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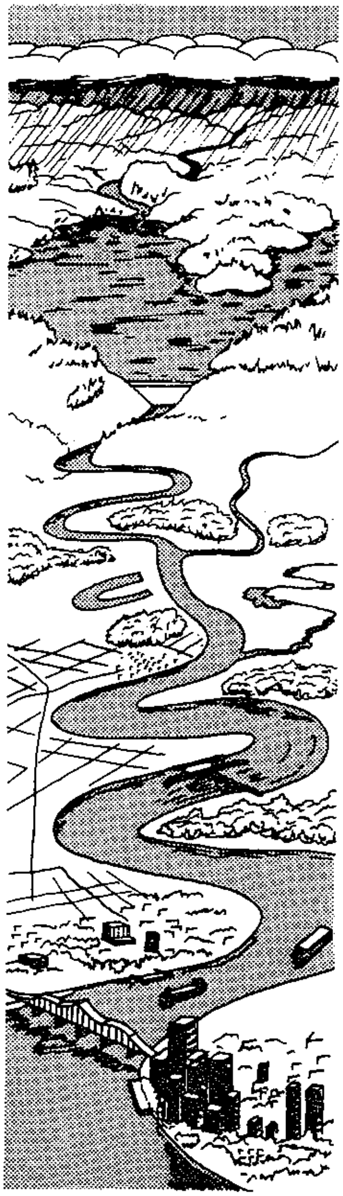

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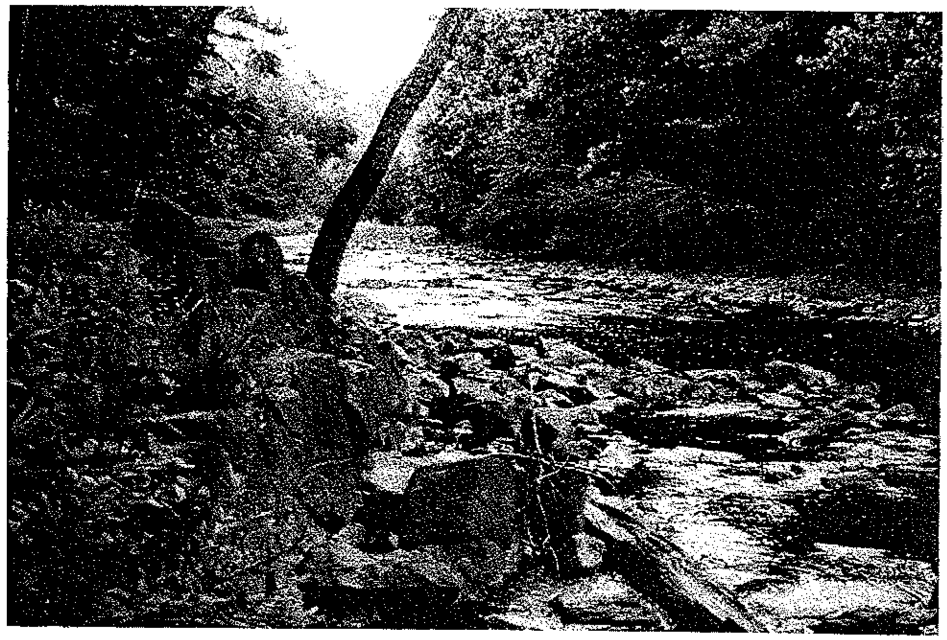
VOL E-88-2 | INFORMATION EXCHANGE BULLETIN | NOV 1988



Upstream view at station D in the tailwater of Lake Greeson

Research on Water Quality of Reservoir Tailwaters

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Many reservoirs experience seasonal thermal stratification often accompanied by dissolved oxygen (DO) depletion in bottom waters (hypolimnion). Oxygen depletion and the establishment of reducing conditions in the hypolimnion increase mobilization of dissolved nutrients (such as ammonium and inorganic phosphorus), sulfide, reduced metals (such as iron and manganese), and organic substances (such as simple organic acids and methane) from the sediments. These substances can accumulate in the hypolimnion, affecting in-pool and release water quality.

