FACTORS AFFECTING DISSOLVED OXYGEN IN HYDROPOWER RESERVOIRS

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ABSTRACT

Dissolved oxygen (DO) is becoming a significant issue for hydropower projects. This paper identifies some key factors that can help hydropower operators better understand the nature of DO dynamics at their projects. Site-specific information which is readily available can be used to categorize projects and identify major tendencies with respect to anticipated DO levels in reservoir releases. Also, the effects on DO in reservoir releases of DO levels in the reservoir are discussed, as well as the effects of annual variations in watershed hydrology. In addition, the paper discusses the effects that contaminants in the watershed can have on DO in reservoir releases.

INTRODUCTION

In the late 1930s, TVA reported the first DO observations for a hydropower reservoir. Additional information on DO patterns in several other hydropower reservoirs was reported during the 1950's and 1960's, including the effects of large reservoir inflows and low-level outlet depths, illustrating many differences from natural lakes. For the past two decades, the Corps of Engineers, Bureau of Reclamation, Tennessee Valley Authority, Environmental Protection Agency, and other organizations have conducted or sponsored limnological studies on various impoundments in the United States, progressing to the use of 2-dimensional computer models to simulate DO. An earlier paper included an analysis of this information and provided some generalizations that could be useful at hydropower projects where data are limited (Ruane and Hauser, 1990). This paper identifies the major factors that affect DO at TVA projects and attempts to summarize the information in a way that will make it useful for other hydropower projects.

Reservoir DO characteristics are greatly influenced by physical factors. The most important are often the volume and through-flow of the project, which can be represented by the calculated retention time (summer volume/average annual flow rate) of water in the project. "Mainstem" projects typically have retention times of 25 days or less; "storage" projects typically have retention times of 200 days or more; "transitional" projects have retention times between 25 and 200 days.

Retention time, depth of outlet, and inflow temperature are the main reservoir factors that affect thermal stratification, which in turn affects the routing of "density currents" through reservoirs. Density currents define the water movement through each reservoir and, therefore, affect how DO varies in reservoirs.

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Environmental processes affecting DO can be separated according to three longitudinal zones and four thermal layers (Ruane and Hauser, 1990). These zones and layers are shown Figure 1 which explains why DO within a storage reservoir is usually low just above the sediments and in the warmer metalimnion. The longitudinal zones include the riverine, transitional, and lacustrine zones. The thermal layers include the epilimnion, the warmer portion of the metalimnion (interflows that occur in southern reservoirs, usually from May through September), the cooler metalimnion (inflows usually during March and April), and the hypolimnion. In storage reservoirs, stratification is strong (large difference in temperature between the top and bottom) and persists through the summer and fall. In some cases the colder water that is in the reservoir originally during the winter may remain until the next fall. This is especially true if the outlet is at a midlevel point within the reservoir and the withdrawal zone does not extend to the reservoir bottom. In areas where inflows are comprised of significant amounts of snowmelt, cooler inflows can persist longer, to about June.

