

## **Oxygen Diffuser System to Create Fish Habitat and Enhance Hydropower Water Quality in J Strom Thurmond Reservoir**

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Mark H. Mobley, P.E., Mobley Engineering, Inc.  
PO Box 600 Norris, TN 37828  
[mark@mobleengineering.com](mailto:mark@mobleengineering.com) (865) 494-0600

Paul Gantzer, Ph.D., P.E., Gantzer Water Resources Engineering, LLC  
14816 119th PL NE, Kirkland, WA 98034  
[Paul.Gantzer@gmail.com](mailto:Paul.Gantzer@gmail.com) (206) 999-1878

Gary E. Hauser, P.E., Loginetics, Inc.  
P.O. Box 18274, Knoxville, TN 37928  
[gehauser@loginetics.com](mailto:gehauser@loginetics.com) (865) 688-8401

Richard Jim Ruane, Reservoir Environmental Management, Inc.  
900 Vine Street, Suite 5, Chattanooga, TN 37403  
[jjiruane@comcast.net](mailto:jjiruane@comcast.net) (423) 265-5820

Jamie A Sykes, District Fisheries Biologist, U. S. Army Corps of Engineers, Richard B. Russell Project, 4144 Russell Dam Drive, Elberton, GA 30635  
[james.a.sykes@usace.army.mil](mailto:james.a.sykes@usace.army.mil) (800) 944-7207 Ext. 3425

### **Abstract**

An oxygen diffuser system was installed at the U. S. Army Corps of Engineers' (USACEs') J. Strom Thurmond (JST) Reservoir to create striped bass habitat and improve reservoir releases. This system is part of a litigation agreement to mitigate fish habitat that was being impacted by operation of the hydropower pumpback units located upstream at the Richard B. Russell (RBR) project. After years of efforts to solve fish entrainment issues, the pumpback units at RBR were approved for operation in 2002. With this approval, theUSACE Savannah District agreed to limit pumpback operations to two units out of four during the summer months until a fish habitat mitigation system was implemented in JST. The JST oxygen system is designed to place oxygen in the reservoir at the specific temperature range suitable for striped bass habitat, as well as enhance dissolved oxygen (DO) levels at the dam. Extensive modeling was conducted to determine the best diffuser location and plume strength. Since the elevation of the target temperature range changes during the stratification season, it was determined that diffusers would be placed at several depths. The final design includes a total of

nine diffusers spread over four elevations roughly 50 to 90 feet deep at summertime pool elevations. Each diffuser is over 1,300 feet long and as much as 60 feet off the bottom of the reservoir. The diffuser system is located five miles upstream of the dam and is capable of distributing up to 200 tons of oxygen per day. The system was operated to meet performance goals during the summer of 2011 with great success. The oxygen-enhanced water volume exceeded performance requirements and used less oxygen than predicted. An operational tool was developed to assist the USACE with choosing diffuser elevations and oxygen flow rates for varying reservoir conditions. This paper presents field measurements from the first season of operation, comparison of model predictions, and a description of the operating tool development.

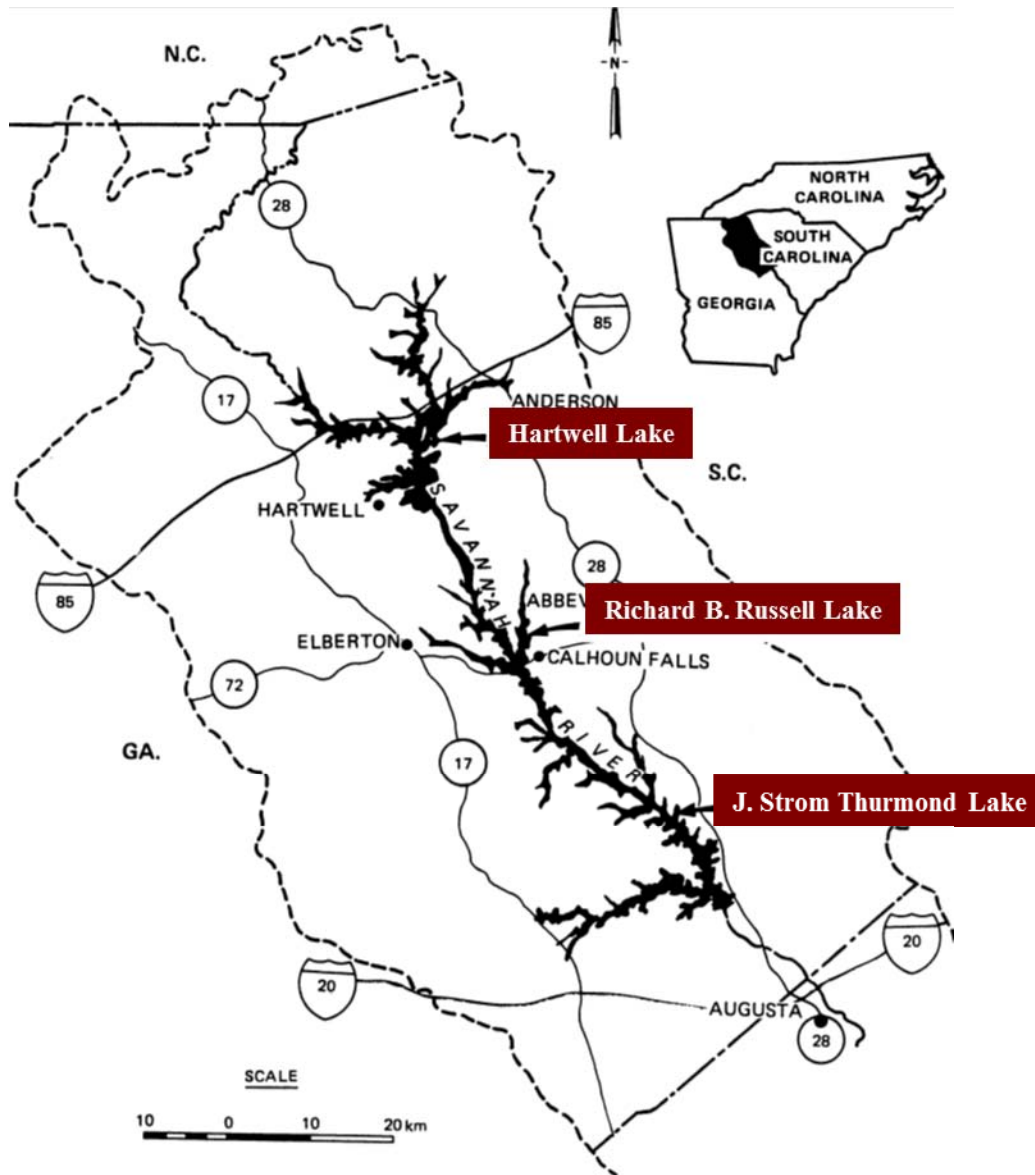
## 1.0 INTRODUCTION

The reservoir oxygenation system in J. Strom Thurmond Lake is designed to improve dissolved oxygen (DO) levels in the water column to create and maintain striped bass habitat and hydropower releases by distributing oxygen approximately five miles upstream of the dam. This system is part of a litigation agreement to mitigate fish habitat that was impacted by operation of the hydropower pumpback units at the RBR project upstream.

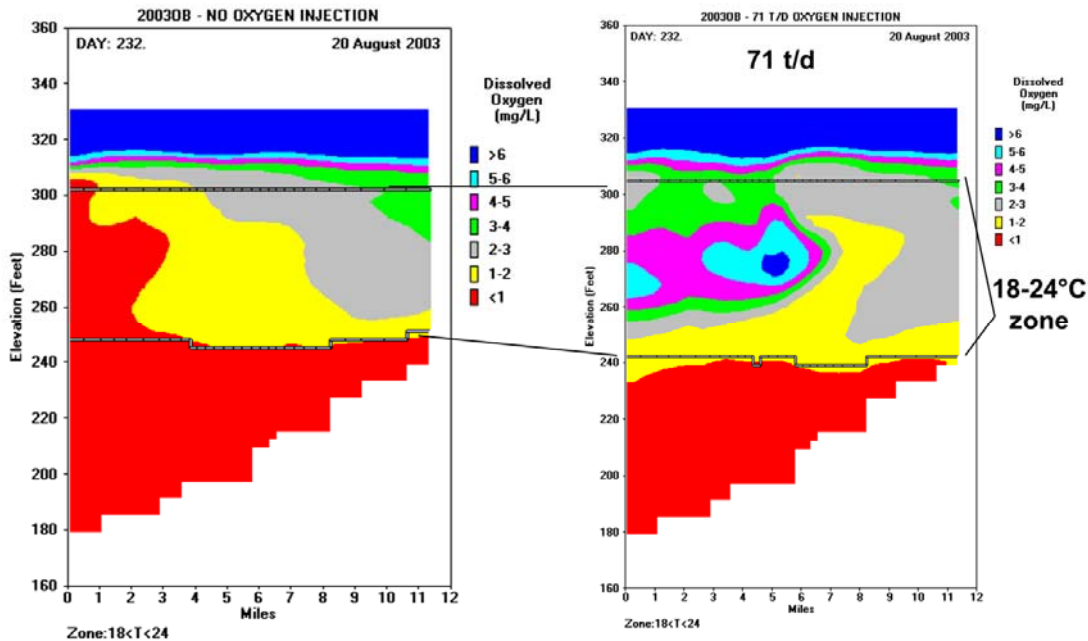
Construction of the JST project took place from 1946 – 1954, known as Clarks Hill Dam at the time. The power plant contains seven turbines with an installed capacity of 380 MW. Thurmond Lake comprises nearly 71,100 acres of water with a shoreline of 1200 miles. RBR Dam is 37 miles upstream from JST Dam. The RBR project was built between 1974 and 1983. Lake Russell contains 26,650 acres of water and 540 miles of shoreline. The power plant contains four conventional turbines and four pumpback turbines, with a total installed capacity of 600 MW. Figure 1.1 is a vicinity map that shows the relative locations of the projects.

After years of efforts to solve fish entrainment issues, the pumpback units at RBR were approved for operation by a Federal District Court in 2002. With this approval, the USACE agreed to limit pumpback operations to two units out of four during the summer months until a fish habitat mitigation system was implemented in Thurmond Lake downstream to replace habitat that was lost when the pumpback units bring warm surface water into the RBR tailwater.

A study was conducted to evaluate the feasibility of using an oxygen diffuser system to create and maintain the desired fish habitat in Thurmond Reservoir. Hydrodynamic modeling was used to evaluate the amount and placement of oxygen required to meet design goals (Reservoir Environmental Management, Inc., 2008). This study recommended a diffuser system capacity of 200 tons per day, a 7-diffuser array that employed a high flux rate of oxygen to create strong plumes, and three diffuser elevations. An example of the modeling results is shown in Figure 1.2. The results of this study were used to prepare the initial design and contract documents to put the system in place.



