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Tailwater Quality Model (TWQM) development

by
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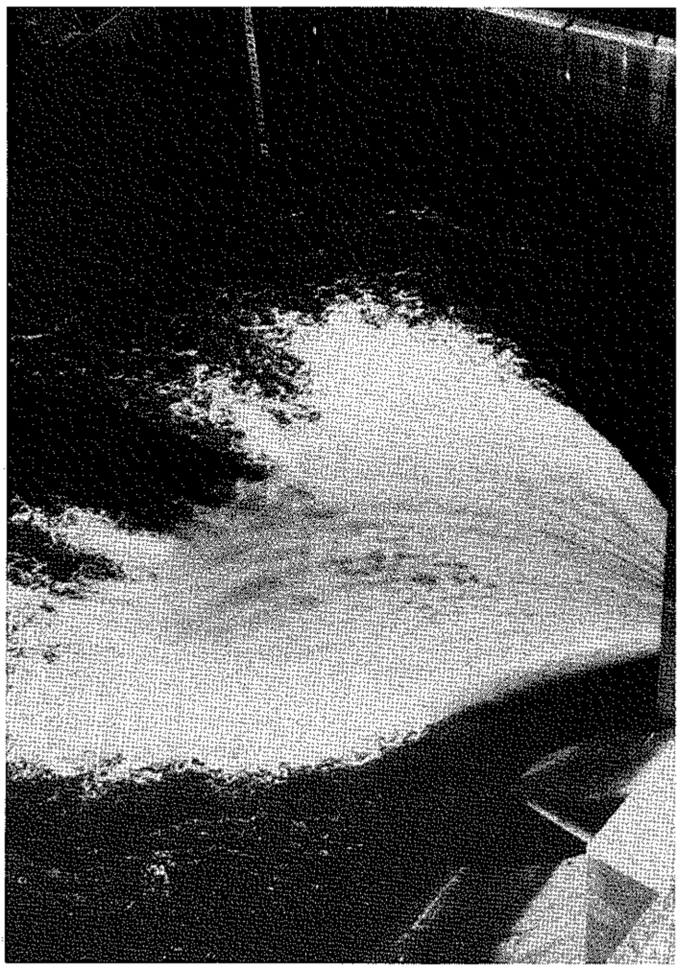

Reservoir release from Nimrod Reservoir

Thermally stratified reservoirs releasing hypolimnetic waters that commonly experience oxygen depletion release more dissolved nutrients (ammonium and inorganic phosphorus), sulfide, reduced metals (iron and manganese), and specific organic substances (simple organic acids and methane) into tailwaters than reservoirs with epilimnetic releases. U.S. Army Corps of Engineers (USACE) projects commonly experience this situation during the summer.

Under the Water Quality Research Program, a work unit entitled Techniques for Evaluating Water Quality of Reservoir Tailw7aters was initiated to gain a better understanding of the recovery mechanisms and chemical transformations of these substances in the tailwaters of Corps projects. Three major objectives have been addressed by this research — developing an improved understanding of chemical transformations in reservoir tailwaters, providing guidance on sampling and analysis of tailwater quality, and developing an easy-to-use personal computer (PC) model to predict the water quality of tailwaters based on in-pool or release concentrations.

This article presents an overview of the PC model Tailwater Quality Model (TWQM) developed from this research. The model development approach is discussed along with a model description and an overview of model operations and applications.

Model development approach

Effective water quality management of reservoir tailwaters requires an assessment of existing conditions and prediction of future conditions resulting from structural or operational modifications of the dam and tailwater system. For example, the conversion of a non-hydropower release to a hydropower release can lead to water quality problems. Releases through hydropower turbines are not subjected to the usually high degree of reaeration that non-hydropower releases are subjected (Bohac and others 1983); so low dissolved oxygen (DO) may persist for several miles downstream, causing detrimental effects to downstream aquatic life.

