Diffuser System Modeling and Design for Dissolved Oxygen Enhancement of Reservoirs and Releases

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ABSTRACT

In support of the Tennessee Valley Authority's Lake Improvement Program, a line diffuser system was developed that was applied and proven effective at six TVA hydropower projects. To be effective, the 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 were relatively straightforward designs with consistent water flows, deep intakes, and the single objective of release DO enhancement. While line diffuser applications have typically been oriented longitudinally in the old river channel, 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. 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 hydro generation. Highly intermittent hydropower applications have created a need for a base load oxygen rate combined with intermittent generation load oxygen rate. New applications often require aeration at specific locations in a reservoir to meet fish habitat or oxygen demand requirements. Such increasing complexity in diffuser designs has led to increased use of mathematical modeling to predict diffuser performance in the context of dynamic reservoir conditions. Models are now used to help optimize size, placement, and operation of the line diffuser. New pre- and post-processors are available that reduce the time and cost of using sophisticated models in the design of demanding diffuser applications. This paper describes the line diffuser design and several modeling applications. Results from operational line diffuser systems and model predictions for systems currently under design are presented.

INTRODUCTION

Need for DO Enhancement

In many reservoirs, solar heating creates a stable temperature stratification during the summer months when warm surface water floats over the colder deep water referred to as the hypolimnion. Oxygen demands in the water column and sediments continue to consume dissolved oxygen (DO) as the temperature (density) stratification acts to seal off the hypolimnion from most oxygen sources (surface gas exchange, wind mixing, algae photosynthesis). Depending on water flows, temperature, and strength of oxygen demands, hypolimnetic DO can become depleted. If the DO levels are driven low enough, anoxic products like hydrogen sulfide, dissolved iron, and manganese can reach high levels in the water nearest the sediments. If this water is then withdrawn through hydropower intakes, low DO water and anoxic products are released downstream. The water quality of reservoir releases is a recognized issue for many hydropower projects, and many FERC licenses now include dissolved oxygen mitigation requirements for such releases.

Enhancement Alternatives

Each reservoir and hydropower project has site-specific characteristics that impact both the need for and the means to improve reservoir releases. Each project should be evaluated for site-specific requirements and the best alternative or combination of alternatives then applied. In 1997, TVA completed the Lake Improvement Plan, a five-year program to improve

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minimum flow and dissolved oxygen levels at 16 hydropower projects (Brock and Adams, 1997). Several new and innovative aeration alternatives were developed and applied over the course of the program, including six applications of the line diffuser. The TVA program included 8 applications of turbine venting, 2 of forced air into the turbines using blowers, 2 of surface water pumps, 2 of downstream aerating weirs, and 1 application of auto-venting replacement turbines. Several projects required combinations of as many as three alternatives to meet target aeration levels. This paper focuses on line diffuser applications for TVA and other utilities.

LINE DIFFUSER

Diffuser Concept

A reservoir diffuser distributes gas bubbles in the reservoir upstream of the turbine intakes to increase dissolved oxygen in the water that will be withdrawn by hydropower operations, as shown in Figure 1. The diffuser systems are 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. High oxygen transfer efficiency reduces the amount of gas and the size of the delivery system required to meet DO targets. To be effective, the placement of the diffusers and distribution of the oxygen input must be suitable for site-specific water quality and water flow conditions.

Oxygenation within the reservoir can be an economical means to meet DO requirements for hydropower releases. The purchase of liquid oxygen is expensive, but other aeration alternatives may not be applicable at a specific hydropower site or may be insufficient to meet DO requirements. Oxygen diffuser systems are well suited for use as a topping off system to augment other less expensive aeration systems that are unable to achieve the water quality objectives alone. Oxygenation within the reservoir can accomplish DO requirements without causing adverse effects on turbine generation, and is usually the only alternative that has the potential to eliminate anoxic products and DO demands that may cause water quality problems (e.g., a DO “sag ” or decrease) in the releases.