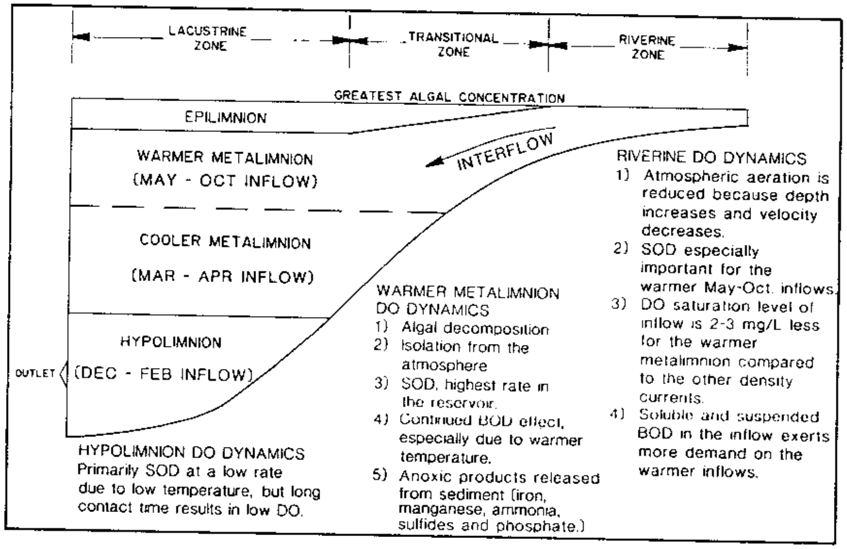

Figure 1. *Zones and layers of a typical hydropower storage reservoir in the southern U.S., as they typically appear sometime during August through October. The density currents flowing through the reservoir include the hypolimnion, cooler metalimnion, and the warmer metalimnion. Over the period of spring through fall each year, they travel from the inflow to the low level outlet. As summer progresses, the hypolimnion and cooler metalimnion decrease in volume as power generation occurs and warmer metalimnion increases in volume as interflows continue. The dominant processes that affect dissolved oxygen (DO) are depicted in the figure.*

Transitional reservoirs are similar to storage reservoirs but have a more dynamic DO pattern. A warmer metalimnion generally forms in the spring and perhaps early summer but is drawn down in depth more rapidly because the colder hypolimnetic and cooler metalimnetic water is released earlier in the season. In reservoirs with bottom-level outlets, the warmer metalimnion eventually occupies the entire lower depths and length of the reservoir, exposing it to more sediment oxygen demand. This exposure results in a greater DO uptake than occurs in the hypolimnion due to the warmer temperatures. Usually these types of reservoirs will maintain some form of stratification even though it will be weaker than that of storage impoundments.

For mainstem reservoirs, the colder water is released even more rapidly and the resulting stratification is weaker, particularly in June, July, and August. Often during these latter two months stratification may not even occur, except under low flow conditions such as those that occur during droughts. Mainstem reservoir DO levels in the lower depths are primarily a function of the mass of DO in the inflow and the retention time in the reservoir. The DO deficit in the releases is proportional to the retention time and indirectly proportional to the mass of DO in the inflow. DO dynamics in mainstem reservoirs are much more sensitive to flow through the project than those in the other two types of reservoirs (e.g., DO levels in most Tennessee River reservoirs are not less than 5 mg/l except during low flow conditions.)

FACTORS AFFECTING DO AT TVA PROJECTS

Using these limnological considerations, major factors that affect DO in the releases from TVA hydropower projects were evaluated in Figure 2. The factors are retention time, level of outlet, and the DO concentration in the warmer metalimnion. Figure 2 presents the median and minimum annual low DO levels from 20 years of weekly data for 26 projects. Average retention time was calculated using average annual flow (except for mainstem projects where average summer flows were used) and the volume at normal maximum summer pool levels. Metalimnion DO levels were determined using data collected intermittently for various purposes over the period of record. This figure vividly illustrates the effects that retention time, bottom-level outlets, and low (less than 2 mg/L) metalimnion DO have on the potential for low DO levels in hydropower releases. It is also interesting to note the range of annual variability in DO levels in reservoir releases from some projects. Such variability is important for the aeration system designer to keep in mind if the project has only limited historical DO data.

