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EFFECTS OF TVA IMPOUNDMENTS ON DOWNSTREAM WATER QUALITY AND BIOTA

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INTRODUCTION

The Tennessee Valley Authority (TVA), a corporate agency of the United States Government, was established in 1933 to develop the resources of the Tennessee Valley. The Tennessee River is an integral part of the interconnected Inland Waterway System of the United States, the final portion being the Tennessee-Tombigbee Waterway, presently under construction. The 106,000-square-kilometer watershed, shown in Fig. 1, encompasses portions of seven southeastern states with a population near 4 million people.

In the 1930s, the TVA area was subject to floods that claimed many lives and inflicted severe property damage. In addition, navigation and commerce were restricted during periods of low flow. The TVA system of nine large, multiple-purpose dams on the main stem of the Tennessee River brought flood control and guaranteed depths for navigation. Supplemented by the operation of multipurpose dams on the major Tennessee River tributaries, the TVA reservoir system made the shoreline safe for industries and jobs and has helped to restore thousands of hectares of agricultural lands to productivity. The growth of the TVA system has not been without adverse ecological effects, however.

A prime objective of the agency was to produce power at the lowest possible cost. Beginning with low-cost hydroelectric power, TVA is now the largest producer of electric power in the U.S., using a mixed system of 29 hydro plants, 12 coal-fired plants, 7 nuclear plants (operating, planned, or under construction), 48 gas turbines, 12 industrial dams, and 8 U.S. Army Corps of Engineers dams.

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Although the three principal purposes of the TVA reservoir system (flood control, navigation, and power production) remain unchanged, new demands for water have complicated operation of the system. Recreation, municipal and industrial water supplies, wastewater treatment, vector control, aquatic life, and other factors must all be considered in managing the system. Another factor adding to the complexity and cost of managing the TVA system is the growing concern for protecting the quality of the environment that is reflected in increasingly stringent environmental legislation.

EFFECTS OF IMPOUNDMENTS ON DOWNSTREAM WATER QUALITY

Of prime interest in this discussion are the water quality changes that result from impounding a free-flowing river, in particular as they affect downstream biota. Inasmuch as the mainstem dams on the Tennessee River mostly discharge into backwaters, the emphasis in this discussion will be on the tributary dams in eastern Tennessee, shown in Fig. 1. As will be demonstrated subsequently, the impoundment of water may have significant effects on water quality parameters that are vital to aquatic life, the most drastic changes being in temperature and dissolved oxygen.

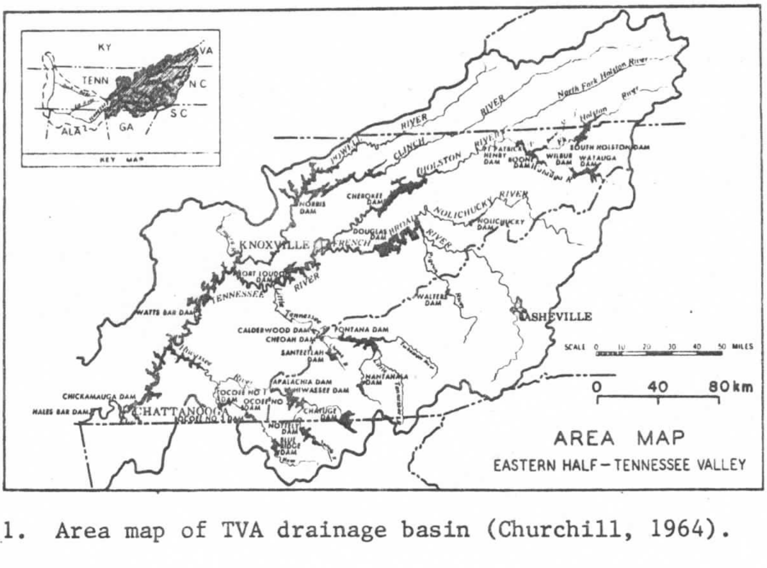


Fig. 1. Area map of TVA drainage basin (Churchill, 1964).

Thermal Structure in Reservoirs

The impoundment of a river usually markedly affects the thermal characteristics of the impounded water and of the water downstream from the dam. The resulting thermal structure of the impounded water can markedly affect the significance to water quality of certain contaminants, such as aquatic plant nutrients, within the reservoir as well as downstream from it. At the end of a winter season, the impounded water is usually of rather uniform quality and has a relatively low temperature. As summer approaches, the surface water and the incoming water temperatures are increased. The less dense water tends to "float" on the colder, higher density water already in the reservoirs. As a result of this phenomena, two strata are formed: the epilimnion, or surface stratum, and the hypolimnion, or lower stratum, which are separated by the metalimnion, a transition zone of rapid temperature-density change with depth. These conditions may exist until autumn, when the reservoir begins to exhibit a net heat loss. As the surface water becomes cooler and more dense, the metalimnion sinks, unstable conditions occur, and the reservoir mixes (overturns), returning to the conditions found at the beginning of the season.