Mathematical water quality modeling is a very cost-effective tool for predicting future conditions resulting from changes to a system. However, water quality models are often limited in the context of kinetic process descriptions. For example, consider a first-order loss or decay of a substance (such as biochemical oxygen demand). This process states that the time rate of decrease of a constituent concentration, C, is directly proportional to the concentration, which is mathematically stated as

$$\frac{dC}{dt} = -KC$$

where t is time and K is the reaction rate. This equation has been successfully used to describe the kinetics of numerous water quality constituents, but the difficulty in applying it in practice is estimating or calibrating K. The modeler usually tries to fit the model to observed concentrations by varying K during calibration. In reality, K can vary with environmental conditions, such as temperature, pH, or DO. One of the greatest limitations of water quality modeling is that little is known about predicting values for rate coefficients. Observations for a future (proposed) condition do not exist.

An improved understanding of water quality processes can be obtained through carefully designed field studies. Laboratory studies, though useful, may fail to include some environmental factors that affect water quality kinetics.

During this research, short-term intensive field studies were conducted at four reservoir tailwater sites where physical and water quality conditions were measured to quantify chemical transformations — Little Missouri River, Arkansas, below Lake Greeson; Fourche La Fave River, Arkansas, below Nimrod Reservoir; Rough River, Kentucky, below Rough River Reservoir; and Guadalupe River, Texas, below Canyon Reservoir. Narrows Dam (that is, Lake Greeson) has hydropower; Canyon Dam was retrofitted for non-Federal hydropower shortly after this study. The other sites were non-hydropower.

For each field site, Nix and others (1991) presented a detailed discussion of field and analytical techniques used in analyzing the water quality in addition to all water quality results collected for this research. All sites had deep releases characterized by the presence of reduced substances with low DO. The study sites provided a range of physical and environmental conditions such as varying stream slope, substrate, and pH.

Samples were collected for water quality analyses at a number of stations extending over the tailwater reaches. The study reaches extended from the dam to about 10 to 36 river kilometers downstream depending on the flow conditions and stream characteristics which impact the particle travel time. The particle travel time is the time required for a "parcel" of water to move from the release point to a given distance downstream. The study reaches were generally limited to a travel time of about two days because most of the chemical reactions occurred within this time period.

The release flow rate from the dam was held constant during each field study to provide steady flow and nearly steady-state conditions (with the exception of diel effects). This approach greatly simplifies interpretation of results. Lagrangian sampling, which tracks a water parcel as it moves downstream, and snapshot sampling, where samples are collected at all stations at or near the same point in time, yielded similar results for steady flows (Nix and others 1991), confirming the systems were approximately at steady-state. Dye studies were conducted to determine the travel time to each station. With concentrations measured at the stations and travel time to the stations, it was possible to evaluate the reaction kinetics of various constituents such as the disappearance of reduced manganese and iron. From the analyses of the field data, equations to predict the kinetic rates (K in the earlier equation) for various constituents were developed and included in the TWQM. With equations to estimate K values, calibration requirements are reduced.

Numerical model description

The purpose of the Tailwater Quality Model TWQM (Dortch, Tillman, and Bunch 1992) is to predict the downstream transformation of problem constituents such as DO and reduced substances (for example, iron, manganese, sulfide, and ammonium). In developing the model, the intent was to have the model require as little input data as possible, allowing modest resources for application. To reduce input requirements the model dimensionality was restricted; the model is one-dimensional (1-D) in the streamwise direction. The model was also restricted to steady-state applications so that time-varying input files are not required. Therefore, TWQM does not allow time-varying flow or water quality inputs, and a steady-state solution is performed.

Steady-state solutions for 1-D problems can often be performed analytically, rather than numerically (Dortch and Martin 1989). However, a numerical modeling approach was selected for the TWQM because it allows more flexibility in state variables interactions. Additionally, with the microcomputer resources available today, numerical solutions are rapidly attainable.

TWQM is based on the 1-D, stream water quality model QUAL2E (Brown and Barnwell 1987). The major modification to QUAL2E included subroutines to model the reduced substances in tailwaters and an interface to provide easier model application. QUAL2E was selected because it is widely used and accepted, provides for steady-state solutions, contains other water quality processes that could be used if desired, and the most recent version of QUAL2E has been developed for microcomputers with simpler input requirements.

The TWQM combines several components within an interface that uses menus for selecting alternatives. In addition to the QUAL2E-based tailwater component, there is a reservoir release component. Reservoir release water quality is required for the upstream boundary condition of the stream component. 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 the in-pool temperature stratification, the outlet features, release flow rate, and vertical distribution of water quality constituents, SELECT computes the release concentrations.

