solids, turbidity	

<sup>1</sup> Depending on the variables and as set by statute

<sup>2</sup> Requirements vary according to industrial use, e.g., food processing should require pathogen monitoring

<sup>3</sup> The number and location of the sites depends on the complexity of the reservoir basin and its discrete water masses

Desirable water quality objectives may vary with the location of the off-take structures within the reservoir basin. For example, if the dendricity of the reservoir effectively isolates a bay in which an irrigation water off-take is located, a lower quality water may be accepted or tolerated in that bay than in the main body of the reservoir where a potable water off-take might be located. The depth distributions of water quality variables should be considered in a similar manner, as illustrated by the metalimnetic oxygen minimum created by selective withdrawal of waters at that depth (see Figure 8.11).

### **8.5.1 Selection of sampling site**

As noted above, the assessment of reservoir water quality should reflect the uses of the water, as well as the conditions at the site where water is withdrawn. In impoundments this is often at a location close to the dam wall. Thus, the popular selection of the “deep hole” (generally near the dam wall) as the principal sampling site in such reservoirs is based on an intuitive application of this convention. It is also noteworthy that when intensive sampling has been carried out throughout a reservoir basin to generate a “true” mean for the more common trophic state variables such as nitrogen, phosphorus and chlorophyll concentrations, the volume-weighted mean values have often been statistically indistinguishable from those measured in the deep hole or main basin. This is probably due to the greater volume represented by the water at the deeper dam-end of the impoundment.

In regularly shaped, off-river reservoirs, it is commonly found that the water quality may be characterised by a few notional sub-basins, even if they do not physically exist. The number and extent of such volumes are greatly influenced by the operational regime and physical structure of the reservoir. For example, in a well-mixed, near-circular reservoir, the main water body (except for a small volume near the inlet) is usually sufficiently homogeneous to be well characterised by a single sampling site. The characteristic pattern of water masses within a given reservoir may generally be deduced by a preliminary survey (see Chapter 2) under representative conditions, from which an appropriate, general sampling strategy may be subsequently derived (Steel, 1975). Internal walls or similar internal structures can frequently give a good indication of the likely sub-basins for sampling purposes. Therefore, in many respects, sampling station selection for more regularly shaped reservoirs is similar to that detailed in Chapter 7 for natural lakes.

In physically more complex reservoirs, the degree of dendricity and sinuosity arising from river impoundment can result in actual, distinct differences in water quality over the length of an impounded water course (see Figure 8.15). In these instances, a single sampling site does not usually provide an adequate assessment of water quality for the entire impoundment. In very large impoundments several sampling sites, defined by basin morphology or geography, are more appropriate. In Lake Kariba, for example, five

such basins were defined and used as the basis for water quality classification (Balon and Coche, 1974). In effect, for modelling and management purposes, Lake Kariba can be considered as a cascade of five small lakes, each discharging into its immediate neighbour in a downstream direction. Therefore, the “deep hole” sampling site approach should be considered only as an operational approach and it should not be used in situations where a scientific and statistically valid assessment of water quality is required.

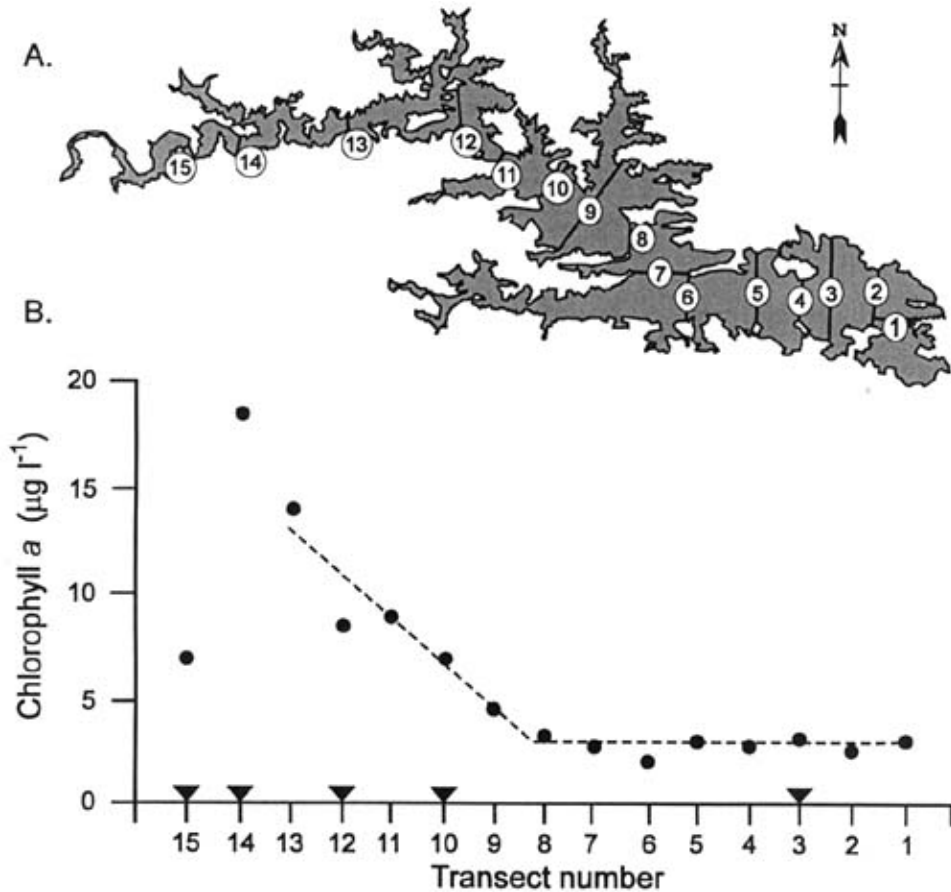
As with natural lakes, the monitoring of inflows is generally carried out in addition to the selected site(s) described above as a means of providing an early warning of possible changes in water quality at the water withdrawal points or in the various basins.

