SIMULATIONS FOR DESIGN OF OXYGEN INJECTION SYSTEMS IN RESERVOIRS

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ABSTRACT

Tools for designing aeration systems are improving as reservoir applications become more complex. TVA is currently using bubble plume models, CE-QUAL-W2 reservoir water quality model, and specialized CE-QUAL-W2 inputs to simulate injection of oxygen into reservoirs with porous hose line diffusers. Two-dimensional reservoir-wide effects of the oxygen injection are then evaluated to help size, locate, and develop operational plans for oxygen system installation. This paper will describe design tools and applications at reservoirs in the eastern United States.

INTRODUCTION

The Tennessee Valley Authority's Lake Improvement Program (1991-1996) was responsible for improving dissolved oxygen (DO) and minimum flow conditions in over 300 miles of TVA hydropower tailwaters (Brock and Adams, 1997). Line diffusers using oxygen were employed for DO enhancement at six of sixteen TVA reservoirs that were improved. Line diffuser systems have also been installed to meet re-licensing requirements at Duke Energy's Buzzard Roost Hydroelectric Station, and a preliminary line diffuser design has been submitted for re-licensing of Northeast Utilities' Shepaug Dam. Other design efforts or assessments are underway for J. Percy Priest (USACE Nashville District), J. Strom Thurmond and Richard B. Russell (USACE Savannah District), Brownlee (Idaho Power), and several TVA reservoirs (Tims Ford, Hiwassee, Normandy). As line diffuser objectives have expanded beyond just release improvement (e.g., for maintaining fish habitat, iron and manganese control), design efforts have been supplemented with diffuser and reservoir modeling. This paper describes a modeling system based on CE-QUAL-W2 for predicting line diffuser effectiveness over a range of reservoir operations for optimal design of line diffusers.

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LINE DIFFUSER

A reservoir forebay line diffuser system distributes gas bubbles in the reservoir upstream of the turbine intakes to increase DO in water withdrawn by hydropower operations (Figure 1). The diffuser is supplied with compressed air or oxygen from a supply facility on shore. Pure oxygen is usually preferred over air to avoid potential total dissolved gas problems in the tailrace. The smaller, deeper, and more disperse the bubbles, the more oxygen is transferred to the water. Line diffusers aerate with minimal disruption of temperature destratification and sediments by spreading gas bubbles over a large area of the reservoir.

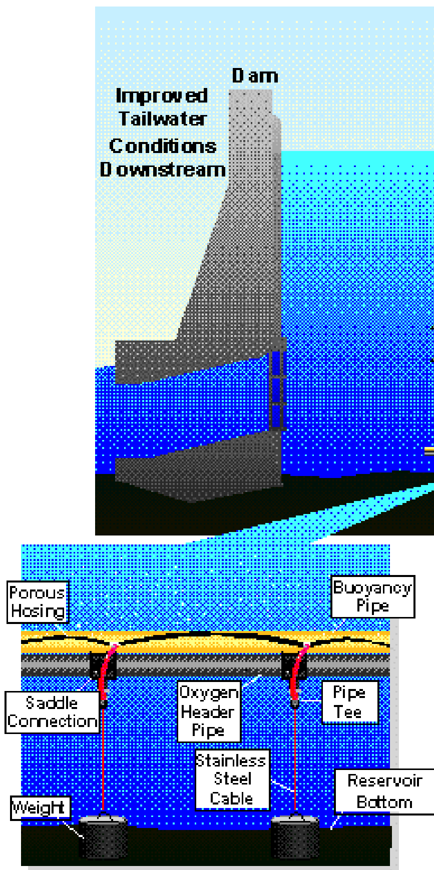

Figure 1. Schematic of Line Diffuser and Turbine Withdrawal

Porous hose runs the entire length of the diffuser, which can sometime extend for miles up the reservoir thalweg. Small, dispersed bubbles and hydrostatic pressure in the reservoir contribute to high oxygen transfer efficiency of the line diffuser, which reduces the oxygen needed and the size of the delivery system, controlling operating and capital costs of the system. The line diffuser is constructed of readily available materials and is deployed without the use of divers for economical installation and maintenance. Mobley, et al. (2000) describes line diffuser history and design in more detail.

