Application of a Reservoir Oxygen Diffuser System to Meet Dissolved Oxygen Requirements at the Tillery Hydroelectric Plant, North Carolina.

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Abstract

The Yadkin-Pee Dee Hydroelectric Project located in piedmont North Carolina is currently undergoing FERC relicensing. The hydroelectric project is owned by Progress Energy Carolinas, Inc. and consists of the Tillery and Blewett Falls Developments, which provide 109 MW of peaking and load-following generation capacity. As specified in the North Carolina Water Quality Certificate requirements for the Tillery Development, Progress Energy was required to meet state water quality dissolved oxygen (DO) standards in the generation releases and minimum flows from the power plant's reservoir. Progress Energy tested several DO enhancement technologies over a 5-year period to meet the required DO standards. Technologies tested included turbine venting, reservoir surface mixers, compressed air turbine aeration, compressed air bubble diffusers, and selective withdrawal of reservoir surface waters. Achieving limited success with the evaluated technologies, Progress Energy pursued a reservoir oxygen diffuser system to bring the Tillery Plant releases into DO compliance. A preliminary modeling study using historical plant operation and environmental data over a 5-year period evaluated the

feasibility of the reservoir oxygen diffuser system. The entire system was designed, permitted, and installed in an eight month period. The system includes four 3,500 ft. oxygen diffuser lines deployed in the hydro reservoir; a land-based liquid oxygen facility to convert liquid oxygen to gaseous oxygen; and a Programmable Logic Control System which interfaces system operation with power plant generation. Field trials of the system conducted during August 2011 verified the system met design specifications under varying generation levels and provided the desired DO compliance target level of 5 mg/L. While turbine venting capability at the Tillery Plant is limited, it can be used supplementary to reduce the amount of oxygen used. Minimum flows can be aerated using surface releases through a crest gate.

Introduction

Progress Energy Carolinas, Inc. (PEC) is currently relicensing the Yadkin-Pee Dee Hydroelectric Project with the Federal Energy Regulatory Commission (FERC Project No. 2206). The Project consists of the Tillery and Blewett Falls hydroelectric developments and provides 109 MW of peaking and load-following generation capacity. Relicensing proceedings for the Project occurred from 2003 to 2008 and included filing of a license application with FERC in April 2006 and a 401 Water Quality Certificate (WQC) application with the North Carolina Division of Water Quality (NC DWQ) in May 2007 (Progress Energy 2006a, 2007). The FERC issued the Final Environmental Impact Statement for the Project during April 2008 (FERC 2008). The new license is still pending FERC review and approval, and currently the Project is operated under an annual, renewable license subject to the same terms and conditions as the original 1958 license.

During relicensing proceedings, seasonally low dissolved oxygen (DO) levels in the Project tailwaters was identified as an environmental condition to address in the new license term. Water quality studies by Progress Energy and the NC DWQ showed that, on occasion, DO levels were below the state water quality standards (i.e., instantaneous DO standard of 4 mg/L and a daily average of 5 mg/L) when the Tillery and Blewett Falls hydroelectric plants were generating. Portions of the Pee Dee River tailwaters below each power plant have been listed by the NC DWQ as impaired due to low DO conditions under the Clean Water Act 303(d) listing (NC DWQ 2012). Besides hydropower generation events, the DO levels in the Project tailwaters are seasonally influenced by aquatic plant photosynthesis and respiration cycles and inflow of low DO water from tributaries (Progress Energy 2005, 2006b, 2010, 2011).

In its 401 WQC application to NC DWQ, Progress Energy outlined a DO Enhancement Plan to systematically test different equipment technologies and determine what option would provide the best engineering and operations and maintenance solution. The NC DWQ issued the 401 WQC during February 2008 which was subsequently amended and reissued during September 2008 (NC DWQ 2008). The 401 WQC outlined requirements for PEC to meet the state DO water quality standards including a schedule of implementing the most technologically feasible solution by the end of 2011.

The objectives of this paper are to: (1) outline the technical evaluation process that PEC undertook to select the appropriate DO enhancement technology for the Tillery Plant—a reservoir oxygen diffuser system; (2) present predictive modeling and empirical field data regarding the testing of the installed reservoir oxygen diffuser system; and (3) provide information regarding the economic costs of constructing and the expected operating costs of the diffuser system.

Project Site Description

The Yadkin-Pee Dee Hydroelectric Project was constructed in the early 1900s. Blewett Falls was placed in operation in 1912, and the Tillery Development began operation in 1928 (Progress Energy 2006a). The Project's primary purpose is for load-following and on-peak generation. The original license for the Project was issued in 1958.

The Tillery Powerhouse is a concrete, indoor-outdoor structure containing four generating units, each with a dedicated penstock and head gate, and Moody-type draft tubes (Progress Energy 2006a). The power plant consists of four generating units; three vertical Francis units (Units 1-3) installed in 1928 and one vertical fixed blade unit (Unit 4) installed in 1962. Each turbine drives a direct-connected vertical-shaft generator. The generators for Units 1, 2, and 3 are Allis-Chalmers three-phase, 60-cycle units. Units 1 and 3 are rated at 22 MW (4,456 cfs) while Unit 2 is rated at 18 MW (3,627 cfs). Unit 4 is a Westinghouse three-phase, 60-cycle generator rated at 22 MW (5,145 cfs). Total generating capacity of the hydroelectric plant is 84 MW at about 18,000 cfs with a gross head of 72 ft. The turbine flow exits directly to the Pee Dee River. The powerhouse is integral with the dam which is a 1,550 ft of concrete gravity structure. The spillway at the Tillery Dam is controlled by 18 radial gates.

The Tillery Hydroelectric Development is located on the Yadkin-Pee Dee River in the central Piedmont region of North Carolina (Figure 1). The Tillery Development began operation in 1928 and is located at about mile 218 on the Pee Dee River. The Blewett Falls Development is located approximately 30 miles downstream of Tillery. Lake Tillery is the hydroelectric development's reservoir, and it has a normal pool elevation of 278.2[1] feet above mean sea level. Lake Tillery extends approximately 15 miles upstream to the tailrace of Aloca, Inc.'s Falls

[1]1929 National Geodetic Vertical Datum (NGVD 29).

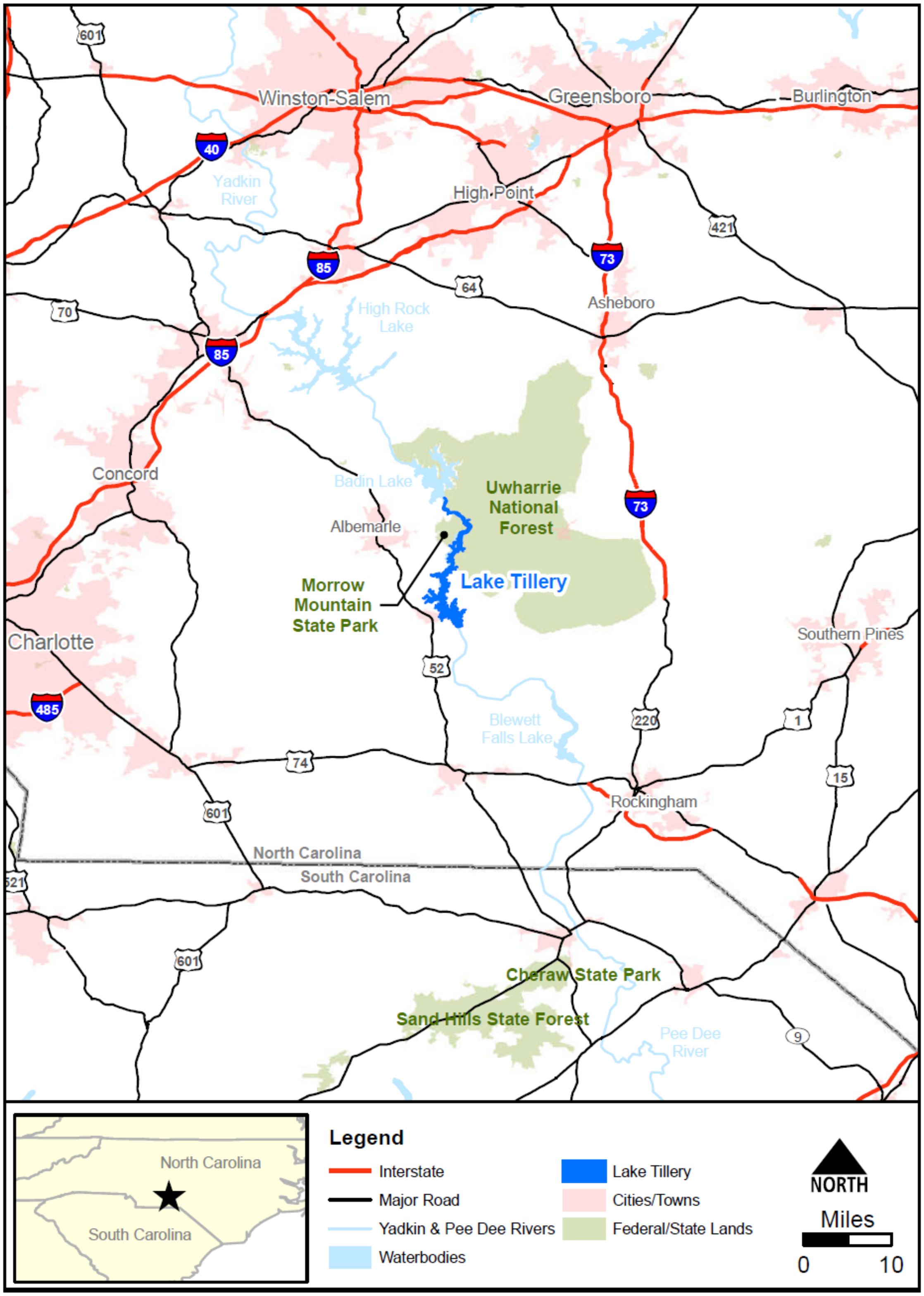

Figure 1. Yadkin-Pee Dee Hydroelectric Project, Tillery Development.