### **8.5.2 Sampling for horizontal and vertical characterisation**

The need to provide statistically valid descriptions of water quality in reservoirs poses a number of concerns, fundamentally due to the possible horizontal, vertical and temporal variations in water quality in larger reservoirs. This is particularly true in impoundments, where their size, bathymetry, sinuosity, complex shorelines and operation all tend to allow relatively local water quality conditions to be maintained (see section 8.3). Vertical stratifications of varying complexity are a further complicating factor. Designing a sampling programme to deal adequately with such variability requires specific recognition of these concerns (for details of statistical approaches see Appendix 10.1). A statistically valid mean result for the whole reservoir would be applicable, for example, to the siting of withdrawal points or recreational facilities, identification of water quality variables of concern and significant differences in these variables between sites, and development of valid functional relationships amongst reservoir water quality variables (a prerequisite for modelling reservoir water quality).

A practical example of site selection for horizontal and vertical characterisation of a reservoir is given by Thornton *et al.* (1982) and described briefly below. This example represents the advanced level of monitoring as defined in Chapter 2. The optimal location of the minimum number of sampling stations and depths required to characterise the water quality along the length of the reservoir were determined in DeGray Lake, USA (Figure 8.15). Preliminary data were obtained from a series of close interval, horizontal and vertical transects in order to distinguish statistical similarities and differences between the sampling sites.

**Figure 8.15 A. The complex shape of DeGray Lake, USA showing the sampling transects chosen for a detailed study. B. Chlorophyll a concentrations determined for each transect. Arrows indicate the sites which represent the overall water quality of the reservoir (see text for further details). (After Thornton *et al.*, 1982)**



DeGray Lake was theoretically partitioned into 15 transects, averaging 5 stations per transect. The reservoir was sampled for total phosphorus, turbidity and chlorophyll *a* at 0, 2, 4, 6, and 10 m, and at 5 m intervals thereafter to the bottom, in July 1978, and in January and October 1979. Statistical analysis of the results showed that transects 1 through 5 had similar means for all variables over all dates. Thus, one station was sufficient to characterise the entire area represented by these five transects. The type of variation amongst the mean values of transects 6 through 13 suggested that two stations were necessary to characterise the water quality in that area. Transects 14 and 15 were either distinct or varied in a manner similar to transects 6-13 and, therefore, these two transects each needed a separate sampling station. Based on this analysis, a minimum of five sampling stations (on transects 3, 10, 12, 14 and 15) was required to characterise statistically DeGray Lake along its longitudinal water quality gradients (see Figure 8.15).

In addition to the number of sampling stations, it is also necessary to consider the number of samples needed from each sampling station to characterise the vertical variability in water quality. The number of samples required is influenced by the data variability and the desired precision of the estimate and can be obtained using statistical

methods (see Appendix 10.1). Such approaches (e.g. Thornton *et al.*, 1982) reflect an advanced approach to monitoring and assessment.

The approach used by Thornton *et al.* (1982) and others (e.g. Gaugush, 1986) identify areas or segments within a reservoir which exhibit statistically distinct water quality. They do not, however, address how this information can, or should, be used to assess the overall water quality or trophic state of a reservoir (given the presence of longitudinal and vertical gradients in water quality, such as those identified by Kimmel and Groeger (1984)) (see Figure 8.4). This approach actually highlights the fact that the water quality or trophic status of highly dendritic and sinuous reservoirs, in particular, cannot be readily characterised by a single average value.

As a result of the complexity involved in completely assessing the water quality of reservoirs, the most logical approach to the management of such water bodies is to assess water quality with respect to the most sensitive use of the water at the point of withdrawal of that water. Thus, for water supply reservoirs this would be at the point of withdrawal, while recreational water bodies would require a more comprehensive assessment, possibly covering several segments in the reservoir (see Table 8.3). Although this site- and use-specific approach still does not provide specific guidance for the management of water quality along the course of the reservoir (or in the reservoir as a whole), it does provide an approach that is practical (and practicable) given the present state of knowledge and available techniques for management of water quality (Ryding and Rast, 1989).

### **8.5.3 Variable selection**

The variables measured as part of any given sampling programme should reflect consideration of the uses to which the water is put as well as any known or anticipated impacts on the water quality. Collection of data pertinent to such usage, and the assessment of actual and potential water quality problems, should provide as full as possible an understanding of the sources, impacts and subsequent behaviour of pollutants, as well as aiding the identification, evaluation and outcome of appropriate and possible mitigation methods. Although the general selection of variables is described in Chapters 1, 3 and 7, operational procedures may also influence such selection in reservoirs because slight modifications in their operation can often resolve their water quality problems. For example, in Lake Chivero modification of the outlet structure to permit multi-level withdrawal, and its relocation to an upwind position, resolved many of the algal problems previously experienced with the original off-take (McKendrick, 1982). Similarly, de Moor (1986) showed that small variations in the timing of releases from the Vaalharts Diversion Weir could obviate simuliid problems in the Vaal River, South Africa (the blackfly *Simulium* spp. is the vector of river blindness).

