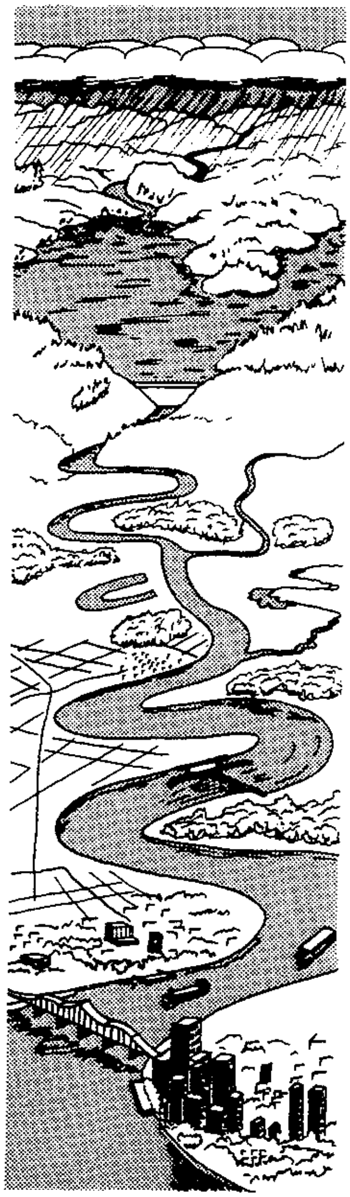
US Army Corps of Engineers
Waterways Experiment Station

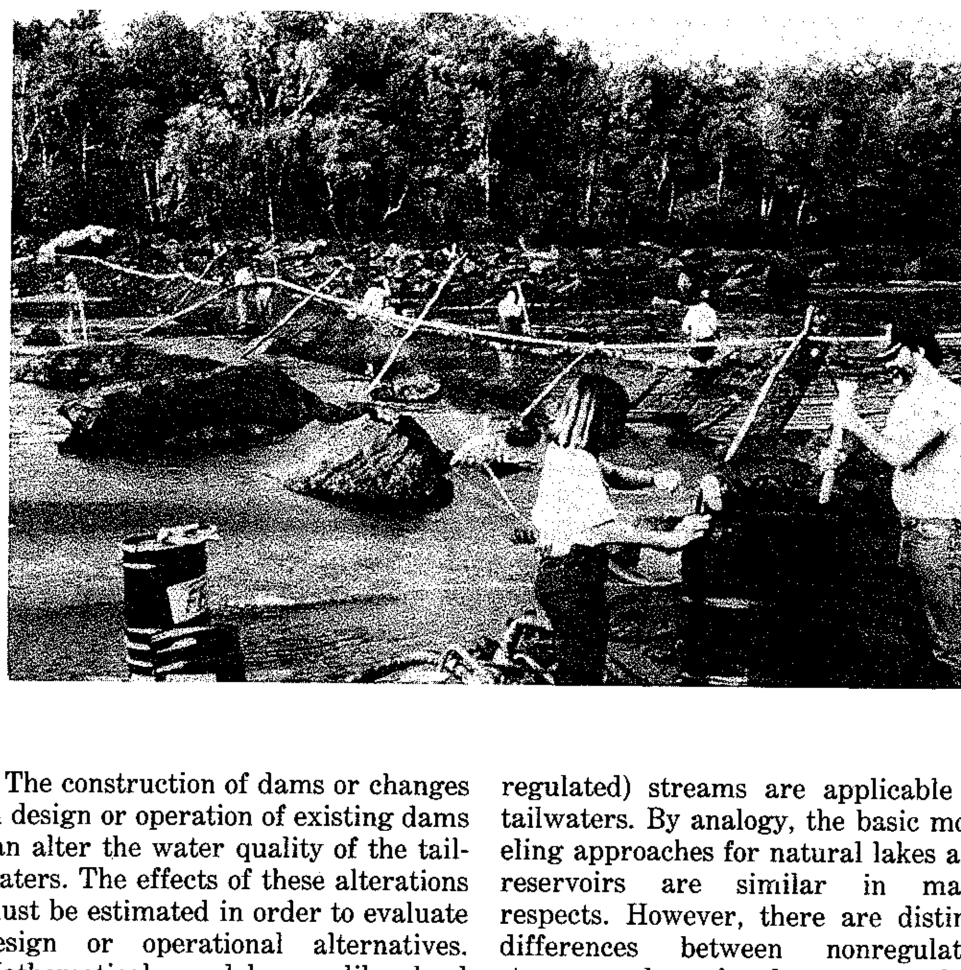


WOTS/ Water Operations Technical Support

VOL E-87-2 INFORMATION EXCHANGE BULLETIN JUN 1987

Water Quality Modeling of Reservoir Tailwaters

James L. Martin and Mark S. Dortch
Environmental Laboratory, WES



The construction of dams or changes in design or operation of existing dams can alter the water quality of the tailwaters. The effects of these alterations must be estimated in order to evaluate design or operational alternatives. Mathematical models readily lend themselves to such an impact assessment and can provide rational aid for management decisions.