Also included in SELECT is a structural reaeration component that predicts uptake of dissolved oxygen as flow passes through the release structure. Release concentrations are provided by SELECT to the tailwater component for predicting downstream concentrations. Except for DO, variables are treated as conservative as they pass through the outlet structure because of the short residence time in the structure. The combination of SELECT with the tailwater model allows the user to evaluate the impact on downstream water quality of various release schemes such as hydropower retrofit or moving the vertical location of the intakes of the outlet structure.

TWQM has the capability of simulating the following water quality constituents (in any combination) —

- DO.
- Carbonaceous biochemical oxygen demand (CBOD).
- Temperature.
- Algae as chlorophyll *a*.
- Total organic nitrogen.
- Ammonium nitrogen.
- Nitrite plus nitrate nitrogen.
- Total organic phosphorus.
- Dissolved inorganic (orthophosphate) phosphorus.
- Dissolved (reduced) iron.
- Dissolved (reduced) manganese.
- Total dissolved sulfide (HS^- and H_2S).
- Iron sulfide.
- Arbitrary nonconservative constituent.
- Two conservative constituents.

Most of the above constituents were originally in QUAL2E; the reduced substances — iron, manganese, sulfide, and iron sulfide — were added. The kinetics for these reduced substances were developed based on literature and analysis of the observed data collected at the four field sites mentioned earlier. The model's compartmental diagram (Figure 1) illustrates the various state variables and how they interact. The model solves the steady-state mass balance equation (that is, mass transport equation or advection-diffusion equation with mass sources/sinks) for each state variable. This equation is referred to as the energy equation for temperature.

The tailwater is physically described by subdividing the stream system into reaches (the basic division of the model). Reaches represent portions of the river having similar channel geometry, hydraulic characteristics, and chemical/biological coefficients. Reaches are further divided into equally spaced units called computational elements or nodes. An example schematic of a model system is illustrated in Figure 2. Each computational element has inputs, outputs, and reaction terms. The energy and mass balance equations are solved simultaneously (implicitly) for each computational element. This solution is repeated in an iterative fashion, using the previous solution results, until convergence for the steady-state solution is reached (that is, the