### **8.5.4 The use of management models**

Reservoir management facilities often provide a considerable range of options which may be used to attain a water quality suited for the main purposes of the reservoir. In order to make the most effective use of the management options, it is essential that there is a clear understanding of the interplay between the effects of the management control measures and the natural dynamics of the reservoir system. This understanding

is necessary to exploit effectively processes beneficial to a particular reservoir water use, and to ensure as far as possible that no unacceptable detriment is caused for other uses.

A useful tool for such informed control is a model of the reservoir system. Models range from empirical, statistical descriptions to analytical, mathematical models (see section 10.7). Either approach would normally imply the need for a specialised assessment, including surveys and data analyses appropriate to the task of constructing such models. Operational management may make day-to-day use of a combination of models. Regular operational surveillance may, therefore, also have to include sampling sites and variables required as input data for reservoir management models, even though such variables may not be specifically required for assessment of the water quality use or issue of concern (see Table 2.2).

Straskrabá and Gnauck (1985) give a wide-ranging account of modelling in freshwater systems. It is important to realise that there is not likely to be a single “best” model or model type for a given reservoir. Experience shows that overly complex mathematical models which attempt a complete description of reservoir dynamics are invariably not used, because of their extensive data demands, often complex nature and high relative costs of operation. However, operational management can be aided by quite simple models (Steel, 1978 a, b). Figure 8.13 illustrates the prediction of a contaminant concentration in a reservoir under different operating conditions. Appropriate modelling, sometimes based on water bodies with similar characteristics, may be of greater benefit when considering facilities to be included at the construction phase or to be added at a later date, such as phosphorus elimination by pre-impoundment (Benndorf and Pütz, 1987 a, b) or mixing the water within reservoirs with air (Goossens, 1979) or water-jets (Cooley and Harris, 1954).

## **8.6. Approaches to reservoir assessment**

There are numerous examples of water quality assessments of reservoirs in the published literature and the majority of examples (in terms of number) are from industrialised nations of Europe and North America. Nevertheless, in relation to the total number of natural lakes and reservoir assessments in the developing world, there are more examples of reservoir assessments.

### **8.6.1 General basic surveys**

The same types of bathymetric and thermal surveys undertaken in natural lakes are necessary to establish the physical environment of reservoirs. The methods given in Chapter 7 can also be applied to reservoirs, although some differences can be identified.

Generally, the bathymetry of reservoirs is easier to determine than that of natural lakes for the simple reason that reservoir basins were once dry land. The construction of reservoirs requires detailed design drawings and land surveys which then also identify the subsequent bathymetry in detail. This feature simplifies the process of water quality modelling prior to impoundment by allowing the assessor to make forecasts based on the predetermined full supply level contour.

In contrast to lakes, the thermal regime of reservoirs can be more variable (see section 8.3). Unnatural variability is added as a result of the terminal location of some reservoirs

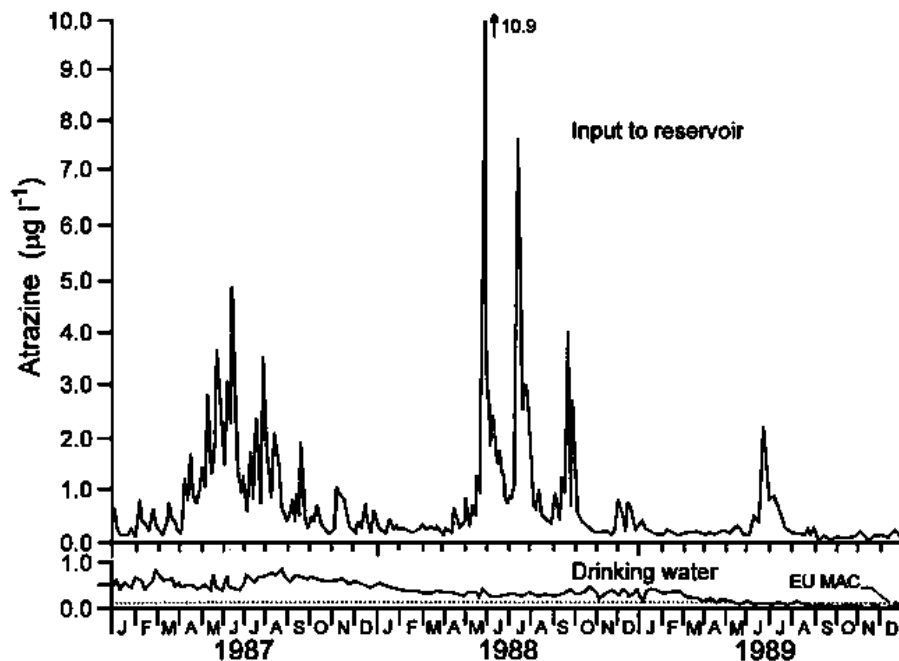


at the downstream end of a drainage basin, their tendency to develop density currents, their operating regime (which can result in modification of the thermal profile), and morphology (which tends to be less deep than natural lakes and, therefore, more likely to encourage periodic water mixing) (Ward and Stanford, 1979).