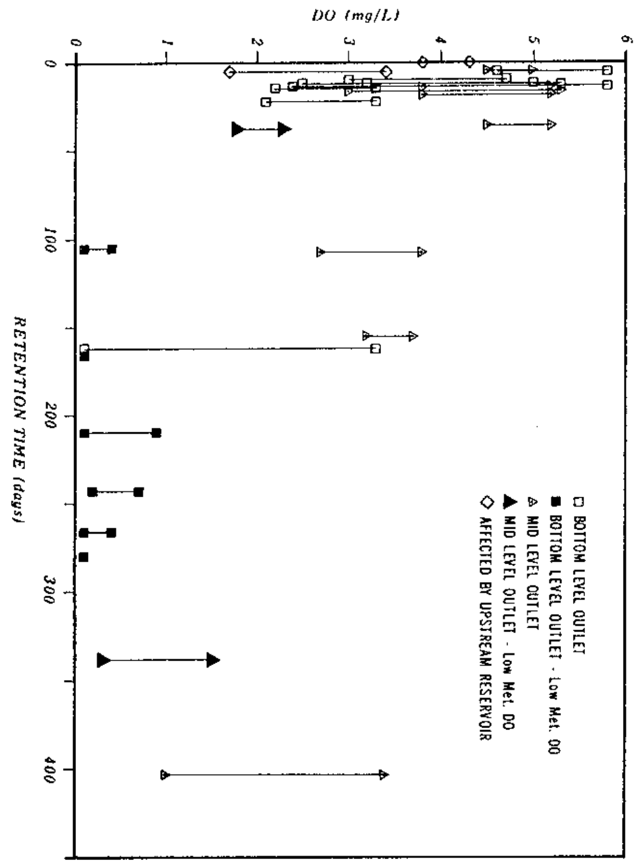

Figure 2. *Annual low Do characteristics (represented by the median and minimum of the lowest annual DO measurements—taken weekly—over a 20-year period) for TVA reservoirs with average retention times ranging up to 400 days. The figure shows that retention time, level of outlet, and DO level in the metalimnion significantly affect the level of DO in releases. Annual variation in retention time affects the annual variation in DO as shown in Figure 4.*

CHARACTERISTICS OF TVA DAMS AND RESERVOIRS AND OBSERVED DO CONCENTRATIONS

Reservoir Name	Drainage Area (miles)	Reservoir Length[a] (miles)	Volume[a] (1000 ac-ft)	Surface Area[a] (1000) Acres	Reservoir Flow[a] (cfs)[a]	Hydraulic Retention Time,[a] Days	Generating Capacity (MW)	Depth at Dam[a] (ft)	Depth of Penstock Invert[a] (ft)	18-yr Median Low DO (mg/l)	18-yr Minimum Low DO (mg/l)
Watauga	468	16.0	569	6.4	711	400	58	274	177	3.4	2.2
South Holston	703	24.0	658	7.6	980	336	39	239	135	1.5	0.6
Fontana[d]	1,571	29.0	,420	10.6	3,820	186	239	417	259	3.4	3.4
anteetlah (Alcoa)	176	7.5	156	2.8	508	154	45	200	NA	3.7	3.2
Blue Ridge	232	11.0	193	3.3	601	161	20	156	120	3.3	0.1
Chatuge	189	13.0	234	7.0	442	265	10	124	134	0.4	0.1
Tims Ford	529	34.0	530	10.6	890	315	45	143	148	0.1	0.1
Nottely	214	20.0	170	4.2	410	207	15	167	163	0.9	0.1
Hiwassee	968	22.0	422	6.1	1,980	106	117	255	154	3.8	2.7
Norris	2,912	73.0	2,040	34.2	4,230	241	101	202	163	0.7	0.2
Cherokee	3,428	54.0	1,481	30.3	4,520	164	135	163	128	0.1	0.1
Boone[d]	1,840	17.4	189	4.3	2,540	37	76	129	99	2.3	1.8
Apalachia[b]	1,018	9.8	58	1.1	2,090	14	83	110	68	5.2	3.8
Douglas	4,541	43.0	1,408	30.4	6,750	104	121	127	112	0.4	0.1
Wilson[c]	30,750	16.0	634	15.5	32,800	9.7	630	108	38, 60	4.7	3.0
Chilhowee[b],(Alcoa)	1,977	9.2	49	1.8	4,770	5.1	50	70	NA	5.8	4.6
Fort Patrick Henry[b,d]	1,903	10.0	27	0.9	2,630	5.1	36	93	70	3.4	1.7
Watts Bar[c]	17,300	72.0	1,010	39.0	22,900	22	167	105	76	3.3	2.1
Fort Loudoun[c,d]	9,550	50.0	363	14.6	12,400	15	139	94	89	3.3	2.2
Pickwick Landing[c]	32,820	53.0	924	43.1	34,600	13	224	84	67	5.8	2.4
Melton Hill[c]	3,343	44.0	120	5.7	5,010	12	72	69	64	5.3	2.5
Guntersville[c]	24,450	76.0	1,018	67.9	28,300	18	115	65	54	5.2	3.8
Wheeler[c]	29,590	74.0	1,050	67.1	33,000	16	375	66	58	5.3	3.0
Kentucky[c]	40,200	184.0	2,839	160.3	40,300	35	175	88	77	4.5	2.3
Chickamauga[c]	20,790	59.0	628	35.4	27,300	12	120	83	68	3.2	2.4
Wilbur[b]	471	1.8	1	0.1	711	0.7	11	60	30	3.8	7.2
Nickajack[c]	21,870	46.0	241	10.4	27,200	4.4	104	60	54	4.5	4.0