**Figure 1.1:** Map of the Upper Savannah River Basin Indicating the Locations of Hartwell Lake, Richard B. Russell Lake, and J. Strom Thurmond Lake



**Figure 1.2:** Example Modeling Results Showing Placement of 71 Tons Per Day of Oxygen to Create Fish Habitat

The design goals of the fish habitat mitigation system are as follows:

- PURPOSE: Provide striped bass habitat
- WHERE: Lower 8 miles of JST Reservoir
- THERMAL LAYER: 18-24°C
- WHEN: June-Sept (low DO season)
- OXYGENATED ZONE IN THE RESERVOIR:
  - 5 mg/L for 1 mile (no less than 4.5 mg/L)
  - 4 mg/L for 4 miles (no less than 3.5 mg/L)
- HYDROPOWER RELEASES:
  - 3 mg/L at entrance to the turbines

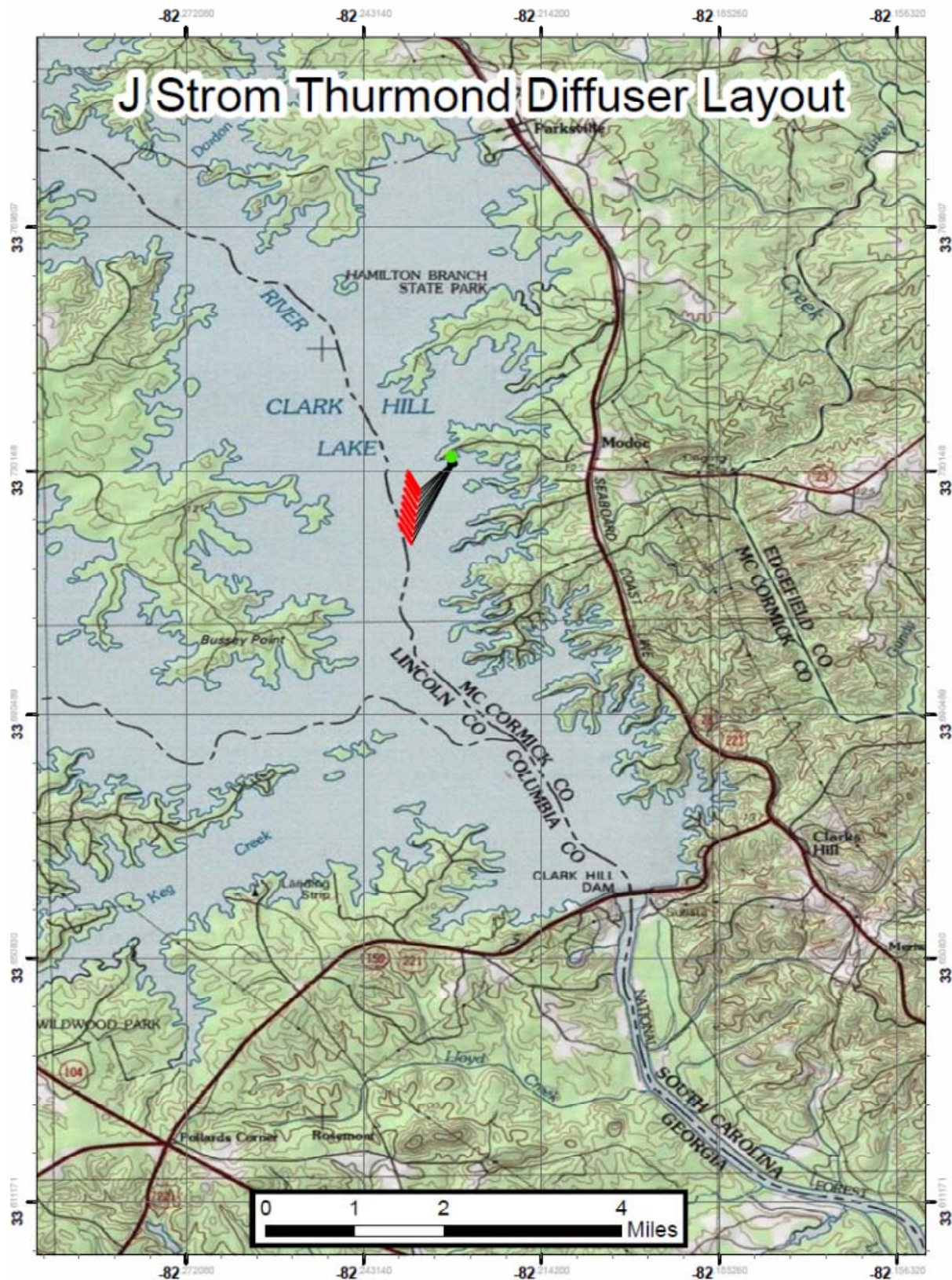
## **2.0 CONTRACTORS**

A contract for the installation of the reservoir diffuser system and flow control manifold was awarded to SpecPro Environmental Services (SES) of Oak Ridge, TN in 2010. The bulk liquid oxygen facility was provided by others. The reservoir diffusers were designed and installed by Mobley Engineering, Inc. (MEI) of Norris, TN. The flow control manifold was designed by Barge Waggoner Sumner & Cannon, and built and installed by Hardy Welding of Appling, GA. Control systems were provided by ProLectric of Savannah, GA.

## **3.0 DETAILED DIFFUSER DESIGN AND CONSTRUCTION**

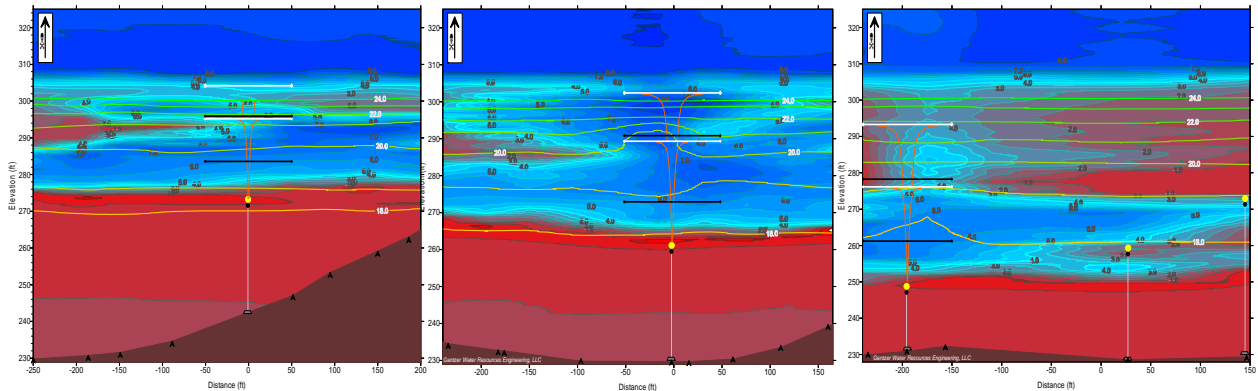
The USACE awarded the diffuser contract as a performance-based contract with SES and MEI was responsible for meeting all design goals of the fish habitat. Therefore, MEI contracted additional hydrodynamic modeling to Reservoir Environmental Management, Inc. (REMI) and Loginetics to verify design details. The additional modeling included calibrating CE-QUAL-W2 to JST Reservoir using three hydrologic years and using a proprietary embedded bubble plume module to quantify oxygen capacity and guide diffuser elevations. In the course of the modeling, MEI and the modeling team developed a hi-flux diffuser design to obtain plume characteristics needed to place the oxygen in the target temperature zone. The final design consists of nine 1,320-foot long diffusers in the reservoir near Modoc, South Carolina, approximately five miles upstream of the dam. A diffuser layout map is presented in Figure 3.1. The diffusers are placed at four elevations to provide flexibility in the vertical placement of oxygen in the reservoir as the target temperature range changes during the oxygenation season.





**Figure 3.1:** Fish Habitat Oxygen Diffuser System Layout

The diffuser system was installed during 2010 and 2011 by MEI. Three diffusers were installed in 2010 and tested utilizing a temporary oxygen supply to verify actual oxygen placement and operation in the field. The three diffusers were at elevations 274, 262 and 250 feet, respectively, providing bubble plumes that place oxygen at three distinct elevation ranges as shown in Figure 3.2. The results from the August 2010 testing confirmed the vertical oxygen placement predicted by the modeling. Had the results been different, MEI would have modified the diffuser design as necessary to obtain the desired oxygen placement.



**Figure 3.2:** Dissolved Oxygen Measurements around Diffuser Lines #1 - #3 (Yellow Circles) Showing Oxygen Placement (Blue Plumes)

With confirmation of the diffuser layout, detailed design of the remaining six diffusers, supply lines, flow control manifold, and remote operation system proceeded. Contractor construction crews were onsite for six months in 2011. The entire diffuser system was completed in May 2011, with a delivery acceptance test on August 18, 2011.

## 4.0 DESCRIPTION OF FACILITIES

### 4.1 Flow Control Manifold

The flow control manifold is equipped with shut-off valves, flow control valves, V-cone flow measurement, vent valves, pressure gages and bypass for each diffuser line (Figure 4.1). The manifold is equipped with a control system for independent local or remote control of each diffuser line.



Below each supply pipe connection on the manifold there is a single additional ball valve that is closed with hose connection and cap. This valve is used to provide oxygen to pressurize the buoyancy piping of the diffuser lines during activities that require the diffusers to be re-floated to the surface. A connection hose, equipped with hose connection fittings on each end, was supplied to connect diffuser buoyancy piping of each line to the supply valve on the manifold as needed. An additional 2-inch connection to the buoyancy piping for each diffuser is located between the flow control manifold and the fence, terminated with a cap (Figure 4.2). This connection is used to pump water back into the buoyancy piping to sink the diffuser.



**Figure 4.1: Flow Control Manifold**



**Figure 4.2:** Underground Piping and Buoyancy Piping Connections

#### ***4.2 Gaseous Oxygen Delivery Piping***

High Density Polyethylene (HDPE) piping is used to deliver the gaseous oxygen from the Flow Control Manifold to the reservoir. There are twelve 3-inch HDPE SDR 7.3 pipes providing oxygen supply and twelve 2-inch HDPE SDR 11 pipes providing buoyancy connection for the nine independent diffuser lines and three spares. The HDPE oxygen delivery piping is in a trench from the flow control manifold connections to the reservoir shoreline. The HDPE piping is routed through four 14-inch diameter protective sleeve pipes (14" 3408 HDPE SDR 32.5) at the shore embankment that are anchored with 115-pound concrete anchors and stainless steel straps (Figure 4.3). The sleeve for the spare lines extends about 40 feet out from the shoreline embankment. Active supply lines are routed in sleeve pipes that extend 400 feet into the reservoir to approximately elevation 275 feet.