Reservoir releases that are low in DO and high in reduced substances can cause problems for Corps reservoir managers. For example, releases with high levels of reduced substances can be hazardous to aquatic life, cause water treatment problems, and affect downstream recreational uses. Releases through hydropower turbines are not subjected to the usually high degree of reaeration that nonhydropower releases are subjected to; thus, low DO releases may occur, which can be detrimental to downstream aquatic habitat. The conversion of nonhydropower releases to hydropower releases could lead to water quality problems associated with deep releases.

When water is released to the downstream environment, reaeration occurs, and chemical transformations take place under oxidizing conditions. Eventually, the water quality recovers to a more natural stream condition. The recovery distance, which depends on physical and biogeochemical factors, is often on the order of miles. The recovery mechanisms and chemical transformations in tailwaters must be better understood to address issues concerning tailwater quality and to better manage tailwater quality problems. To address this need, a research work unit entitled "Techniques for Evaluating Water Quality of Reservoir Tailwaters" was initiated in the Water Quality Research Program. This research focuses on poor water quality associated with deep, anoxic releases. The objectives of the research are:

- To develop an improved understanding of chemical transformation in tailwaters.
- To provide guidance on sampling and analysis of tailwater quality.
- To develop an easy-to-use PC model to predict impacts of reservoir releases on tailwater quality.

This work unit was started in FY 86 and will be completed in FY 90.

Short-term intensive field studies are being conducted at several sites to quantify chemical transformations in tailwaters. A mathematical model describing chemical transformations is being developed and tested on each study site.

The field studies involve four sites. The tailwater of Lake Greeson, Little Missouri River, AR, was studied during 1987. The tailwaters of Nimrod Reservoir (Fourche La Fave River, AR) and Rough River Reservoir (KY) were studied in 1988; the Buford Dam tailwater (Chattahoochee River, GA) is being considered for study during 1989. Two of these dams (Greeson and Buford) have hydropower. The study sites also provide a range of physical and environmental conditions, such as varying stream slope, substrate, and pH.

The flow rate is held constant during the sampling program at each field site. This

Tailwater below the dam at Nimrod Reservoir

provides nearly steady-state conditions, which greatly simplifies analysis of data and interpretation of results. Samples are collected for water quality analyses at a number of stations (for example, six to eight stations) extending over the tailwater reach. The study reach typically extends from the dam to about 5 to 20 river miles downstream, depending on the flow conditions and stream characteristics which affect particle travel time. Particle travel time is the time required for a parcel of water to move from the release point to a given distance downstream. Study reaches are generally limited to a travel time of about two or three days since most chemical reactions occur within this time period.

Water samples are collected in two ways--Lagrangian sampling, which tracks a water parcel as it moves downstream, and snapshot sampling, which samples all stations at or near the same point in time. So far both sampling methods have yielded similar results for steady flows, which means the system is approximately at steady-state. The samples are subsequently analyzed for a number of water quality constituents (see box).

Water samples are analyzed for these water quality constituents. Not all constituents are included in the mathematical model.

- Temperature
- Dissolved oxygen
- Specific conductance
- pH
- Alkalinity
- Free carbon dioxide
- Total inorganic carbon
- Total organic carbon
- Dissolved organic carbon
- Carbonaceous biochemical oxygen demand
- Total phosphorus
- Soluble reactive phosphorus
- Ammonia nitrogen
- Nitrite nitrogen
- Nitrate nitrogen
- Total Kjeldahl nitrogen
- Dissolved Kjeldahl nitrogen
- Chloride
- Sulfate
- Sulfide
- Total iron
- Dissolved iron
- Total manganese
- Dissolved manganese
- Suspended solids
- Turbidity

Additionally, a dye study is conducted to determine the travel time to each station and to provide the basis for the Lagrangian sampling method. With travel time, the reaction kinetics of various constituents, such as the oxidation of reduced manganese, can be evaluated.

The mathematical model includes several of the constituents analyzed from samples, but not all. The focus of the model is on the prediction of transformation of problem constituents, such as DO and several of the reduced substances (such as iron, manganese, and sulfide). Only those variables that affect the problem constituents will be retained in or added to the model, thus reducing the complexity and difficulty of applying the model. The field studies provide the data base for developing and evaluating the model.