These strata may possess different water quality characteristics. The water quality of the discharge from the dam during stratification will obviously depend on the depth of the discharge. A primary factor governing the water quality characteristics of the epilimnion and hypolimnion is the areal plant nutrient load. These loads (usually nitrogen and phosphorus) typically control the phytoplankton production in a reservoir. Vollenweider (1976), Lee et al. (1978), and Rast and Lee (1978) have demonstrated that for a wide variety of waterbodies in various parts of the world, phytoplankton production is usually correlated with the phosphorus load, normalized by mean depth and hydraulic residence time (filling time). Newbry et al. (1979) have recently demonstrated that the nutrient load-eutrophication response relationships developed by Rast and Lee (1978) for approximately forty U.S. waterbodies, based on Vollenweider's load-response model, is applicable to the fourteen TVA impoundments evaluated by Newbry et al. (1979). All TVA impoundments evaluated were found to have P load-hydrological-morphological characteristics typical of eutrophic waterbodies and would therefore likely have one or more of their beneficial uses impaired.

Probably the most important impact of the thermal stratification that occurs in many reservoirs is the inhibition of mass transfer between the hypolimnion and epilimnion. Oxygen depleted in the hypolimnion by oxygen-demanding materials, such as dead phytoplankton, is not replaced from the oxygen-rich epilimnion, and the water quality of the hypolimnion deteriorates. Rast and Lee (1978) and Lee et al. (1978) have shown that oxygen depletion in the hypolimnion can be correlated with the areal P load to the waterbody as normalized by the mean depth and hydraulic residence time. Therefore, the excessive P load to such a waterbody as a TVA impoundment may have a significant adverse effect on the water quality within the impoundment and, most important for this review, in the water downstream from it.

The thermal structure of an impoundment and the temperature of the inflowing waters may cause density currents within the impoundment. This appears to be prevalent in certain TVA impoundments. As shown in Fig. 2, the density currents may appear in three ways: the overflow, where the incoming water is lighter than the receiving water; the underflow, where the incoming water is heavier than the receiving water; and the interflow, where the incoming water has a density intermediate to that of a stratified-flow regime. Each of these density flows occurs in the TVA system and, as discussed in subsequent sections, may have different effects on downstream water quality.

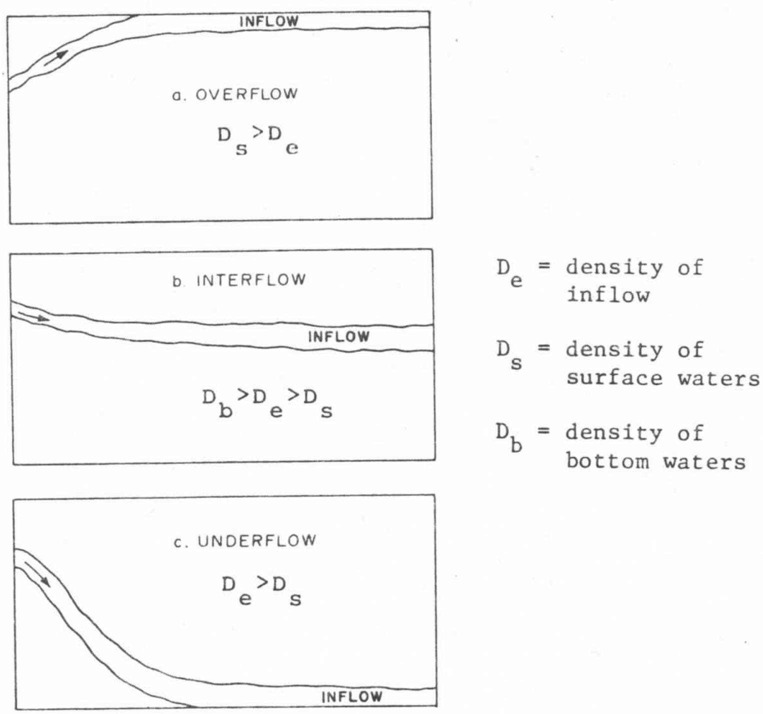
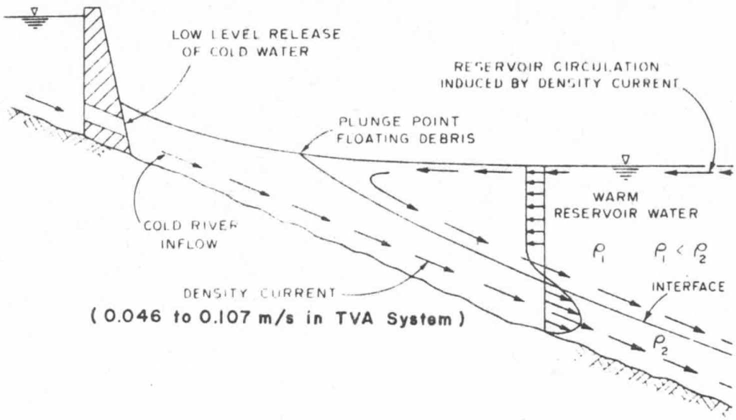


Fig. 2. The forms of density currents (Parker and Krenkel, 1969).