**Figure 4.3:** HDPE Piping and Sleeve Pipes before the Trench is Closed

HDPE piping uses a standard dimension ratio (SDR) pressure rating system. HDPE piping can be utilized for various gases with appropriate de-rating environmental factors. Table 4.1 presents pressure ratings for oxygen for the piping used at JST. These ratings should be considered maximum working pressure limits for each pipe. Therefore, the maximum operating pressure for the diffuser oxygen supply piping is 120 psi. The maximum operating pressure for the buoyancy piping is 37 psi. Pressure relief on the oxygen supply piping is set at 120 psig to protect the HDPE piping.

**Table 4.1: HDPE Pipe Pressure Ratings for Oxygen**

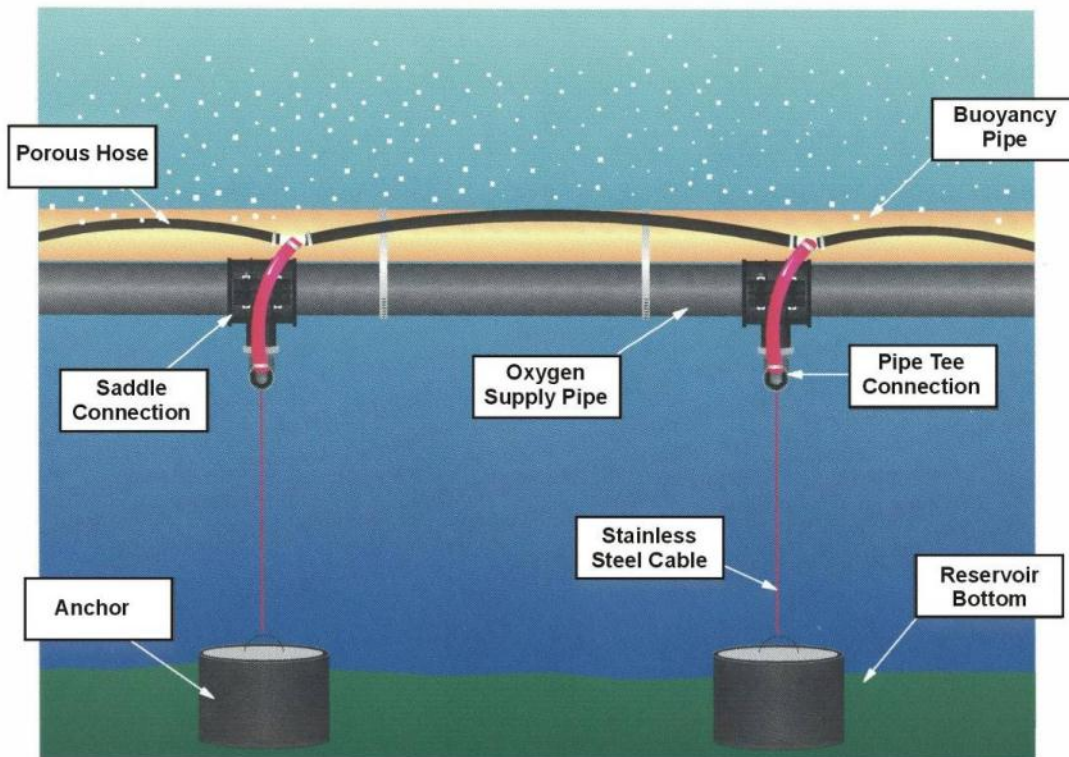
<b>Oxygen Supply Pipe</b>			Operating Temperature (°F)	Pressure Rating for Oxygen (psi)	Minimum Hydrostatic Pressure (psi)	Pipe Working Pressure at Depth (psi)
In Sleeve	3"	SDR 7.3	100	127	0	127
Underwater	3"	SDR 9	80	121	0	121
Diffuser	2"	SDR 11	73	102	25	127

<b>Buoyancy Pipe</b>			Operating Temperature (°F)	Pressure Rating for Oxygen (psi)	Maximum Hydrostatic Pressure (psi)
In Sleeve	2"	SDR 11	100	79.9	
Underwater	4"	SDR 21	80	37.7	
Diffuser	4"	SDR 21	73	40.0	28.1

Pressure ratings are based on Technical Note PP 831-TN, Chevron Phillips Chemical Company LP, September 2002

### **4.3 Oxygen Diffuser System**

The basic line diffuser system design installed by MEI at JST was originally developed for the Tennessee Valley Authority for hydropower applications to improve the oxygen content of the reservoir releases. The line diffuser design has been applied at 20 hydropower projects and 15 water supply reservoirs since 1994. The diffuser assembly is shown in Figure 4.4. The line diffuser is deployed and retrieved without the use of divers. The elevation of each diffuser segment is maintained using custom anchor cable lengths to hold the diffuser the desired distance off the bottom of the reservoir. Each line diffuser is constructed from HDPE pipe that supplies oxygen to porous hoses and a buoyancy chamber for deployment and retrieval. The diffuser hoses have an orifice at their point of connection to the supply pipe to equalize the flow along the length of the diffuser and to minimize losses in the event of a hose break. Operation of similar systems at TVA and other utilities have resulted in efficient oxygen distribution with minimal maintenance expenditures.



**Figure 4.4** Line Diffuser Detail

The diffuser system at JST includes nine diffusers in the reservoir. Each diffuser is 1,320 feet long with additional underwater supply piping to reach the shoreline connections to the oxygen supply facility. The layout of the diffusers is shown in Figure 4.5. The diffusers are positioned off of a peninsula near Modoc, South Carolina, about five miles upstream of the dam. In order to provide flexibility in the vertical placement of oxygen in the reservoir, the diffusers are installed at four elevations, as shown in Table 4.2. Diffusers #1 and #4 are at elevation 274 (54 feet deep at nominal 330 pool elevation). Diffusers #2, #5, and #7 are at elevation 262 (68 feet deep). Diffusers #3, #6, and #8 are at elevation 250 (80 feet deep). Diffuser #9 is at elevation 238 (92 feet deep). Figure 4.6 is a photograph of the actual bubble plumes of all nine diffusers in operation, as shown on the display of a depth finder. The diffusers are oriented from #1 on the left to #9 on the right (looking downstream). The vertical yellow stripes are bubble plumes and the dark brown is the reservoir bottom.



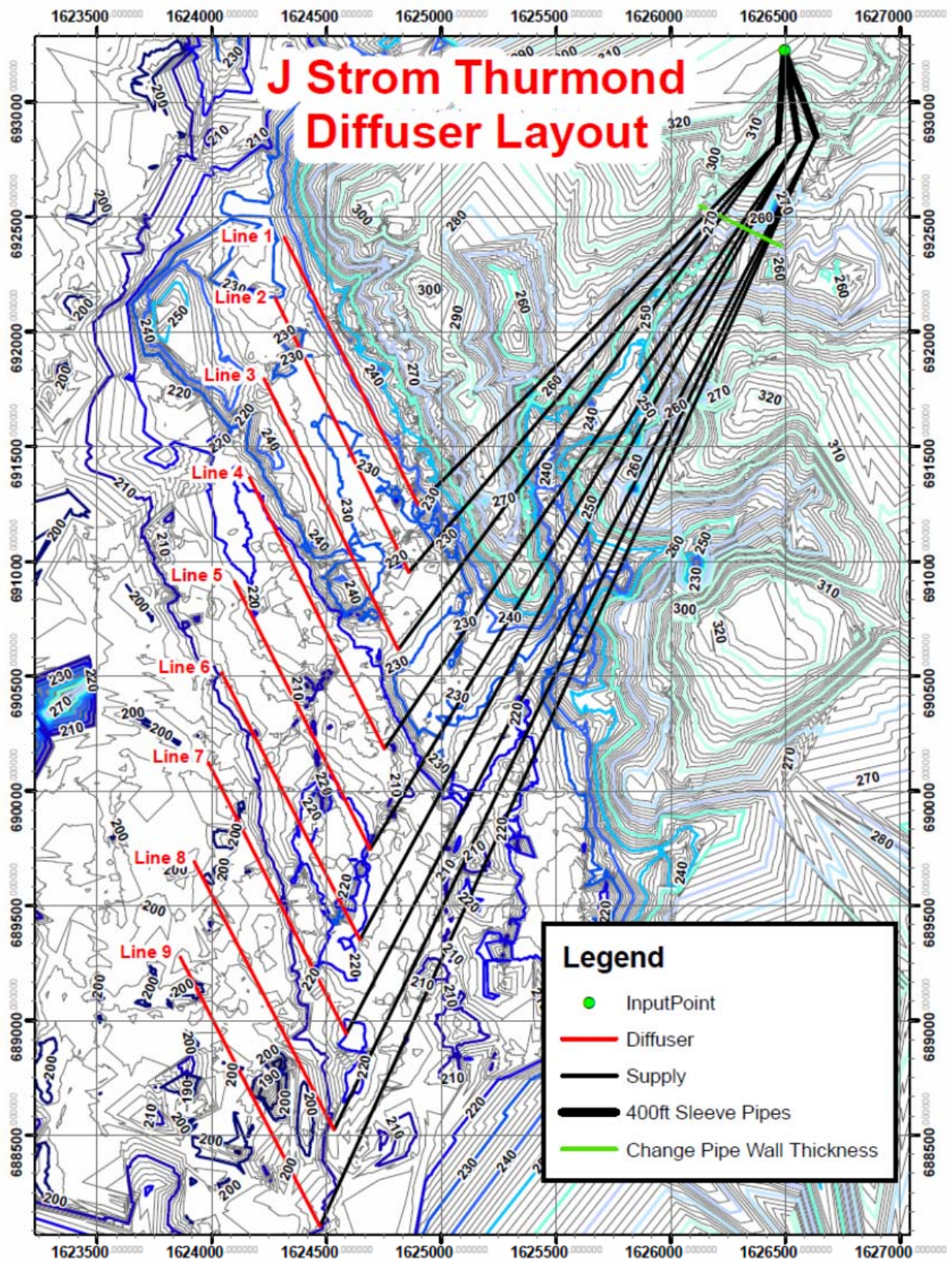
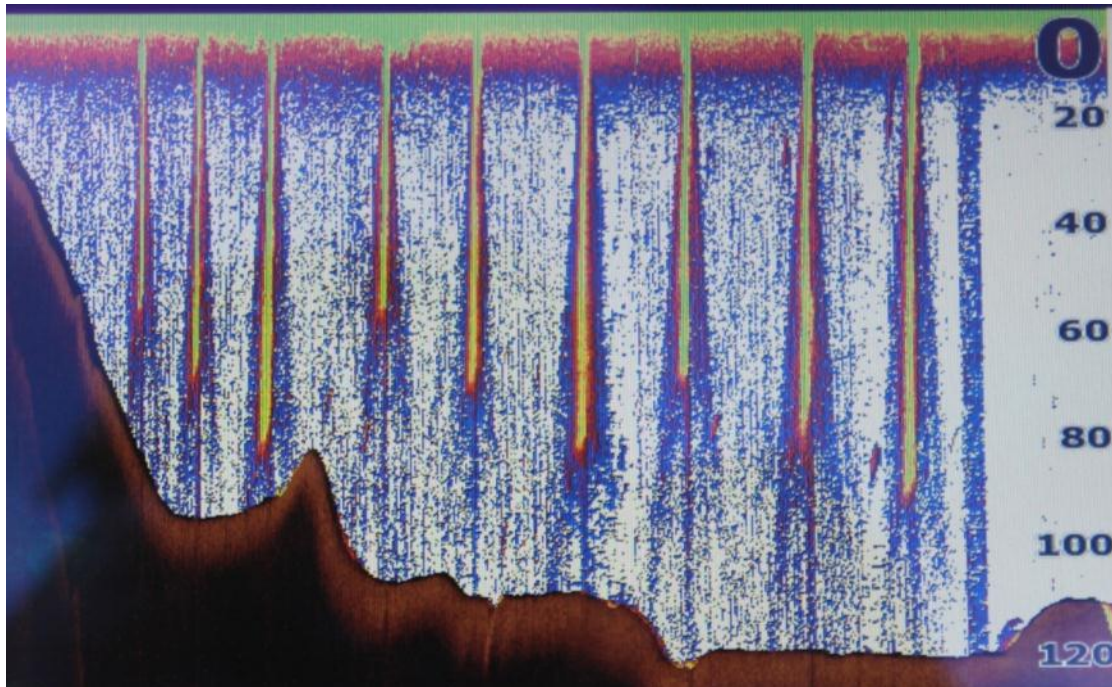