The modeling system combines several components within a user-friendly interface that uses menus for selecting alternatives. The tailwater component is based on the US Environmental Protection Agency's QUAL2E stream water quality model (Brown and Barnwell 1987), which is being modified to include reduced substances. QUAL2E solves for each water quality variable the mass balance equation, which includes advection, dispersion, and source/sink terms. The kinetic algorithms for reduced substances will be developed and generalized as much as possible from the information gained from the field studies. To reduce input data requirements and facilitate ease of application, the model will be limited to steady-state applications, which means the release flow and water quality are considered constant for a given application.

Reservoir release water quality is required to drive the stream model. The user may specify this information from observations or can predict the release concentrations based upon observed in-pool concentrations using the SELECT model (Davis and others 1987). Given in-pool temperature stratification, outlet features, release flow rate, and vertical distribution of water quality constituents, SELECT computes release concentrations. Also included in SELECT is a structural reaeration component that predicts the uptake of dissolved oxygen as flow passes through the release structure. After allowing for structural reaeration (thus, some oxidation), the adjusted release concentrations are then provided to the tailwater component for predicting downstream conditions. The combination of SELECT with the tailwater model will allow the user to evaluate the impact on downstream water quality of various release schemes, such as hydropower retrofit.

Preliminary Results

At the time this article was written, only the Greeson tailwater study had been completed. The Greeson site was chosen as the first study site because a previous study had been conducted by Nix (1986) which looked at similar constituents in the tailwater; the existing knowledge base helped in performing follow-on work. Also this site met study needs, such as hypolimnetic, hydropower releases. The study reach extended approximately 17 miles downstream of Narrows Dam on the Little Missouri River, AR. Water quality data (Table 1) were collected during late summer/early fall 1987 at one in-pool station near the dam and seven sampling stations (Figure 1) that had been established in the previous study (Nix 1986).

The primary difference between the previous Greeson field study and the present study was that sampling in the previous study occurred during peaking hydropower operations. For the present study, steady release flows were maintained, which eliminated complicated transient conditions associated with unsteady peaking flows.

The mathematical model was applied to a 1987 Greeson field study. Problem constituents, such as low DO and reduced iron and manganese, were modeled and compared with observed data (Figure 2). Since sulfide was not detected, it was not modeled. The kinetic components describing the oxidation and subsequent loss of reduced iron and manganese were modeled as a simple first-order reaction, where the change (loss) of reduced iron or manganese with respect to time is expressed as

$$dC/dt = -kC$$

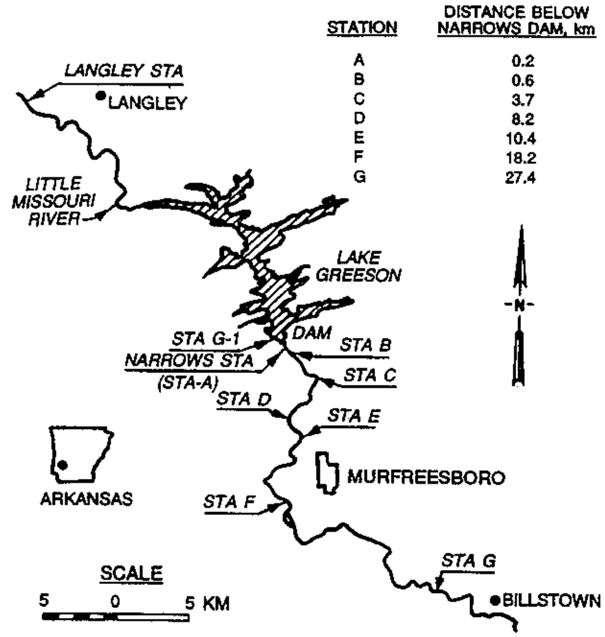


Figure 1. Location of seven sampling stations at Little Missouri River and Lake Greeson (Nix 1986)

where

C = constituent concentration, mg/ℓ

t = time, days

k = oxidation rate, per day

Values for k of 4.6 per day for manganese and 6.5 per day for iron were used for the model results shown in Figure 2. These values were obtained through calibration with the observed data.