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a. Measurements based on normal maximum pool and average flows.
b. DO concentrations affected significantly by an upstream reservoir release.
c. DO samples are collected from the tailrace; all other projects were sampled from the penstocks or scroll case.
d. DO data were deleted for earlier years when the reservoir received significant point sources from upstream.

As shown in the figure, transitional and storage projects with bottom level outlets and low metalimnion DO (less than 2 mg/L) have the lowest DO in their releases (typically less than 1 mg/l). Projects with midlevel outlets but low metalimnion DO also have relatively low DO (2 mg/l or less). All the other projects with midlevel outlets have better DO levels in releases. All mainstem projects have median low DO values greater than 3 mg/l, but here again the projects with bottom-level outlets have lower DO levels, especially for the minimum observed DO (2-3 mg/L). The physical characteristics of these projects is provided in Table 1.

Kennedy and Gaugush (1988) summarized information on U.S. Army Corps of Engineers hydropower projects that appears to be consistent with Figure 2. They reported that reservoirs with relatively shallower depths of low DO tend to have lower DO concentrations in their releases, whereas reservoirs with anoxia limited to deeper waters "tend to exhibit acceptable dissolved oxygen conditions in their tailwaters". They reported that the reason for these observations was that their turbine intakes are generally located at midlevel.

The seasonal variation of DO in reservoir releases depends to a large extent on the type of project. Storage reservoirs tend to have lowest DO conditions in the late summer and fall because of relatively long retention times, whereas transition and mainstem projects have lowest DO conditions during the summer (Figure 3).