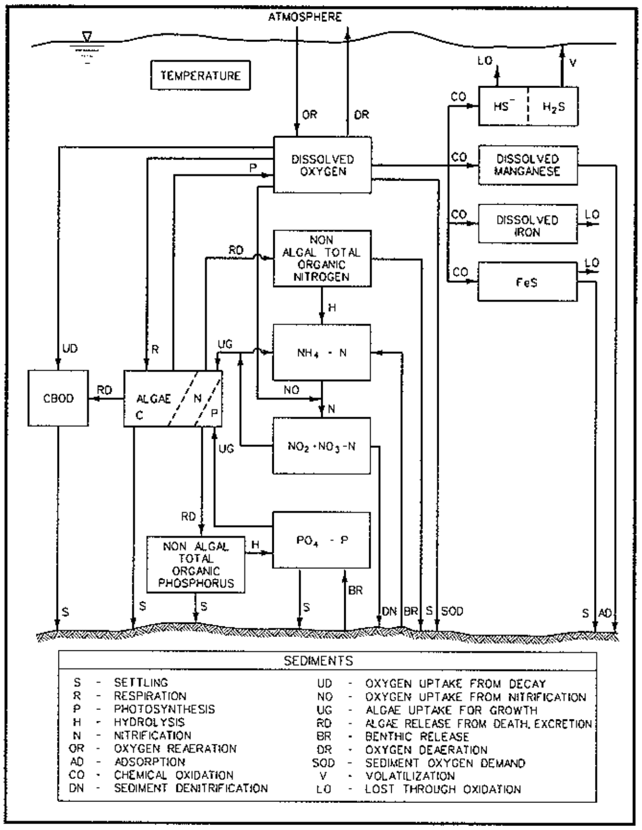

Figure 1. TWQM compartmental diagram

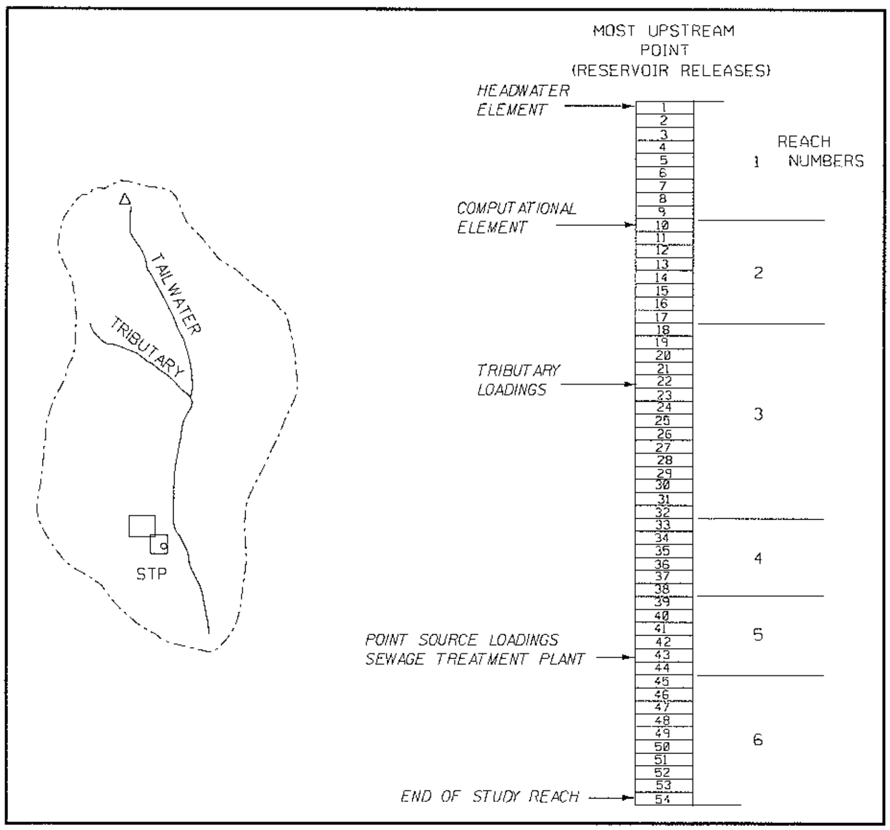

Figure 2. Example schematic of a model stream system

concentrations quit changing within a small tolerance).

The model assumes steady, nonuniform flow. Hydraulic conditions (velocity and depth) used within the energy and mass balance equations are entered for each reach and are assumed uniform throughout the reach. Steady flow implies that the flow rate, velocity, width, and depth at any point in the stream are constant with time. Nonuniform flow is allowed, which means flow rate, velocity, width, and depth can change in the longitudinal direction from reach to reach.

Overview of model operations

TWQM is an interactive, menu-driven, PC-based model of water quality for tailwaters to help evaluate downstream water quality characteristics given in-pool or release concentrations. The numerical portion of TWQM computes the 1-D, longitudinal, steady-state distribution of water quality along the stream axis beginning at the reservoir release and progressing downstream for any number of miles as specified by the user. Examples of the types of issues affecting tailwater quality that might be addressed include:

- Changes in the reservoir outlet elevation or release flow.
- Changes in release reaeration characteristics, such as adding hydropower.
- Changes in release water quality due to degradation of in-pool water quality.
- Changes in the downstream channel, such as reregulation.

The TWQM is actually composed of several programs which perform different functions. The SELECT (Davis and others 1987) program allows the user to estimate release concentrations if none are available. Preprocessor programs allow the user to create a new input data set or modify an old one. The numerical 1-D model predicts (based on release conditions and stream characteristics) the water quality concentrations in the tailwater. Finally, postprocessor programs allow the user to plot the results. For a complete description of each program, its function, and its output, see Dortch, Tillman, and Bunch (1992).

The main batch program which executes all the programs in the model is TWQB.BAT. The order in which TWQB calls each program is shown in Figure 3. The first four files make up the preprocessor portion of the program. Whether the user chooses to alter an existing data file or create a new one will determine which files are called. The next file called is the numerical portion of the model, TAILWTR.EXE. This program uses the input data set specified by the user. The last group of files called are the postprocessor files. The user has a choice of graphic options — TPLOT (Benton 1987) or GRAPHER (Golden Software, Inc. 1988). TPLOT software is distributed with the model, but the GRAPHER software must be acquired by the user.