### 8.6.2 Operational surveillance

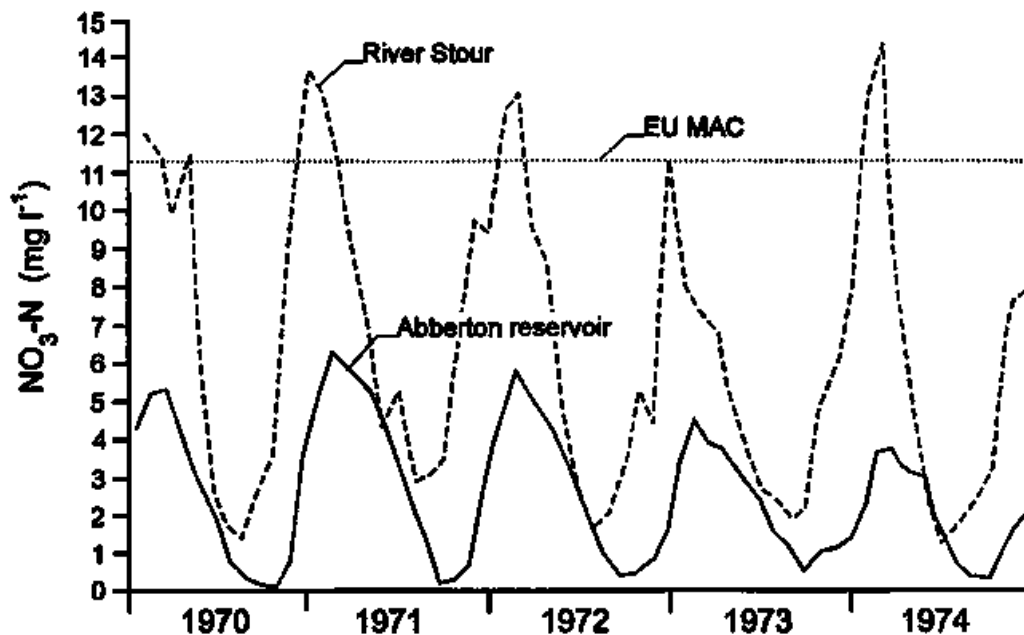
In reservoirs used mainly for drinking water supply, it is imperative that all management and monitoring should be appropriate for that main purpose. Of particular consequence are those substances identified as potentially harmful to consumers, and which may interfere with, or resist, standard water treatment technologies. The widespread use of pesticides in many areas of the world presents a particular problem in this respect. Some of the more persistent pesticides which enter water courses may eventually be carried into reservoirs. Figure 8.16 shows the results of monitoring over a four year period the inlet of the Hullern reservoir in northern Germany (volume  $11 \times 10^6 \text{ m}^3$ ; area  $1.5 \text{ km}^2$ ) for the widely used herbicide, atrazine. Large seasonal fluctuations in pesticide concentrations entering reservoirs can be dampened by water storage in the reservoir, thereby reducing possible problems at the subsequent water treatment stages. These effects are particularly useful if the reservoir water is to be used as a source for drinking water supplies. After initial difficulty in meeting the maximum admissible concentration (MAC) for atrazine as given by the European Union Drinking Water Directive (80/778/EEC), the final drinking water supply derived from the Hullern reservoir (Figure 8.16) eventually attained the MAC in 1989/90 (LAWA, 1990).

**Figure 8.16 A comparison of fluctuations in the concentrations of the herbicide atrazine in the inlet water to the Hullern water supply reservoir, Germany, with the concentration in the drinking water supply derived from the reservoir. EU MAC: European Union Maximum Allowable Concentration (After LAWA, 1990)**



Nitrate monitoring forms a routine aspect of water quality assessments in reservoirs concerned with drinking water supply in Europe because of a European MAC for this variable of  $11.3 \text{ mg l}^{-1} \text{ NO}_3\text{-N}$  (the new World Health Organization guideline value is given as  $50 \text{ mg l}^{-1} \text{ NO}_3^- [\equiv 11.3 \text{ mg l}^{-1} \text{ as NO}_3\text{-N}]$ ; see Table 3.4). Nitrates are a potentially serious problem for drinking water supplies in areas of intensive agriculture, especially where inorganic nitrogenous fertiliser is used heavily. For example, within Europe, the eastern UK is an area of high nutrient inputs to water bodies combined with relatively low rainfall. In this area, nitrates accumulated in soils are washed into water courses in large quantities during the rains of late autumn and early winter. These fluctuations in nitrate loads can cause considerable problems for water supplies drawn from affected water courses. Figure 8.17 shows the results of routine measurements of  $\text{NO}_3\text{-N}$  concentrations in the River Stour in eastern Britain, and the associated Abberton reservoir (volume  $25.7 \times 10^6 \text{ m}^3$ ; area  $4.9 \text{ km}^2$ ). Without the reservoir and its associated de-nitrification processes, the responsible water company would require specialised treatment facilities to deal with this extreme seasonal problem. The reservoir, therefore, not only serves as a multi-purpose water body, but also ensures a suitable quality water for drinking water supply.