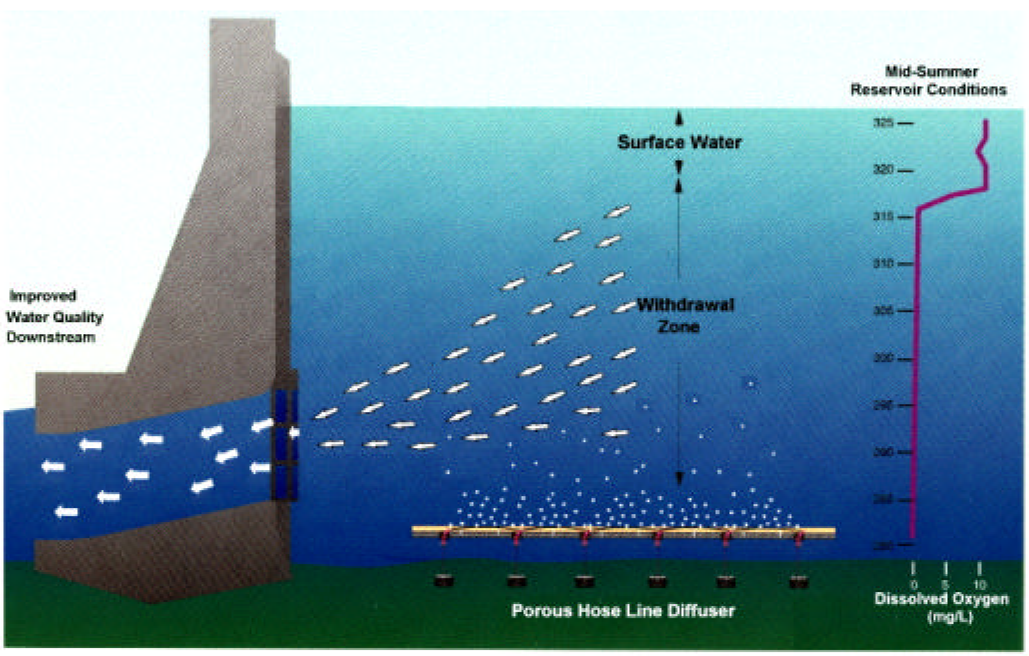

Figure 1: Schematic View of Reservoir Diffuser and Turbine Withdrawal

Line Diffuser Description

The line diffuser is constructed of readily available materials and is deployed without the use of divers so that installation costs are economical. Porous hose runs the entire length of the diffuser, distributing the oxygen in small bubbles over as large an area as possible. The small, dispersed bubbles and hydrostatic pressure in the reservoir contribute to the high oxygen transfer efficiency obtained by the line diffuser, which controls operating costs of the system. A section of a line diffuser is shown in Figure 2.

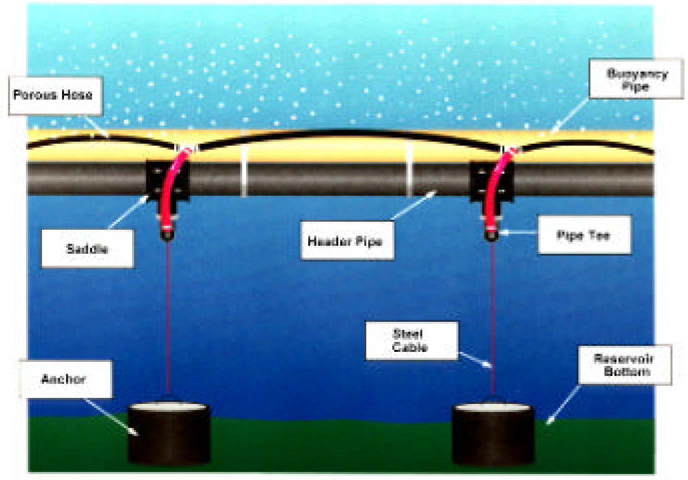

Figure 2: Schematic View of Line Diffuser Section

Line Diffuser Usage

The line diffuser design has been installed, and operated successfully at eleven projects. It has proven to be an efficient and economical aeration diffuser design that transfers oxygen efficiently, and minimizes temperature destratification and sediment disruption by spreading the gas bubbles over a very large area in the reservoir. The line diffusers are installed from the surface, as shown in Figure 3, and can be retrieved for any required maintenance without the use of divers. A forebay diffuser system can be designed to continuously aerate a large volume in the reservoir to handle peaking hydro turbine flows.