Figure 4.5 JST Diffuser Layout



**Table 4.2:** Diffuser Elevations

Diffuser #	Elevation (ft)	Elevation (m)
1, 4	274	83.5
2, 5, 7	262	79.9
3, 6, 8	250	76.2
9	238	72.5



**Figure 4.6:** Depth Finder Display of the Bubble Plumes of All Nine Diffusers in Operation

## **5.0 RESERVOIR MONITORING AND OXYGEN PLACEMENT RESULTS**

Extensive monitoring of oxygen placement in the reservoir was conducted in June, July and August 2011. Diffuser operation and oxygen distribution meeting performance goals under varying seasonal conditions were verified during these tests. Detailed results from these tests are reported by Mobley and Gantzer (2010). Data were collected on 29 individual days during June – August 2011 to track the oxygen distribution in JST Reservoir as a result of operating the oxygen diffuser system to oxygenate the 18 – 24°C temperature range for striped bass fish habitat. Water column data were collected at least every mile along the length of the reservoir between the dam and river mile 26 using a high-resolution water column profiler. Additional data were collected in the specific water column depth range that corresponded to the 18 – 24°C temperature range using a towed array of high-resolution water column profilers. Diffuser operation and oxygen distribution meeting performance goals under varying seasonal conditions were verified during these tests. Results from these tests follow.

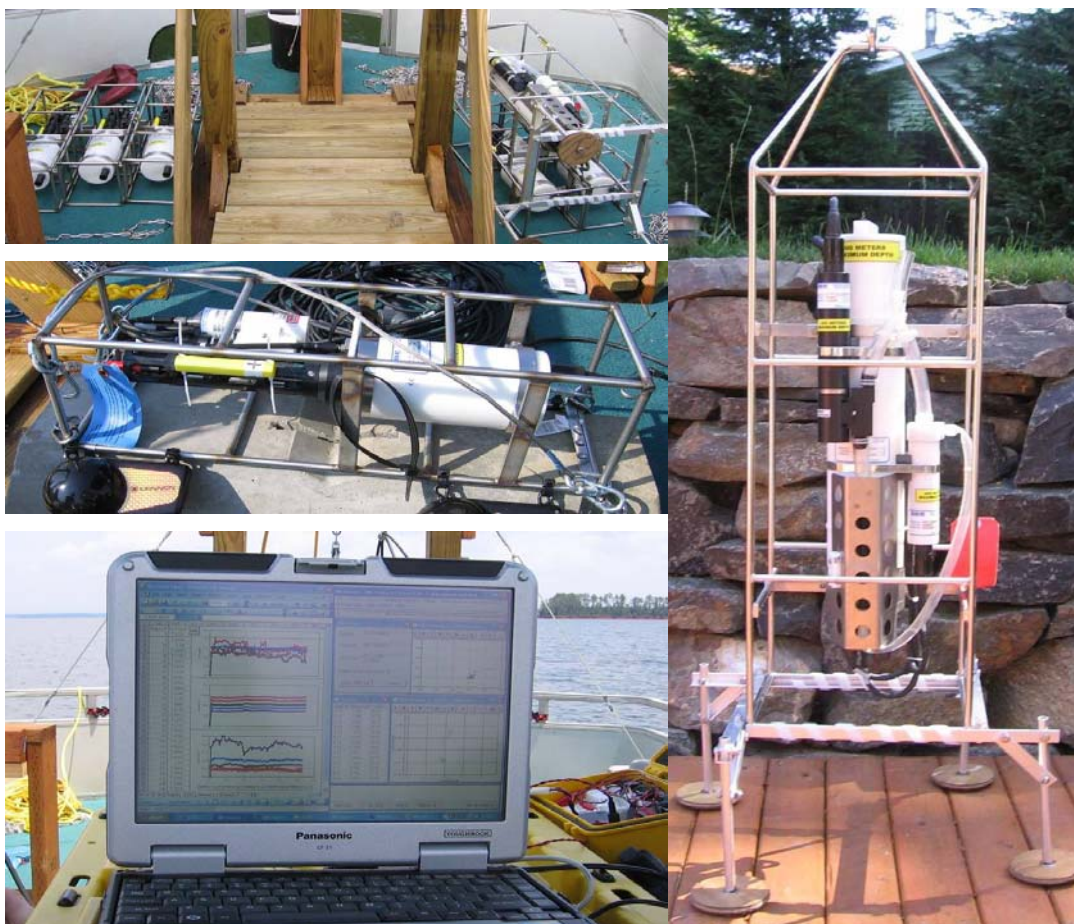
### **5.1 Water Column Profiles**

#### **Procedure**

Data collection occurred daily June 22 – 29, July 24 – August 7, and August 13 – 18, 2011. During the beginning of June, data collection was focused on identifying boundary conditions of the plume near the diffusers and getting the towed array set up to collect the quality data necessary. Nine individual profiles were collected each day. Gantzer Water Resources Engineering (GWRE) was on site between June 22 and July 31. These data collection sites corresponded to river mile 19 – 26 and used the USACE water quality buoys when available. Starting on August 1, three additional profile locations were added at the ½-mile increments between USACE 21 and 23 water quality buoys, totaling twelve sample locations each day. This region was identified to be that most directly influenced by the oxygenation system, and the increased resolution aided in confirmation of the extent of oxygen distribution through this region. On two occasions, August 1 and 4, forty-four profiles were collected, which consisted of five profiles across the sample location located between river mile 23.5 and 21. These extra profiles were conducted to track the lateral distribution beyond that which the towed array could capture due to the potential of running the towed array aground.

#### **Instrumentation**

Water column profiles were collected with a Seabird Electronics SBE 19Plus high-resolution profiler to collect conductivity, temperature, and depth (CTD) with optional SBE 43 DO sensor, having a response time of 1.4 seconds at 20°C, at a 4 Hz sampling rate (Figure 5.1).



**Figure 5.1:** Data collection apparatus (top left) showing the SBE 52MP (middle left), SBE 19PlusV2 (right), and data monitoring set up (bottom left).

## ***5.2 Towed Array Data Collection***

### **Procedure**

On days when towed arrays were conducted, the depth range was determined from the previous day water column data. During June, probes were evenly spaced throughout the depth range corresponding to the 18 – 24°C. Starting in July, the spacing was modified to reflect the specific elevations/depths for each 1°C between 18 and 24°C; for example, the spacing on July 24, 2011 was identified to be 14, 11, 5, 3.5, and 3.5 ft between 18-19, 19-20, 20-21, 21-22, 22-23°C, respectively. Towed arrays were conducted along a pre-determined path, being sure to keep the probes a safe distance from the bottom as well as away from any trees. On average, the boat traveled at two mph, but was adjusted as needed depending on the observed temperature and depths of the probes. Once the path was completed, probes were downloaded, recovered, and stored for deployment for the next towed array data collection voyage.

## Instrumentation

A Seabird Electronics SBE 19Plus high-resolution profiler and five additional Seabird Electronics SBE 52MP (moored CTD) with optional SBE 43 DO sensor, having a response time of 1.4 seconds at 20°C, to collect conductivity, temperature, depth, and DO data at a 1 Hz sampling rate were deployed for the towed array configuration. GPS location data was logged using SeaSave software from SeaBird Electronics that collected the output data from a Garmin GPS 60 Cx. The SBE 52 MPs were retrofitted with an RS-232 to RS 485 modbus chip with memory to allow for data logging as well as real-time output. Aqua4Plus software provided by Instrumentation NorthWest, INC. (INW) was used to program and record data on the SBE 52MP chips. Windmill software was used to poll the 52MPs, which in turn was logged and plotted in Excel through a DDE link.

## 5.3 Results

The results throughout this report are presented chronologically. Data collected along the length of the reservoir are presented in Surfer 2-D imagery. In these plots, the dam is at the far left vertical axis, the reservoir bottom is depicted in brown and the distance from the dam is labeled on the horizontal axis. Low DO is shown in red and high DO is shown in blue, as indicated by the legend on the right side of the plot. In each plot, the diffusers are depicted as yellow and black lines at the correct elevation and distance from the dam. The target fish habitat temperature zone is framed by a yellow line at 18°C and a green line at 24°C.

Figure 5.2 presents a longitudinal transect plot of nine reservoir profiles taken on June 22, 2011. The target temperature range is high in the water column (elevation 280 to 300 feet). Two diffusers (#31 and #4) have been in operation at the design flow rate of 400 scfm. These diffusers are the shallowest available (at elevation 274 feet). A zone of enhanced DO is clearly visible just downstream of the diffusers with peak DO over 7 mg/L. These DO levels meet or exceed project performance goals.