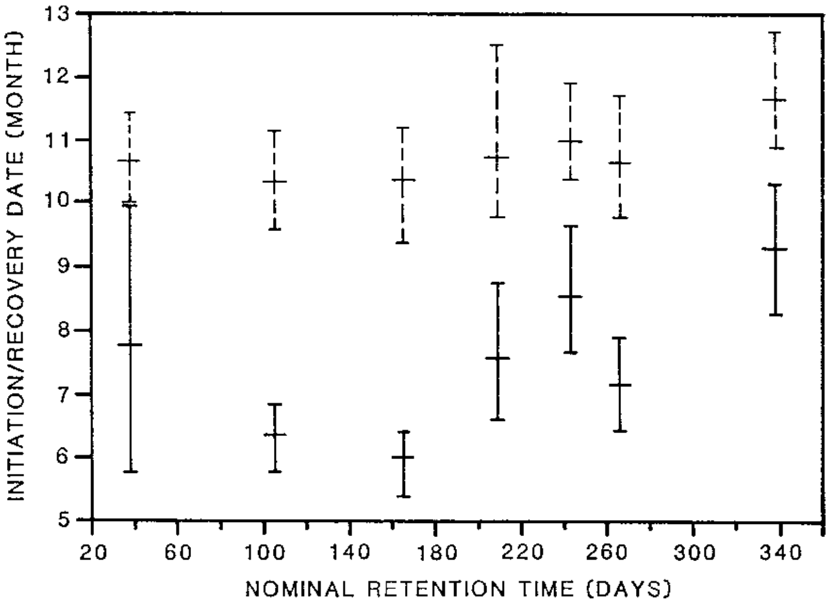

Figure 3. *The maximum, minimum, and mean dates that DO drops below (——) and recovers from (— — —) 4 mg/L for various TVA projects having the indicated nominal retention times (calculated using normal maximum volume and average annual flow). The projects included had median annual minimum DO concentrations less than 3 mg/L.*

The pattern of DO in the releases may change year to year, primarily due to variations in hydrology and meteorology. Figure 4 shows how DO varied during 1986 and 1989 at four storage projects and two mainstem projects. These two years were near-record drought and high rainfall years, respectively. These graphs vividly illustrate how DO in these releases varied over the course of the year, as well as how hydrology can affect DO in different types of projects. The South Holston and Watauga Projects have mid-level outlets and the former usually has lower DO in the warmer metalimnion than the latter project. Also, the Watauga Project has a longer retention time. The result of these two factors in combination was that the Watauga Project did not experience DO