MODELING TOOLS

To be effective, placement of the diffusers and distribution of the oxygen input must be optimized for site-specific water quality and water flow conditions. Most TVA applications involved consistent water flows, deep intakes, and the single objective of release DO enhancement – all of these conditions were highly suited to line diffuser oxygenation. Line diffusers have typically been oriented longitudinally in the old river channel, but they can be arranged in any configuration for special purposes. A forebay diffuser system can be designed to continuously aerate a large volume in the reservoir to handle daily volumes associated with peaking hydro turbine flows, or it can be designed with capacity to handle instantaneous peak discharges. New applications require aeration at any location or elevation in a reservoir for specific habitat, such as in layers with good temperatures for certain fish species. Aeration at the proper location in a reservoir can eliminate hydrogen sulfide, iron, and manganese in water supply withdrawals or prevent release of these compounds during hydrogeneration. Highly intermittent hydropower applications have created a need for a baseload oxygen rate combined with intermittent generation load oxygen rate. This increasing complexity in diffuser designs has led to mathematical modeling to predict diffuser performance in the context of dynamic reservoir conditions; models now are used to help optimize size, placement, and operation of the line diffuser. New pre- and post-processors can reduce the time and cost of using sophisticated models in the design of demanding diffuser applications. Modeling tools in current use are described in the following sections.

CE-QUAL-W2 Model

CE-QUAL-W2, or simply W2, is a two-dimensional, laterally-averaged hydrodynamic and water quality model developed by the U.S. Army Corps of Engineers (Cole and Buchak, 1995). Longitudinal and vertical water quality gradients are determined across a computational grid by solving the equations of water mass and momentum conservation and mass transport with detailed kinetics for each modeled constituent. W2 applications typically include 10 to 25 water quality constituents, including temperature, DO, algae, nutrients, dissolved and particulate organic matter, ammonium, suspended solids, and related variables. W2 is a flexible, well-documented hydrodynamic and water quality model used extensively throughout the U.S. and internationally. The model is well-suited for the hourly transients and circulations associated with hydropower. W2 has been successfully employed to model effects of oxygen input for porous hose line diffuser designs in four reservoir applications, after model calibration to local field data. Characteristics of modeled reservoirs varied from deep, storage reservoirs to run-of-river reservoirs to small water supply reservoirs, demonstrating the utility of W2 across a range of reservoir types and flow conditions.

Plume Model

Wuest et al. (1992) developed a plume model based on a momentum balance applicable for both oxygenation and destratification applications. The model accounts for changes in density and buoyancy of the plume according to entrainment of ambient water, temperature and salinity of the entrained water, and the change in gas volume. The model accounts for bubble volume and buoyancy changes due to mass transfer (nitrogen and oxygen) into and out of the bubble in response to changes in hydrostatic pressure and temperature. The plume model includes eight constituents resulting in eight nonlinear differential equations that are solved numerically until plume water velocity becomes zero or the plume reaches the lake surface. The fall back depth is the depth where water density matches the final plume density (with no bubbles present).

Discrete Bubble Model

McGinnis and Little (2000, in preparation) developed a discrete bubble model in a modification of the mass transfer equations used in the plume model. The model predicts oxygen and nitrogen transfer across the bubble based on initial bubble volume at the diffuser plus temperature, velocity, and dissolved gas profiles from the plume model. Using fundamental principles, the model tracks a single bubble rising through a water column, while accounting for changes in bubble volume due to mass transfer, temperature, and hydrostatic pressure changes. The model is useful for determining the location of nitrogen and oxygen dissolution in the reservoir, as well as stripping. The model has been verified using data collected in the lab with reasonably good results (McGinnis and Little, 2000, in preparation).

The plume and bubble models were used to predict the vertical distribution of oxygen mass loading created by the porous hose line diffuser under average water column conditions representative of the low DO season. This vertical distribution was input into W2 using a pre-processor tool, as described in the next section.

W2 Pre-Processor for Line Diffuser Oxygen Injection

A pre-processor tool was developed for W2 to provide a flexible and convenient means for representing a line diffuser's time-varying oxygen mass injection at various locations or elevations in a reservoir. This tool builds necessary files for W2's "tributary" input feature for user-specified injections of wastewater, tributary inflow, oxygen, heat, or other W2 constituents into any model grid cell or cells. To avoid disruption of the water mass balance, the diffuser's oxygen mass loading was introduced as a very small, time-varying flow with a very high constant DO concentration. A neutrally buoyant temperature was assumed. To simulate line diffusers that spanned several model columns, each of the columns received a share of the loading, in proportion to column length. Oxygen loading was input into each cell of a column according to the vertical distribution from the discrete bubble model, which was executed separately from W2. This injection method neglected upwelling momentum and mixing associated with a real diffuser plume as it interacts with ambient water. However, the line diffuser produces minimal upwelling. This injection method also lacked a feedback mechanism whereby variables that affect mass transfer in the plume model were dynamically based on W2 results. However, line diffusers operate during seasonal low DO periods with stable thermal stratification. Overall, assumptions for predicting diffuser behavior with W2 were considered reasonable.