Figure 3: Line Diffuser Deployment Without Divers

The development of the line diffuser design is described in more detail in a related paper in the HydroVision conference (Mobley, 2000). Most of the TVA applications were relatively straightforward designs with consistent water flows, deep intakes, and the single objective of DO enhancement in the releases. Figure 4 shows the line diffuser application results at TVA's Blue Ridge Reservoir.

Increasingly complex objectives for diffuser applications have led to more use of mathematical modeling to predict bubble plume performance and reservoir conditions. New tools have been developed to enable economical use of hydrodynamic and water quality models and the incorporation of plume models in the design of these more complex diffuser applications. The next sections describe the reservoir water quality model and the tools that have been applied to aid the more recent diffuser designs.

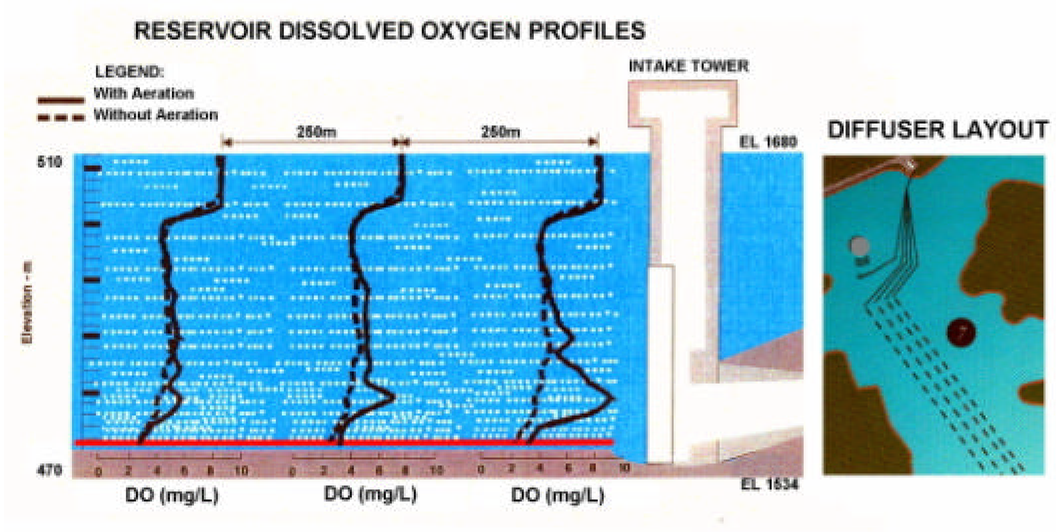

Figure 4: Blue Ridge Diffuser Layout and Results

CE-QUAL-W2 RESERVOIR WATER QUALITY MODEL

W2 Model Description

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 the mass transport equation with detailed kinetics for each modeled constituent. W2 applications typically involve 15 to 25 water quality state variables, including temperature, dissolved oxygen, algae, nutrients, dissolved and particulate organic matter, ammonium, suspended solids, and related variables. In the 1990s, CE-QUAL-W2 and the powerful post-processing software that has been developed for it have evolved into a solid performer for reservoir water quality modeling on desktop computers.

W2 Model Usage

W2 has been used extensively throughout the US and internationally to simulate reservoir hydrodynamics and water quality for improved management of reservoirs. It is a flexible, well-documented water quality model that is especially suited for the hourly transients and hydrodynamics associated with hydropower.

