RESERVOIR DEVELOPMENT AND EXPLOITATION FOR A NORMAL TROPHIC STATE

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The availability and management of water resources has always played an important role in the development of human civilisation, in every part of the world. Reservoirs serve the purpose of collecting water from various sources, primarily precipitation, and making this water available on a more uniform basis than would otherwise be possible. Reservoir water quality is severely affected by certain interrelated biological and chemical processes, that give rise to the phenomenon of eutrophication. This paper presents a series of technical solutions to the problem of eutrophication, whose application implies modifications in reservoir development and exploitation.

General Considerations

The total volume of our planet's water reserves is an impressive 1.4 billion km3. Of this amount, 1.362 billion km3 make up the oceans, and 38 million km3 make up the fresh water mass, namely glaciers, water vapour, and surface and underground water deposits. As a result, fresh water mass constitutes approximately 2.7% of the total available water mass, and the remaining 97.3% is distributed among oceans and seas (Table 1).1 However, the total fresh water mass available for use by terrestrial ecosystems and, as a result, for human consumption, constitutes merely 0.4% of the 38 million km3 - that is 150,000 km3.

Usable fresh water resources reach 3,800x109 m3 annually. If this volume were to be used in its entirety, the beginning of the third millennium would see an annual per capita water consumption of approximately 475 m3. This amounts to a daily per capita water consumption of 1,300 litres, a modest quantity for the current rate of development of our civilisation. Taking into account that the annual regeneration of fresh water reserves is not uniform, but depends on weather conditions and precipitation levels, desired water availability can only be achieved through reservoir development and management, which greatly depends on available funds.

Table 1. Distribution of global fresh water reserves

Source	Volume (km^3x10^3)	Percentage
Glaciers	29,300.00	77.20%
Underground Water	8,550.00	22.40%
Lakes and Marshes	131.10	0.35%
Atmospheric Water Vapour	15.10	0.04%
Rivers and Streams	3.80	0.01%
Total	38,000.00	100.00%

In order to meet increasing rates of water consumption, it has been necessary to exploit additional fresh water reserves, such as natural lakes and underground water deposits, as well as developing desalination techniques, so as to take advantage of abundant salt water reserves (oceans and seas). In view of the current economic, technological and demographic progress in all parts of the world, it is easy to predict that, at least at the beginning of the third millennium, reservoir development will continue to be the only efficient way to control the availability of fresh water reserves.

Reservoir Management and Utilisation

In order to achieve uniform annual and seasonal water availability, reservoirs have to contain a minimum volume of water, which will form the basis for further reservoir development and exploitation. For this to be economically feasible, it is necessary for dams to be narrow and for reservoir beds to permit the construction of stable dam foundations. In addition, reservoir beds have to be deep enough to prevent the need for very tall dams. These conditions are usually met in mountainous regions.

In the post World War II years, when most mountainous regions had already been exploited for different purposes, reservoir construction began in flatter areas. Reservoirs constructed in plains are usually shallow and result from the erection of short dams. They mostly serve urban, agricultural and industrial areas, and do not play a regulatory role in water resource management.

According to its function, reservoir water volume can be classified in the following four categories (Figure 1):

- *overflow limiting volume* - surface volume for overflow regulation
- *functional volume* - available for water supply and reservoir replenishment
- *emergency volume* - deeper reserves to be used for emergency water supply
- *residual volume* - no functional usage

As a result, water is conventionally drawn from the functional volume layers, and possibly from the emergency volume layers, leaving the residual volume intact. In case the reservoir needs to be emptied, special care is taken not to disturb the residual volume, which is removed only in very special circumstances. If the reservoir in question receives its water supply from a river, river-flow to the reservoir has to be specifically regulated, in order to avoid compromising other water supply demands. The extent of flow-rate regulation is subject to State law.2