Table 1. Measured and Computed Reaeration Coefficients

Segment	*River Miles*	ΔH* *ft*	*Travel time between segments t, hr:min*	*Average Velocity v, ft/sec*	*Average Depth h, ft*	*Measured Reaeration Coefficient, K2** (1/day)*	*Computed Reaeration Coefficient, K2*† *(1/day)* *Tsivoglou*	*Computed Reaeration Coefficient, K2*† *(1/day)* *O'Connor-Dobbins*
B-C	105.3-103.4	12.5	1:41	1.65	3.11	6.24	9.63	3.00
C-D	103.4-100.2	25.5	3:07	1.50	2.50	7.03	10.59	3.97
D-E	100.2-99.2	7.0	1:40	0.88	2.80	5.62	5.48	2.56
E-F	99.2-94.4	21.0	9:20	0.75	2.63	0.62	2.92	2.60

* Change in streambed elevation.

** K2 is measured at 20° C.

† K2 is computed from Tsivoglou and Wallace (1972) formulation at base e at 20° C using K2 = 0.054 (ΔH) and the O'Connor-Dobbins (1956) formulation at base e at 20° C using $K2 = 12.81v^{0.5} \div h^{1.5}$

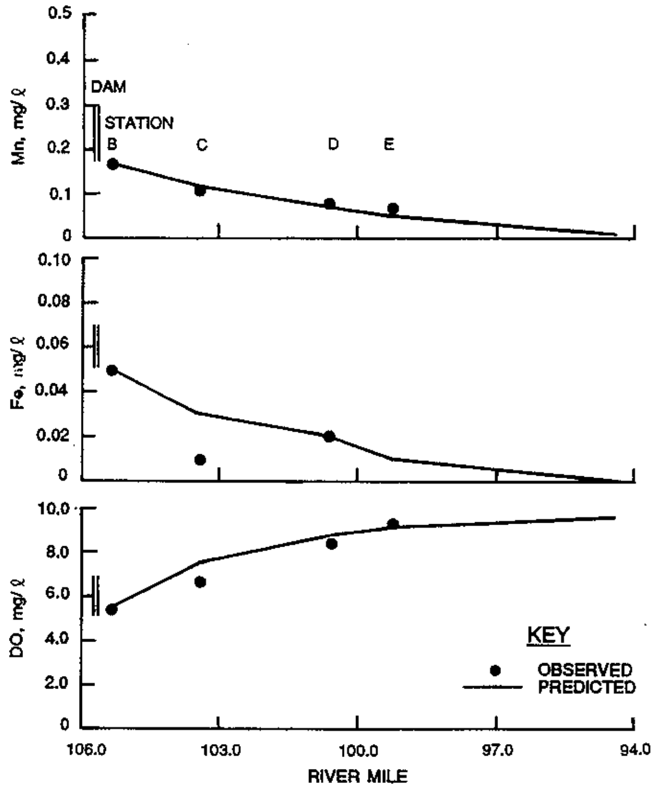
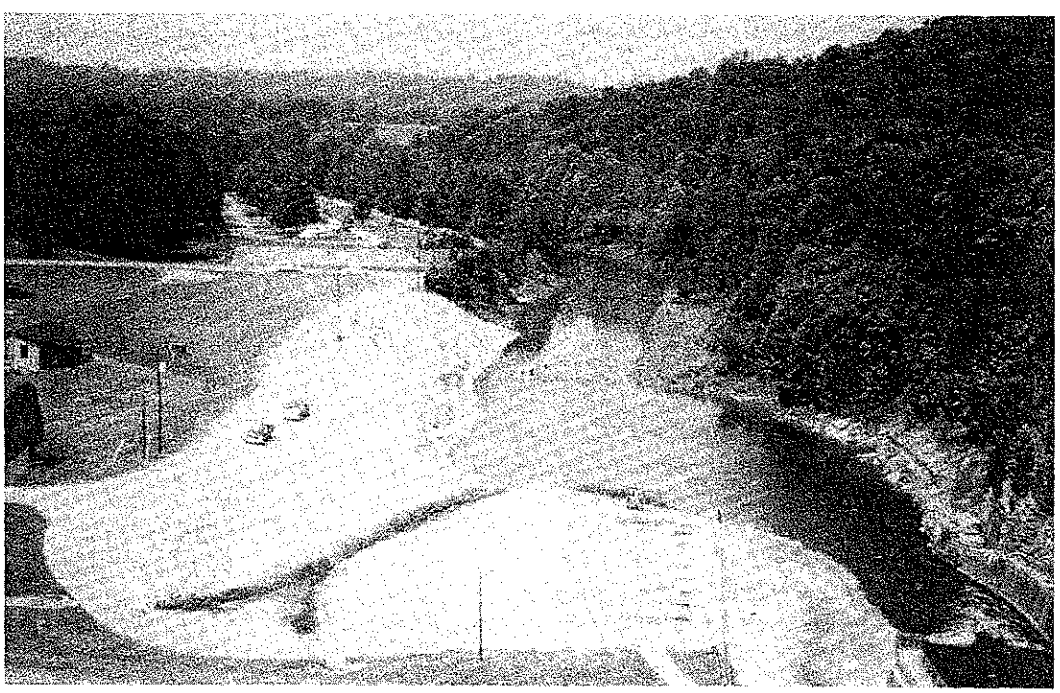