Figure 5.3 presents a horizontal transect taken through the diffuser array location looking downstream with the South Carolina shoreline on the left side. Here the operating diffusers (#1 and #4) are depicted by yellow and black circles at elevation 274. The gray lines depict cable lengths that hold the diffusers in location. In this figure, the DO plume near the diffusers includes local DO levels as high as 10 mg/L. The enhanced DO spreads bank to bank in a strong plume just below the 24°C elevation. The lateral spreading had been a concern during the design process as the CE-QUAL-W2 model is laterally averaged and actual spreading was unknown. With these results it is clear that the oxygen plume is spreading in a manner that is very much like the way it was modeled.



On June 23<sup>rd</sup>, the operation of the diffuser system was changed to test the oxygen placement of a deeper diffuser. Diffuser #7 was operated at 400 scfm, with Diffuser #4 at 200 scfm. The profiles in Figures 5.4 and 5.5 show the resulting deeper oxygen placement on June 24<sup>th</sup>, with much of the enhanced DO volume below the 18°C target.

Reservoir monitoring was continued late in July with Diffusers #4 and #7 in operation since June 23<sup>rd</sup>. The profiles for July 25<sup>th</sup> are presented in Figure 5.6. In this plot, it is clear that the target temperature range has widened and deepened (260 to 300 feet elevation). The operation of Diffusers #4 and #7 has created a zone of enhanced DO that is well positioned in the target habitat zone extensive enough to meet or exceed project performance goals.

On July 30<sup>th</sup>, the diffuser operation was changed, bringing Diffuser #2 on to place more oxygen deeper in the target temperature range that has moved deeper in the water column. Profiles from July 30<sup>th</sup> are presented in Figure 5.7. DO levels increased to 7 mg/L near the diffusers, as shown in profiles from August 4<sup>th</sup> in Figure 5.8. By August 6<sup>th</sup>, the enhanced DO volume has been spread upstream by a consistent strong wind event. The DO plume was measured more than two miles upstream of the diffusers, as shown in Figure 5.9. The wind movement of the enhanced DO volume was predicted by the hydrodynamic modeling and the contract performance requirements were changed to take it into account; so, it was interesting to see the dramatic water movement in the monitoring results.

Reservoir monitoring was continued with daily profile sets taken through August 17, 2011. During this period, the diffuser operation was maintained with Diffusers #1, #2, and #7 in operation at 100, 300, and 300 SCFM, respectively. The target temperature range deepened to almost elevation 240. Project performance goals were met for the entire period. Selected plots for this period are presented in Figures 5.10 and 5.11. At the very end of the period, diffuser operation was changed to include Diffuser #8 at elevation 250. A plume of deeper oxygen placement is noticeable in the profiles from August 18<sup>th</sup> in Figure 5.12.

The larger data sets requiring 3-D plotting are presented in a couple of formats or configurations. First, the data collected along the length of the reservoir are displayed as a 3-D graphic, and then the towed array data are superimposed. Reservoir bottom contour data are shown at the base of these images to show the approximate extent of the main channel. Diffusers are also shown on each of the images, and the diffusers in operation are shown in yellow. Figure 5.13 presents the profiles from August 2 in two dimensions, with a box indicating the region of the towed array data collection.

Figure 5.14 presents the center channel profile data in three dimensions. The profiles appear as vertical colored lines. The perspective is looking upstream from near the dam. Figure 5.15 presents the overlay of the towed array data. Figures 5.16 and 5.17 are the same August 2 data sets viewed from upstream.

## **6.0 OPERATION**

Operation of the JST diffuser system is complex due to the wide variety of operating conditions during the oxygenation season. Therefore, an operating guide and software program were developed to assist with selection of diffuser elevations and oxygen flow rates (Loginetics et. al., 2011). The software program, DiffuserOps, was developed to provide recommended O<sub>2</sub> fluxes and diffuser selections to support Savannah District's day-to-day operation of the system. DiffuserOps recommendations are based on available temperature and DO profiles and JST total discharge, including projected discharges. The software is intended for weekly application to provide O<sub>2</sub> flux recommendations. DiffuserOps was calibrated to observations and measurements from the 2011 diffuser system testing, including Savannah District's weekly temperature and DO profiles and additional daily profiles by GWRE as part of performance testing by MEI.

## **7.0 INSTALLATION AND OPERATING COSTS**

The JST Fish Habitat Enhancement System was funded by The American Recovery and Reinvestment Act of 2009. The overall installation costs were about \$11.5M, including the oxygen supply facility. Operating costs are expected to be \$300K to \$500K annually. Operation of the JST Fish Habitat Enhancement System will allow the pumpback hydro turbines at RBR to operate without restriction, providing an excellent return on investment.

## **8.0 FACTS AND FIGURES**

The fish habitat oxygenation system includes two 20,000-gallon liquid oxygen tanks; twelve ambient air vaporizers; over 45,000 feet of HDPE pipe; and 4,000 concrete anchors. The system is capable of delivering up to 200 tons per day of oxygen to the reservoir. The diffusers extend over a mile from the oxygen supply facility.

## **9.0 OTHER STUDIES**

Several studies tracking the response of the fish to the new habitat are currently underway by various state agencies.

## **10.0 CONCLUSIONS**

Diffuser operation and oxygen distribution meeting performance goals under varying water quality and operational conditions were verified with reservoir monitoring during tests conducted in 2010. In June, the oxygen was distributed high in the water column utilizing the diffusers at the highest elevation. Diffuser choices were exercised throughout the summer to demonstrate the capability of the system to place oxygen in the desired elevation range. Design goals were maintained or exceeded in every set of profiles taken over the summer.

The oxygen plume was observed to spread uniformly east and west as it propagated towards the dam. Increased oxygen levels were spread almost bank to bank, providing a good correlation with 2D modeling that uses lateral averaging. Movement of the reservoir water by sustained wind events shifted the oxygenated volume several miles upstream of the diffusers (August 5 and 6). In some cases, the oxygenated volume was moved back and forth over the diffusers resulting in DO levels much higher than design goals (August 13).

The towed data and the forty-four data points collected on August 1 and 4, verifies even distribution of the oxygen content along the centerline of the reservoir. Therefore, it can be concluded that the data collected along the centerline is representative of the oxygenation of the reservoir and can be used to monitor operation of the system.

## **11.0 REFERENCES**

“J. Strom Thurmond Dissolved Oxygen System CE-Qual-W2 Modeling for Oxygen Diffuser Placement,” November 15, 2008, by Reservoir Environmental Management, Inc., under the administration of Dial Cordy and Associates, Inc.

“J. Strom Thurmond Oxygenation System Verification Tests and Results,” December 2010, by Mobley Engineering, Inc. and Gantzer Water Resources Engineering.

“J. Strom Thurmond Oxygenation System Operations Guide,” December 22, 2011, Loginetics, Inc., Reservoir Environmental Management, Inc., and Mobley Engineering, Inc.

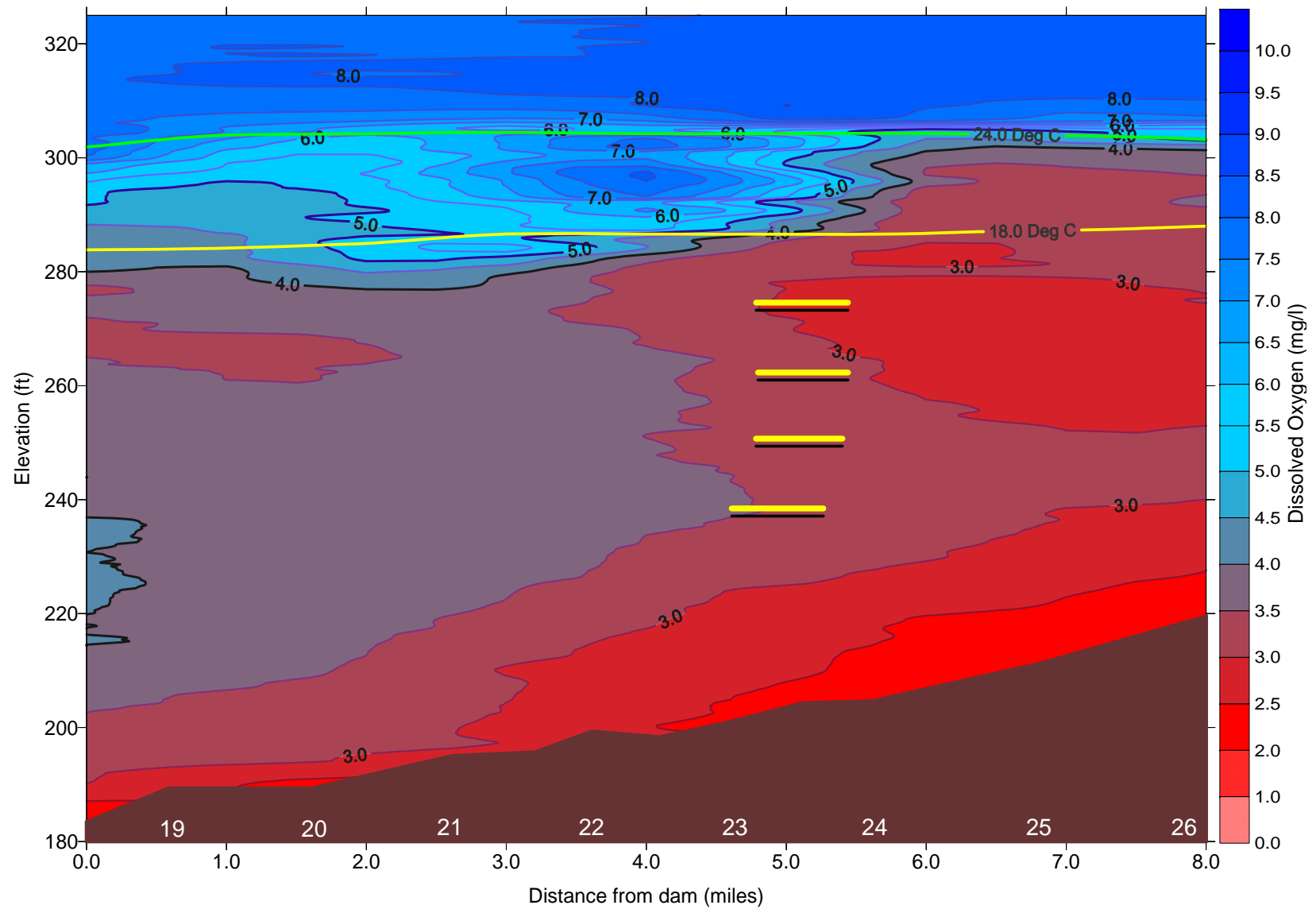


Figure 5.2: June 22, 2011 Diffuser #1 (400 SCFM, Elevation 274 ft.) and #4 (400 SCFM, Elevation 274 ft.)