Generally, all reservoirs in the TVA system discharge water from the hypolimnion rather than from the epilimnion in order to increase hydro-power efficiency. The mainstream reservoirs are sufficiently closely spaced that the discharge of one reservoir is into the backwaters of the next. This creates a density flow, similar to that depicted in Fig. 3, in which there is essentially no free-flowing river between reservoirs. Another, more typical, situation is when there are a number of kilometers of free-flowing river down-



ρ_1 = density of surface water

ρ_2 = density of inflowing water

Fig. 3. Density-current underflow in a reservoir (Parker and Krenkel, 1969).

stream. In this situation an opportunity exists for establishing a riverine ecosystem and also for heating the reservoir discharge waters in summer. This heating could affect the formation of density currents in the downstream impoundment.

Effects of Thermal Structure on Water Quality Characteristics

A typical water characteristic profile for a eutrophic reservoir under stratified conditions is shown in Fig. 4. In addition to increased concentrations of iron and manganese in anoxic hypolimnia, many reservoirs show increased concentrations of sulfides in deep waters. The concentration of sulfides can be sufficiently high in

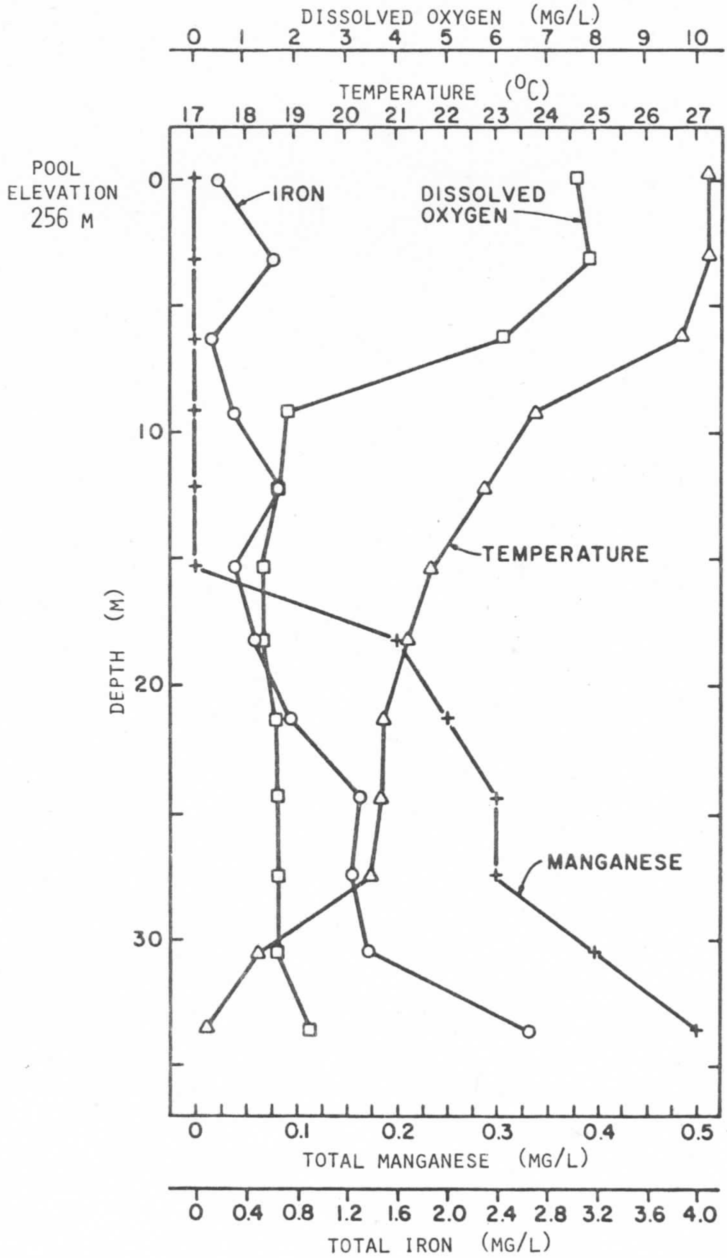
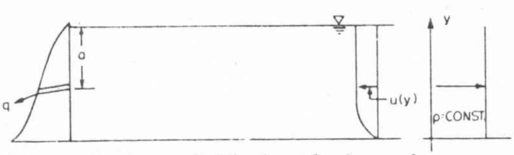


Fig. 4. Water quality characteristics profiles under stratified conditions (adapted from Parker and Krenkel, 1969).

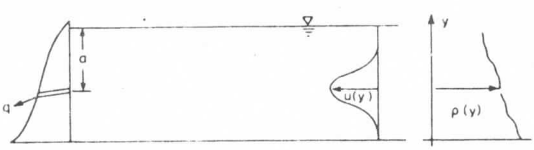
some reservoirs to cause large releases of sulfides to the atmosphere downstream from the dam. This does not, however, appear to be a problem associated with TVA reservoirs.