**Figure 8.17 Annual variation in the nitrate-nitrogen concentrations in the River Stour, UK compared with the concentrations in the waters of the Abberton reservoir which is supplied by the river. De-nitrification in the reservoir helps to reduce the nitrate-nitrogen concentrations to below guideline levels for drinking water. (After Slack, 1977)**

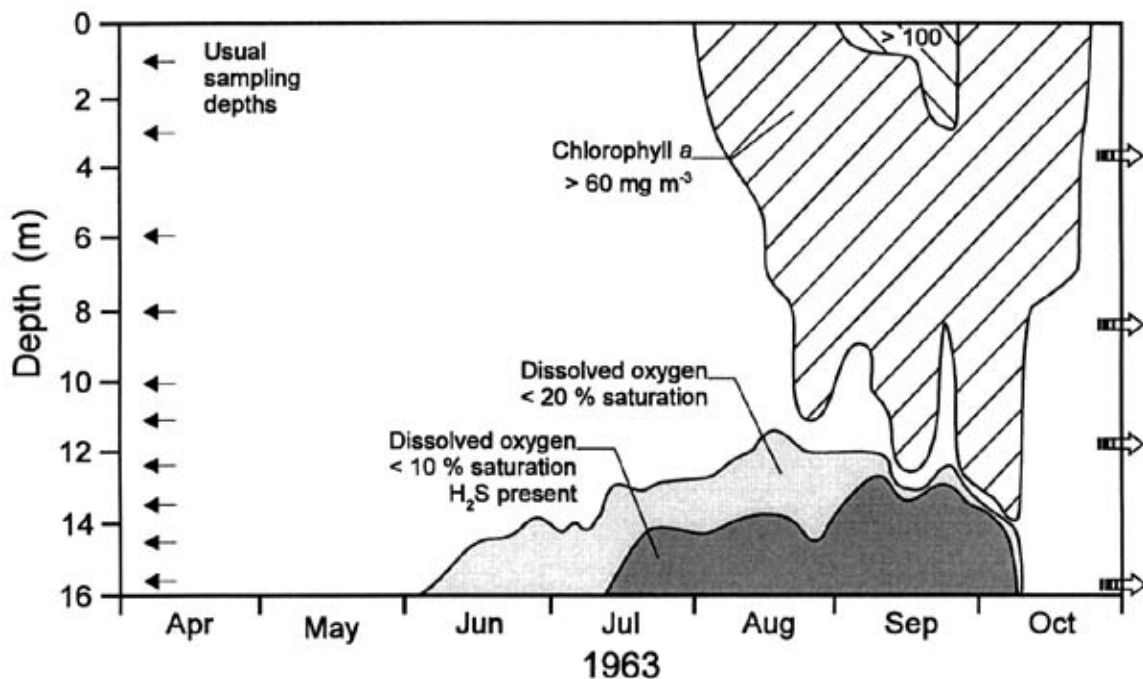


### 8.6.3 Eutrophication studies

Reservoirs have been subjected to much, long-term investigation of the effects of nutrient enrichment, principally to attempt to understand its effects in reservoirs and to identify possible ways of reducing any nutrient associated problems. Figure 8.18 illustrates a typical situation in the highly eutrophic King George VI reservoir (volume

20.2 × 10<sup>6</sup> m<sup>3</sup>; area 1.4 km<sup>2</sup>) in the southern UK prior to the intervention of any management regime. The routine sampling of the water column at fixed depths (indicated in Figure 8.18) for temperature and dissolved oxygen was combined with the results of a special survey of phytoplankton species and biomass. The results showed that the water body thermally stratified, resulting in deoxygenation of the hypolimnion and an eventual build-up of hydrogen sulphide. At the same time, a substantial population of the cyanobacterium *Aphanizomenon flos-aquae* developed in the epilimnion. The possible (shore-line) outlets for drinking water supply are also shown in Figure 8.18. From mid-June onwards (as summer water demands increased) it was difficult to extract water of a suitable quality for treatment by the available water treatment processes. When internal seicheing was also considered, the ability to select a particular water layer of desired water quality was also compromised. Detailed assessments such as these led to the search for solutions to the problems of thermal stratification and algal production in nutrient rich reservoirs (see sections 8.3 and 8.4 for examples of management solutions).

**Figure 8.18 Depths distributions of chlorophyll a and dissolved oxygen concentrations in relation to the water withdrawal points in the highly eutrophic King George VI reservoir, UK, during the summer months, prior to the application of any management regime (compare with the managed reservoir in Figure 8.12) (After Steel, 1972)**



#### 8.6.4 Assessment of trends

The routine collection of information for operational surveillance in reservoirs often allows the associated long- and short-term trends in water quality variables to be identified without additional effort. However, changes in reservoir operational procedures or water use over time can influence long-term trends and/or their significance to

reservoir water use. Inter-annual variation may be induced for operational reasons as well as being a function of climatic and other anthropogenic factors.

## **8.7. Summary and conclusions**

Reservoirs are essential sources of freshwater for consumptive (e.g. drinking or process water) and non-consumptive (e.g. fisheries and recreational) human use. They have also contributed to industrial development by providing cheap sources of hydropower and hydroelectric power and many continue to provide hydroelectric power throughout the world. Although the development of reservoirs is usually economically beneficial to communities, in some geographic zones they can have negative impacts, such as encouraging the spread of water-borne diseases (e.g. bilharzia and river blindness). Some large impoundments may even require the displacement of the local populations while attracting new people to the reservoir shores.

Reservoirs are, essentially, managed water bodies and, therefore, there is a particular need for the managers to understand their physics, chemistry and biology. This knowledge is acquired through assessment of water quality data gathered during well-planned monitoring programmes. In turn, the management operations, themselves, can affect the water quality characteristics and behaviour of the reservoir. There is also a particular need for further evaluation of monitoring strategies in relation to operational changes over time.