Hydroelectric Development powerhouse. The lake is dendritic in shape and has approximately 118 miles of shoreline with a surface area of 5,697 acres.

Lake Tillery is a warmwater, moderately productive reservoir, with moderate amounts of nutrients and ions. The lake has an average hydraulic retention time of 8.3 days. Water clarity of the lake is periodically influenced by precipitation-related events associated with tributary input and upstream contributions of sediment from the Yadkin River (Progress Energy 2006c). Generally, seasonal lake thermal stratification and DO deficits in the hypolimnion occur from May through October, depending upon annual climatic factors, river basin inflow, and power generation levels. The NC DWQ has classified the lake as fully supporting its designated primary uses of recreation, swimming, and water supply (NCDENR 2010).

Selection of Dissolved Oxygen Enhancement Technology

PEC undertook an extensive testing program at the Project from 2005 to 2010 to evaluate several DO enhancement technologies at both the Tillery and Blewett Falls developments. The following technologies were evaluated:

- **Turbine Aeration with Passive Air Admission (Tillery and Blewett Falls Plants)**–The units' vacuum breaker or draft tube vents were used for the air admission during field tests. Initially, the Tillery Plant tests were performed without baffle plates and then baffle plates were installed in the draft tubes to increase the passive air flow (DTA 2007, 2008; ARCADIS 2010a, 2010b).
- **Turbine Aeration with Forced Air Injection (Tillery Plant)**–The air inlet locations for the forced air field tests included the vacuum breaker, draft tube vents, and through a nose cone ring that was fabricated for these tests and installed at the top of the draft tube (DTA 2008; HDR-

DTA 2009; ARCADIS 2010a, 2010b). An air compressor delivered the forced air injection. A desktop engineering feasibility study also evaluated the potential of high volume air blowers in providing turbine aeration (ARCADIS 2010c).

● **Selective Surface Water Withdrawal (Tillery Plant)**–These field tests involved blocking off the lower section of the intake trash rack of Unit 1 with canvas tarps (ARCADIS 2010a). Tests were performed with the lower 20 and the lower 40 feet of the trash rack blocked off. A follow-up feasibility modeling study was conducted evaluating a flexible curtain weir that would be located in the intake forebay area (ARCADIS 2010d).

● **Surface Water Mixing (Tillery and Blewett Falls Plants)**–These field tests included testing an array of four smaller impellers and testing a single large impeller mounted on a pontoon boat platform (DTA 2008; HDR-DTA 2009).

● **Compressed Air Bubble Diffusers (Tillery and Blewett Falls Plants)**–These field tests involved placing two diffuser racks in front of the turbine intake trash racks. During unit operation, compressed air was provided to the diffusers to aerate the water flowing into the power plants' turbines (DTA 2008; ARCADIS 2010a). A test was also performed with a diffuser installed in the Blewett Falls tailrace (HDR-DTA 2009).

● **Surface Water Mixers Operating in Combination with Draft Tube Vent Passive Air Admission (Tillery and Blewett Falls Plants)**—Various field test combinations of surface water mixing and passive air admission with turbine venting were conducted at different unit generation settings (DTA 2008; HDR-DTA 2009).

● **Compressed Air Bubble Diffusers at the Intake Structure in Combination with Draft Tube Passive Air Admission (Tillery Plant)**—Various field tests of both technologies operated in tandem were conducted at different unit generation settings (DTA 2008; HDR-DTA 2009; ARCADIS 2010a).

● **Reservoir Oxygen Diffuser System (Tillery Plant)**—A desktop engineering feasibility study for the Tillery Plant was conducted during 2010 using historical plant operating and environmental data (Mobley et al. 2010).

The DO enhancement technology selected at the Blewett Falls Development was direct venting through the existing draft tubes (ARCADIS 2010b; Progress Energy 2012). The units are a horizontal, quad-runner configuration. The power plant design and head differential provided sufficient air uptake to increase DO levels by 1-2 mg/L to meet the state DO water quality standards. New vents were installed on draft tubes in 2010 and the system underwent successful trial testing in 2011 (Progress Energy 2012). Generation losses were less than a 0.5 MW for all units in a venting mode.

At the Tillery Development, there were challenges in meeting the DO water quality standards. Water quality studies showed a 2.5-3.0 mg/L DO deficit that had to be overcome to meet the standards during the peak reservoir hypolimnetic stratification period during late July through August (Progress Energy 2005, 2006b, 2010, 2011). Testing with draft tube venting indicated about a DO increase of about 0.6 to 1.4 mg/L, with Unit 2 showing the lowest DO uptake performance in this regard (ARCADIS 2010a, 2010b; Ruane et al. 2011). Unit 4 venting provided a substantially higher DO update at about 2.7 mg/L, but only at lower power outputs less than 13 MW, which would constrain the unit generation output and affect peaking power capacity. It was apparent from these tests that draft venting as a sole DO enhancement means would not be sufficient at the Tillery Plant. Other tested technologies (forced air injection, surface mixers, air bubble diffusers, and selective withdrawal with intake curtain weir) were rejected either based on the inability to solely provide sufficient DO uptake; costs to install and operate; or an unproven industry track record to meet the DO standards. The only option that appeared feasible was the use of a liquid oxygen diffuser system. Diffuser systems have been used successfully at 15 other hydroelectric facilities and 14 water supply reservoirs for the 20 past years to improve DO and other water quality parameters (Mobley Engineering, Inc. 2012). Replacing the existing unit turbine runners with aerating technology was not considered because the units are well-maintained and in good operating condition.

Predictive Modeling for Reservoir Diffuser System Requirements

Model Assumptions and Parameters

PEC contracted with Mobley Engineering, Inc. (MEI), Norris, TN, to evaluate the feasibility of a reservoir oxygen diffuser system at the Tillery Development during the summer of 2010 (Mobley et al. 2010). MEI used a time-invariant model to determine the system size and expected annual operating cost requirements to meet the DO water quality standards based on plant generation patterns, project inflows and outflows, and annual DO hypolimnetic deficits. In addition, supplemental DO uptake using Units 1-3 draft tube venting was included in the model to help determine the liquid oxygen cost offsets of using venting in tandem with the diffuser system. Five years of hourly archival data (2005 and 2007-2010 data sets) were used to create input data for the model that included hourly power plant flow rates, head pond and tailwater elevations, influent reservoir DO levels, and plant power generation. This five year period encompassed an operational period with years of average precipitation and inflows as well as very wet and dry years. These data were then synchronized to the DO measured at the N.C. Highway 731 Bridge, the selected DO compliance point approximately 0.8 km downstream of the power plant. The bridge DO data were used to represent the influent DO to the turbines. In general, data from May 1 to October 31 were analyzed for these years. However, in 2008, the available data were from June 12 to October 15. In 2006, there were insufficient DO measurements to use for model input. For some months, there were several days for which archive DO measurements were not available. The oxygen usage for these months was scaled by the number of days for which data existed versus the number of days for which data did not exist to make the data consistent on a year-to-year basis.

An oxygen transfer efficiency (OTE) of 85% was used to compute the amount of oxygen that is dissolved in the intake forebay as a function of the total oxygen flow rate of the forebay diffusers. The primary mechanism for the 15% oxygen loss is that the oxygen is released through the water surface before it dissolves. As the oxygen is released in the intake forebay, both organic and inorganic components in the reservoir are oxidized and consume oxygen before it is drawn into the turbines. Two factors were used to represent these processes, which included an instantaneous oxygen demand (IOD) to model the short-term consumptive processes and a biological oxygen demand (BOD) to represent the longer term consumptive processes. Field sampling indicated the IOD was negligible (<0.5 mg/L) and therefore was not a factor that affected the oxygen requirements of the diffuser system.

The BOD, in conjunction with the OTE, was used to determine the quantity of oxygen that will be required to meet DO compliance. Typical operation of the reservoir forebay diffusers involves a continual maintenance flow of oxygen that maintains the forebay DO at a prescribed level. This ensures that there will be sufficient DO in the reservoir hypolimnion during the initial turbine releases at startup to meet compliance. Because the intake forebay diffuser maintains DO at higher levels, longer term processes consume some of the DO, which is represented by the BOD. The BOD was modeled by reducing the DO in the hourly flow rate by 0.5 mg/L.

The DO supplied by supplemental turbine venting aeration was provided by a discrete bubble model (DBM) that computed the airflow and DO uptake on a unit basis as a function of unit water flow rate and tailwater elevation. The DBM was calibrated to test data acquired during the preliminary turbine aeration and DO tests performed on August 2-5, 2011 (Ruane et al. 2011). The oxygen that is saved with turbine aeration, relative to providing it by intake forebay diffusers, is computed by multiplying the DO uptake for the given unit by the unit flow rate and then dividing by 0.85 to account for the OTE of the forebay diffusers.

The oxygen use for each time step, when the plant flow was larger than zero, was computed by assuming that the turbine draft tube aeration system provided the maximum oxygen it could provide and that the remaining oxygen was supplied by the intake forebay diffusers to meet a DO compliance target of 5.0 mg/L. The 5.0 mg/L target was chosen as the conservative target compliance level to ensure the diffuser system maintains DO levels to meet the instantaneous and daily average DO water quality standards. The model did not include an intake forebay or tailrace model to predict the time-variant production and consumption of DO. Therefore, the model did not account for the time delay required to oxygenate the forebay before the DO is available to the turbines. This may produce additional oxygen requirements not accounted for in this analysis. The impact of aquatic plant photosynthesis and respiration on DO dynamics in the tailrace, which would be included as part of a tailrace model, were also ignored.

Given these input data, the time invariant model predicted whether the DO compliance targets could be achieved and how to operate the reservoir diffuser system to achieve DO compliance. The model also provided a prediction of the quantity of oxygen required to meet the

DO compliance level. The model was set to provide a target DO compliance level of 5.0 mg/L at the proposed water quality compliance monitoring station.