In hardwater systems, thermal stratification can promote a significant increase in the calcium concentration in hypolimnetic waters. Precipitation of $CaCO_3$ in the surface waters (caused by increased pH arising from photosynthesis and the loss of CO_2 resulting from elevated temperatures) tend to soften surface waters. The lower-pH, colder, hypolimnetic waters tend to dissolve $CaCO_3$ particles that rain down from the epilimnion as well as particles in the sediment. There is evidence for this phenomenon occuring in Cherokee Reservoir of the TVA system. For further discussion of the dynamics of $CaCO_3$ in freshwater systems, consult Morton and Lee (1968) and Lee and Delfino (1969).

The importance of the location of the intake for hydro-power generation (reservoir discharge) is demonstrated by comparing Fig. 4 with Fig. 5, which shows the process of selective withdrawal.



(A) Withdrawal from full depth in a homogeneous fluid



(B) Selective withdrawal in fluid with density varying as function of depth

q = flow
a = depth of withdrawal
u = velocity
y = depth
ρ = density

Fig. 5. The process of selective withdrawal (Elder and Garrison, 1964).

Under stratified conditions, waters tend to be withdrawn from a relatively narrow layer of approximately constant density. It is possible that as a result of density currents within the reservoir, waters may pass through the reservoir in relatively short periods of time without ever completely mixing with the epilimnetic or hypolimnetic waters of the waterbody. Under these conditions, the downstream thermal and chemical characteristics would be similar to those of water entering the reservoir. It is important to note that density currents within waterbodies may occur for relatively short periods of time. In Cherokee Reservoir in the TVA system, they appear to be a significant feature in the reservoir only during late summer and early fall. Investigators of water quality downstream from a reservoir must be fully cognizant of the water quality, physical-hydrodynamic characteristics, and the operation of the reservoir.

Dissolved Oxygen

Because of the previously mentioned processes, the dissolved oxygen concentration in the hypolimnion may become exhausted during the stratification period. Thus, the water released from the impoundment may be extremely low in oxygen and adverse to downstream aquatic life. In the TVA system the reservoir exhibiting the worst conditions regarding oxygen is Cherokee Reservoir, located on the Holston River. The low oxygen concentrations have been attributed to many factors, including excessive productivity, nitrogenous oxygen demand, and benthic demand. The relative significance of each of these factors has yet to be defined but is under investigation by Newbry et al. (1979). Preliminary results indicate that the low oxygen concentrations result primarily from phytoplankton production in the surface waters that exert an oxygen demand in the bottom waters. It appears that the oxidation of ammonium, present at the onset of thermal stratification, is also a significant contribution to oxygen demand. According to Taylor (1971), Cherokee Reservoir is the most productive of the TVA storage impoundments, having a mean value of 1,416 mgC/m^2/day assimilated by the phytoplankton and the highest total nitrogen content, on the order of 2.7 mg/liter. Newbry et al. (1979) have also indicated that the planktonic algal chlorophyll levels of Cherokee Reservoir are among the highest of the TVA waterbodies investigated.

An oxygen concentration pattern typical of summer conditions at Cherokee Reservoir is shown in Fig. 6. Fig. 7 shows the downstream oxygen profile as a function of distance and discharge rate from Cherokee Dam. Under stratified conditions in the reservoir, the dissolved oxygen content may be below the US EPA-recommended criterion of 5 mg/liter for a warm-water fishery for as much as 50 km downstream.