Figure 2. Predicted versus observed concentrations for stations

Ideally, generalized algorithms are needed for predicting, within the model, the k values based on local conditions, such as pH, DO concentration, and temperature. This work unit will attempt to reach this goal, or at least provide guidance for k values based on site characteristics.

Stumm and Morgan (1981) provide guidance (based on laboratory experiments) for predicting reduced iron and manganese oxygenation kinetics. Using their formulation for iron oxidation (with observed field values for temperature, DO concentration, and pH) yields a value of about 2.5 per day--considerably lower than the calibration value of 6.5. Ferrous iron oxidation rates in the field, however, may occur at a faster rate due to the presence of other trace metals and complexes or iron anions that act as catalysts (Stumm and Morgan 1981). Nix (1986) analyzed coatings of gravel taken from the Lake Greeson tailwater and verified that trace metals are present.

Similarly, a relatively high oxidation rate for manganese (4.6 per day) was required to match the model to observed data. This value is one to two orders of magnitude higher than values found in laboratory studies (Hsiung 1987; Chen, Gunnison, and Brannon 1983; and Chen, Brannon, and Gunnison 1984). Gordon (1983, 1984) also found field values to be generally higher than laboratory rates. This finding may be attributed to catalysts present in the stream (Nix 1986 and Gordon 1984).



Tailwater below the dam at Rough River Reservoir

Nix (1986) conducted laboratory experiments with the presence of Little Missouri River gravels, which were coated with hydrous oxides of manganese. Manganese oxidation rates in these experiments were one to two orders of magnitude greater than found in experiments without the gravel. The removal process may include an autocatalytic oxidation involving absorption onto the surface of a hydrous oxide of manganese, such as the coated gravels in the Greeson tailwater (Nix 1986).

The manganese oxidation rate of 4.6 per day found in the present study, while approximately three times higher, was about the same order of magnitude as rates determined during studies of the Duck River, TN (Gordon 1984 and Hess 1984). Similarly, this value is about three times higher than the values found in the earlier study by Nix (1986) on the Greeson tailwater. Gordon reported that the rates he observed were first order and varied with the flow rate. Of course, flow rate influences travel time, thus contact time, but time is taken into account as a variable in the earlier equation. Therefore, other effects on the oxidation rate must be caused by flow rate. If the substrate acts as a catalyst, then it would be reasonable to suspect that the removal rate might vary with flow rate, since flow rate affects the amount of bottom contact area relative to the total flow area. Thus, higher flow rates in a given stream might result in lower oxidation rates than lower flow rates. The flow rate in the earlier Greeson study (Nix 1986) was about five times higher than the flow rate in the present study, which would result in about a 2.6 reduction factor in the ratio of bottom contact area to flow area. This difference in flow rate may explain the manganese oxidation rate differences between the previous and present Greeson studies.

A generalized formulation for reduced iron and manganese oxidation kinetics may need to account for the local temperature, DO concentration, pH, and possibly a flow-related variable. Additionally, the type of substrate in the stream may affect catalytic processes and will have to be taken into account. Results from the field studies are being analyzed with these needs in mind.

The major process affecting DO concentrations in the Greeson tailwater was stream reaeration. Release concentrations of oxygen-demanding substances were low and had little impact on DO; however, this may not be the case at other sites. Stream reaeration rates were measured* using a hydrocarbon gas (propane) tracer method (Rathbun and others 1977, 1978). Measured propane gas-transfer rates were subsequently converted (Rathbun and others 1978) to reaeration rates. The measured reaeration rates are compared with predicted rates using the O'Connor-Dobbins (1956) and Tsivoglou and Wallace (1972) formulations for reaeration (Table 1). The model results shown in Figure 2 were obtained with the Tsivoglou formulation.