Many of the water quality modeling approaches developed for natural (nonregulated) streams are applicable to tailwaters. By analogy, the basic modeling approaches for natural lakes and reservoirs are similar in many respects. However, there are distinct differences between nonregulated streams and regulated systems, such as tailwaters, just as there are differences between natural lakes and reservoirs. These differences must be considered in the selection and application of a modeling approach as well as in the collection of supportive data. This article describes some of the basic considerations in the selection and application of water quality models to tailwaters.

Model Selection

The type of modeling approach used for reservoir tailwaters depends largely upon the assumptions that can be justified. Generally, the simplest approach that is justifiable is the one of preference. Common assumptions governing model selection concern dimensionality in space and variability in time.

Assumptions pertaining to mixing dictate the spatial dimensions of models. Most tailwater quality issues can and should be addressed with a one-dimensional (1-D) longitudinal model. Models of this type assume cross-sectional homogeneity and simulate quality variations only along the longitudinal axis (streamwise direction). Models for simulation of two- or three-dimensional water quality variations are available but are rarely required for tailwater applications.

Assumptions pertaining to time variability dictate the selection of either steady-state or dynamic (unsteady) models. If flow and quality conditions do not change with time, then the steady-state assumption is justifiable. Steady-state conditions are rarely achieved in nature. However, this condition may be approached where the flow duration exceeds the travel time for the tailwater reach of interest. Steady-state simulations may also provide an indication of average quality conditions that may be satisfactory for many applications. Where simulation of time-varying water quality conditions is required, then dynamic models must be used.

Some water quality models perform dynamic water quality simulations while assuming steady-state flow conditions. For example, diel water quality conditions may be simulated during a long-term relatively constant flow event, such as average annual low flow, seven-day low flow that occurs every ten years, etc. Other models may perform both dynamic flow and water quality simulations. Such models have been used to simulate tailwaters below peaking hydropower dams where the flows and water quality may change substantially during each day.

Steady-State Models

A variety of models are available to simulate 1-D steady-state water quality variations in rivers. These models are often extensions of the 1925 Streeter and Phelps model of dissolved oxygen (DO) and biochemical oxygen demand (BOD) that allows mathematically exact or analytical solutions. Often used with these BOD/DO models are fairly simple first-order decay, dilution, and sedimentation models of additional conservative and nonconservative substances (Gromiec et al. 1983). Gromiec et al. (1983) provide formulations for a number of these models. Because steady-state models often have easily solvable analytical solutions, they can be quickly applied and have minimal data requirements.

Computerized models based on steady-state analytical solutions are also available. These models often allow simulation of stream networks or other system characteristics that would otherwise be tedious to calculate by hand. The STEADY model (Martin 1986a), for example, allows comparisons of different flow regimes, inflow loadings, and meteorological conditions on the spatial distribution of water temperatures and DO in stream systems under steady-state flow and water quality conditions. STEADY simulates a series of piecewise nonuniform subreaches, which means a series of subreaches with different but steady flows can make up the total river reach modeled. The effects of withdrawals, branches, and tributaries can be simulated. STEADY has few data requirements relative to other models and can be quickly applied. A user-friendly menu-driven PC version is available.

STEADY was originally developed for the Nashville District by the Waterways Experiment Station (WES) to allow a reconnaissance-level assessment of temperature variations above and below a proposed reregulation dam downstream of Wolf Creek Dam, Kentucky. The model has also been applied by the Walla Walla District (1986) to assess temperature variations in river reaches affected by proposed drainage from Lake Malheur, Oregon.

Dynamic Models

Where flow and quality conditions are known to vary with time, dynamic water quality models may be required. Dynamic models must generally resort to numerical methods for their solution and are more data intensive and time consuming to apply. Dynamic models can also be used to obtain steady-state solutions by simply holding their boundary conditions constant. Since the numerical schemes allow solution of more complex descriptions of constituent kinetics, steady-state solutions are obtainable that would not be possible if users had to rely solely on analytical solutions.