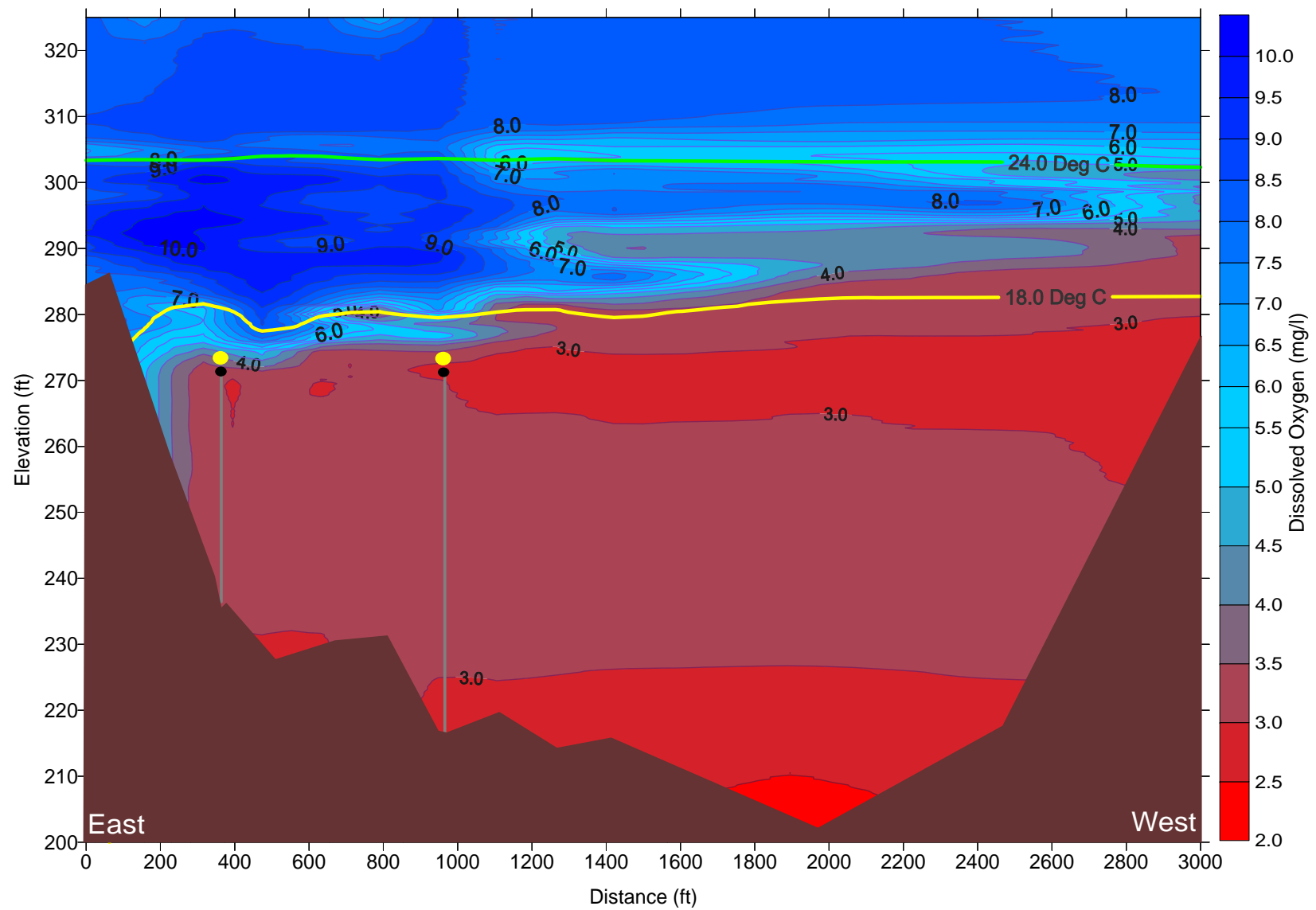


Figure 5.3: June 23, Profiles across the Diffuser Field, Diffusers #1 (400 SCFM, 274 ft.) and 4 (400 SCFM, 274 ft.)



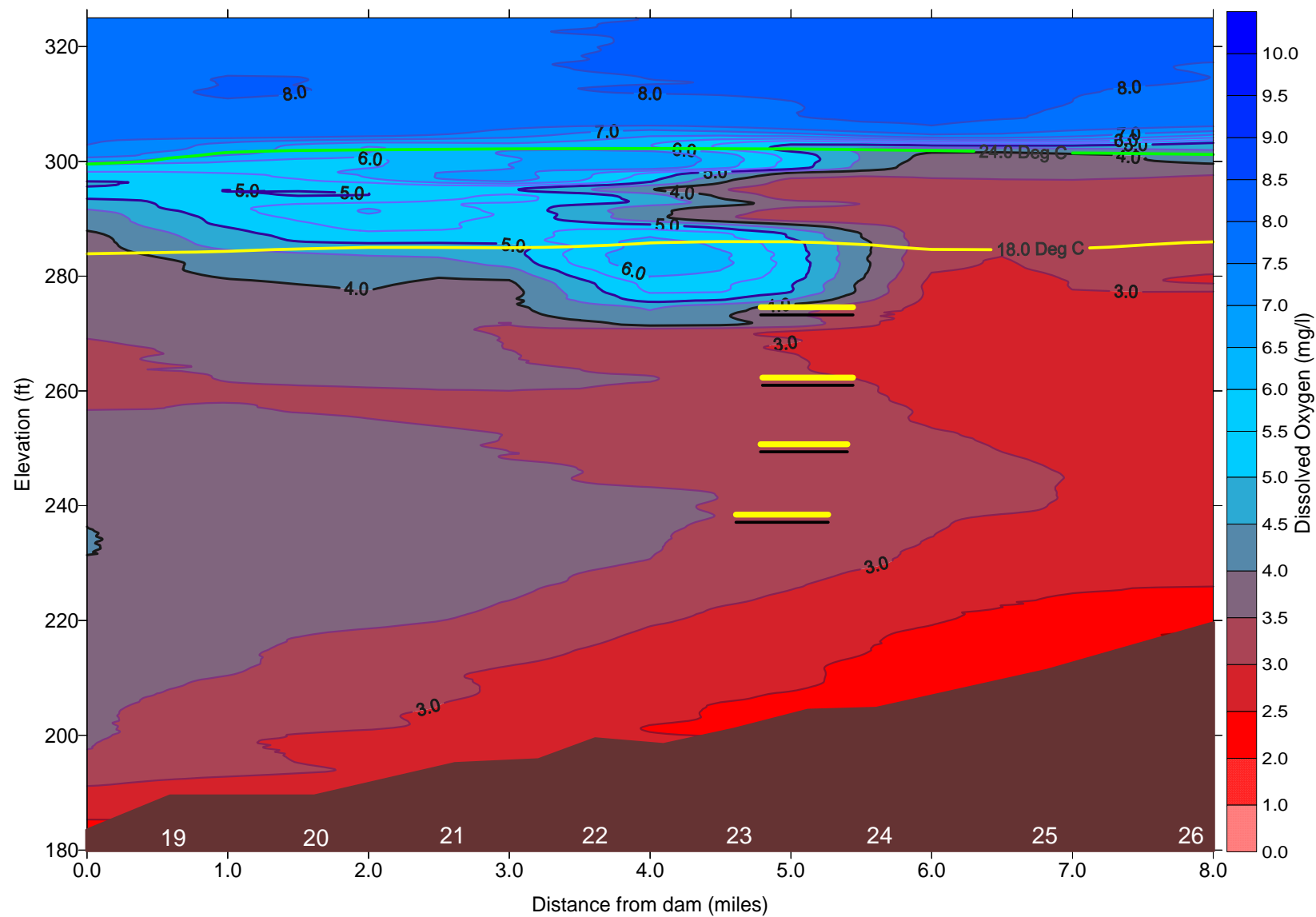


Figure 5.4: June 24, 2011 Diffuser #4 (200 SCFM, Elevation 274 ft.) and #7 (400 SCFM, Elevation 262 ft.)

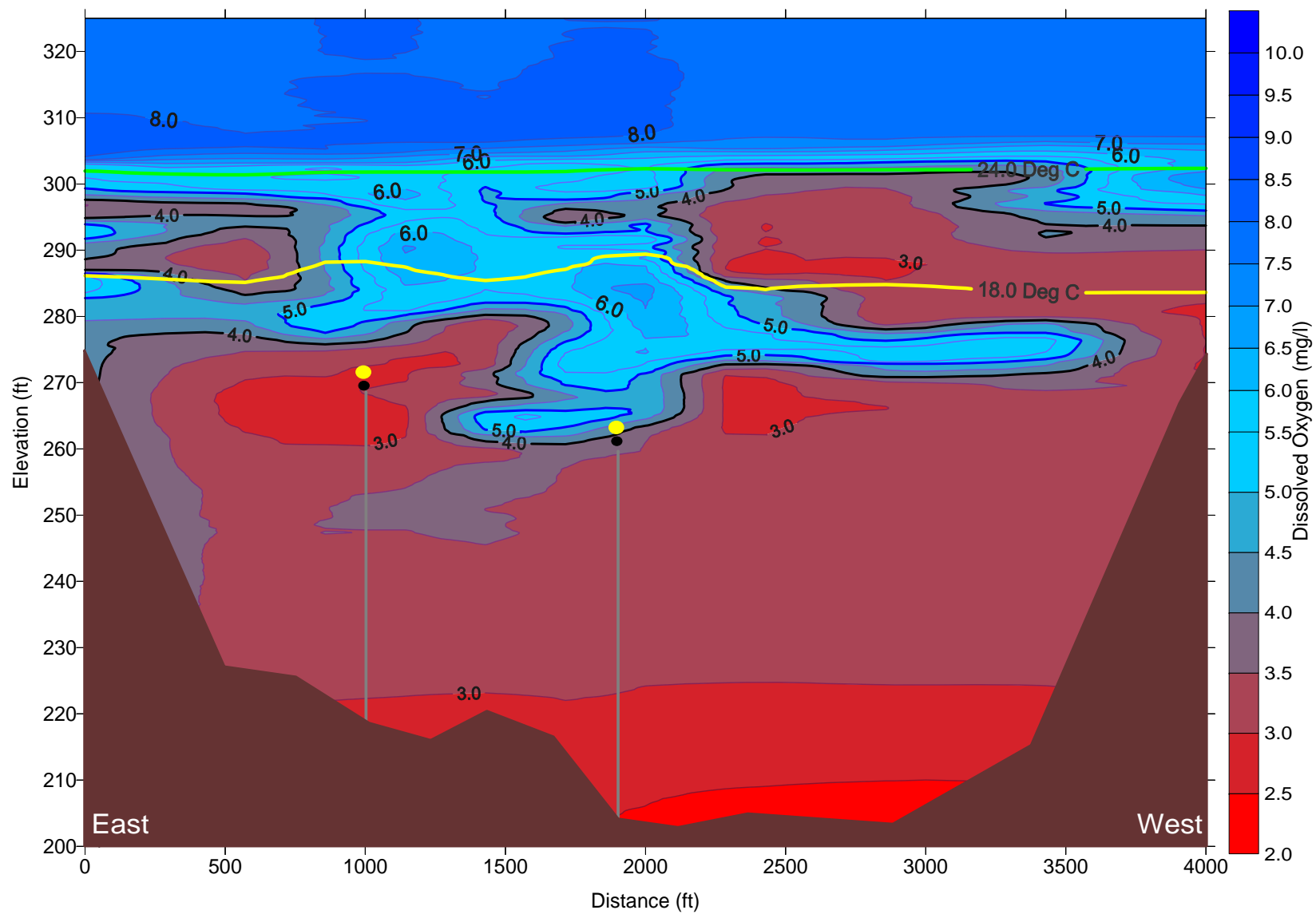


Figure 5.5: June 24, Profiles across the Diffuser Field, Diffusers #4 (200 SCFM, 274 ft.) and #7 (400 SCFM, 262 ft.)