* *S. Wilhelms. 1987. "Results of Reaeration Study on Little Missouri River, Narrows Dam, Arkansas," Memorandum for Record, US Army Engineer Waterways Experiment Station, Vicksburg, MS.*

Conclusions

Results from the remaining field studies will provide additional information concerning chemical transformations in reservoir tailwaters and will be used to improve the model's kinetic formulations. The kinetic process descriptions that are developed will be transferable to other stream models that might be used below impoundments. Knowledge gained from conducting the field studies will be used to publish guidance for conducting future water quality surveys in reservoir tailwaters. Application of the model to each field study site will provide guidance for future model applications. The model will be documented and made available to field offices and the public.

Reservoir project operations can affect not only release water quality but stream water quality as well for miles downstream. As a result of the knowledge gained during this project, the US Army Corps of Engineers will have an improved capability for understanding, evaluating, and managing water quality downstream of reservoirs.

References

Brown, L. C., and Barnwell, T. O. 1987. "The Enchanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual," EPA/600/3-87/007, US Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.

Chen, R. L., Gunnison, D., and Brannon, J. M. 1983. "Characterization of Aerobic Chemical Processes in Reservoirs: Problem Description and Model Formulation," Technical Report E-83-16, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Chen, R. L., Brannon, J. M., and Gunnison, D. 1984. "Anaerobic and Aerobic Rate Coefficients for Use in CE-QUAL-R1," Technical Report E-84-5, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Davis, J. E., and others. 1987. "SELECT: A Numerical One-Dimensional Model for Selective Withdrawal," Instruction Report E-87-2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Gordon, J. A. 1983. "Iron, Manganese, and Sulfides Mechanics in Streams and Lakes--A Literature Review," Department of Civil Engineering, Tennessee Technological University, Cookeville, TN.

Gordon, J. A. 1984. "Iron, Manganese, and Sulfides in the Duck River below Normandy Dam," Report TTU-CE-82-2, Tennessee Technological University, Cookeville, TN.

Hess, G. W. 1984. "A Transport Model of Manganese in Rivers," M.S. thesis, Georgia Institute of Technology, Atlanta.

Hsiung, Tung-Ming. 1987. "Manganese Dynamics in the Richard B. Russell Impoundment," M.S. thesis, Clemson University, Clemson, SC.

Nix, J. 1986. "Spatial and Temporal Distribution of Sulfide and Reduced Metals in the Tailwater of Narrows Dam (Lake Greeson), Arkansas," Technical Report E-86-14, prepared by Ouachita Baptist University, Arkadelphia, AR, for the US Army Engineer Waterways Experiment Station, Vicksburg, MS.

O'Connor, D. J., and Dobbins, W. E. 1956. "The Mechanism of Reaeration in Natural Streams," *Journal of Sanitary Engineering Division*, American Society of Civil Engineers, Vol 82, pp 1-30.

Rathbun, R. E., Shultz, D. J., Stephens, D. W., and Tai, D. Y. 1977. "Experimental Modeling of the Oxygen Absorption Characteristics of Streams and Rivers," *Proceedings: Seventeenth Congress of the International Association for Hydraulic Research*, 15-19 August, Baden, Federal Republic of Germany.

Rathbun, R. E., Shultz, D. J., Stephens, D. W., and Tai, D. Y. 1978. "Laboratory Studies of Gas Tracers for Reaeration," *Journal of the Environmental Division*, American Society of Civil Engineers, Vol 104, No. EE2, pp 215-229.

Stumm, W., and Morgan, J. J. 1981. *Aquatic Chemistry: An Introduction Emphasizing Chemical Equilibria in Natural Waters*, John Wiley, New York.

Tsivoglou, E. C., and Wallace, J. R. 1972. "Characterization of Stream Reaeration Capacity," US Environmental Protection Agency, Report No. EPA-R3-72-012, Washington, DC.

This article discusses research into the mechanisms and chemical transformations in reservoir tailwaters. Research focuses on the poor water quality associated with deep, anoxic releases. Studies of the tailwaters of Lake Greeson, Nimrod Reservoir, and Rough River Reservoir have been conducted, and another study at Buford Dam is being planned for 1989.

WATER QUALITY

RESEARCH PROGRAM

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