The objectives of the assessment programme and the associated monitoring strategies will often be governed by the operational requirements for a specified water quality. Nevertheless, in many situations, the monitoring activities will be similar to those carried out in natural lakes, although the interpretation and assessment of the data can differ markedly as a result of the modifying influences of the operating regime of the reservoir. Awareness of the effects of the location and depth of water withdrawal points on the water quality characteristics and behaviour within the reservoir is essential to their management to achieve the optimum water quality for intended uses. In addition, in order that managers may make the maximum use of physical and water quality data gathered from reservoirs, it is necessary to determine and understand the effects of inflows and outflows, retention time, in-basin facilities and actions, and morphometry and location of the reservoir within its watershed.

Reservoirs, and their associated water quality, can benefit from the ability to site and to construct them, within the limitations of topography, to best operational advantage. The water quality of established reservoirs can be managed by altering operating regimes, changing water uses, and blending waters of varying quality. In water-poor climates, the development of elaborate inter-basin transfer schemes provides additional opportunities to ensure safe and reliable supplies of water throughout countries and regions. Such schemes, however, can increase the likelihood of the transfer of undesirable species and habitat destruction.

Unlike natural lakes, reservoirs create environmental impacts, as well as suffer from impacts due to human activity. By modifying the flow regime of natural water courses (in some cases completely diverting river flows from one watershed to another) reservoirs can alter species compositions both upstream and downstream, change thermal regimes, and also modify the chemical content of waters. In addition, changes in the quality and

quantity of reservoir discharges, arising from changes in operational regime, into rivers and downstream lakes can affect the water quality of the receiving water body. The impact of these, possibly variable, water quality discharges should be taken into account in monitoring and assessment programmes for the receiving water bodies.

## 8.8. References

Balon, E.K. and Coche, A.G. 1974 *Lake Kariba: A Man-made Tropical Ecosystem in Central Africa*, Monographiae Biologicae **24**, Dr W. Junk, The Hague.

Benndorf, J. and Pütz, K. 1987a Control of eutrophication of lakes and reservoirs by means of pre-dams. I. Mode of operation and calculation of the nutrient elimination capacity. *Wat. Res.*, 21(7), 829-838.

Benndorf, J. and Pütz, K. 1987b Control of eutrophication of lakes and reservoirs by means of pre-dams. II. Validation of the phosphate removal model and size optimization. *Wat. Res.*, 21(7), 839-842.

Benndorf, J., Schultz, H., Benndorf, A., Unger, R., Penz, E., Kneschke, H., Kossatz, K., Dumke, R., Hornig, U., Kruspe, R., and Reichel, S. 1988 Food web manipulation by enhancement of piscivorous fish stocks: long-term effects in the hypertrophic Bautzen reservoir. *Limnologia*, **19**, 97-110.

Bernhardt, H. 1978 Die hypolimnische Belüftung der Wahnachtalsperre. [The hypolimnetic aeration of the Wahnbach reservoir]. *GWF-Wasser/Abwasser*, 119(4), 177-182 [In German].

Bloom, H., Dodson, J.J., Tjitrosomo, S.S., Umaly, R.C. and Sukimin, S. 1991 *Inland Aquatic Environmental Stress Monitoring*. Biotrop Special Publication **43**, Southeast Asia Regional Centre for Tropical Biology, Bogor, 262 pp.

Bryan, J.G. 1964 Physical control of water quality. *J. Brit. Watwks Assn*, 19 pp.

Cole, T.M. and Hannan, H.H. 1990 Dissolved oxygen dynamics. In: K.W. Thornton, B.L. Kimmel and F.F. Payne [Eds] *Reservoir Limnology: Ecological Perspectives*. Wiley, New York, 71-107.

Cooley, P. and Harris, S.L. 1954 The prevention of stratification in reservoirs. *J. Inst. Wat. Engrs.*, **8**, 517-537.

Davies, B.R. 1979 Stream regulation in Africa: A review. In: J.F. Ward and J.A. Stanford [Eds] *The Ecology of Regulated Streams*, Plenum Press, New York, 113-142.

de Moor, F.C. 1986 Invertebrates of the Lower Vaal River, with emphasis on the Simuliidae. In: B.R. Davies and K.F. Walker [Eds] *The Ecology of River Systems*. Monographiae Biologicae **60**, Junk, The Hague, 135-142.

DWA 1986 *Management of the Water Resources of the Republic of South Africa*. Department of Water Affairs, Government Printer, Pretoria.

Ebel, W.J. and Koski, C.H. 1968 Physical and chemical limnology of Brownlee Reservoir, 1962-1964. *Fish. Bull. Bureau Commercial Fisheries*, **67**, 295-335.

Gaugush, R.F. 1986 *Statistical Methods for Reservoir Water Quality Investigations*. U.S. Army Corps of Engineers Waterways Experiment Station Instruction Report E-86-2, Vicksburg, 214 pp.

Goossens, L.H.J. 1979 *Reservoir Destratification with Bubble Columns*. Delft University Press, Delft, 200 pp.

Horn, W. 1981 Phytoplankton losses due to zooplankton grazing in a drinking water reservoir. *Int. Revue ges. Hydrobiol.*, **66**(6), 787-810.