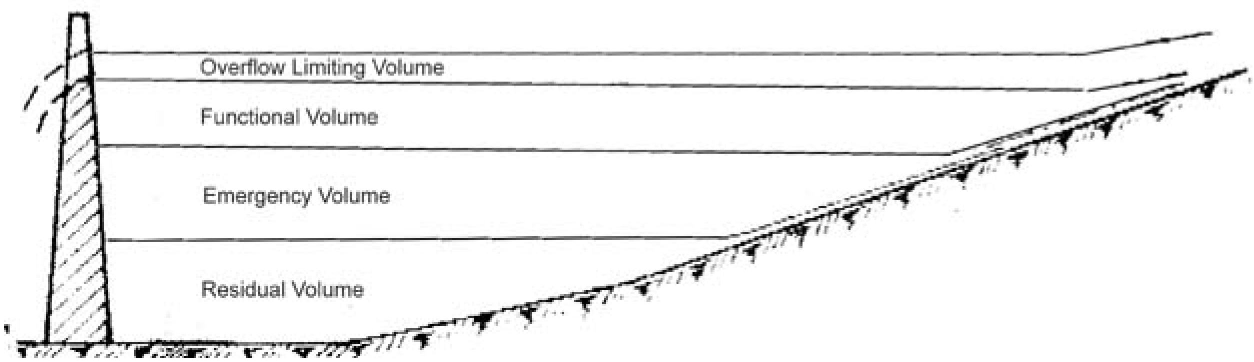

Figure 1

Reservoir Water Quality

When reservoirs receive their water supply from rivers, the water retains the physical and chemical properties of the river supplying it. However, biological properties differ, since, when river-flow is interrupted and water starts accumulating in the reservoir bed, significant changes take place, as a result of the following factors:

- nutrients (primarily nitrogen and phosphorus) accumulating naturally or as by-products of human activity
- thermal energy from solar radiation, which is directly proportional to the level of water turbulence and the intensity of solar radiation
- thermal stratification
- presence and distribution of convection and advection currents
- nature of the existing reservoir bed biomass

Thermal stratification results in a rapid increase in nutrients and, consequently, a spectacular aggregation of algae and macrophytes, which, in turn, cause a deterioration in water quality. This phenomenon is "self-sustained," due to the decomposition of organic materials in the hypolimnion (the bottom layers of the reservoir), that brings about an additional release of nutrients in the water. This biochemical process is known as eutrophication.

In the surface layers, which are subject to increased solar and thermal radiation, oxygen concentration levels vary extensively during the day. However, oxygen consumed through primary production is balanced by the oxygen produced by photosynthesis from the aggregated algae. As a result, oxygen concentration levels in the epilimnion are generally satisfactory. This is not the case, however, for the metalimnion and the hypolimnion, since oxygen concentration levels decrease at increasing depths. In these deeper zones, metabolic activity uses up oxygen which cannot be replaced, because photosynthesising organisms are absent at these depths (Figure 2).