OXYGEN TRANSFER MODELING – DIFFUSER PLUME

Plume Model Description

This effort utilized a plume model developed by Wuest et al. (1992), which is based on a momentum balance applicable for both oxygenation and destratification applications. The model accounts for the change in density and therefore buoyancy of the plume due to the entrainment of ambient water, the temperature and salinity of the entrained water, and the change in the volume of gas bubbles. The model accounts for bubble volume changes and the effect on buoyancy by incorporating 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. Using an appropriate time step, these equations are solved numerically until the plume water velocity becomes zero, or the plume reaches the lake surface. The fall back depth is the density of water at a given depth that matches the final density in the plume (with no bubbles present).

Discrete Bubble Model Description

The discrete bubble model is a modification of the mass transfer equations used in the plume model (McGinnis and Little, in preparation). The model predicts oxygen and nitrogen transfer into and out of the bubble based on knowledge of the initial bubble volume formed at the diffuser and the plume conditions predicted by the plume model. These conditions include: temperature, velocity, and dissolved gas profiles. Using fundamental principles, the model tracks a single bubble rising through the water column while accounting for changes in the 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 good results.

Model Usage

The plume and bubble models were used to predict oxygen transfer based on an applied oxygen flow rate and the initial bubble size distribution created by the porous hose line diffuser. This resulted in a vertical distribution of oxygen mass loading that was subsequently input into W2 using the pre-processor tool described in the next section.

TOOLS FOR USING W2 FOR SIMULATION OF LINE DIFFUSER OXYGEN INPUT

Pre-processor Tool Description

A pre-processor tool was developed for W2 to provide a flexible and convenient means for simulating a line diffuser's time-varying oxygen injection into multiple grid cells of a W2 model (Loginetics, 1999). This tool made use of the W2 "tributary" input feature that enables wastewater discharges or tributary inflows into the main reservoir. In W2, a "tributary inflow" is an injection of flow and concentration of any W2 constituent (including temperature) into a model column (vertical stack of cells). To avoid disruption of the water mass balance, the diffuser's oxygen mass loading was introduced into the reservoir as a time-varying, low flow with a large DO concentration and a neutrally buoyant temperature. Mass input was divided among cells in a column of the model according to a vertical distribution predicted by the discrete bubble model.

Pre-processor Usage

Figure 5 shows how the pre-processor was used to distribute injections into a vertical stack of cells as a percentage of the total mass input for each column. Each column selected for injection received a part of the total mass in proportion to the column length (upstream to downstream). Each cell was handled by the pre-processor as a separate "tributary" for W2 so injections could be spread over multiple, non-contiguous cells. Oxygen loading was input into each cell of a column according to a vertical distribution from the discrete bubble model (executed separately from W2). This arrangement neglected the upwelling momentum and resultant mixing that would be produced

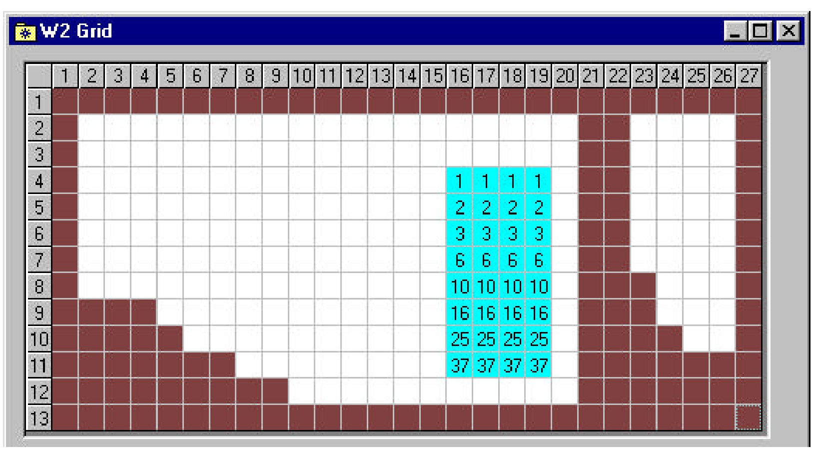

Figure 5: Cells and Distribution for Oxygen Diffuser Input – Shepaug Reservoir

by a real diffuser plume as it interacts with ambient water. However, upwelling has been shown to be minimal due to the sparse distribution of bubbles produced by the line diffuser. Since the vertical oxygen input distribution is quantified in a plume model apart from W2, this method further assumes unchanging vertical profiles of variables that affect mass transfer in the plume model. However, the diffusers are typically used only during the low DO period after stratification develops and before overturn is experienced. Thus, these assumptions are considered reasonable for approximating the plume behavior.