The liquid oxygen cost was assumed to be $103/ton ($0.428/100 scf), and no energy or fuel transport surcharges were included in the cost analysis. No escalation factor was used in the liquid oxygen cost estimates. PEC negotiated a seven year contract with an oxygen supplier to provide the liquid oxygen and lease the land-based diffuser system equipment. The liquid oxygen cost used in the modeling was based on the negotiated contract pricing requirements.

Model Results

Modeling results indicated an oxygen diffuser maximum capacity of 150 tons/day was appropriate for continually meeting DO water quality standards during the expected six month compliance season (Figure 2; Mobley et al. 2010; Ruane et al. 2011). The modeling results also showed that the maximum oxygen flow rate from the reservoir oxygen diffuser system was required for only two years of operation (2005 and 2007) and for less than one percent of the operating time. Therefore, the system is adequately sized to meet the oxygen requirements for the target DO compliance levels.

The diffuser system is expected to meet the target compliance DO level of 5.0 mg/L. The only exception noted in the 5-year modeling occurred on August 30, 2005, when the DO fell to 4.1 mg/L. On this date, high flows in excess of 16,000 cfs occurred due to a tropical storm while the influent DO was less than 1.0 mg/L. A dam tainter gate spill flow of 4,500 cfs was provided in the model simulation which was required to achieve the instantaneous DO standard of 4.0 mg/L.

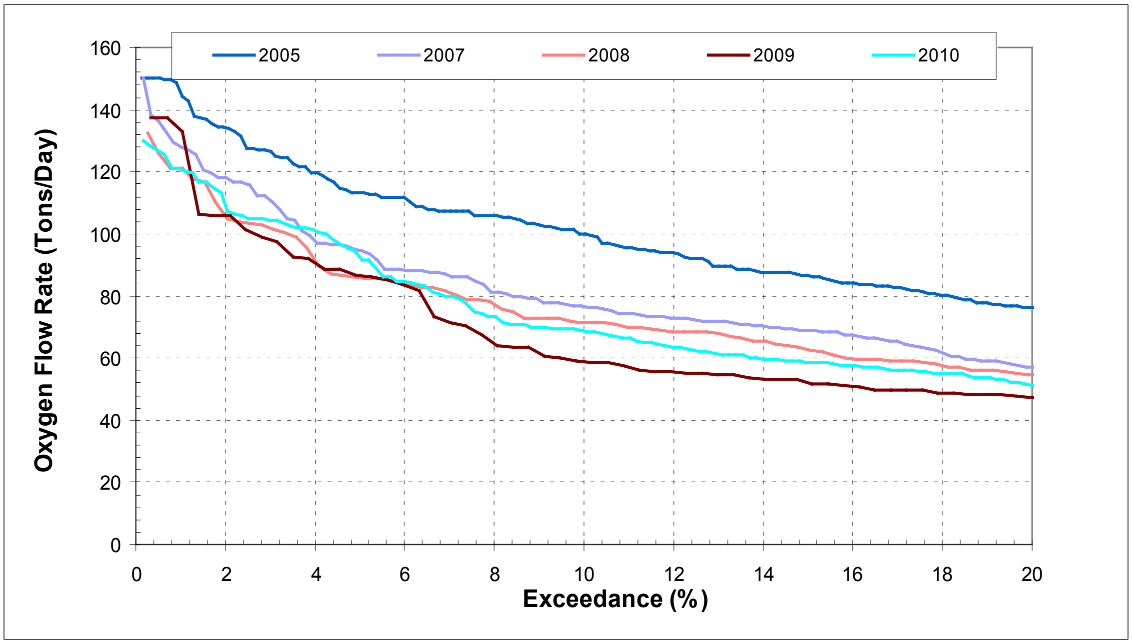

Figure 2. Exceedance plot of modeled diffuser system oxygen flow rate, 2005-2010.

The oxygen required to meet target levels for each day will vary depending on seasonal incoming water quality conditions and turbine operation (Figure 3). Oxygenation with the diffuser system will typically begin to be required around mid-June each year when supplemental draft tube venting as a sole means to meet DO requirements will be insufficient to meet the reservoir DO hypolimnetic deficit. The use of the diffuser system is expected to increase to a maximum by the end of July into late August and then taper off by the end of September with fall turnover and mixing of the reservoir water layers. Use of the diffuser system during May and October is expected to be minimal with supplemental draft tube venting providing most of the necessary aeration during these transitory periods. Turbine operations and oxygen usage are expected to vary hourly each day with power generation needs. Generally, the greatest amount of oxygen usage will be required during the afternoon and evening peak power demand hours.

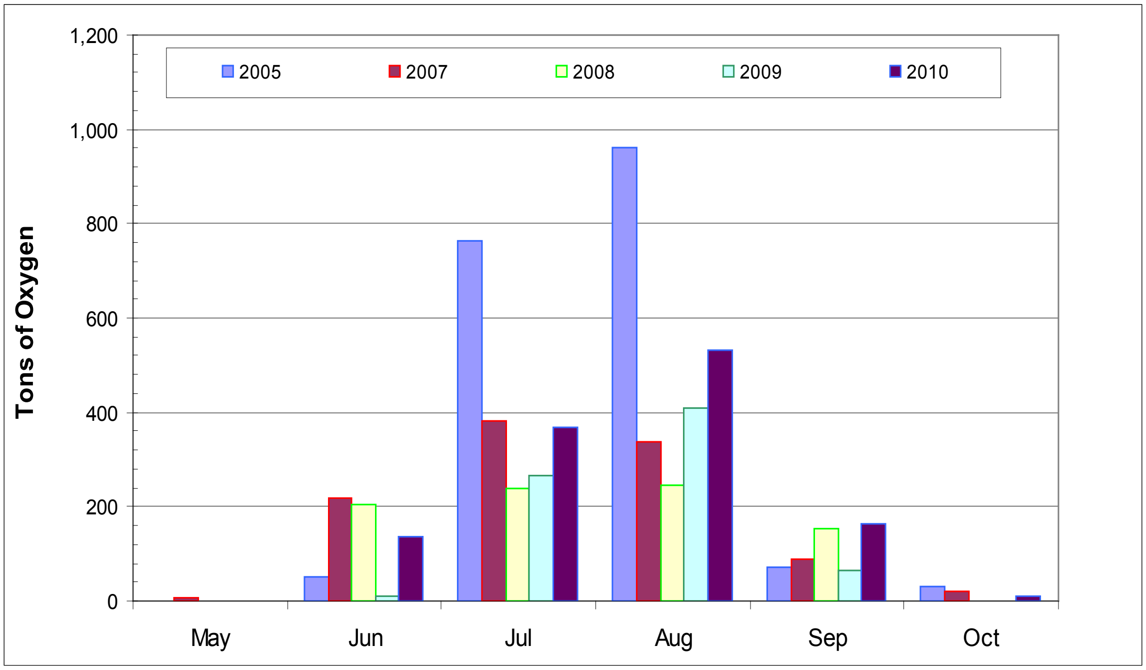

Figure 3. Monthly modeled oxygen requirements for the Tillery reservoir diffuser system, 2005-2010.

The amount of liquid oxygen that is predicted to be used by the diffuser system varied annually and ranged from 750 tons in 2009 to 1,880 tons in 2005 (Figure 4). The estimated annual operating costs for liquid oxygen ranged from $77,250 to $193,640 with a median estimated cost of $106,000. A challenge of operating the diffuser system will be to manage the annual O&M liquid oxygen costs depending upon annual environmental and plant generation conditions. The supplemental use of Units 1-3 draft tube venting will help reduce liquid oxygen usage and shoulder DO enhancement during the early and late season transition months of May and late September through October.

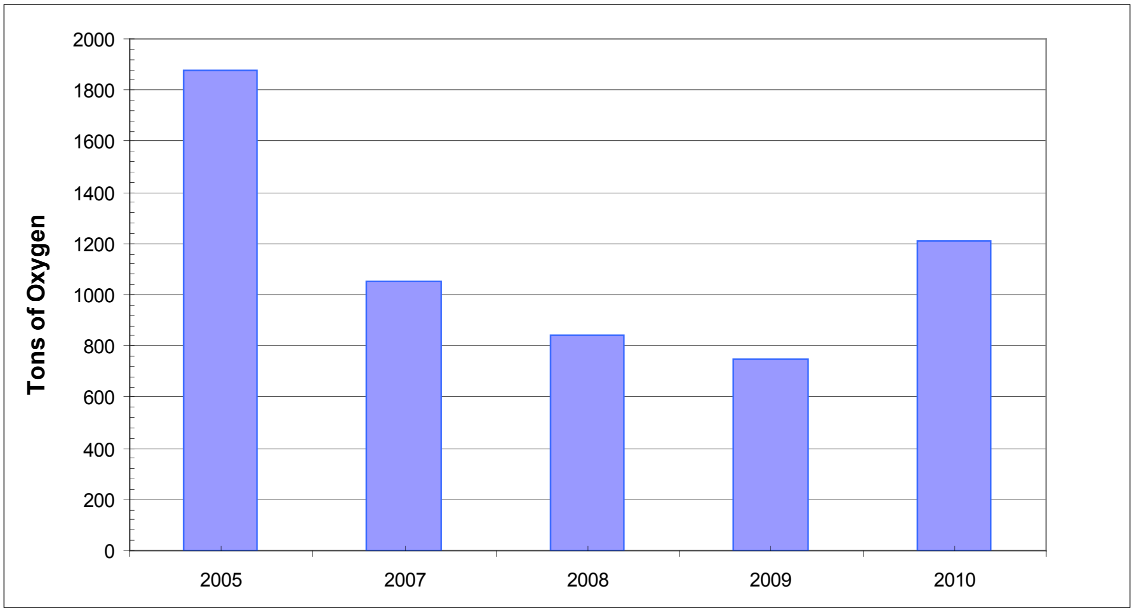

Figure 4. Annual modeled oxygen requirements of the Tillery reservoir diffuser system, 2005-2010.