When the user is prompted for data or information necessary for model operations, questions or menu screens appear, which contain default values where appropriate. For example, in Figure 4, the default values set for the rate coefficients of DO and CBOD are shown to the user, who is then prompted for changes. In all cases, the required input will be an answer to a direct question appearing on the screen. The user is only required to enter a real or integer number, yes or no answer, data file name, or short amount of text (for example, river name).

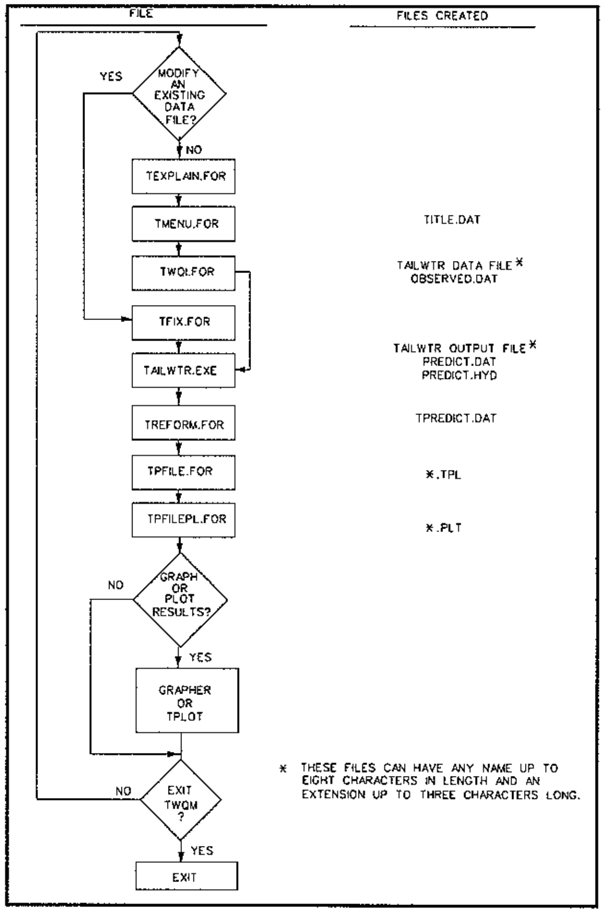

Figure 3. TWQB Structure

SCREEN SEVEN
DATA TYPE 6: DO/BOD COEFFICIENTS
REACH 1

REACTION COEFFICIENT TYPE	DEFAULT
CBOD DECAY RATE (1/day)	0.150
CBOD SETTLING RATE (1/day)	0.000
SOD RATE (g 02/sq ft-day)	0.200
K2 OPTION	3.000

ANY CHANGES TO REACTION COEFFICIENTS (Y/N)?

K2 OPTION	K2 COMPUTATIONAL METHOD
1	READ IN VALUE
2	CHURCHILL
3	OCONNER AND DOBBINS
4	OWENS AND GIBBS
5	THACKSTON AND KRENKEL
6	LANGBIEN AND DURUM
7	K2 = aQ**b

Figure 4. DO/CBOD default rate coefficients

Applications

TWQM was applied to each of the four field study sites (Lake Greeson, Nimrod Reservoir, Rough River Reservoir, and Canyon Reservoir) discussed in Nix and others (1991). Water quality constituents modeled during each application were DO, CBOD, ammonium nitrogen, organic nitrogen, nitrate nitrogen, dissolved manganese (Mn^{+2}), dissolved iron (Fe^{+2}), and total dissolved sulfide (if measured). Temperature and pH were not modeled, but were input for each reach.

Reaction rates for Mn^{+2} and Fe^{+2} removal at Nimrod Reservoir were modeled using equations developed during the study (see Dortch, Tillman, and Bunch 1992 for complete discussion). Figure 5 shows model results for DO, Mn^{+2}, and Fe^{+2} for the Nimrod tailwater. Comparison to observed data was favorable for DO and Mn^{+2}, but Fe^{+2} was underpredicted. Dissolved iron at Nimrod Reservoir did not decrease after traveling through the first few kilometers of the tailwater. Fine particulate iron (oxidized iron) may have passed through the filter during analysis yielding an inflated value for measured dissolved iron. For a complete discussion of each model application see Dortch, Tillman, and Bunch (1992).