W2 Post-Processor for Analysis of Results

Output from W2 was analyzed using the Animation and Graphics Portfolio Manager (AGPM-2D) (Loginetics, 1999). This W2 post-processor includes options for plotting animations, profiles, time-series, dam releases, and time-depth profiles for W2 modeled constituents.

HYDROPOWER DIFFUSER DESIGN

Shepaug Dam - Connecticut Light and Power

A small reservoir with hydro turbine operations that are intermittent over each week required hydrodynamic modeling to predict the movement of the oxygen input at this proposed application to meet Federal Energy Regulatory Commission (FERC) requirements. The single 43-MW hydro turbine at this project is often operated only every third or fourth day during the summer. The 74,000 acre-feet reservoir does not supply much storage and hydropower operations have strong effects on reservoir conditions. The objective of the proposed oxygen diffuser system is to provide 3 mg/L uptake in releases to meet FERC re-licensing requirements. Placement and operation of the diffusers was modeled using W2 with oxygen inputs to determine the best diffuser location and oxygen input schedule to meet requirements. Figure 6 shows the effect of diffuser location on high flow events that tended to move low DO water into the mid-level intakes.

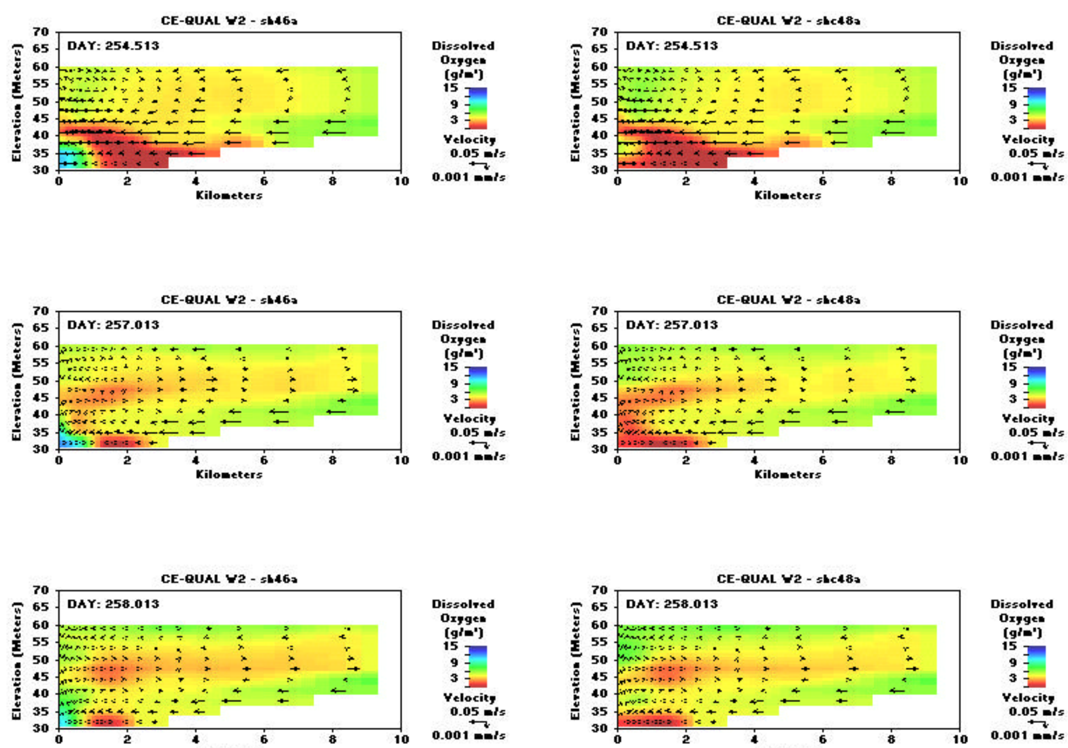

Figure 6: Shepaug Forebay and Reservoir

J. Percy Priest - U.S. Army Corps of Engineers, Nashville District