Construction of the Reservoir Diffuser System

Construction of the reservoir diffuser system, including engineering planning and regulatory agency approval, took approximately eight months to complete. The reservoir oxygen diffuser system consists of three components: (1) a land-based liquid oxygen facility, (2) the diffuser lines for reservoir oxygen distribution, and (3) a Programmable Logic Control computer program system. Cost to construct the diffuser system was approximately $2.5M which included the liquid oxygen facility infrastructure, reservoir diffuser lines, computer programming software, and installation of DO compliance monitoring equipment.

The liquid oxygen facility has two 15,000 gallon horizontal storage tanks for liquid oxygen; four 26 ft vertical tower vaporizers to convert liquid oxygen to gaseous oxygen; and an oxygen flow control skid to regulate gaseous oxygen flow into the diffuser lines. The system maximum operating pressure is 125 psi. Liquid oxygen is delivered to the facility by tanker truck. The liquid oxygen facility equipment is leased from the vendor at a monthly lease fee and service maintenance fee. The PLC system regulates the amount of oxygen delivered by the diffuser system via oxygen flow controls based on the oxygen deficit in the reservoir water column and amount of flow with power generation.

The reservoir diffuser system consists of four 3,500 foot long diffuser lines upstream of the intake forebay supplied with gaseous oxygen from a liquid oxygen facility on the east shoreline of Lake Tillery. The diffuser system is designed to distribute oxygen almost from lake bank to bank for about a mile upstream of the dam. Each line diffuser is constructed of a 2 inch high-density polyethylene pipe that supplies oxygen to two 0.5-inch porous hoses (Figure 4). A four inch buoyancy pipe allows for deployment and retrieval of each diffuser line via compressed air introduction and venting. The diffuser hoses have an orifice at the point of connection to the supply pipe at 15-foot intervals to equalize the flow along the length of the diffuser and to minimize losses in the event of a hose break. The expected life span of the porous 0.5-inch diffuser hoses is 10 years. Each oxygen supply pipe line is connected to a 3 inch oxygen supply line that transitions from the land-based oxygen flow control skid into the reservoir. Concrete anchors attached to stainless steel cable are attached to each diffuser line at 15 foot intervals.

The diffuser lines were positioned in the submerged riverbed in front of the intake forebay oriented in an upstream direction and numbered 1-4 from the east shoreline outward, corresponding to the turbine unit designations. The lines are spaced apart approximately 125 ft. In order to provide flexibility in the vertical placement of oxygen in the reservoir depending upon DO seasonal deficits, the diffusers are installed at two elevations. Diffuser lines Nos. 1 and

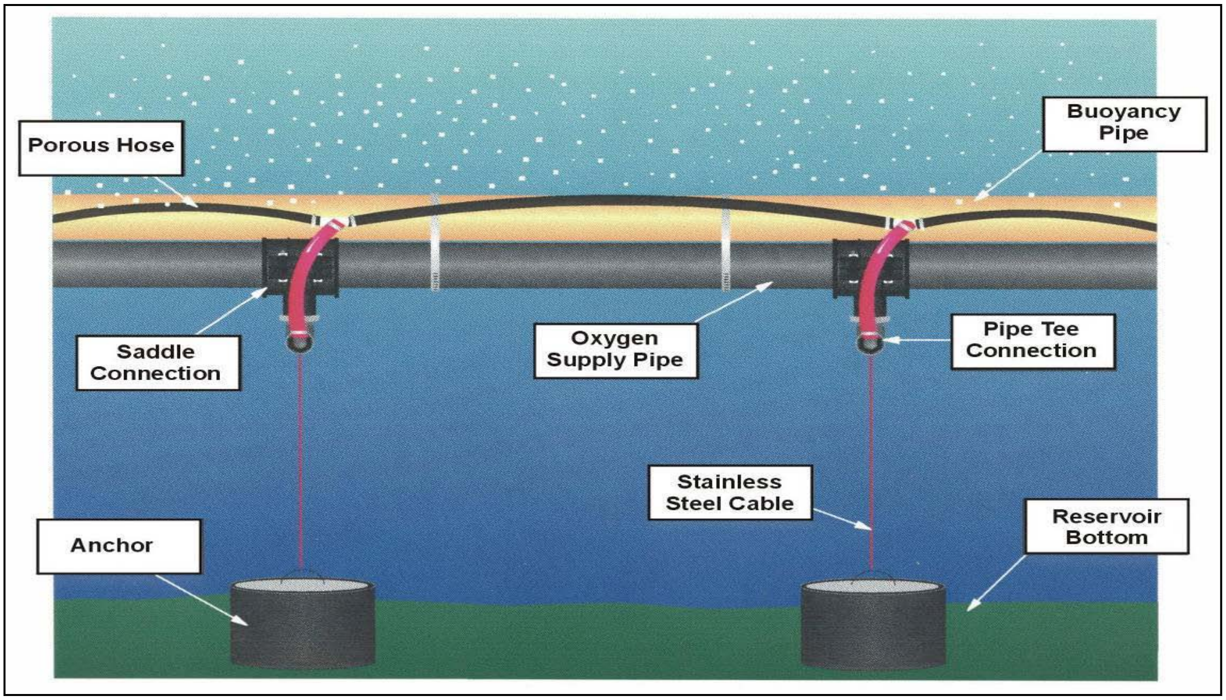

Figure 4. Schematic drawing of reservoir oxygen diffuser line.

4 are at elevation 224 ft (54 feet deep at nominal 278 ft normal lake elevation). Diffusers lines Nos. 2 and 3 are at elevation 212 ft (66 feet deep at nominal 278 ft normal lake elevation). Typically, one diffuser line will operate continuously at a pre-determined “maintenance” flow to ensure oxygenated conditions in the reservoir forebay with power plant generation startup. The additional lines will deliver oxygen after plant start-up depending upon the amount of flow with power generation. These additional lines will shut-down when the power plant ceases the generation event. Maintenance and generation oxygen flow rates are adjusted as needed, as each compliance season progresses, to achieve 5 mg/L target level in the tailrace during generation. Adjustment of the oxygen flow rates is based on the oxygen deficit in the reservoir hypolimnion. The diffuser system can operate in an auto or manual mode.

Trial Testing of the Reservoir Diffuser System and Supplement Draft Tube Venting

Trial testing of the diffuser system began during July and continued through mid September 2011. Systematic trials of the diffuser system were performed from August 8-12 to demonstrate the oxygenation capability of the system over a wide range of power plant operating conditions including number of operating units and generation loads (Ruane et al. 2011). These trials were performed in conjunction with tests using Units 1-4 draft tube/vacuum vents and the dam crest gate for minimum flows. In summary, the first day of testing involved acquiring forebay and tailrace DO measurements with no oxygen flow from the diffuser system and with turbine aeration turned off. For the second day of testing, the diffuser was operated while turbine draft tube aeration was off. For the following three days, various combinations of diffuser flow rates with turbine draft tube aeration from the generating units were tested.

Dissolved oxygen measurements for each individual generating unit were obtained in the tailrace using a boat to maneuver a DO probe directly into the outflow of the unit. Continuous recording DO probes were also deployed adjacent to the U.S. Geological Survey (USGS) compliance location on the N.C. Highway 731 Bridge pier, and in the west channel of the tailrace just below the dam (Figure 5). Water quality vertical profiles were taken at 17 locations along the installed diffuser lines in Lake Tillery. A Seabird Electronics SBE 19 plus high-resolution profiler (CTD) with optional SBE 43 dissolved oxygen sensor, having a response time of 1.4 seconds at 20°C, was used to collect conductivity, temperature, depth, and DO data at a 4 Hz sampling rate.

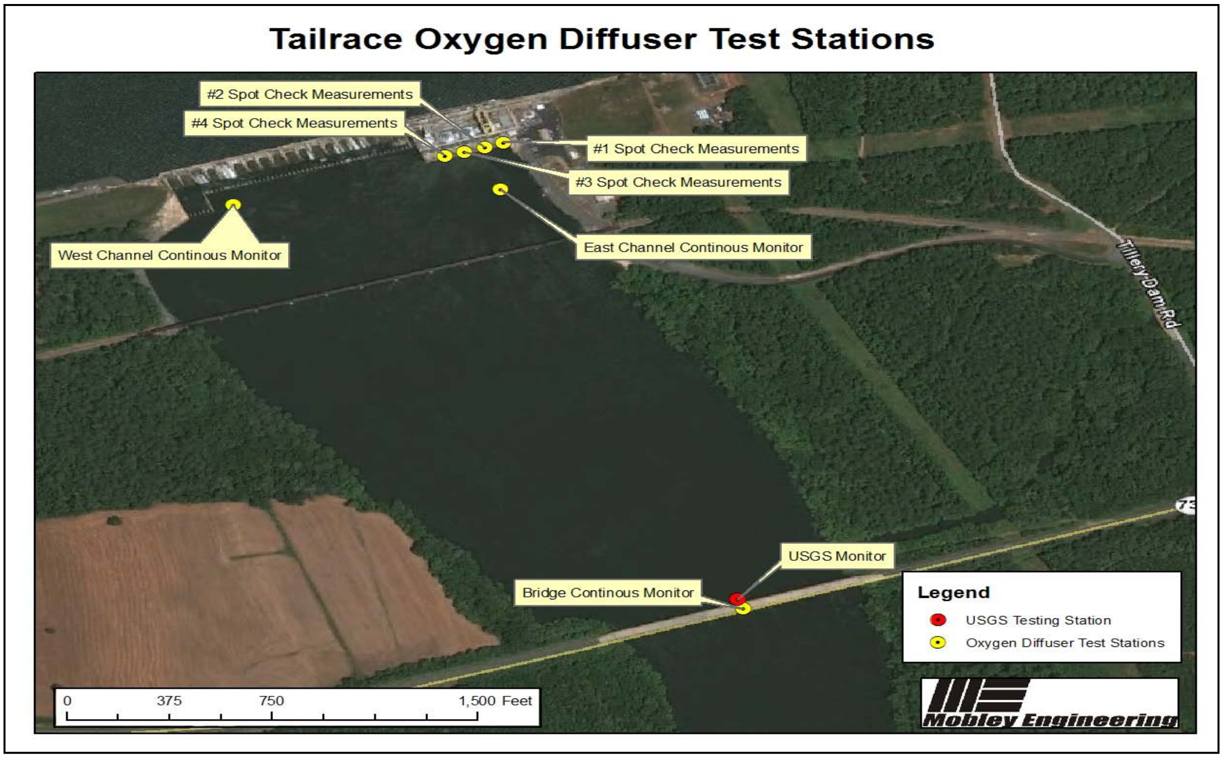

Figure 5. Tillery Hydroelectric Plant tailrace monitoring stations for oxygen diffuser tests.