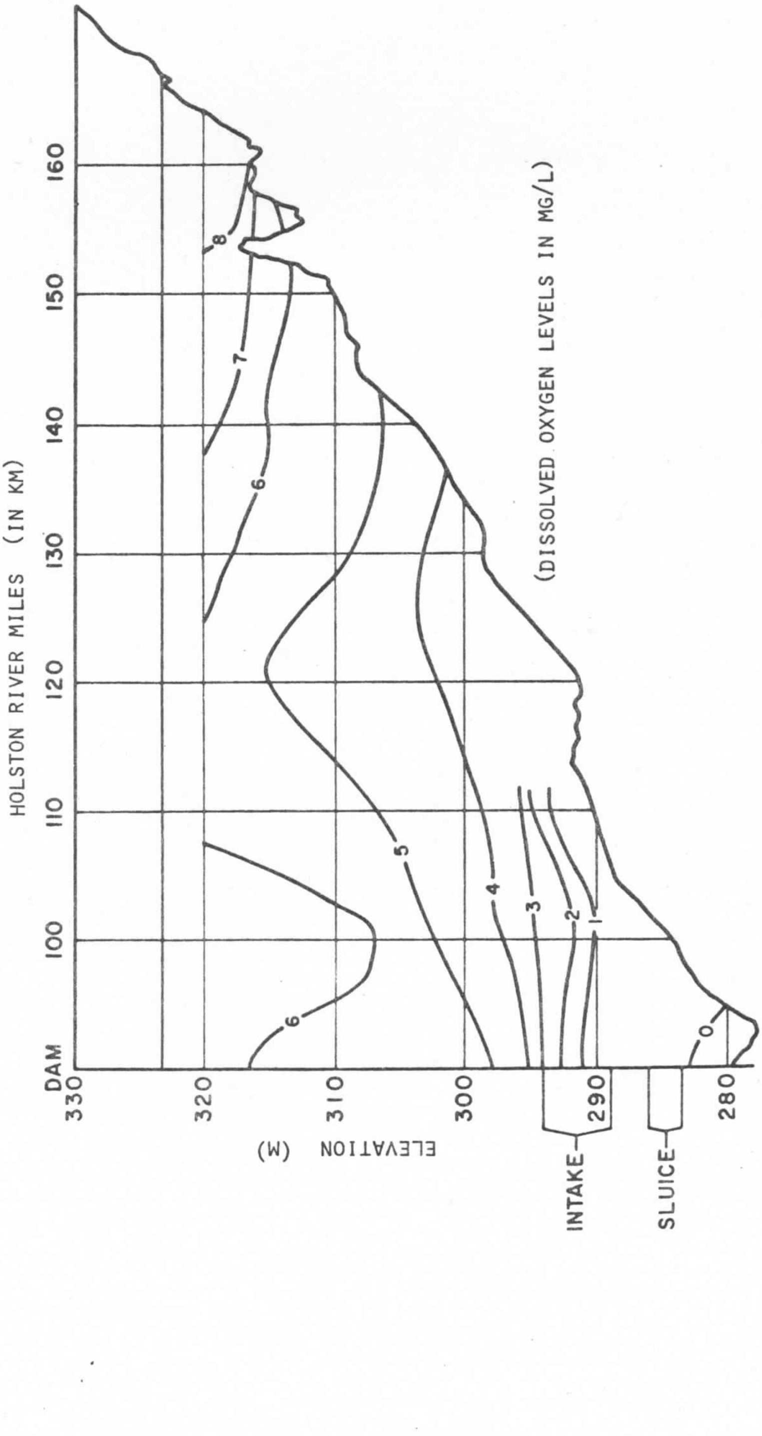


Fig. 6. Oxygen levels in Cherokee Reservoir (adapted from Churchill, 1964).

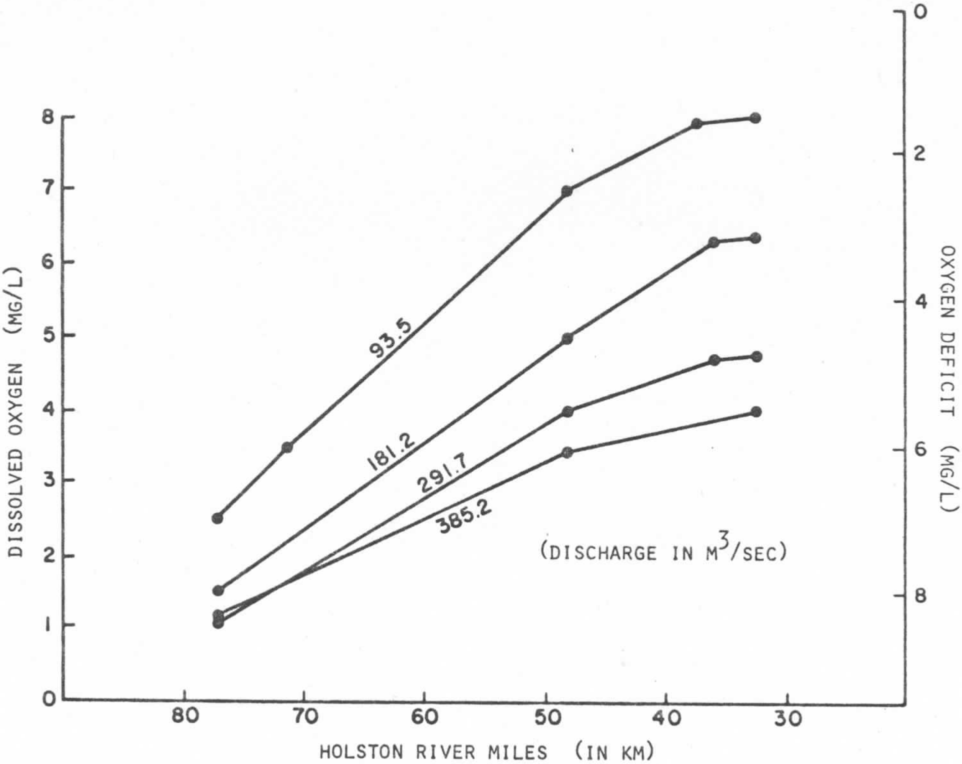


Fig. 7. Concentrations of oxygen in releases from Cherokee Reservoir at different discharge rates (adapted from Churchill, 1964).