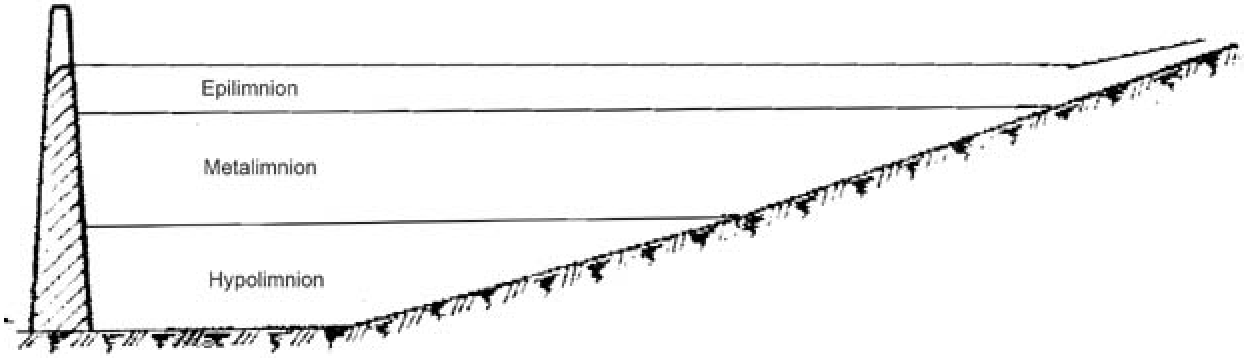

Figure 2

Research has revealed that eutrophication generally takes place within 20-30 days from the advent of thermal stratification. There is also a direct relationship between water temperature and oxygen concentration. A broad zone, the thermocline, which separates the epilimnion from the hypolimnion, is characterised by a rapid change in temperature and oxygen concentration with increasing depth. Eutrophication can be controlled and oxygen concentration increased by introducing CBO5-rich water in the hypolimnion. This procedure can be effective in controlling algae growth and, consequently, eutrophication, because, in the presence CBO5, oxidation of organic phosphates will yield products with low nutritive value that cannot be efficiently metabolised by the algae.4

These observations are particularly interesting, since they allow the development of improved measures for keeping the phenomenon of eutrophication in check.

Models for Improving Reservoir Trophic States

Before World War II, it was necessary to control minimum functional volume, for reservoirs fed by rivers, through State regulation. Lately, two new concepts have emerged: minimum sanitary volume and ecological balance volume. Minimum functional volume determines the minimum volume required to supply the reservoir with enough water to guarantee that its function will not be affected by any outside perturbations. Minimum sanitary volume is supposed to guarantee the high quality of the reservoir water, especially with regard to certain pollutants subject to regulation by law.

Ecological balance volume is a more complex concept, related to the previous two but, also comprising certain hydrobiology principles, especially with regard to species conservation. The careful control of ecological balance volume becomes obligatory in the cases of endemic icthyofauna and flora. It is not the scope of this paper to discuss the way of assigning values to these three different types of reservoir water volume, but it has to be born in mind that, no matter what the nature of the reservoir may be, these elements have to be carefully controlled.

If it is possible to evacuate the functional and sanitary volume from the hypolimnion then, doing so will greatly contribute towards alleviating eutrophication, as it will lead to the renewal of the deep reservoir layers. This evacuation should be carefully controlled during the summer months, and the volume evacuated should only represent a fraction of the hypolimnion, in order to have enough volume left to regulate the eutrophication process.

It is, therefore, necessary for dams to have a network of evacuation pipes of reduced capacity, connected through a series of outlets to the hypolimnion. Evacuation has to take place carefully, in order to avoid clogging and other adverse effects.

Another possibility for countering eutrophication is the introduction of oxygen-rich water in the hypolimnion. This procedure has to be carefully controlled, in order to achieve a "trans-layer" circulation of oxygen-rich water. Such a circulation, through the process of convection, can result in oxygen-rich water reaching the surface layers and, therefore, preventing the development and the onset of thermal stratification, which takes place during the summer months (Figure 3).