Time series and contour plots demonstrate the DO enhancement that the oxygen diffuser system provided over the 5 day testing period in the tailrace and reservoir intake forebay (Figures 6-15). In addition to DO concentrations, these plots also show the total project and individual unit flow rates, and the oxygen flow rates for the diffuser system and results of DO aeration with minimum flow tests of the dam crest gate.

On August 8, Day 1 of the trials, the power plant turbines were operated on a normal operating schedule without oxygenation to provide background DO values in the reservoir intake forebay and tailrace (Figures 6 and 7). During the daytime period preceding power plant generation, photosynthesis from the large amount of aquatic plants in the tailrace produced an initial high DO concentration of 10.0 mg/L. With peak generation of all four units operating at approximately 17,000 cfs, the tailrace DO declined to a minimum of 2.8 mg/L which is below

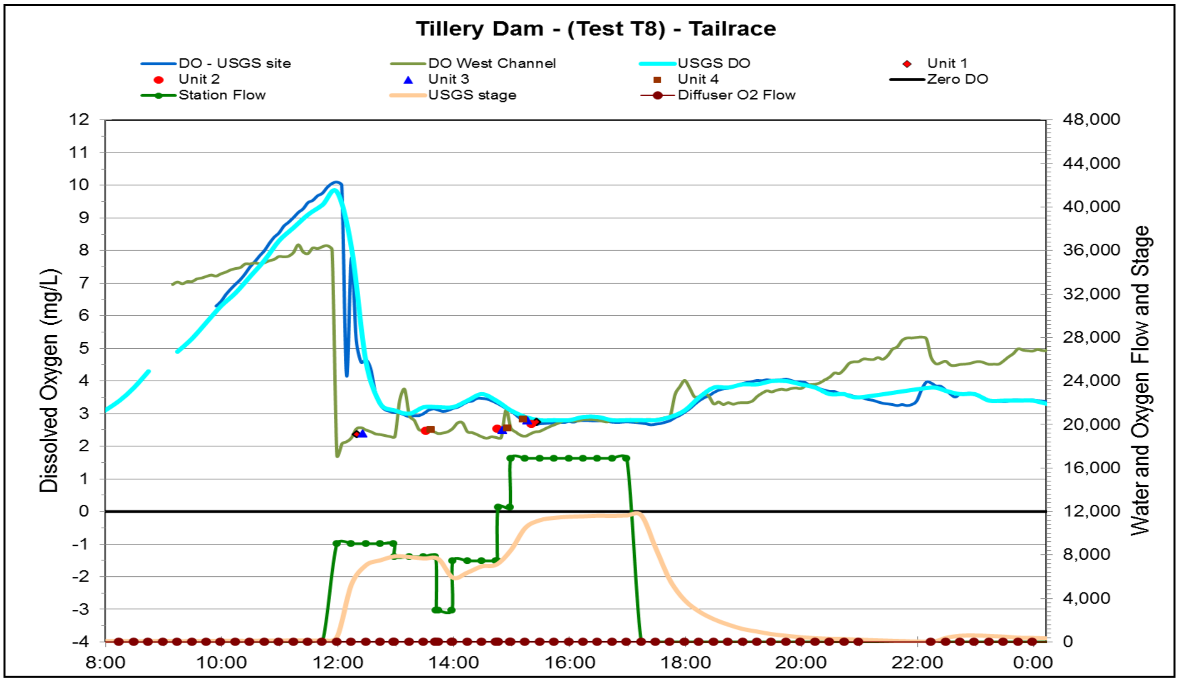

Figure 6. Unit turbine operations and tailrace DO measurements, August 8, 2011.

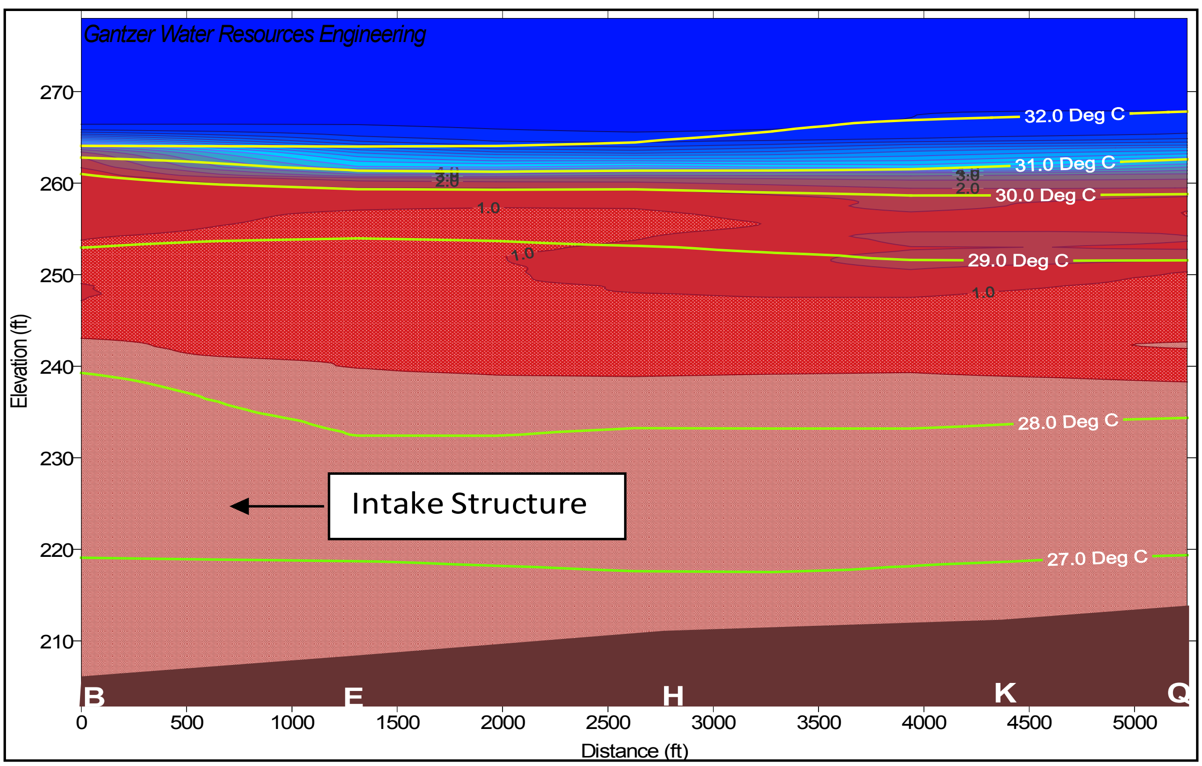

Figure 7. Longitudinal DO and temperature contours in the Tillery reservoir intake forebay, August 8, 2011 (Note red shading indicates low DO conditions while blue shading indicates higher DO conditions).

the instantaneous DO water quality standard of 4 mg/L. DO concentrations in the intake forebay at the depth of the water withdrawal were less than 2 mg/L and largely reflected anoxic conditions in this stratum of the water column (Figure 7).

On the Day 2 (August 9) of the trials, power plant turbines were scheduled to operate the same as on August 8. The oxygen diffuser system was operated with the start of the available generating units (Figures 8 and 9). The oxygen flow was set to provide approximately 2.4 mg/L of DO increase, based on the instantaneous water flow as calculated from the total unit power. The PLC automatically adjusted the total oxygen flow, as needed, and provided the desired flow rate and distribution of oxygen to the four diffusers in the reservoir in the order chosen by the operator. Since the reservoir forebay was not oxygenated at the initiation of hydro generation operations, the diffuser release of DO started out at levels similar to or lower than that measured

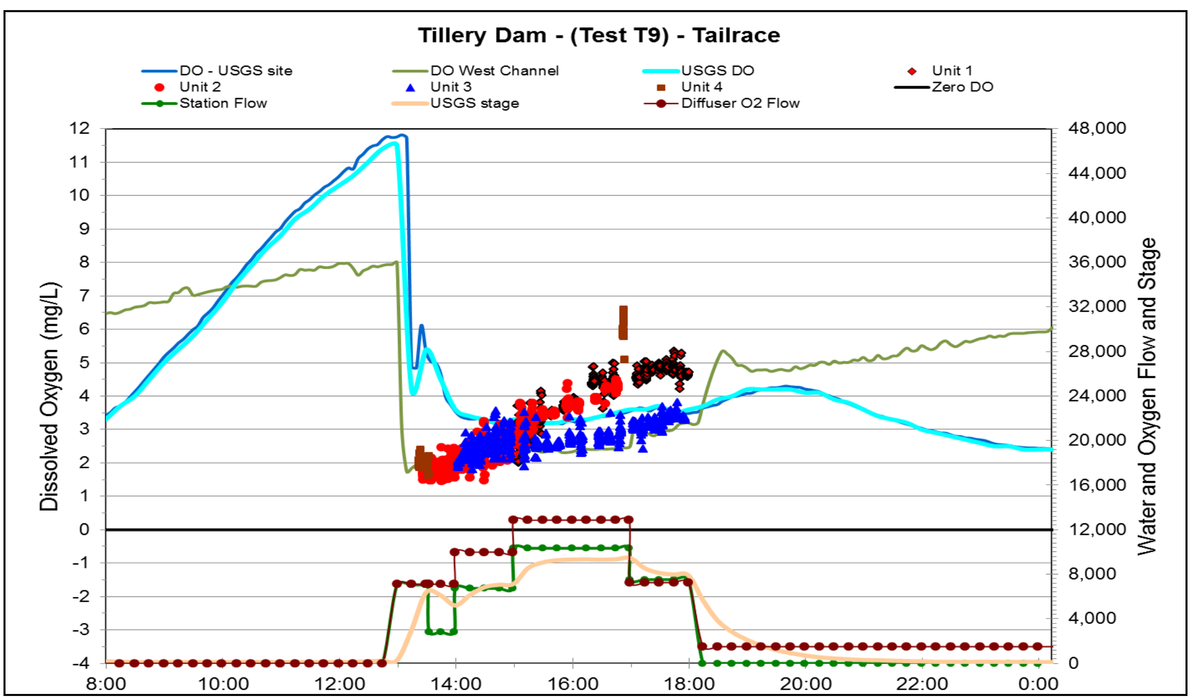

Figure 8. Unit turbine operations and tailrace DO measurements, August 9, 2011.