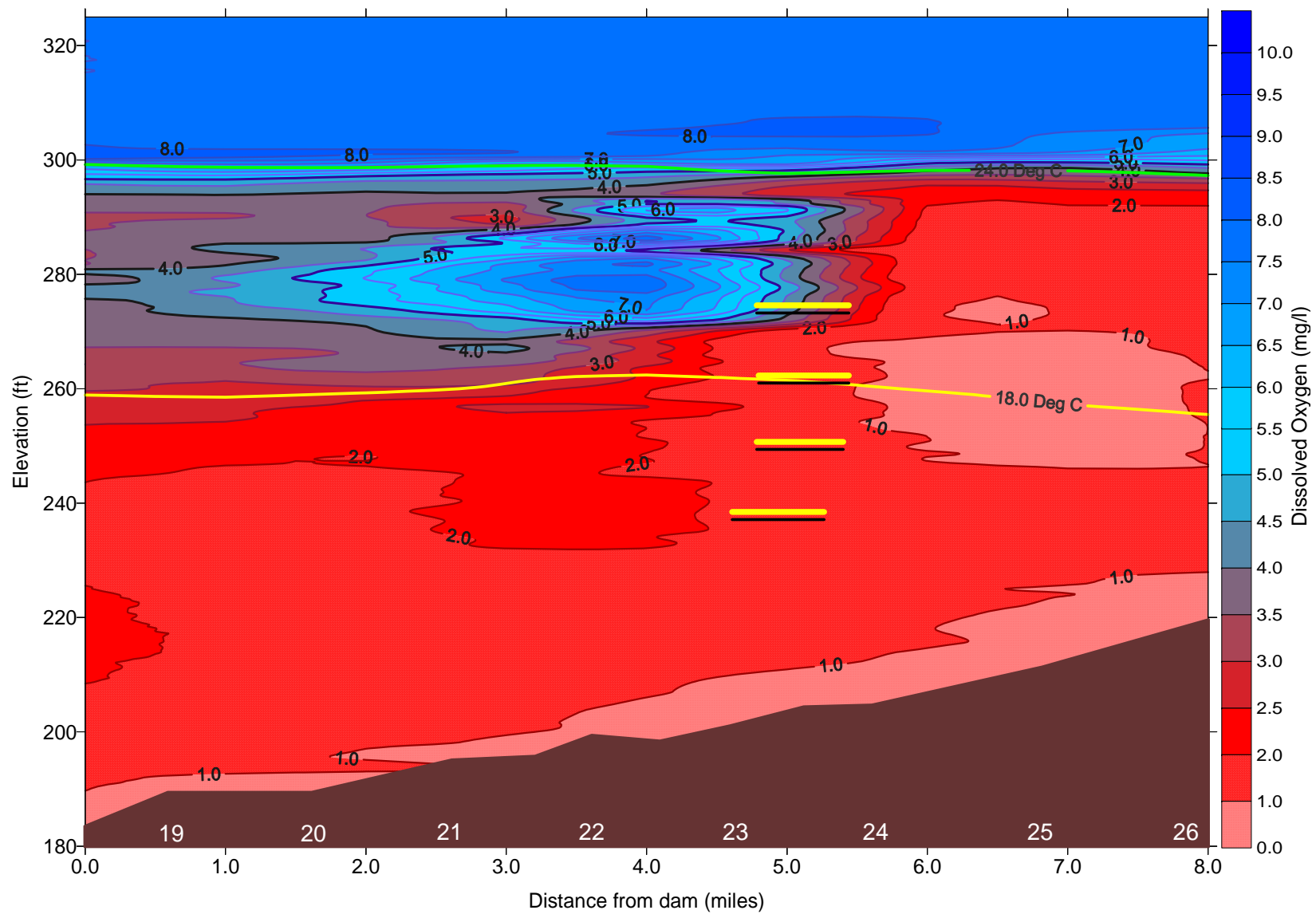


Figure 5.6: July 26, 2011 Diffuser #4 (200 SCFM, Elevation 274 ft.) and #7 (400 SCFM, Elevation 262 ft.)

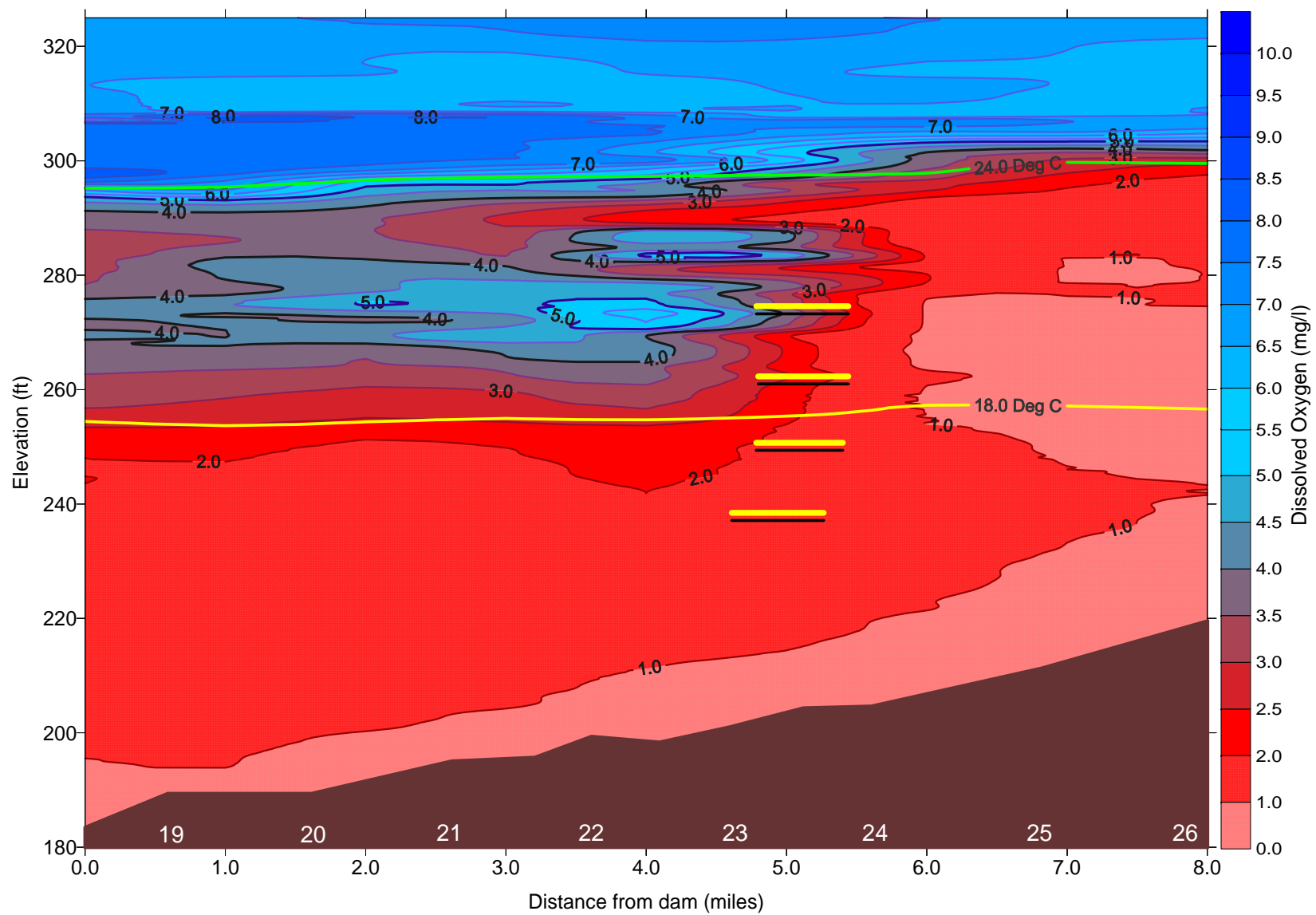


Figure 5.7: July 30, Diffuser #1 (100 SCFM, 274 ft.), Diffuser #2 (100 SCFM, 262 ft.) and #7 (400 SCFM, 262 ft.)