Infrequent hydropower operation during the summer months leads to build-up of high oxygen demands in the reservoir. A diffuser system to improve release DO must handle the oxygen demands and high turbine flows to be effective. For this proposed design, diffusers were strategically placed deep in the forebay to meet the oxygen demands of the incoming water from the reservoir during turbine operations, as shown in Figure 7. Additional diffusers were placed higher in elevation nearer the turbine intakes to place oxygen directly in the turbine withdrawal zone. The extent of the spread of oxygen inputs from the diffusers during non-turbine operation was of interest and was modeled using CE-QUAL-W2.

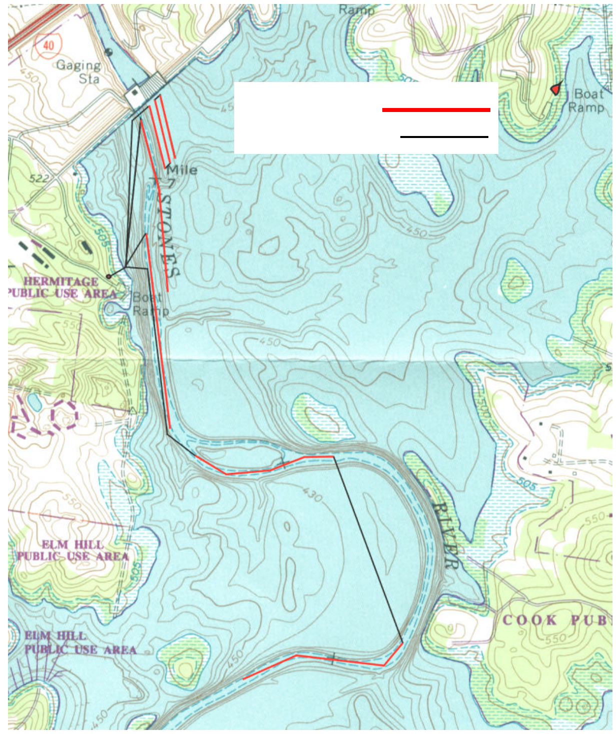

Figure 7: Proposed Line Diffuser Layout at J. Percy Priest

FISH HABITAT/HYDROPOWER DIFFUSER DESIGN

J. Strom Thurmond - U.S. Army Corps of Engineers, Savannah District
A reservoir oxygen diffuser system has been proposed as a means to meet the dual objectives of fish habitat creation in the reservoir and DO improvements in the releases of J. Strom Thurmond Hydro. The dual objectives have justified the extensive use of hydrodynamic modeling to predict reservoir responses. The proposed diffuser location is almost 10 km upstream of the dam to create a 5-mile stretch of water between 18° and 24°C, maintained at 4 to 5 mg/L. Model results from a typical test case are shown in Figure 8. A DO improvement of 3 mg/L is predicted for the releases from the dam.