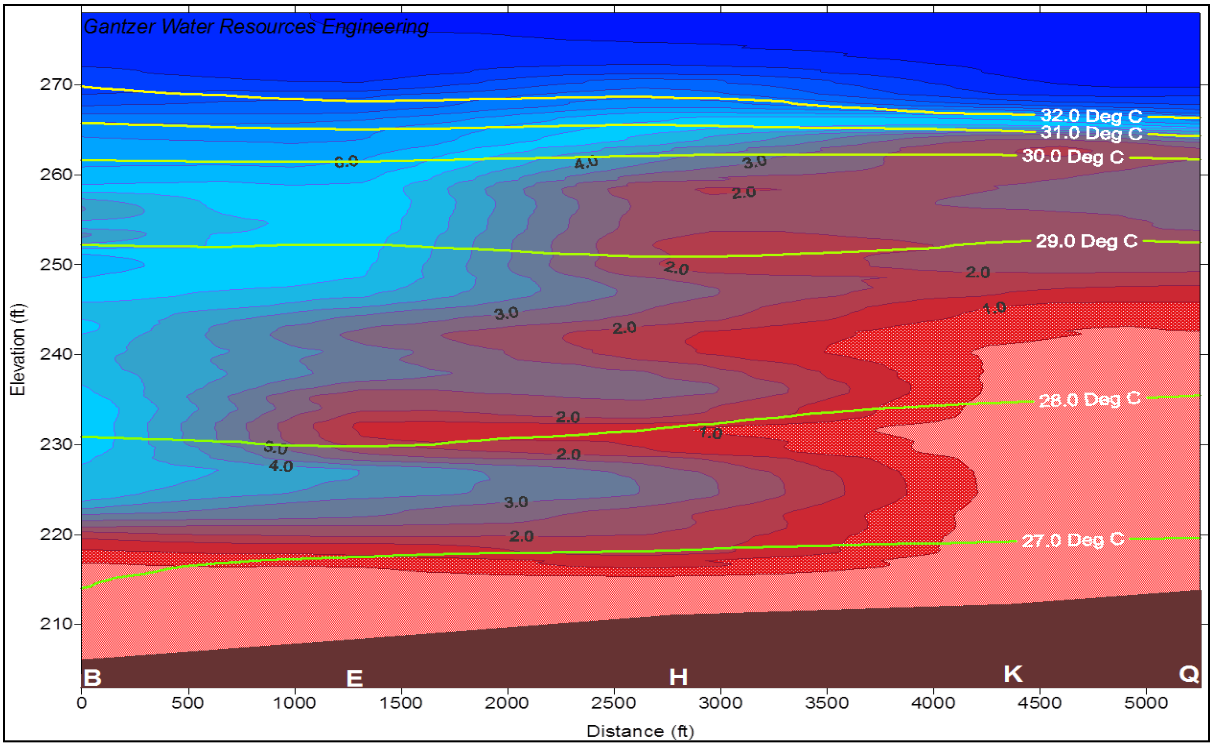

Figure 9. Longitudinal DO and temperature contours in the Tillery reservoir intake forebay, August 9, 2011 (Note red shading indicates low DO conditions while blue shading indicates higher DO conditions).

on the first day of testing but increased as the day progressed (Figure 9). Unit 2 started with a DO concentration at about 1.7 mg/L and increased to 4.3 mg/L over the testing period (Figure 8). Unit 3 started at DO concentration of 2.3 mg/L and increased to 3.5 mg/L while Unit 1 started at 2.9 mg/L and increased to 4.7 mg/L.

Several different unit generation combinations were tested on August 10 for DO enhancement verification of the diffuser system (Figure 10). Additionally, two draft tube venting tests were performed. Unit 1 operating alone started at 3.6 mg/L and increased to 4.7 mg/L with turbine venting. With Units 1 and 2 operating, Unit 1 started at 4.3 mg/L and increased to 5.1 mg/L with turbine venting. Unit 2 started at 4.1 mg/L and increased to 4.7 mg/L with turbine venting.

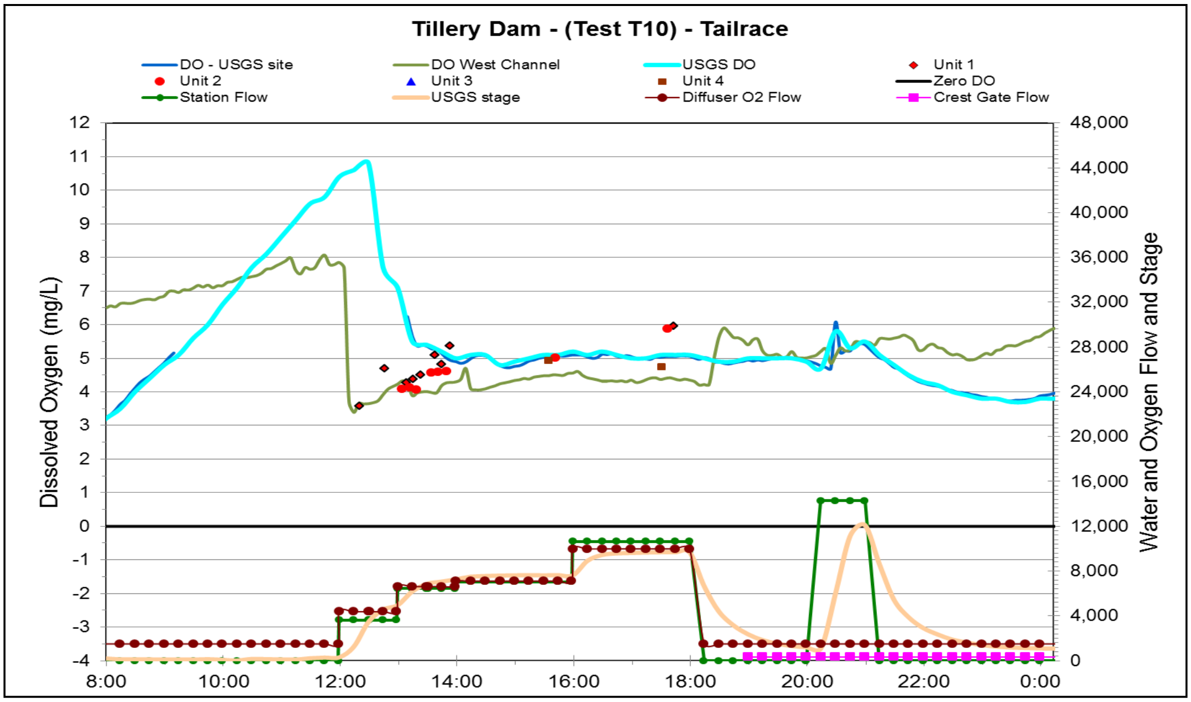

Figure 10. Unit turbine operations and tailrace DO measurements, August 10, 2011.

During generation, oxygen concentrations increased in the forebay due to operation of the diffuser system (Figure 11). After approximately 5 hours of operation, Units 2 and 4 were both maintaining 5.0 mg/L without turbine venting. After approximately 7 hours of operation, Units 1 and 2 were close to 6.0 mg/L and Unit 4 was 4.8 mg/L. Target DO levels of 5.0 mg/L were maintained at the compliance point for most of the hydro generation period (Figure 10).