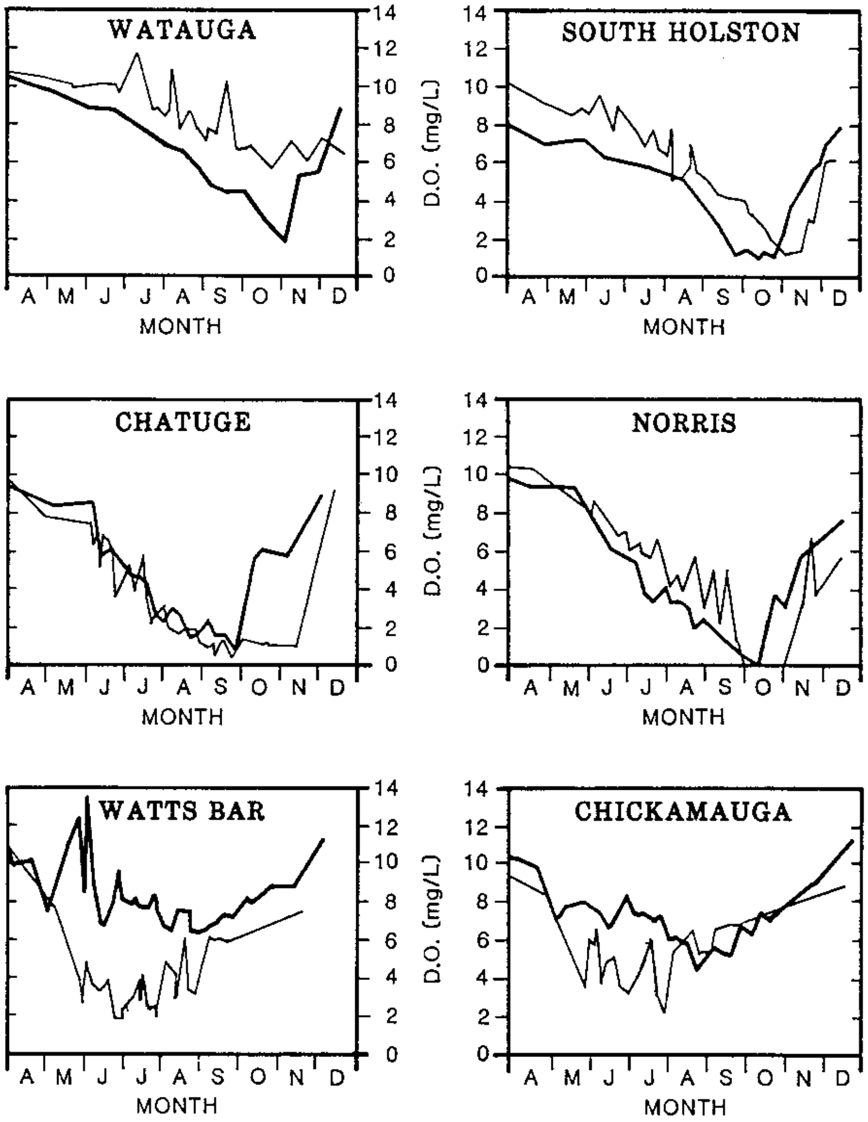

Figure 4. *Variation of DO in the releases from several TVA projects, for a low flow year (1986 —— thin lines) and a wet year (1989 —— heavy lines). Notice that at Chickamauga and Watts Bar (mainstem projects) DO was higher in the wet year, whereas at the other projects DO was lower or about the same during the wet year.*

less than about 6 mg/L during 1986, but did experience a low DO of about 2 mg/L in 1989 when the volume of the warmer metalimnion was sufficient to reach the outlets. The minimum DO at South Holston was not much lower in 1989 compared with 1986, but the lowest DO occurred about six weeks earlier in 1989 and was generally lower the period beginning in March and extending to October.

At Norris, the DO was about 2 mg/L lower in 1989 during June, July, and August, but increased rapidly in mid-September, either because the reservoir destratified earlier or the large inflows diluted the effects of the DO demands in the warmer metalimnion. The DO at the mainstem projects at Watts Bar and Chickamauga increased in proportion to flow, as expected for these types of projects.

Another factor to consider for DO variation in releases is the effect of hydropower operations. Turbine operations can significantly affect DO in the releases at mainstem projects. For example, at Watts Bar Dam, a special study was conducted to determine the variation of DO concentration below each of the four turbine units as well as at various times after generation had been initiated. The results showed that as the quantity of flow being released through the project (i.e., the number of turbines that were generating at any one time) increased, the DO level increased about 2 mg/L because the withdrawal zone in the reservoir expanded to include more of the high DO water from the epilimnion. Another interesting observation was that the turbine releases nearest the right bank of the river had DO concentrations about 1 mg/L higher than that from the distant unit.

Another consideration for characterizing the DO at hydropower projects is the mass of DO deficit in reservoir releases that are below desired target concentration levels of DO. This deficit is a function of turbine discharges during the period of insufficient DO, the concentration of DO, and the desired target level of DO. Figure 5 summarizes the mean, maximum, and minimum tons/yr. of DO deficit for TVA storage and transitional projects which have median annual minimum DO concentrations less than 3 mg/L. This shows there is considerable difference in the amount of deficit for various projects and that turbine discharge is a key factor in considering the magnitude of a site-specific problem. This mass deficit is particularly important if commercial oxygen is considered as a potential solution, but also provides a measure for considering other potential solutions. Hence, turbine discharge in conjunction with the deficit DO concentration is a pertinent factor to consider when evaluating alternatives. It is also important to note the proportionally greater increase in mass deficit for a 5 mg/L DO target compared to a 4 mg/L target, especially for the larger projects (average annual flow greater than 2,000 cfs).

WATERSHED FACTORS THAT AFFECT DO IN RELEASES

From the previous discussion, it is obvious that the amount of precipitation and inflow temperature variation affects density currents and DO, but other factors can also be important. For example, the size of the watershed draining into the reservoir also affects the natural organic loading and nonpoint sources to the reservoir as well.

Groeger and Kimmel (1984) referenced one study where 40 percent of the annual allochthonous organic matter input to a mainstream Michigan reservoir entered and flowed through the system during a four-week period of high spring flow. Wastewater discharges and nonpoint sources affect the characteristics of the inflow. Another consideration is the effect of a system of reservoir projects which can act to increase DO if the upstream projects retain organic substances and nutrients from the upstream watershed. On the other hand, dissolved phosphates are released from some reservoirs and are more readily available for contributing to greater algal growths in downstream projects (Elser and Kimmel, 1985).