W2 Post-Processor for Analysis of Results

W2 outputs were analyzed using the Animation and Graphics Portfolio Manager (AGPM-2D). This W2 post-processor includes options for plotting animations, profiles, time-series, dam releases, and time-depth profiles for W2 modeled constituents.

MODEL APPLICATIONS IN DIFFUSER DESIGN

The modeling system described above is being used to compare diffuser alternatives in a variety of diffuser applications, including hydropower releases, fish habitat creation, and treatment of water supply reservoirs. Figure 2 shows results of an example application to evaluate alternative diffuser elevations for the J. Strom Thurmond project, where the objective was to create fish habitat zones by oxygenating certain layers in the water column that contained suitable temperatures. Diffusers positioned at higher elevations were better able to aerate critical temperature layers, but loss of efficiency resulted due to less depth for oxygen transfer from the bubbles. These results and those of other applications will be provided in more detail during presentation of this paper.

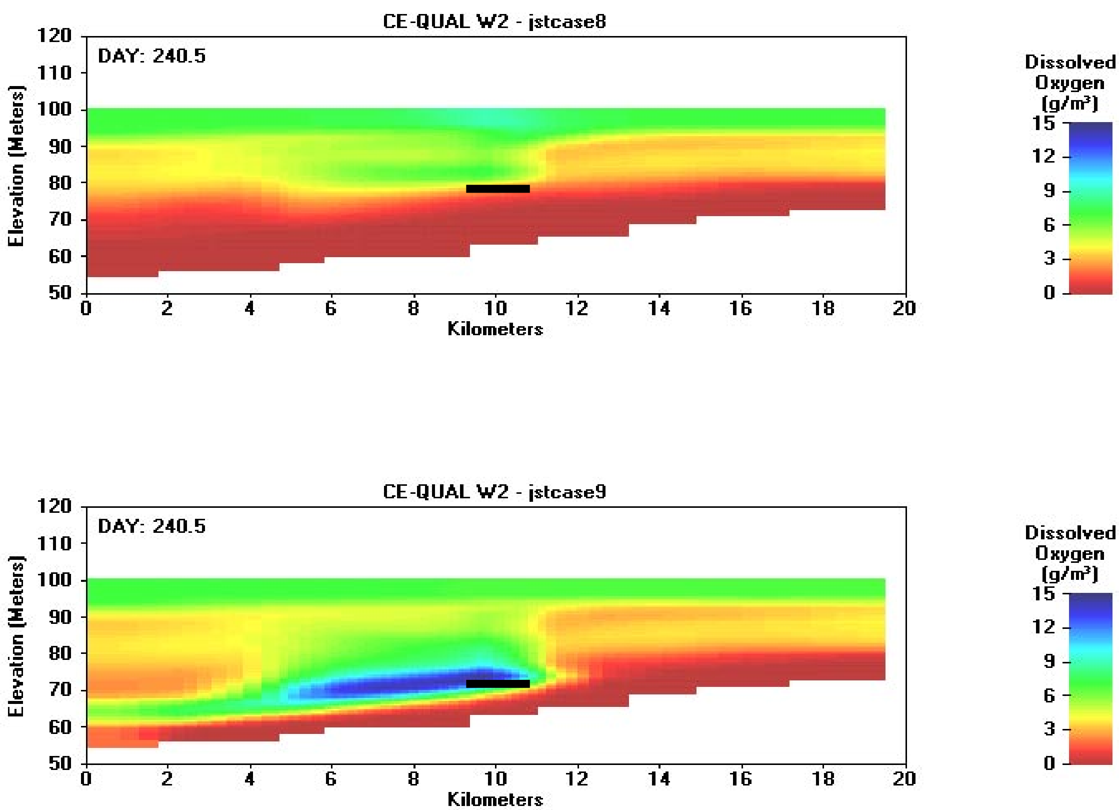

Figure 2. DO Patterns With Diffuser at Different Elevations - Thurmond Reservoir

CONCLUSIONS

Modeling tools that are evolving offer effective improvements over previous diffuser design techniques because they allow assessment of 1) effects of a full dynamic range of reservoir operations on the diffuser plume behavior; and 2) effects of time-varying diffuser injections on far-field reservoir and release water quality. These models will continue to be used for increasingly complex diffuser applications, and development efforts will improve accuracy and scientific rigor of the modeling tools. For example, upwelling produced by the plume is not felt by the reservoir model with the current decoupled modeling tools. Although adequate for the low upwelling induced by line diffusers, current linkages are limited for high gas flux situations. Also, existing tools do not satisfactorily incorporate temporal changes in stratification and ambient DO into diffuser predictions. New collaborative efforts between TVA, Virginia Tech, and other scientists involved in bubble plume prediction are providing opportunities for improved coupling of near-field plume models with the CE-QUAL-W2 far-field reservoir model.

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