An intermediate modeling approach between fully dynamic and steady-state models is found in QUAL-2E (Brown and Barnwell 1985), which is maintained by the US Environmental Protection Agency (EPA). QUAL-2E is a numerical 1-D (longitudinal) water quality model that assumes steady flows (steady-state hydraulics) but allows simulation of dynamic water quality variations, such as diel variations in temperatures or algal productivity and respiration. The model allows simulation of a total of 15 water quality constituents. Like STEADY, QUAL-2E simulates a series of piecewise nonuniform segments that make up a river reach. The effects of withdrawals, branches, and tributaries can also be included. The effects of hydraulic control structures (run-of-the-river dams) can be accounted for indirectly by inputting the depth and velocities for impounded (backwater) reaches.

QUAL-2E has been widely used, particularly for waste-load allocation studies of riverine systems. The model has also been applied by WES (Hamlin and Nestler 1987) to study 108 miles of the Rogue River downstream of Lost Creek Dam in Oregon. The study objective was to provide the Portland District with a model to predict the downstream water temperatures as affected by Lost Creek Dam operation. Flow changes in the river were gradual, allowing use of the QUAL-2E model as opposed to a fully dynamic model. The model was also used by WES to assess the impact of a series of five locks and dams (presently under construction) on DO concentrations in the Red River, Louisiana (Martin 1987). The QUAL-2E model was used with constant loadings to obtain steady-state quality predictions for constant low-flow events. The water quality was run in a dynamic mode so that diel variations could be studied.

A number of fully dynamic water quality models are also available and are applicable to tailwaters. A fully dynamic model allows simulation of both unsteady hydraulics and unsteady water quality. Fully dynamic models are required when transient events are of importance and where flow variations occur over periods that are much less than the travel time for the reach of interest. For example, if the travel time for a particular flow is greater than its duration, then only a portion of the reach would be exposed to that flow and its associated quality at a given time. Using steady-state hydraulics, such as in QUAL-2E, the flows for the entire reach would be incremented to the new flow condition instantaneously. In a fully dynamic model, the effects of time-varying flows and quality along the reach are simulated. As such, fully dynamic models usually consist of coupled unsteady hydraulic and unsteady quality models.

CE-QUAL-RIV1 (originally developed by Bedford et al. 1983) is a fully dynamic 1-D riverine water quality model that has been used to simulate quality in tailwaters. The model is comprised of two submodels: a hydrodynamic model, RIV1H, which can stand alone; and a water quality model, RIV1Q, which requires output from RIV1H or another routing model to drive it. RIV1H uses the four-point implicit finite-difference scheme to solve for flows and elevations. The model's formulation allows unequal steps in time and space and simulation of branched river systems with multiple hydraulic control structures (flow regulating structures such as weirs and dams). RIV1Q uses a two-point fourth-order accurate numerical scheme to calculate advective transport. This allows sharp gradients in water quality constituents to be accurately resolved. Ten water quality variables can be simulated: temperature, DO, carbonaceous BOD (CBOD), organic nitrogen, ammonia, nitrate, phosphate, dissolved iron, dissolved manganese, and coliform bacteria. Additionally, algae/macrophyte photosynthesis, respiration, and nutrient interactions are included. This model's versatility in simulating time-varying flows and water quality has led to its use in a variety of situations, including streams below peaking hydropower facilities on the Cumberland River, Kentucky (Martin 1986b), and Chattahoochee River, Georgia (Zimmerman and Dortch 1987). This model is being applied to evaluate the impacts of adding hydropower facilities to several dams on the lower Ohio River.

Model Application

Reservoir tailwaters differ from natural streams in that their flows and quality are regulated by upstream impoundments. The effects of this regulation have been the subject of numerous texts, including those of Ward and Stanford (1979), Lillehammer and Saltveit (1984), and Petts (1984). These and other texts provide descriptions of the processes impacting tailwater quality and how they differ from those in nonregulated streams.

Perhaps the most important aspect of a tailwater quality model study is proper specification of the upstream boundary conditions, which are the reservoir release flows and constituent concentrations. For example, the release DO concentration can increase as flow passes through nonhydropower structures, whereas hydropower structures provide little reaeration. It is also important to realize that while release quality depends on the intake elevation, release quality can also change with the discharge rate. For example, the release water quality can vary substantially between peaking hydropower and off-peak (low-flow) releases, especially in the late summer through early fall. For a hypolimnetic intake near the bottom, the release quality may be poor (high concentrations of nutrients and reduced metals and low DO) for low flows, but it may improve during high flows (peaking releases) due to expansion of the withdrawal zone to include water higher in the pool. The reverse of this situation has also been observed for hypolimnetic withdrawal, so the specific effect depends on the characteristics of the project.