Terrestrial characteristics in the west can result in lower contributions of organic matter from runoff. This reduced loading, however, can be offset by increased contributions from stream growths that occur over more extensive stream/river systems in the relatively larger watersheds in the west.

Regarding streamflow, upstream storage reservoirs can significantly alter the natural hydrologic runoff, i.e., natural high spring runoff quantities can be shifted to late summer and fall reservoir releases by flow regulation. Such a shift in flow quantity significantly affects downstream reservoir processes affecting DO. Another significant factor to assess is the dominant source(s)

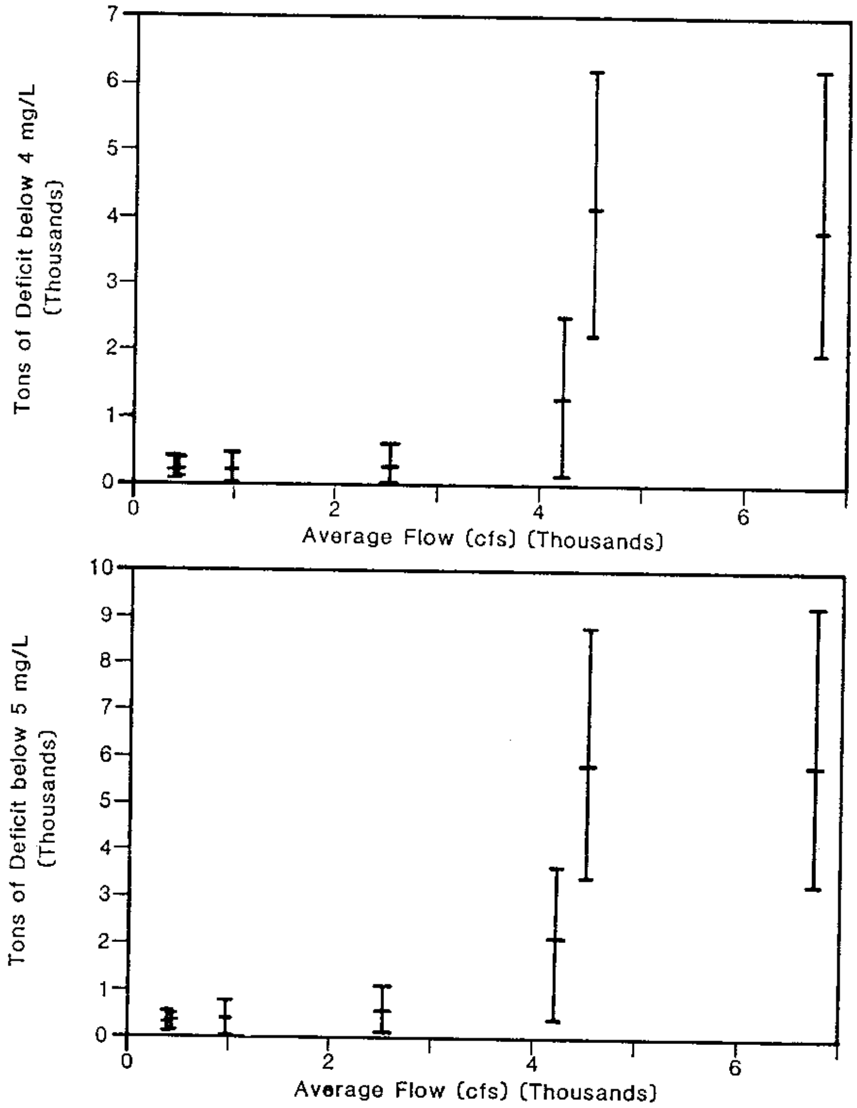

Figure 5. *The maximum, minimum, and mean annual deficits of DO, tons, below 4 and 5 mg/L in the hydropower discharges from TVA projects, having the indicated average annual flows. The projects included had median annual minimum DO concentrations less than 3 mg/L.*