Recommendations

TWQM is considered to have performed well for DO, dissolved manganese, nitrogen species, and total dissolved sulfide for the data collected at the four USACE reservoirs. Although the data for total dissolved sulfide were limited and of questionable quality, the model should provide reasonable estimates since the formulations are based in part on volatilization, which is fairly well understood.

Although the model contains algorithms for modeling dissolved iron and iron sulfide, the lack of adequate field data prohibited the development of general relationships for verifying predictive equations for their kinetic rates. More work is required to better resolve the kinetics of dissolved iron and iron sulfide.

Future extensions of the model should include the capability to predict pH changes in the tailwater. This could be accomplished by including carbon dioxide (CO_2), alkalinity, and carbonate equilibria. The escape of CO_2 through the air-water interface can be modeled like other gas exchange processes, such as reaeration and volatilization of hydrogen sulfide (H_2S). As CO_2 escapes, pH increases. Since pH affects other processes, such as the rate of oxidation of reduced iron, incorporating pH would increase the utility of the model.

The two technical reports (Nix and others 1991 and Dortch, Tillman, and Bunch 1992) resulting from this research work unit are highly recommended as references for USACE Districts and Divisions experiencing tailwater quality problems and will provide guidance for initiating a study. Nix and others (1991) discusses the field and analytical techniques implemented at the four USACE field sites for studying the mechanisms and chemical transformations occurring in the tailwaters and water quality results for the tailwaters. Dortch, Tillman, and Bunch (1992) addresses the modeling of tailwaters and the development of the TWQM with a user's guide.

The recommended PC requirements for running the model are a 386 PC (or better) equipped with a math coprocessor, 4 megabytes of disk space available for file storage, and at least one megabyte of memory for model execution. The point of contact for obtaining the model is Dr. Barry W. Bunch, (601) 634-3617.

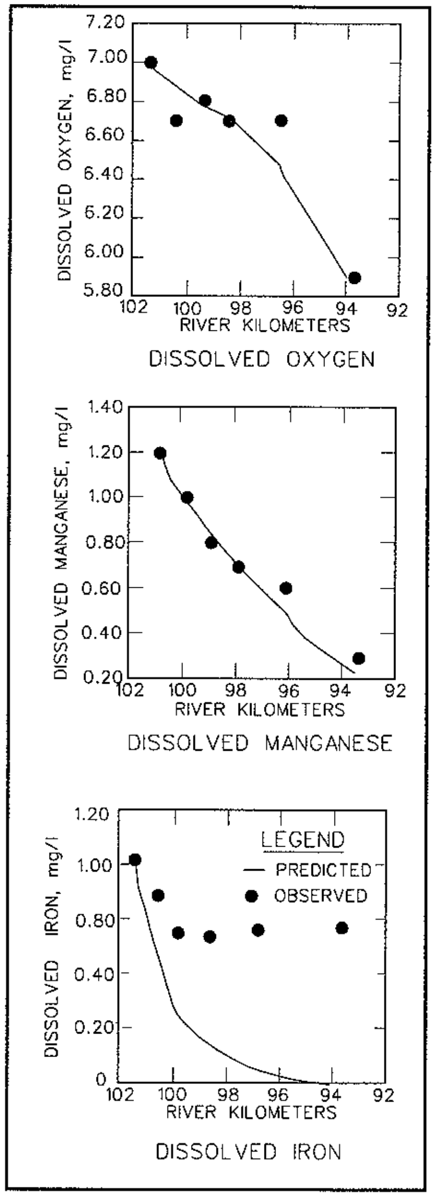

Figure 5. Predicted and observed DO, Mn^{2+}, and Fe^{+2}, Nimrod Reservoir tailwater (concentrations in milligrams per liter)

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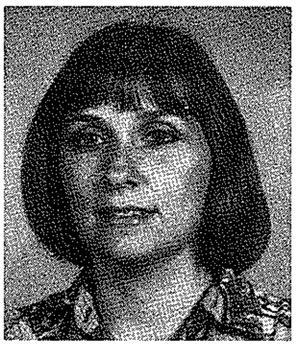