Several additional unit combinations were operated on the fourth day (August 11) of testing to ensure representation of a wide range of potential power plant operational scenarios (Figure 12). The oxygen flow rate was turned up on the diffuser system to add approximately 3.0 mg/L to the turbine inflow so that the oxygen system maximum design flow could be tested during the operation of all four units. Two turbine venting tests were also performed. Unit 3 operating alone started at 4.5 mg/L and increased to 5.4 mg/L with turbine venting. With Units 2 and 3 in operation, Unit 3 maintained a DO concentration of 5.0 mg/L and Unit 2 maintained

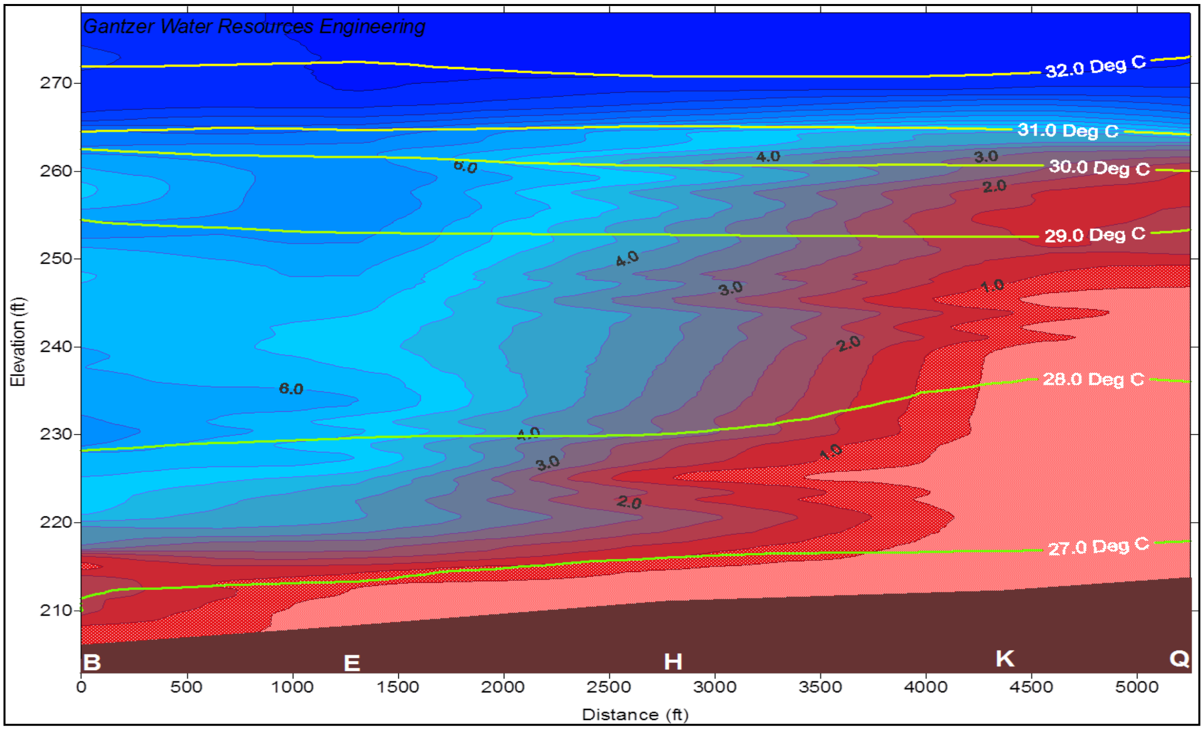

Figure 11. **Longitudinal DO and temperature contours in the Tillery reservoir intake forebay, August 10, 2011 (Note red shading indicates low DO conditions while blue shading indicates higher DO conditions).**

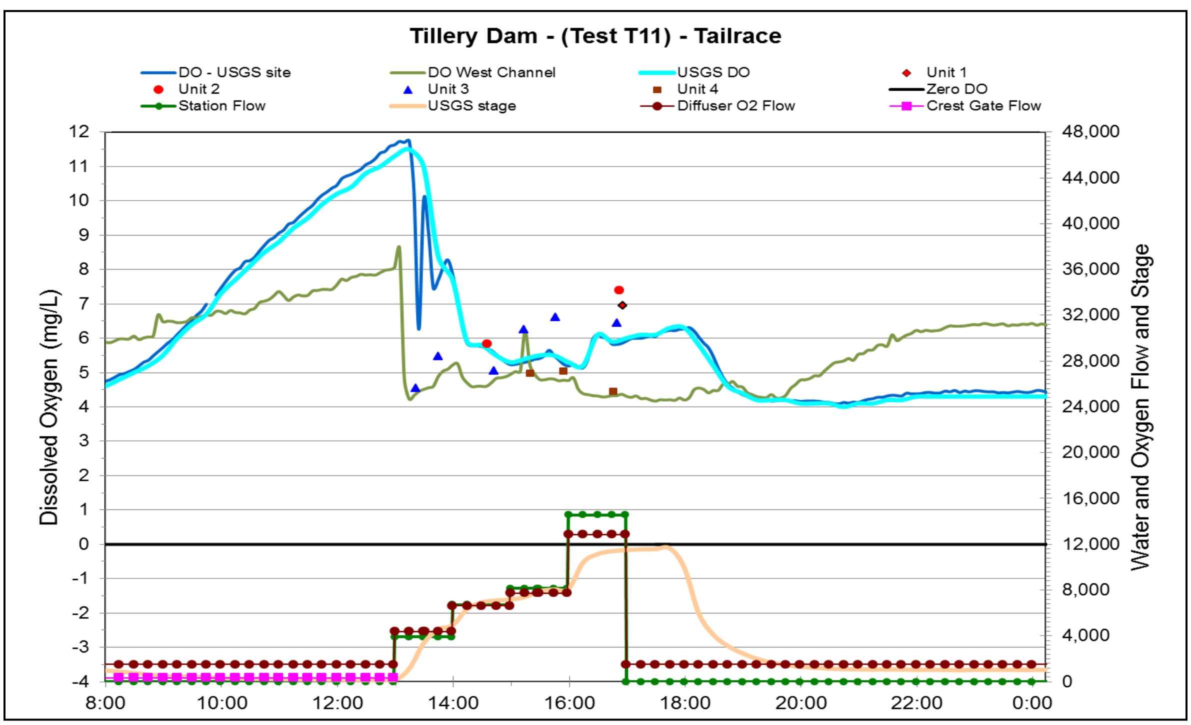

Figure 12. Unit turbine operations and tailrace DO measurements, August 11, 2011.

the DO at 5.8 mg/L without turbine venting. With Units 3 and 4 in operation, Unit 4 maintained the DO at 5.0 mg/L. Unit 3 maintained 6.2 mg/L without turbine venting and 6.6 mg/L with turbine venting.

Dissolved oxygen concentrations of 5.0 mg/L or above were maintained at the compliance point throughout the generation period on August 11. The DO concentrations in the intake forebay continue to increase longitudinally over time with continued operation of the DO maintenance flows from the diffuser (Figure 13). DO concentrations ≥ 5 mg/L were observed at least 3,000 feet upstream of the power plant intake. There was non-uniform DO concentration in the generating units' discharge which was directly related to the lateral distribution of DO in the intake forebay. The DO concentration was greatest near the submerged river channel, which produced a correspondingly higher DO concentration in the Unit 3 discharge because the intake for that unit is nearest the river channel.

On the fifth day (August 12) of testing, additional unit combinations were operated and the oxygen flow rate was turned down to add approximately 2.0 mg/L to the unit turbine flow because downstream DO levels exceeded the desired target compliance level of 5 mg/L on August 11. A turbine venting test was also performed. DO concentrations of 5.0 mg/L or above were maintained at the compliance point for the entire generation period. Unit 4 operating alone maintained 5.7 mg/L (Figure 14). With Units 1 and 4 in operation, the DO concentration was about 6.0 mg/L. With Units 1 and 3 in operation, the DO concentration was approximately 6.0 mg/L without turbine venting and 6.4 mg/L with turbine venting. With all three units in operation, the DO concentrations were again non-uniform with Unit 1 discharge considerably higher in DO than Unit 4.

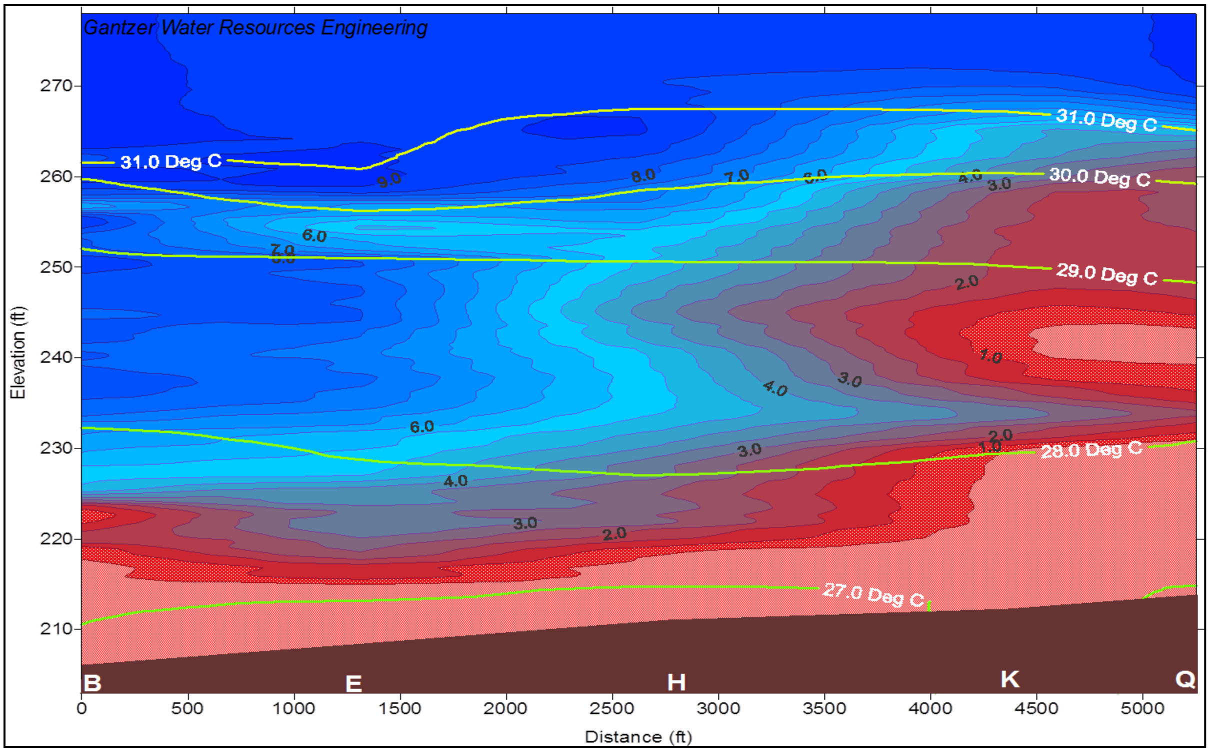

Figure 13. Longitudinal DO and temperature contours in the Tillery reservoir intake forebay, August 11, 2011 (Note red shading indicates low DO conditions while blue shading indicates higher DO conditions).