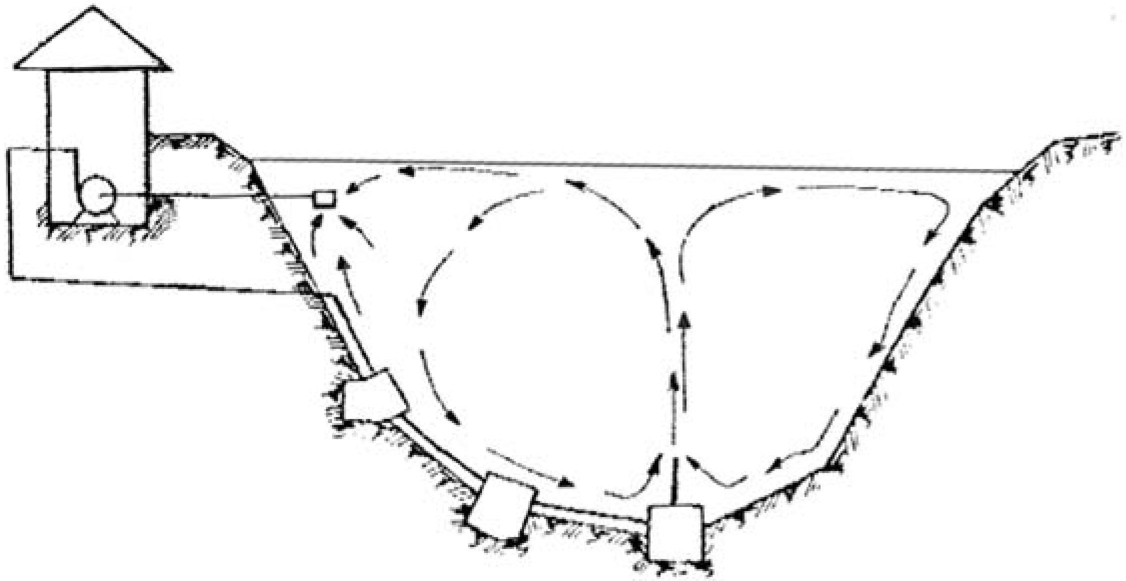

Figure 3

If the above mentioned trans-layer water circulation is not satisfactory, it can be improved by certain artesian jet streams from the hypolimnion. Apart from ensuring trans-layer water circulation in the reservoir, this technique can also help improve oxygenation of the hypolimnion. Piping used for this procedure has to be carefully placed, in order to avoid blockage.

An additional method for increasing oxygen concentration in the deeper reservoir layers, is the injection of compressed air in the hypolimnion. This is an easier process than the introduction of oxygen-rich water and provides similar results. Air bubbles travel towards the surface and improve trans-layer water circulation. They also promote the exchange of water between the epilimnion and the hypolimnion and help in the prevention of thermal stratification during the summer months.

Technical Measures for the Improvement of Reservoir Trophic States

In order to improve the trophic state of a reservoir, it is necessary to consume energy, which, in turn, can be obtained from internal combustion engines or electricity generators. These energy sources, however, in addition to being expensive, are also damaging to the environment, as they produce both noise and air pollution.

Reservoirs used in seasonal, annual or multi-annual water management are usually located in mountainous regions with strong winds. In this case, it is possible to take advantage of non-conventional energy sources, such as aeolic energy, to power the equipment used in pumping oxygen-rich water or compressed air in the reservoir (Figure 4). The number of aeolic energy devices used for this purpose can be determined by the carrying capacity of the area around the reservoir, as well as by available funds. Supplying the reservoir with such devices has to be done progressively, in order to allow time to accurately assess the reservoir's trophic state, as well as determine the exact number of aeolic energy devices needed in each case.