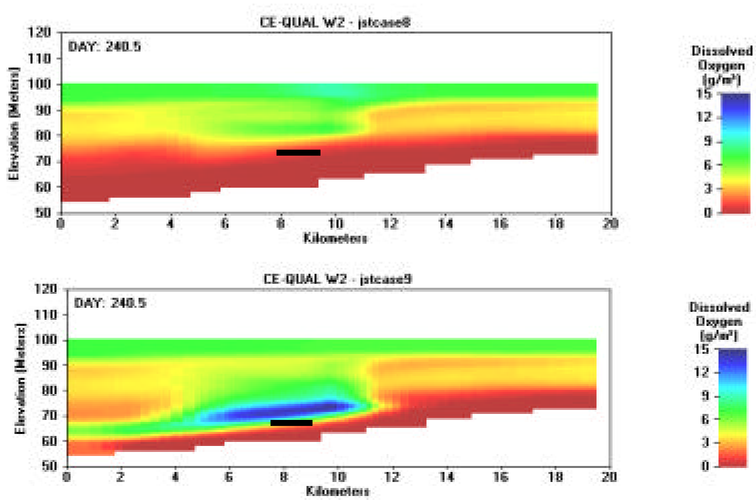

Figure 8: DO Predictions for Different Diffuser Elevations at J. Strom Thurmond

WATER SUPPLY DIFFUSER DESIGN

Spring Hollow Reservoir – Roanoke County Utility District
Spring Hollow Reservoir is a side-storage reservoir located in Roanoke County, Virginia. Construction and filling were completed in June 1996. Hypolimnetic DO levels approach zero in mid-October causing the resolubilization of iron and manganese and the release of phosporus from the sediments. This leads to algal blooms and manganese problems when the

reservoir turns over in mid-December to early January. The line diffuser, using air, is operated on an as-needed basis, typically as DO levels approach 2 mg/L, and early enough towards destratification to allow the precipitation of manganese. Examples of W2 predictions (solid lines) versus field measurements (circles) for Spring Hollow are shown in Figure 9.

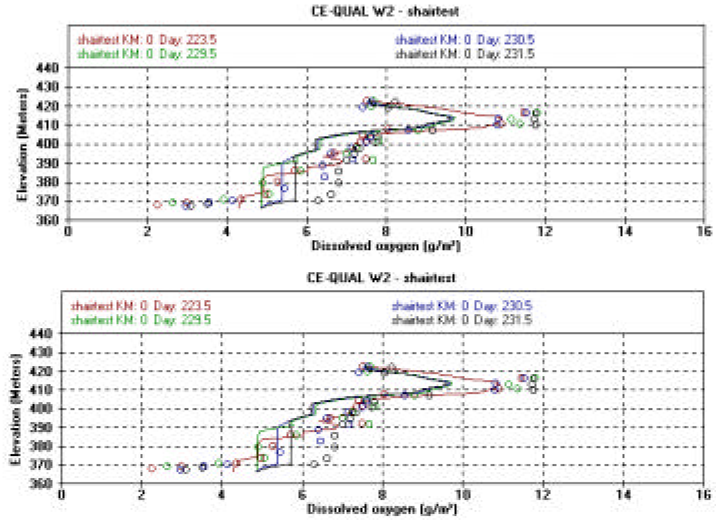

Figure 9: Spring Hollow W2 and Plume Model Verification

Upper San Leandro Reservoir- East Bay Municipal Utility District

Upper San Leandro is a side-storage water supply reservoir operated by East Bay Municipal Utility District located in Oakland, CA. The reservoir experiences problematic blue-green algal booms which cause taste and odor problems. The purpose of the proposed line diffuser system is to maintain aerated conditions in the hypolimnion during the summer stratification period, thereby preventing the release of phosphorus from the sediments. The proposed system is 9,000 feet of line diffuser capable of delivering 6.6 tons/day. The extent of the oxygen input over time was of interest and predicted using W2.

CONCLUSION

W2 has been employed to model the effects of oxygen input from the porous hose line diffuser design in six reservoirs: Spring Hollow (VA) and Upper San Leandro (CA) are side-storage drinking water reservoirs, while Blue Ridge (GA), Shepaug (CT), J. Percy Priest (TN), and J. Strom Thurmond (SC-GA) are all hydropower reservoirs. The characteristics of these reservoirs vary from deep, storage reservoirs to run-of-river reservoirs, demonstrating the utility of the modeling across a wide range of reservoir types and flow conditions. The modeling is limited due to the lack of coupling between W2 and the buoyancy and momentum input by the diffuser plume. Future collaborative efforts are underway to develop a coupled model.

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