A common objective of tailwater studies is the prediction of downstream water temperatures in order to assess impacts on stream biota. The processes affecting and methods used in predicting water temperatures are relatively well established. The reliability of models of water temperatures is very good. However, water-temperature predictions may be complicated by lack of representative meteorological boundary conditions and processes not included in model formulations. For example, Troxler and Thackston (1977) indicated that fog formation and micrometeorological effects may result in overestimation of water temperatures in the tailwaters of some hydroelectric projects. Streams with rock beds, which can store heat, may experience warming from the bed during low-flow periods.

A second common objective of tailwater studies is the prediction of downstream DO concentrations. Many of the processes affecting and methods used in predicting DO concentrations are also well known and established, and predictive reliability is generally good. However, the processes affecting some other constituents that may in turn impact DO predictions are not well established. Presently these processes can only be described by models of tailwater quality based upon calibration against measured data, which detracts from their predictive reliability.

In particular, the processes affecting reduced chemical species released from anoxic reservoir zones are not well described. Gordon (1985a,b) pointed out that very little systematic work has been conducted to evaluate the distribution and dynamics of reduced chemical species after they enter the tailwater environment. Characterization of the behavior of some of these fleeting species, such as hydrogen sulfide, is also complicated by the limitations of present analytical chemistry methods (Nix 1985).

A second difficulty often encountered in predicting tailwater DO concentrations is inadequate characterization of demands due to decomposition of organic materials. In traditional riverine modeling, these demands are expressed by CBOD. However, CBOD measurements are often not available for reservoirs, because the more common means of measuring organic content is total organic carbon (TOC). The relationship between TOC and CBOD is often nebulous. Where the CBODs of release waters are measured, they usually include demands due to oxidation of reduced chemical species that are often modeled as separate variables. Thus, it becomes difficult to fraction their individual contributions from simple CBOD measurements.

Presently, of the models mentioned above, all include algorithms for temperature, DO, and CBOD. Both CE-QUAL-RIV1 and QUAL-2E include nutrient kinetics and nitrification; additionally, CE-QUAL-RIV1 includes first-order oxidation of reduced iron and manganese that must be calibrated to the study site. None of the models contain algorithms for sulfides. Process descriptions for reduced species could be added to the models following improved understanding of those processes. Additional research is presently underway at WES to develop an improved understanding and predictive capability of processes influencing the quality of reservoir tailwaters.

Conclusions

No single method is appropriate for addressing all water quality issues in reservoir tailwaters. Differences in tailwater environments and management issues require that a variety of tools be available for assessing existing or predicting future impacts of reservoir releases.

The various stream water quality models or approaches discussed here have provided an effective means of addressing reservoir tailwater issues. Each model has its own merits and limitations and should be selected based on the specific needs of an application. Several basic considerations in selecting and applying these tools have been discussed.

Research is underway to improve understanding of tailwater processes and to enhance predictive capability.

Additional information on this subject and assistance can be obtained through the WOTS Program.

References

Bedford, K. W., Sykes, R. M., and Libicki, C. 1983. "Dynamic Advective Water Quality Model for River," *Journal of Environmental Engineering Division*, American Society of Civil Engineers, vol. 109, No. 3, pp 535-554.

Brown, L. C., and Barnwell, T. O. 1985. "Computer Program Documentation for the Enhanced Stream Water Quality Model QUAL-2E," EPA/600/3-85/065, US Environmental Protection Agency, Athens, Georgia.

Gordon, J. A. 1985a. "Literature Review: The Oxidation of Manganese in the Natural, Freshwater Environment-Engineering Considerations," Tennessee Technological University, Cookeville, Tenn.

Gordon, J. A. 1985b. "Manganese Oxidation Related to the Releases from Reservoirs," presented at the 1985 Triangle Conference on Environmental Technology, Raleigh, N.C.

Gromiec, M. J., Loucks, D. P., and Orlob, G. T. 1983. "Stream Quality Modeling," In *Mathematical Modeling of Water Quality: Streams, Lakes, and Reservoirs* (Ed. G. T. Orlob), John Wiley and Sons, New York.