Temperature

The effects of stratification on the temperature of releases are similar to those on the dissolved oxygen, since the hypolimnetic waters released will typically have lower temperatures. In many TVA reservoirs, the surface waters may reach 30°C during the summer stratification, while the hypolimnetic waters, released from the dam, may be less than 20°C. Fig. 8 shows the temperature distribution in Cherokee Reservoir which will be reflected in the water released downstream. Thus, the presence of the dam may create thermal conditions amenable to a cold-water fishery (Pfitzer, 1962). Although temperature records before the construction of many of the TVA dams are sparse, data reported by Krenkel and Novotny (1973)

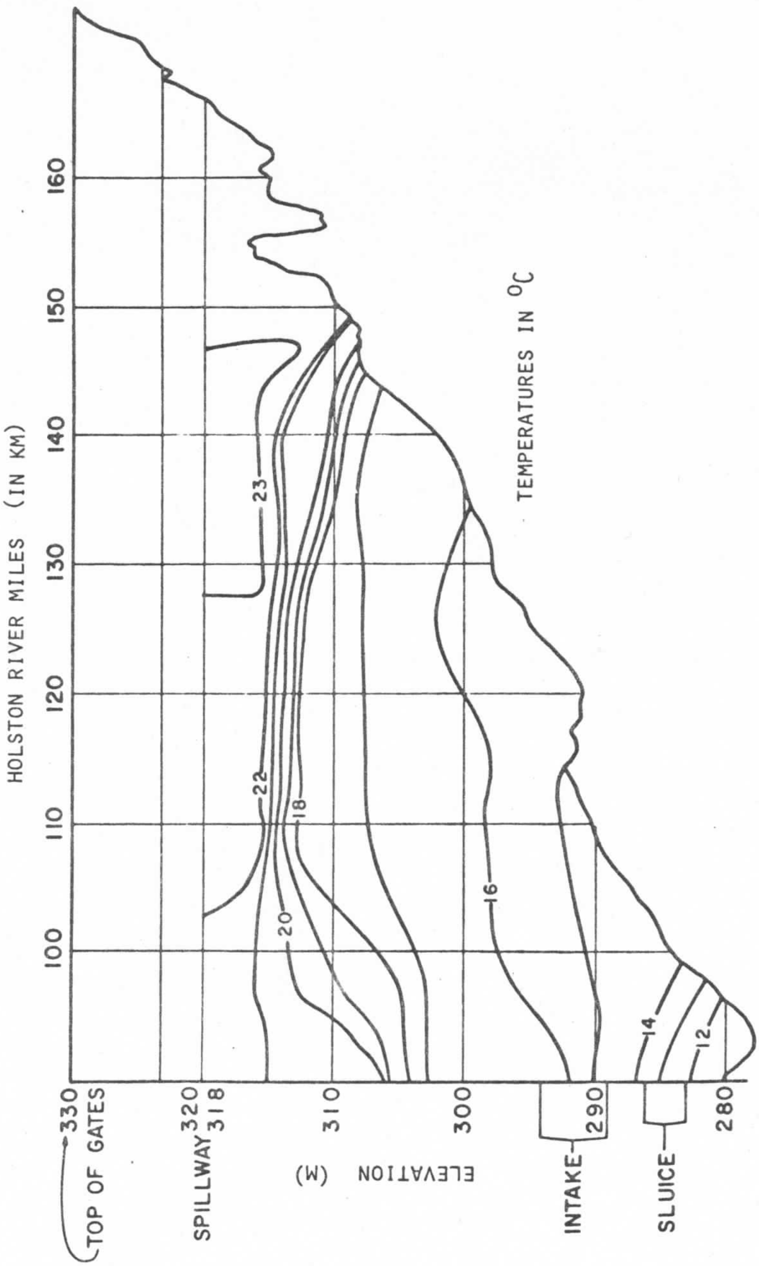


Fig. 8. Water temperatures in Cherokee Reservoir, 6 June 1945 (adapted from Churchill, 1964).

indicate that before the closure of upstream dams, the natural temperatures in the North Fork Holston River reached 31°C, while present releases from Fort Patrick Henry Dam in the same general area are on the order of 20°C.

Turbidity

Because a storage reservoir acts as a large sedimentation basin, the discharges from the dam will show reduced turbidity. A study done by Kittrell and Quinn (1949) demonstrated a 61% reduction in annual turbidity at the Knoxville water treatment plant subsequent to closure of Cherokee and Douglas Dams. Silt alters aquatic environments, primarily by inhibiting light, by changing heat radiation, by blanketing the stream bottom, and by retaining organic material and other substances that create unfavorable conditions for benthos. Thus, in this case, impoundment will result in improved conditions for some forms of aquatic life by reducing silt loads.