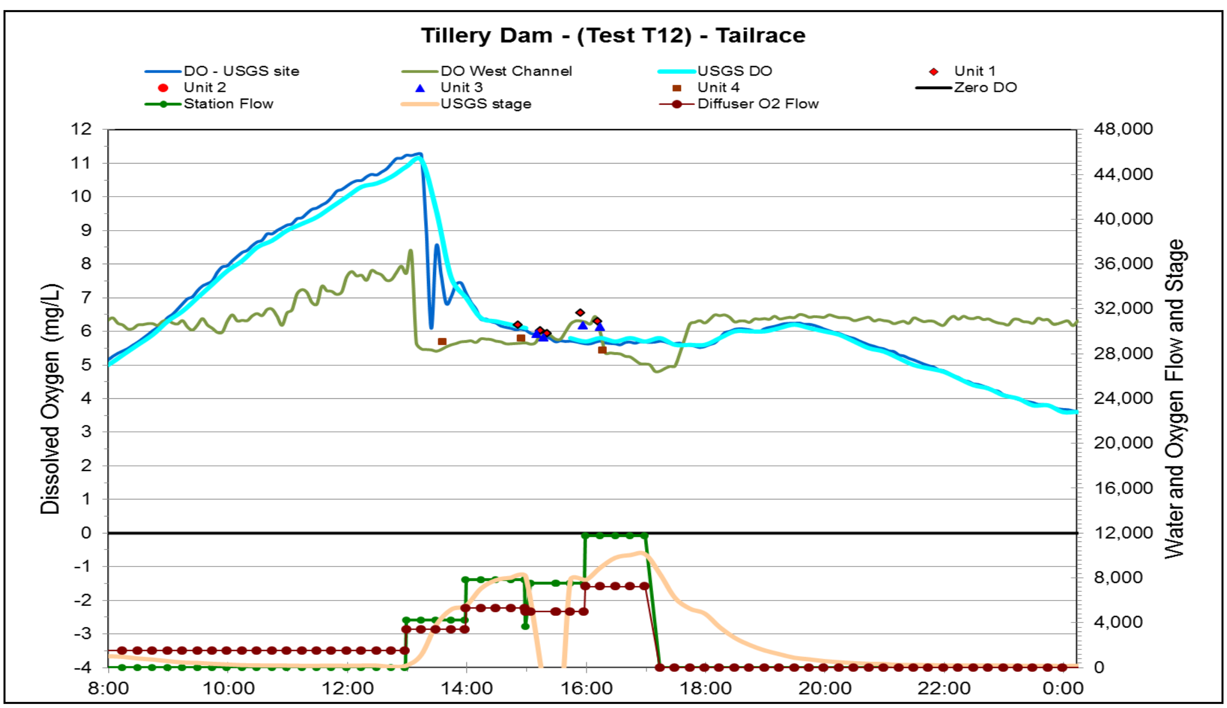

Figure 14. Unit turbine operations and tailrace DO measurements, August 12, 2011.

These trials clearly demonstrated a continual DO increase in the intake forebay as the diffuser operated during the 5-day testing sequence. The diffuser system provided sufficient oxygen to increase the reservoir intake forebay DO concentration so that the tailrace DO compliance target level of 5 mg/L was achieved. For example, on the first day of testing, the reservoir DO is low and consistently below 2.0 mg/L below elevations of 260 ft. By the last day of testing the DO exceeds 4.0 mg/L at elevations above 220 feet, which are next to the dam (Figure 15).

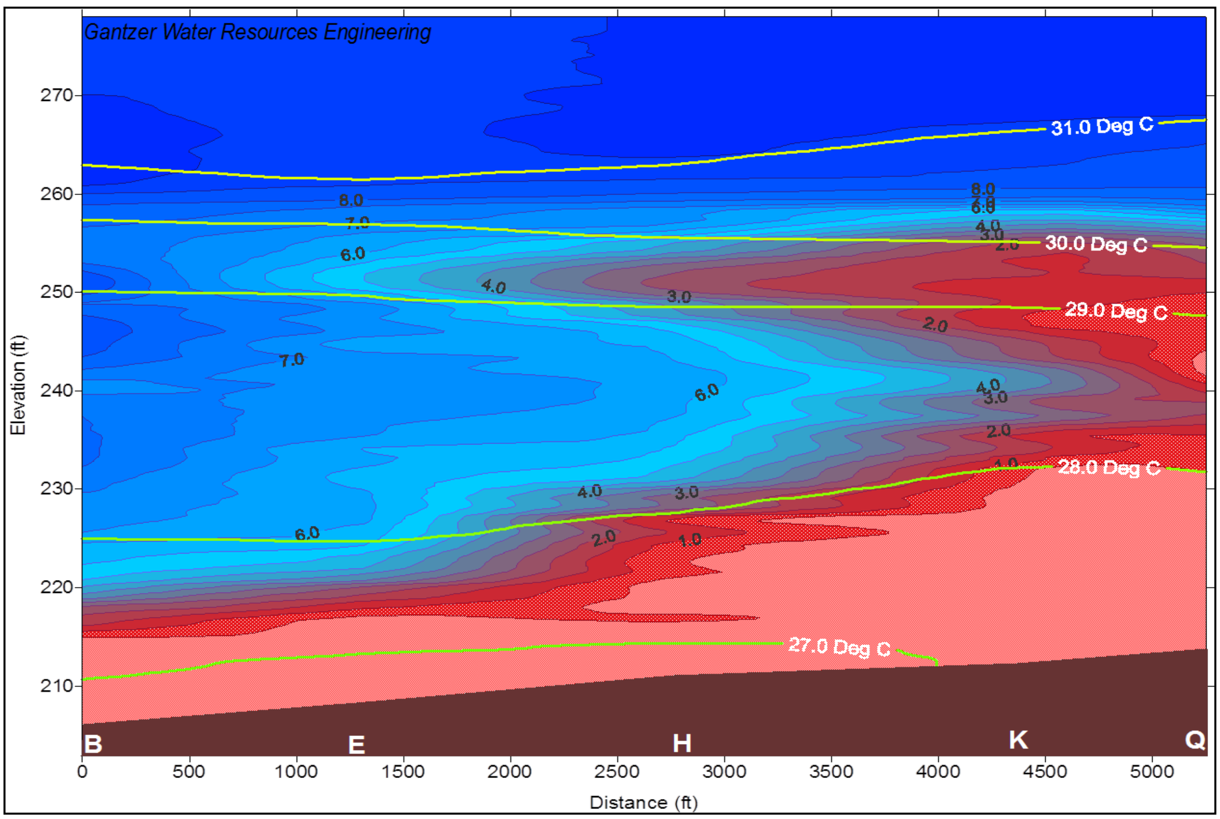

Figure 15. Longitudinal DO and temperature contours in the Tillery reservoir intake forebay, August 12, 2011 (Note red shading indicates low DO conditions while blue shading indicates higher DO conditions).

After the second day of testing, a maintenance oxygen flow of 300 scfm was implemented to eliminate any time lags in meeting the target DO compliance level at the N.C. Highway 731 Bridge when the turbines were started. This maintenance flow rate was maintained for the course of the testing period. Manipulating the diffuser system DO maintenance flow will be essential to respond to increasing DO deficits as the summertime stratification period progresses each year.

Summary

Selecting the appropriate DO enhancement technology for hydro plant facilities often requires a site-specific problem-solving approach. Several factors that must be considered in selection include the: (1) selected technology's ability to consistently meet the DO compliance standards, (2) storage reservoir depth and degree of hypolimnetic DO deficit, (3) length of DO deficit season, (4) reservoir hydraulic residence time, (5) turbine configuration characteristics (turbine type, equipment age, venting capabilities, and hydraulic capacity), and (6) capital and annual O&M costs. In the case of the Tillery Hydroelectric Plant, a systematic program evaluated eight different technologies over a 5 year period before deciding upon the oxygen diffuser system as the primary means to enhance DO in the power plant tailwaters. The fact that oxygen diffuser systems are a proven technology weighed-in on Progress Energy's decision to utilize this DO enhancement technology at the Tillery Plant.

As part of the decision-making process, a modeling study using real-time plant operational and environmental data provided an upfront quantitative means to determine the size of diffuser system and expected O&M liquid oxygen costs required for meeting the DO compliance requirements. The selected model time period also provided years with varying climatological and plant operational characteristics ranging from dry to wet years. Site visits were also made at several hydro facilities that had constructed oxygen diffuser systems as part of the analysis and decision-making process.

The diffuser system construction took eight months to complete which included permitting and developing the supporting infrastructure. Part of this process included negotiating a contract with a gas vendor for leasing of equipment and purchase of the liquid oxygen. A monthly fee covers the leasing and maintenance of the liquid oxygen tanks, vaporizers, and oxygen flow control skid. Discussions with other system users provided an existing framework to develop the PLC software controls for diffuser system operation. No major problems were encountered with system installation or start-up.

Managing the annual O&M costs of liquid oxygen use will be a challenge in using the diffuser system. Liquid oxygen usage is expected to vary annually depending upon the prevailing climatological and plant operations which will directly affect the O&M budget. Supplemental draft tube venting of Units 1-3 will provide an additional means to enhance DO and reduce liquid oxygen use especially during the transitional months when the reservoir hypolimnetic DO deficit will not exceed 2 mg/L. Use of the reservoir diffuser system requires a adjusting the continuous maintenance flow to ensure that an adequate volume of oxygenated water is present during each power plant generation start-up event. Part of this process requires that lake monitoring of temperature and DO must occur on a weekly basis during the compliance monitoring season to have adequate knowledge of DO conditions in the reservoir.

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Acknowledgements

The authors would like to thank Mr. Ken Kennedy, Hydro Operations Manager, for his support during the studies and installation of the diffuser system. A special thanks to the Tillery Plant staff that assisted with this project, particularly Messrs. Max Gardner and Brian Plyler. We also appreciate the assistance of Messrs. Jason Brown and Mike Swing, PEC Environmental Services, who performed the water quality field studies.

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