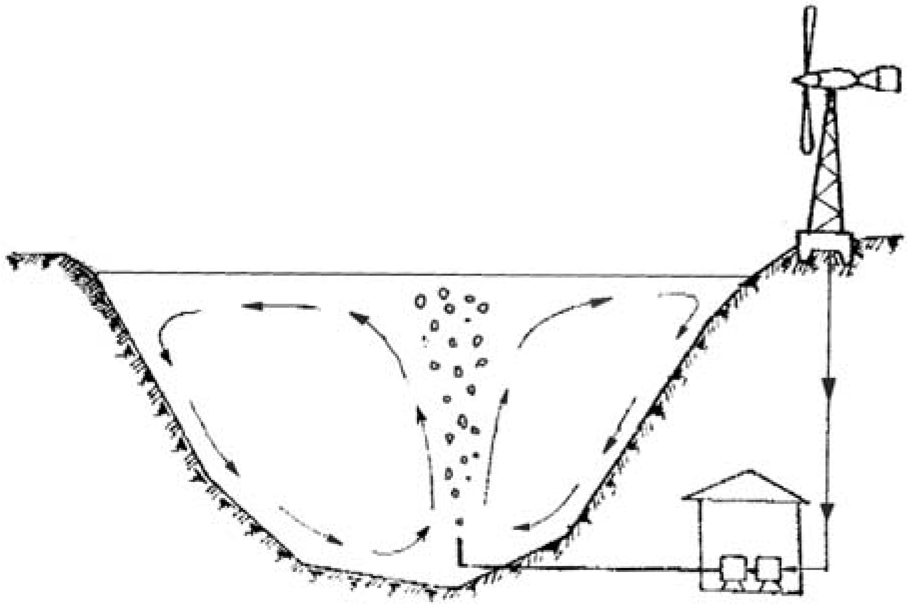

Figure 4

Another energy source that can be used to pump water or air in a reservoir, is hydraulic energy, derived from evacuation procedures performed on the same reservoir. Until recently, the energy produced by evacuations, that were carried out to balance incoming water-flow, was largely dissipated, due to inefficient equipment, which also happened to be quite costly. Harnessing the dissipated energy and applying it towards improving the reservoir's trophic state, is a much worthier goal. The hydromechanical equipment, required for this purpose, is not yet available but, its research and development can create many new opportunities in engineering and business.

While specialised equipment is still to be developed, hydrostatic pressure transformers are currently available and could be employed. A hydrostatic pressure transformer, pumping a quantity of water Q1 under hydrostatic pressure H1, will deliver a new quantity Q2H1. This kind of equipment can be used for delivering oxygen-rich water in the hypolimnion, as well as for introducing artesian jet streams (Figure 5). If the transformer is placed above the water, then it can also be used for pumping compressed air in the hypolimnion. The advantages in using such equipment lie in their relatively simple operation and maintenance.

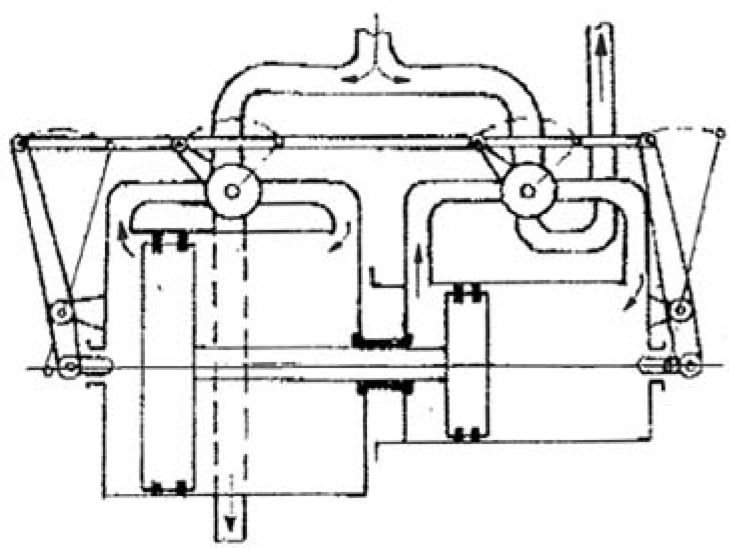

Figure 5

Hydraulic turbo-transformers are composed of a turbine engine and a centrifuge pump, mounted co-axially. These transformers are more expensive and harder to maintain than conventional hydrostatic pressure transformers. They are also limited to pumping water and, consequently, cannot be used for injecting airstreams.

Finally, in order to deliver oxygen-rich water or compressed air in the hypolimnion, a hydraulic ram can be applied. This kind of equipment functions by sonic pressure vibrations. Its installation and maintenance, however, are quite complicated and resemble those of the turbo-transformer.

Conclusion

The variety of equipment that can be used to improve a reservoir's trophic state, is indicative of the many opportunities this field offers. Furthermore, making use of non-conventional energy sources, such as aeolic energy, or the energy derived from reservoir evacuations, can lower management costs to merely covering personnel and equipment maintenance.

Reservoir trophic states can be improved by existing techniques, at relatively low costs, compared with the benefits reaped. Problems to be solved include the acquisition of scientific expertise on air-water mass exchange, under different pressure gradients and temperature variations, as well as on optimal spacing patterns for the equipment used to inject water or air in the hypolimnion.

Once these problems are solved, it will be possible to quantify different parameters for individual reservoirs, thus allowing the maintenance of a satisfactory trophic state.

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