Flow

The influence of discharge on downstrean aquatic life must be noted. The base electricity load in the TVA system is supplied by coal- and nuclear-fired plants, the peak demands by hydroelectric power; hydroelectric power generation and hence flow are dependent on power demand. Therefore, the flow from a hydroeletric power facility may vary greatly. Nighttime and weekend flow may be minimal, while daytime peaks of thousands of cubic meters per second may be suddenly released from a dam. This means that downstream areas may be subjected to little or no flow during weekends and nighttime hours and to flooding during peak daytime hours.

This "peaking" practice may have several adverse effects on downstream aquatic life. For example, fish kills have been reported downstream from Fort Loudoun Dam because of the low dissolved-oxygen content and cold temperatures resulting from the sudden release of hypolimnetic waters after several days of little or no flow (Jones, 1964). In addition, benthic organisms are affected by exposure during periods of low or no flow and by flooding during periods of power production.

Reduced Chemical Species

The characteristics of hypolimnetic water of more fertile waterbodies, such as those discussed above, can have a marked adverse effect on downstream water quality. The buildup of large concentrations of reduced chemical species (e.g., iron, manganese, and sulfur) increases the total oxygen demand of hypolimnetic waters, which, for impoundments that discharge water from below the thermocline in the summer, increases the time-distance over which a balanced aquatic-organism population is not possible. Furthermore, oxygenation of iron and manganese species leads to the formation of insoluble hydrous metal oxides, which may form benthic deposits and coatings within the river downstream from the reservoir. Although not adequately studied, such deposits could significantly affect the numbers and types of organisms present in the river. In addition, because hydrous metal oxides tend to have high sorptive capacity for trace metals and many organics (Lee, 1975), the numbers and types of organisms could be changed as a result of changes in the trace element-compound composition of the water. In general, insufficient attention has been given to the role of aquatic plant nutrients in influencing biological and chemical characteristics of a river downstream from an impoundment. The OECD eutrophication modeling approach (Rast and Lee, 1978) has made significant advances in predicting changes in eutrophication-related water quality. Work needs to be done, however, to relate the nutrient load to a waterbody to the downstream water quality for those streams fed by hypolimnetic waters.

Other Water-Quality Parameters

The free CO_2 concentration in hypolimnetic waters is usually high because of bacterial activity, colder temperatures, and the barrier to gas exchange with the atmosphere. Although the pH of the hypolimnion is frequently lower than that of the epilimnion, the alkalinity is usually the same as that of the inflowing water. However, in hardwater systems, dissolution of calcium carbonate takes place in the hypolimnion, because of the presence of free CO_2, causing an increase in alkalinity.

Coliform bacteria, an indication of potential bacterial contamination, is usually reduced by impoundment. Other water quality parameters, if not changed by impoundments, are modified by storage and dilution, so that their concentrations in the discharge tend to be more uniform than in unimpounded waters.

EFFECTS OF IMPOUNDMENTS ON AQUATIC BIOTA

The changes in water quality caused by impoundment may have significant effects on downstream ecological systems. Although Wiebe (1958) stated that the TVA fishery is now at least 50 times that of the unimpounded river, Pfitzer (1962) noted that the construction of Cherokee Dam resulted in the loss of 52 miles (84 km) of very attractive and valuable stream as a fishery. Unfortunately, little data are available from TVA to document the conditions of fisheries downstream from impoundments.

Aquatic Macrophytes

The importance of aquatic plants can be demonstrated by noting that the dissolved oxygen concentration in the Holston River would fall below 3 mg/liter, even if no wastewater discharges were present, because of the presence of aquatic macrophytes (Anon., 1973). It should be noted that these plants, primarily *Potamogeton*, were not prolific before construction of several upstream impoundments. The presence of increased sediment because of lower flow velocities and smaller depths apparently account for the increased density of the plants.

The effect of aquatic plants on dissolved oxygen is a function of the plant density and distribution, plant species, light intensity, water depth, turbidity, temperature, and oxygen concentration. Meyer et al. (1943) showed that an increase in the depth of immersion of aquatic plants reduced their photosynthetic activity; however, the rate of apparent photosynthesis decreases less rapidly than light intensity with depth of immersion. Peltier (1970) summarized work at four locations and could not find relationships between nitrogen and phosphorus in the water and relative macrophyte abundance.

There is no doubt that the construction and operation of the TVA impoundments has exacerbated the proliferation of aquatic plants in the system. Inasmuch as the oxygen demand of these plants may be significant, it is imperative that the factors controlling the growth of aquatic macrophytes be delineated. For example, will limiting the phosphorus and nitrogen inputs to the reservoirs inhibit their growth?

Benthic Organisms

Tarzwell (1939) investigated the benthos of the Clinch River below Norris Dam, the first high dam with low-level discharges in the TVA system, shortly after water was impounded. Despite this early beginning, relatively few detailed data on benthos of TVA tailwaters have been published.