Hamlin, D. E., and Nestler, J. M. 1987. "Development, Calibration, and Verification of a Model to Predict Longitudinally Varying Temperatures in the Rogue River, Oregon," Miscellaneous Paper in publication, prepared for the US Army Engineer District, Portland, by the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Lillehammer, A., and Saltveit S. J. (Eds). 1984. *Regulated Rivers*, Universitetsforlaget AS, Oslo, Norway.

Martin, J. L. 1986a. "Steady-State Temperature and Dissolved Oxygen Model: User's Guide," Instruction Report E-86-4, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Martin, J. L. 1986b. "Water Quality Study of Proposed Reregulation Dam Downstream of Wolf Creek Dam, Cumberland River, Kentucky," Miscellaneous Paper EL-86-4, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Martin, J. L. 1987. "Water Quality Model Study of Proposed Locks and Dams on the Red River in Louisiana," Miscellaneous Paper in publication, prepared for the US Army Engineer District, Vicksburg, by the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Nix, J. 1985. "Spatial and Temporal Distribution of Reduced Species in the Tailwater of Narrows Dam (Lake Greeson), Arkansas," prepared for the US Army Engineer Vicksburg District, Vicksburg, Miss.

Petts, G. E. 1984. *Impounded Rivers: Perspectives for Ecological Management*, John Wiley and Sons, New York.

Troxler, R. W., and Thackston, E. L. 1977. "Predicting the Rate of Warming of Rivers below Hydroelectric Installations," *Journal of Water Pollution Control Federation*, Vol. 49, pp 1902-1912.

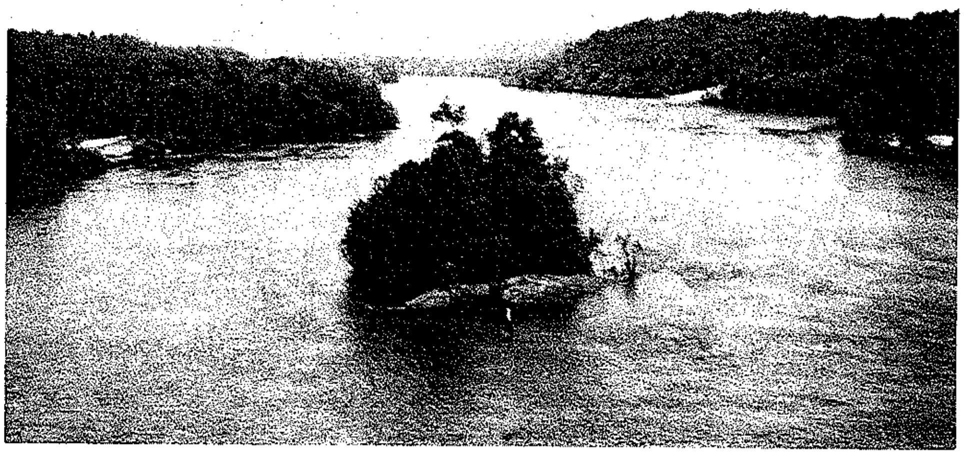
Ward, J. W., and Stanford, J. A. (Eds.) 1979. *The Ecology of Regulated Streams*, Plenum Press, New York.

Walla Walla District. 1986. "Effects of Malheur Lake Releases on Downstream Water Temperatures," draft Malheur Lake Flood Damage Reduction Feasibility Study and Environmental Impact Statement, Walla Walla, Wash.

Zimmerman, M. J., and Dortch, M. S. 1987. "Water Quality Model Study of Proposed Reregulation Dam Downstream from Buford Dam, Chattahoochee River, Georgia," Miscellaneous Paper in preparation, prepared for the US Army Engineer District, Savannah, by the US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Applying Technology for Tailwater Investigations Under the WOTS Program

John M. Nestler
Environmental Laboratory, WES



The CE develops and manages water resources by constructing and operating reservoirs. Tailwaters-- river reaches immediately downstream of reservoirs-- often support valuable fisheries that are known to be sensitive to the timing, quantity, and quality of reservoir releases. Under the EWQOS Program, long-term investigations of tailwater ecology by the Waterways Experiment Station (WES) described effects of reservoir releases on downstream biota (Walburg et al. 1981, 1983). Based on these studies, general guidelines for assessing the downstream effects of reservoirs were developed (Nestler et al. 1986). In many cases, quantitative methods were identified to assess the effects of operation on tailwater biota.