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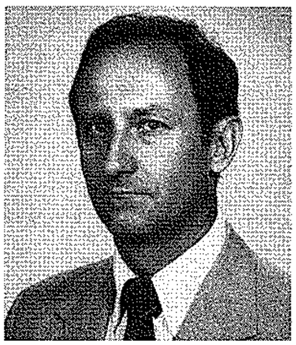
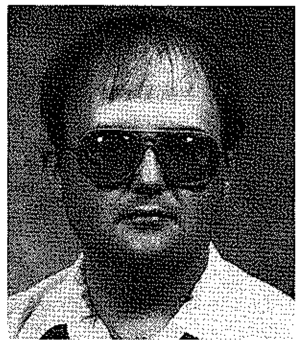


Dr. Mark S. Dortch is a supervisory research hydraulic engineer and Chief of the Water Quality and Contaminant Modeling Branch, Environmental Laboratory, Waterways Experiment Station. His PhD is in civil engineering from Colorado State University. The WQCMB is responsible for developing, maintaining, and applying numerical water quality and contaminant transport/fate models for surface water and groundwater.



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St. Paul District hosts NCD Water Quality Workshop

The tenth North Central Division (NCD) Water Quality Workshop was held on July 21-23, 1992 at Hudson, Wisconsin. The purpose of the workshop was to promote coordination among water quality specialists within the districts, as part of the NCD Water Quality Management Program. The workshop was hosted by the St. Paul District and included participants from the Buffalo, Chicago, Detroit, Rock Island, and St. Paul Districts, NCD, Corps Headquarters, and the U.S. Army Engineer Waterways Experiment Station (WES).

District presentations at the workshop highlighted the diversity of environmental engineering projects and activities being conducted by water quality personnel within NCD. These included automated water quality monitoring at water control projects, modeling of dredged material plumes from riverbank disposal operations, closure plans for lead-contaminated soil discovered at a reservoir construction site, and pilot-scale demonstrations of treatment technologies for contaminated sediments.

Ann Strong and Karen Myers of WES gave presentations on quality assurance (QA) and quality control (QC) in water quality data acquisition. The workshop participants identified QA/QC for non-HTRW (nonhazardous, toxic, and radiological waste) data acquisition as an area where the Corps is in need of guidance and training for the field. NCD (Jan Miller) agreed to work with WES and U.S. Environmental Protection Agency Region 5 to develop a basic QA/QC training workshop for district water quality personnel in FY 1993.

The workshop participants visited the Eau Galle Reservoir in Spring Valley, Wisconsin. The Eau Galle Reservoir has been used extensively for water quality and limnological research by WES, in conjunction with the St. Paul District. Bill James of WES provided a briefing on ongoing research and a tour of the laboratory.

The NCD Water Quality Workshop is held every other year. The Detroit District will host the next workshop, tentatively scheduled for July 1994.

Aerial photo taken of Eau Galle Reservoir. This reservoir has been the site of extensive water quality studies since 1980. Studies have focused on algae control, and have been supported by the Environmental and Water Quality Operational Studies, Water Quality, WOTS, and Aquatic Plant Control Research programs and by the St. Paul District

Committee on Water Quality meeting held

The Corps' Committee on Water Quality met in Nashville, Tennessee, October 19-21, 1992. Members from Headquarters, all eleven divisions, and the U.S. Army Engineer Waterways Experiment Station attended. This meeting marked the beginning of a new activity for the committee; it will now serve as a critical review team for all district/division water quality programs. Water quality chiefs from all four Ohio River Division districts attended the meeting and briefed the committee on the scope of their programs. At all future committee meetings, the host division's districts will be expected to attend for the same purpose.

The committee is currently involved in revising old guidance and preparing new guidance. Engineer Regulations 1130-2-415 and 1130-2-334 are being combined into one regulation that will cover data collection, application, interpretation, and reporting of program activities. The revision is currently in a near final draft phase and should be ready for Headquarters review early next year. New guidance is being written concerning environmental engineering initiatives for water management. A first draft of an Engineer Technical Letter and an outline for an Engineer Manual have been prepared by a work group of district personnel.

The next committee meeting is planned for the spring and will be hosted by North Central Division (NCD). Specific topics to be addressed at that meeting are a performance-based numeric reporting system, standardized division annual water quality reports, and review of NCD water quality programs.

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WATER QUALITY RESEARCH PROGRAM

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