of inflow. The typical storage impoundment will have one or two primary sources of inflow, accounting for 70 or more percent of the reservoir inflow volume; however, some impoundments can have significantly dispersed inflow quantities coming from multiple tributaries, e.g., the inflow to Chatuge Reservoir (TVA) through its primary source the Hiwassee River accounts for only 40% of the inflow. Such dispersed inflows can complicate significantly the reservoir processes that may affect DO within a reservoir.

Temperature of the inflow can be significantly altered by an upstream steam plant or an upstream hydroelectric power plant with low level releases. These two types of operations, of course, have different effects on the temperature of the inflow water and have significant effect on the ultimate thermal layer to which the inflow will flow. Boone Reservoir (TVA) is significantly influenced by the cold water inflows from two upstream hydroelectric power projects. The reservoir has a continual flow of essentially unlimited cold water throughout the summer and fall months and the metalimnion within Boone Reservoir remains essentially isolated throughout this period of time without being drawn through the outlets. The temperature effects on biological DO uptake rates can double with an increase in temperature of about 10°C.

Reservoirs having watersheds with significant snowmelt during the spring can exhibit the same DO dynamics seen for southeastern reservoirs. However, these dynamics will lag in time corresponding with the lag time in the temperature and peak inflow hydrology that is characteristic in the northern regions. In the south, the peak inflow hydrology is dominated by more direct runoff from spring rains which occur during March through May.

Various nonpoint sources of contamination, particularly that from agricultural sources, are suspected of affecting DO in some TVA impoundments, and in some cases could be the incremental load that causes hydrogen sulfide in the releases.

CONSIDERATIONS FOR WATERSHED MANAGEMENT TO INCREASE DO LEVELS

Pertinent man-induced inflow characteristics that affect DO and that can be controlled include organic material (BOD), ammonia, and nutrients that control the growth of algae and aquatic plants. Models can determine fairly reliably the effect of BOD or ammonia on DO consumption, but determining the effects of nutrients on algal growths and subsequent oxygen consumption is much more difficult because of the uncertainty associated with so many environmental processes. For example, phosphorus generally settles into the sediments of reservoirs and cycles back into the water column under anoxic conditions, then sometimes becoming available for algal growths following mixing events. Cooke, et al. (1986) reports that this internal loading of phosphorus is probably impossible to predict using a general rate of decrease for all lakes. Based on very limited documented experience, ten years was reported to be necessary for a significant decrease in internal loading for lakes; however, recovery in 3-4 years was predicted for one lake which had a high flush rate. Of 28 lakes reported, only 12 improved in trophic status following diversion of wastes, thus indicating the importance of site-specific analyses instead of assuming reservoirs will improve with reduction of organics and nutrients in the watershed. Another consideration is that the combination of natural inflow BOD and SOD may consume sufficient quantities of DO so as to account for enough DO uptake to deplete the oxygen resource.

TVA experience has shown that DO in hydropower releases can improve when BOD and ammonia are either substantially reduced or eliminated. Increased treatment for the City of Knoxville improved DO in the releases from Ft. Loudoun by about 1 mg/L. The closing of a papermill resulted in a DO increase of about 2 mg/L in the releases from Fontana, and the closing of a chemical plant resulted in an improvement of about 2 mg/L in the releases from Ft. Patrick Henry Dam. These examples demonstrate that waste loads with organic materials and ammonia can affect DO in reservoir releases; however, it is important to note that these waste loads originally received only a small amount of treatment in comparison with today's effluent standards. Modeling on Ft. Loudoun demonstrated that additional treatment beyond advanced secondary at Knoxville would not measurably increase DO above present levels in the releases. Reduction of manmade nonpoint sources should eventually improve DO levels and/or reduce anoxic chemical products in reservoir releases.

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