Following the completion of EWQOS, efforts shifted from performing research on tailwater ecology to transferring information gained to field offices for assessing the downstream effects of project operation on aquatic biota. The Water Operations Technical Support (WOTS) Program was authorized to ensure maximum technology transfer. Under the program, CE field offices can request assistance in applying EWQOS technology to solve water quality and fishery problems. The following overview presents a few of the requests for assistance addressed by WOTS. This overview is presented to increase the awareness of potential users to the types of assistance available under WOTS to address downstream water quality and fishery problems associated with reservoir operation.

Richard B. Russell Dam. This reservoir on the Savannah River is operated by the Savannah District for conventional generation of hydropower. Future plans call for installation of pumped-storage capability by 1990. WES assisted in preliminary assessments of the potential for fish turbine mortality during pumped-storage operation. As a separate WOTS request, scopes of work for studies to assess potential fish turbine mortality were reviewed and refined.

Lost Creek and Elk Creek Dams. Flows in the Rogue River are regulated by the Portland District, within constraints imposed by other project purposes, to meet requirements of the salmon fishery as determined by the Oregon Department of Fish and Wildlife (ODFW). Under separate WOTS requests, WES provided technical review of methods recommended by the ODFW to assess the effects of Lost Creek Dam operation on the Rogue River salmon fishery, recommended alternative methods to assess operation of Lost Creek Dam, and assisted the District in litigation on Elk Creek Dam (a dam under construction in the Rogue River basin).

Lowering water levels in Malheur Lake. Malheur Lake in eastern Oregon is a natural lake with no outlet near normal lake elevations. Increased rainfall during the last several years has produced rising water levels that resulted in local flooding. WES provided information to Walla Walla District on the cost, time to completion, and complexity of alternative methods of assessing the effects of draining Malheur Lake on water quality and fish habitat in the two receiving streams (Malheur River and Snake River).

Wolf Creek Dam. Wolf Creek Dam, on the Cumberland River, is operated by Nashville District for multiple purposes including hydropower production. The District is evaluating hydropower uprating/upgrading alternatives for this project in response to needs for increased peaking capacity in the region. WES provided guidance to the District on methods to assess the potential effects of altered operation on downstream fish habitat and water quality.

Narrows Dam. Narrows Dam is located on the Little Missouri River, Arkansas. The Vicksburg District is assessing different alternatives to improve downstream water quality. WES assisted the Vicksburg District in choosing proper modeling strategies to evaluate the effects of partial plating (i.e., intake is partially covered to restrict intake depth) of the trash racks at Narrows Dam on inpool and downstream water quality.

Conclusions

The WOTS program has benefited both the Districts and WES. District offices benefit because the research experience gained by WES through the EWQOS program can be applied to solve specific problems. Of equal importance, WES benefits by better understanding District problems and thus better focusing its research efforts.

References

Nestler, J. M, et al. 1986. "Handbook on Reservoir Releases for Fisheries and Environmental Quality," Instruction Report E-86-3, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Walburg, C. E., et al. 1981. "Effects of Reservoir Releases on Water Quality, Macroinvertebrates, and Fish in Tailwaters: A Literature Review," Technical Report E-83-12, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Walburg, C. E., et al. 1983. "Effects of Reservoir Releases on Water Quality, Macroinvertebrates, and Fish in Tailwaters: Field Study Results," Technical Report E-83-6, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

ENVIRONMENTAL AND WATER QUALITY OPERATIONAL STUDIES

This bulletin is published in accordance with AR 310-2. It has been prepared and distributed as one of the information dissemination functions of the Waterways Experiment Station. It is principally intended to be a forum whereby information pertaining to and resulting from EWQOS can be rapidly and widely disseminated to Corps District and Division offices as well as other Federal agencies, state agencies, universities, research institutes, corporations, and individuals. Contributions of any type are solicited from all sources and will be considered for publication as long as they are relevant to the objectives of EWQOS, i.e., to provide new or improved technology to solve selected environmental quality problems associated with Civil Works activities of the Corps of Engineers in a manner compatible with authorized project purposes. This bulletin will be issued on an irregular basis as dictated by the quantity and importance of information to be disseminated. Communications are welcomed and should be addressed to the Environmental Laboratory, ATTN: J.L. Mahloch, U.S. Army Engineer Waterways Experiment Station, P.O. Box 631, Vicksburg, Mississippi 39180-0631, call AC 601/634-3635.

DWAYNE G. LEE
Colonel, Corps of Engineers
Commander and Director

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P O BOX 631
VICKSBURG, MISSISSIPPI 39180-0631

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

WESEV-I