Horn, H. and Paul, L. 1984. Interactions between light situation, depth of mixing, and phytoplankton growth during the Spring period of full circulation. *Int. Revue ges. Hydrobiol.*, **69**(4), 507-519.

Hutchinson, G.E. 1957 *A Treatise on Limnology. Volume I, Geography, Physics and Chemistry*. Wiley, New York, 1,015 pp.

Jorgensen, S.E. and Vollenweider, R.A. 1989 Remedial techniques. In: S.E. Jorgensen and R.A Vollenweider [Eds] *Guidelines of Lake Management*. International Lake Environment Committee, Otsu, Shiga and United Nations Environment Programme, Nairobi, 99-114.

Kennedy, R.H. and Gaugush, R.F. 1988 Assessment of water quality in Corps of Engineers reservoirs. *Lake Reserv. Manage.*, **4**, 253-260.

Kimmel, B.C. and Groeger, A.W. 1984 Factors controlling primary production in lakes and reservoirs: A perspective. In: *Lake and Reservoir Management*. Report EPA-440/5-84-001, United States Environmental Protection Agency, Washington, D.C., 277-281.

Lawton, L.A. and Codd, G.A. 1991 Cyanobacterial (blue-green algal) toxins and their significance in UK and European waters. *J. Inst. Water Environ. Manag.*, **5**(4), 460-465.

LAWA 1990 *Limnologie und Bedeutung ausgewählter Talsperren in der Bundesrepublik Deutschland*. [Regional Water Study Group: Limnology and Importance of Selected Impoundments in the German Federal Republic] Länderarbeitsgemeinschaft Wasser, Weisbaden, 280 pp [In German].

Leidy, G.R. and Jenkins, R.M. 1977 *The Development of Fishery Compartments and Population Rate Coefficients for Use in Reservoir and Ecosystem Modelling*. US Army Corps of Engineers Waterways Experiment Station Contract Report Y-77-1, Vicksburg, A1-A8.

Lind, O.T. 1986 The effect of non-algal turbidity on the relationship of Secchi depth to chlorophyll-a. *Hydrobiologia*, **140**, 27-35.

- Linsley, R.K. and Franzini, J.B. 1972 *Water-Resources Engineering*. McGraw-Hill Book Company, New York, 690 pp.
- Marshall, B.E. and Junor, F.J.R. 1981 The decline of *Salvinia molesta* on Lake Kariba. *Hydrobiologia*, **83**, 477-484.
- Marshall, B.E., Junor, F.J.R. and Langerman, J.D. 1982 Fisheries and fish production on the Zimbabwean side of Lake Kariba. *Kariba Studies*, **10**, 175-231.
- McKendrick, J. 1982 Water supply and sewage treatment in relation to water quality in Lake Mcllwaine. In: J.A. Thornton [Ed] *Lake Mcllwaine: The Eutrophication and Recovery of a Tropical African Man-made Lake*. Monographiae Biologicae **49**, Junk, The Hague, 202-217.
- Moore, L. and Thornton, K.W. 1988 *Lake and Reservoir Restoration Guidance Manual*. United States Environmental Protection Agency EPA-440/5-88-002, Washington, D.C.
- O'Neill, J.G. and Holding, A.J. 1975 The importance of nitrate reducing bacteria in lakes and reservoirs. In: *The Effects of Storage on Water Quality*. Water Research Centre, Medmenham, 91-115.
- Oskam, G. 1983 Quality aspects of the Biesbosch reservoirs. *Aqua*, **6**, 1156, 497-504.
- Petitjean, M.O.G. and Davies, B.R. 1988 Ecological impacts of inter-basin transfers - some case studies, research requirements and assessment procedures. *S. Afr. J. Sci.*, **84**, 819-828.
- Petr, T. 1978 Tropical man-made lakes - their ecological impact. *Arch. Hydrobiol.*, **81**, 368-385
- Prentki, R.T. and Paulson, L.J. 1983 Historical patterns of phytoplankton productivity of Lake Mead. In: *Aquatic Resources Management of the Colorado River Ecosystem*. Ann Arbor Science, Ann Arbor, 105-123.
- Rast, W. 1995 *Salinity Model of the Highland Lakes of Central Texas, USA*. Water Resour. Invest. Report, US Geological Survey, Austin.
- Rast, W. and Lee, G.F. 1978 *Summary Analysis of the North American (US Portion) OECD Eutrophication Project: Nutrient Loading - Lake Response Relationships and Trophic State Indices*. Report EPA-600/3-78-008, United States Environmental Protection Agency, Corvallis, 454 pp.
- Robarts, R.D., Ashton, P.J., Thornton, J.A., Taussig, H.J. and Sephton, L.M. 1982 Overturn in a hyper-trophic, warm, monomictic impoundment (Hart-beespoort Dam, South Africa). *Hydrobiologia*, **97**, 209-224.
- Ryding, S.-O. and Rast, W. 1989 *The Control of Eutrophication of Lakes and Reservoirs*. Man and the Biosphere **1**, Parthenon Press, Carnforth, 314 pp.

Schiemer, F. 1984 *Limnology of Parakrama Samudra, Sri Lanka: A Case Study of an Ancient Man-made Lake in the Tropics*. Developments in Hydrobiology **12**, Dr W. Junk, The Hague, 236 pp.

Serruya, C. and Pollinger, U. 1983 *Lakes of the Warm Belt*. Cambridge University Press, Cambridge, 569 pp.