Pfitzer (1954) described the bottom fauna of the South Holston tailwaters, which he considered typical of other established tailwaters in the Tennessee Valley. Compared to the benthos in the unaltered river, tailwater benthos exhibited greater numbers and volume. Numerical increases were attributed to large numbers of simuliids, chironomids, *Gammarus* and *Hydropsyche*; increases in volume, primarily to large numbers of snails. Benthic forms that were reduced or eliminated included stoneflies *(Acroneuria internata, Phasganophora,* and *Taeniopteryx nivalis)*, ephemerid mayflies, and the hellgrammite *Corydalus cornutus*.

More recently, Isom (1971) reviewed benthic studies of the reservoirs and tailwaters of the TVA system (with an emphasis on Mollusca). He concluded that benthic fauna in the region "may be limited by siltation, rheotactile deprivation, water level fluctuation, increased hydrostatic pressure, light, and most pertinently by hypolimnetic oxygen deficiency in the storage impoundments." He noted that benthic fauna have been almost eliminated from storage impoundments in the valley. He further stated that "benthic fauna below mainstream impoundments is typically rheophilic, and includes mussels and residual populations of Pleuroceridae..." A recent decline in mussels was attributed to both impoundment and overharvest. In addition, a decline of snails and Pleuroceridae was associated with alteration of habitats by impoundment.

Obviously, the reduction in benthic fauna will have an effect on the fisheries, and, as noted by Eschmeyer (1950), the food chain in impoundments relies on planktonic organisms. A significant adverse effect of TVA impoundments has been on mussels, which have been reduced from 100 species to fewer than half that number. Furthermore, the commercial take of mussels has been reduced from 10,000 tons (9,078 metric tons) annually in the 1950s to approximately 2,000 tons (1,816 metric tons) annually (Isom, 1969).

Pfitzer (1962) examined the food habits of trout in several tailwaters below TVA impoundments. It was demonstrated that the stomach contents reflected the composition of the benthic population. A paucity of aquatic insects was found, and fish stomachs contained excessive amounts of algae. In the Cherokee tailwater, the lack of insects and the absence of trout was attributed to the unusual temperature pattern and long periods of no flow during the summer months.

Plankton

Pfitzer (1962) abandoned efforts to determine numbers and types of plankton in tailwaters because of the highly variable nature of the system. This would be expected when the distribution of plankton in the reservoir is considered along with the intake of configuration and selective withdrawal aspects of the sampled reservoirs.

It should be noted that the plankton composition of tailwaters will depend on the elevation of the intake and the hydrodynamics of the reservoir, which are site specific. The intakes in the TVA system are near the reservoir bottom or, in a few deeper reservoirs, near mid-depth. Thus, releases would be primarily from the hypolimnion during periods of stratification.

Fish

As previously indicated, a paucity of data exist on the tailwater fisheries below TVA impoundments. In an effort to understand the factors responsible for the decline in fishing that occurred and to apply appropriate management techniques, the Tennessee Game and Fish Commission instigated the studies referred to by Pfitzer (1962). The tailwaters studied were below South Holston, Watauga, Wilbur, Norris, Cherokee, Douglas, Calderwood and Apalachia Dams (all TVA dams), which create a total of some 500 km of tributary-stream tailwaters. One tailwater was producing a promising trout fishery, while others failed to support either trout or warm-water species.

Results of the pre- and post-impoundment studies showed drastic changes in the fisheries. For example, pre-impoundment studies of the Watauga River showed 32 species, of which only 11 remained in the post-impoundment studies, with 6 species not present in the pre-impoundment survey. Similarly, the pre-impoundment survey of the South Fork Holston River identified 43 species, of which only 16 remained in the post-impoundment studies, with 7 species not found in the pre-impoundment surveys.

The quality of water discharged from the dams affects the type of tailwater fishery that can be supported. Probably the most important water-quality parameter to be considered is temperature, its magnitude, and its rate of change. Temperature in turn depends upon the operation of the dam and the reservoir hydrodynamics.

There is also no doubt that dissolved oxygen is a prime factor in the viability of tailwater aquatic life. Even though Pfitzer (1962) found no direct evidence of adverse effects of low dissolved oxygen concentrations on fish in the tailwaters, low dissolved oxygen concentrations have been shown to be adverse to aquatic life. As with temperature, the tailwater dissolved oxygen concentrations depend on dam operation and reservoir hydrodynamics.

The adverse effects of stratified flow discharges on the available food supply must also be considered as affecting the tailwater fishery. Again, this is a result of the reservoir stratification and operation.

SUMMARY

It has been shown that reservoir construction and operation have significant effects on aquatic life, which vary depending upon the project objectives and the specific requirements of tailwater biota. The large variations in flow and associated water quality parameters may adversely affect downstream fisheries, influence the benthos, and, in general, lessen recreational opportunities.

Water quality parameters, such as temperature and dissolved oxygen, can greatly influence downstream aquatic life, particularly when adverse water quality conditions are combined with peaking power operations to yield periods of low flow, then sudden increases in cold water flow.

Additional information is needed to more clearly define the role of reservoir operation in maintaining downstream fisheries. Also, it is apparent that before meaningful biological studies can be pursued in reservoirs and tailwaters, the hydrodynamics of the systems must be delineated.

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