Slack, J.G. 1977 Nitrate levels in Essex river waters. *J. Inst. Wat. Eng. Sci.*, **31**, 43-51.

Steel, J.A. 1972 Limnological research in water supply systems. In: R.W. Edwards and D.J. Garrod [Eds] *Conservation and Productivity of Natural Waters*. Symp. Zool. Lond. **29**, 41-67.

Steel, J.A. 1975 The management of Thames Valley reservoirs. In: *The Effects of Storage on Water Quality*. Water Research Centre, Medmenham, 371-419.

Steel, J.A. 1978a The use of simple plankton models in the management of Thames valley reservoirs. *DVBW-Schriftenreihe Wasser*, **16**, 42-59.

Steel, J.A. 1978b Reservoir algal productivity. In: A. James [Ed.] *Mathematical Models in Water Pollution Control*. John Wiley & Sons, Chichester, 107-135.

Straskrabá, M. and Gnauck, A.H. 1985 *Freshwater Ecosystems Modelling and Simulation*. Developments in Environmental Modelling, **8**, Elsevier, Amsterdam, 309 pp.

Straskrabá, M. and Straskrabová, V. 1975 Management problems of Slapy reservoir, Bohemia, Czechoslovakia. In: *The Effects of Storage on Water Quality*. Water Research Centre, Medmenham, 449-483.

Straskrabá, M., Tundisi, J.G. and Duncan, A. 1993 *Comparative Reservoir Limnology and Water Quality Management*. Developments in Hydrobiology Volume DH 77, Kluwer Academic Publishers, Boston, 291 pp.

Straskrabová, V. and Komárková, J. 1979 Seasonal changes in bacterioplankton in a reservoir related to algae: 1. Numbers and biomass. *Int. Revue ges. Hydrobiol.*, **64**(3), 285-302.

Thanh, N.C. and Biswas, A.K. 1990 *Environmentally-sound Water Management*. Oxford University Press, Delhi, 276 pp.

Thornton, J.A. 1982 *Lake McIlwaine: The Eutrophication and Recovery of a Tropical African Man-made Lake*. Monographiae Biologicae **49**, Junk, The Hague, 251 pp.

Thornton, J.A. and Rast, W. 1993 A test of hypotheses relating to the comparative limnology and assessment of eutrophication in semi-arid man-made lakes. In: M. Straskrabá, J.G. Tundisi and A. Duncan [Eds] 1993 *Comparative Reservoir Limnology and Water Quality Management*. Developments in Hydrobiology **77**, Kluwer Academic Publishers, Boston, 1-24.



- Thornton, J.A., Williams, W.D. and Ryding, S.-O. 1992 Emigration, economics and environmental pollution in southern Africa. In: R. Herrmann [Ed] *Managing Water Resources During Global Change*, AWRA Technical Publication Series TPS-92-4, American Water Resources Association, Bethesda, 609-617.
- Thornton, K.W., Kimmel, B.L. and Payne, F.F. 1990 *Reservoir Limnology: Ecological Perspectives*. Wiley, New York, 246 pp.
- Thornton, K.W., Kennedy, R.H., Magoun, A.D. and Saul, G.E. 1982 Reservoir water quality sampling design. *Water Resources Bull.*, **18**, 471-480.
- Tundisi, J.G. 1981 Typology of reservoirs in southern Brazil. *Verh. int. Ver. Limnol.*, **21**, 1,031-1,039.
- UNEP 1991 *Freshwater Pollution*. UNEP/GEMS Environment Library, No 6, United Nations Environment Programme, Nairobi, 36 pp.
- UNESCO/UNEP 1990 *The Impact of Large Water Projects on the Environment*. Proceedings of an International Symposium, Paris, 1986, United Nations Educational, Scientific and Cultural Organisation, Paris, 570 pp.
- University of Wisconsin-Madison 1986 *Delavan Lake: A Recovery and Management Study*. Water Resources Management Workshop, Institute for Environmental Studies, Madison, 332 pp.
- van Breeman, L.W.C.A., Dits, J.S. and Ketelaars, H.A.M. 1992 Production and reduction of geosmin and 2-methylisoborneol during storage of river water in deep reservoirs. *Wat. Sci. Tech*, **25**, 233-240.
- Van der Heide, J. 1982 *Lake Brokopondo: Filling Phase Limnology of a Man-made Lake in the Humid Tropics*. PhD Dissertation, University of Amsterdam van der Leeden, F., Troise, F.L. and Todd, D.K. 1990 *The Water Encyclopedia*. Second Edition. Lewis Publishers, Boca Raton, 808 pp.
- Veltrop, J.A. 1993 Importance of dams for water supply and hydropower. In: A.K. Biswas, M. Jellalli and G.E. Stout [Eds] *Water for Sustainable Development in the Twenty-first Century*. Oxford University Press, Delhi, 104-115.
- Ward, J.F. and Stanford, J.A. [Eds] 1979 *The Ecology of Regulated Streams*. Plenum Press, New York.
- Whitehead, P. 1992 Examples of recent models in environmental impact assessment. *J. Inst. Water Environ. Manag*; **6**(4), 475-484.
- Znamenski, V.A. 1975 The role of hydrological factors with respect to water quality in reservoirs. In: *The Effects of Storage on Water Quality*. Water Research Centre, Medmenham, 567-573.
-