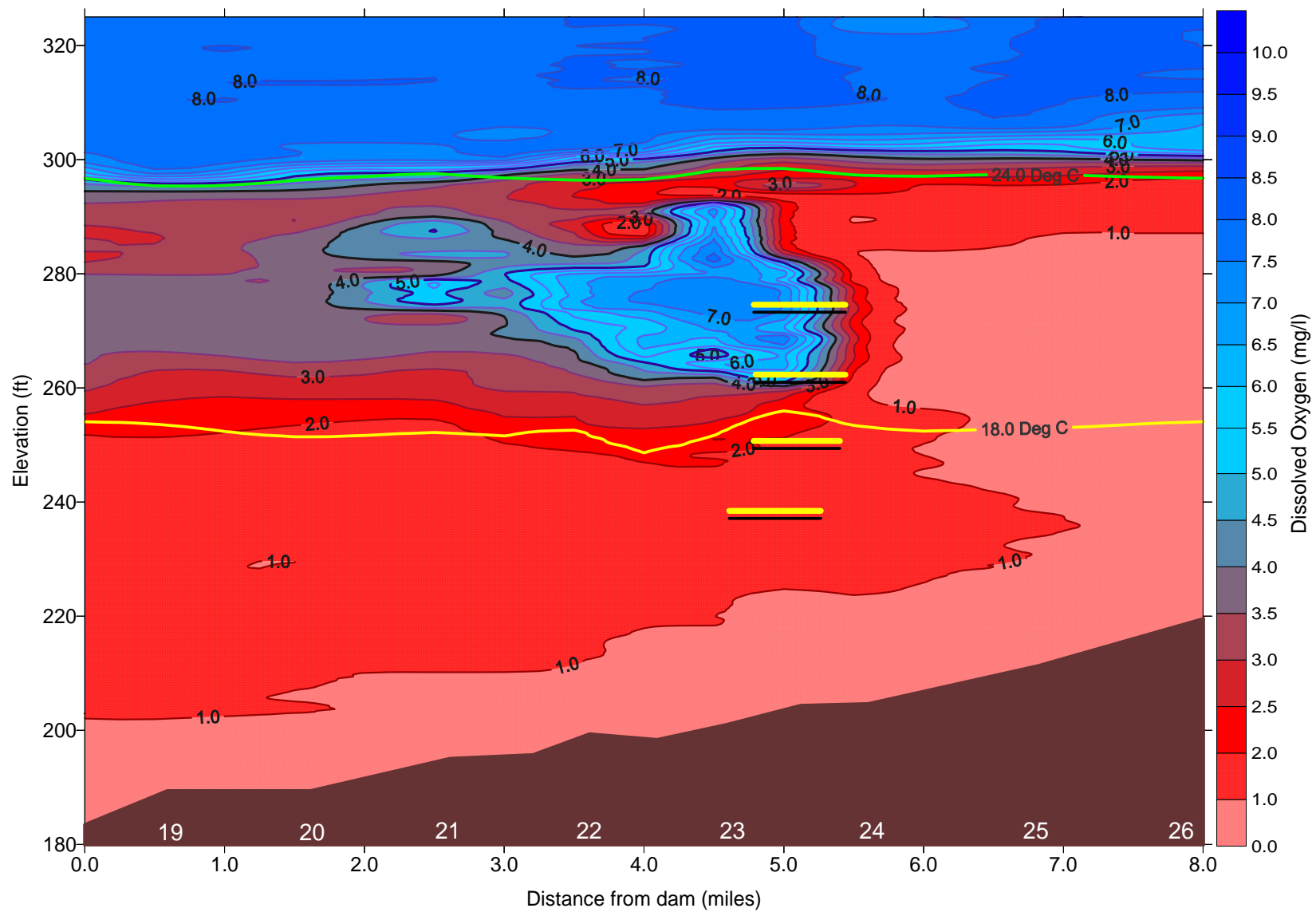


Figure 5.8: August 4, Diffuser #1 (100 SCFM, 274 ft.), Diffuser #2 (100 SCFM, 262 ft.) and #7 (400 SCFM, 262 ft.)



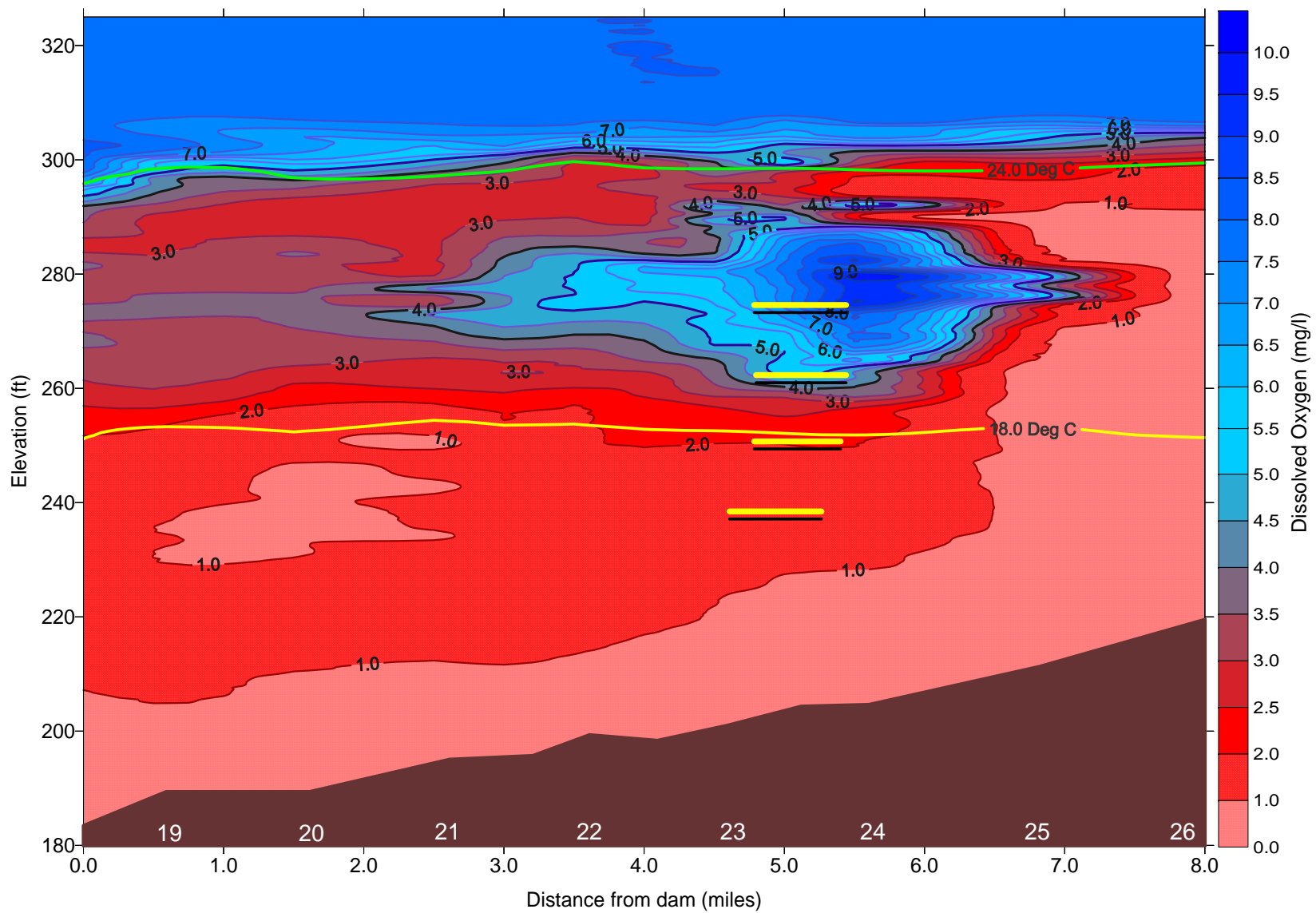


Figure 5.9: August 6, Diffuser #1 (100 SCFM, 274 ft.), Diffuser #2 (300 SCFM, 262 ft.) and #7 (300 SCFM, 262 ft.)

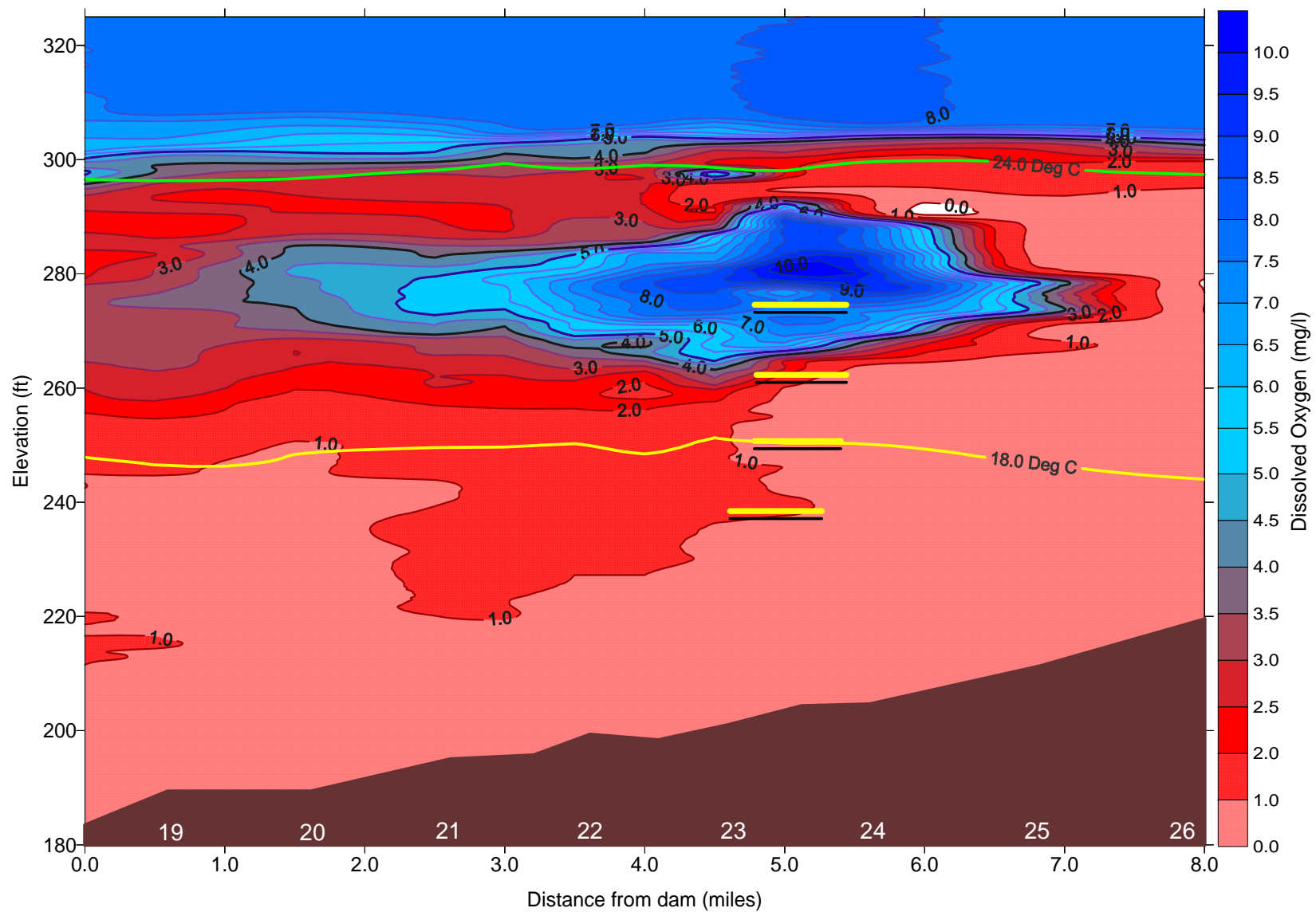


Figure 5.10: August 13, Diffuser #1 (100 SCFM, 274 ft.), Diffuser #2 (300 SCFM, 262 ft.) and #7 (300 SCFM, 262 ft.)

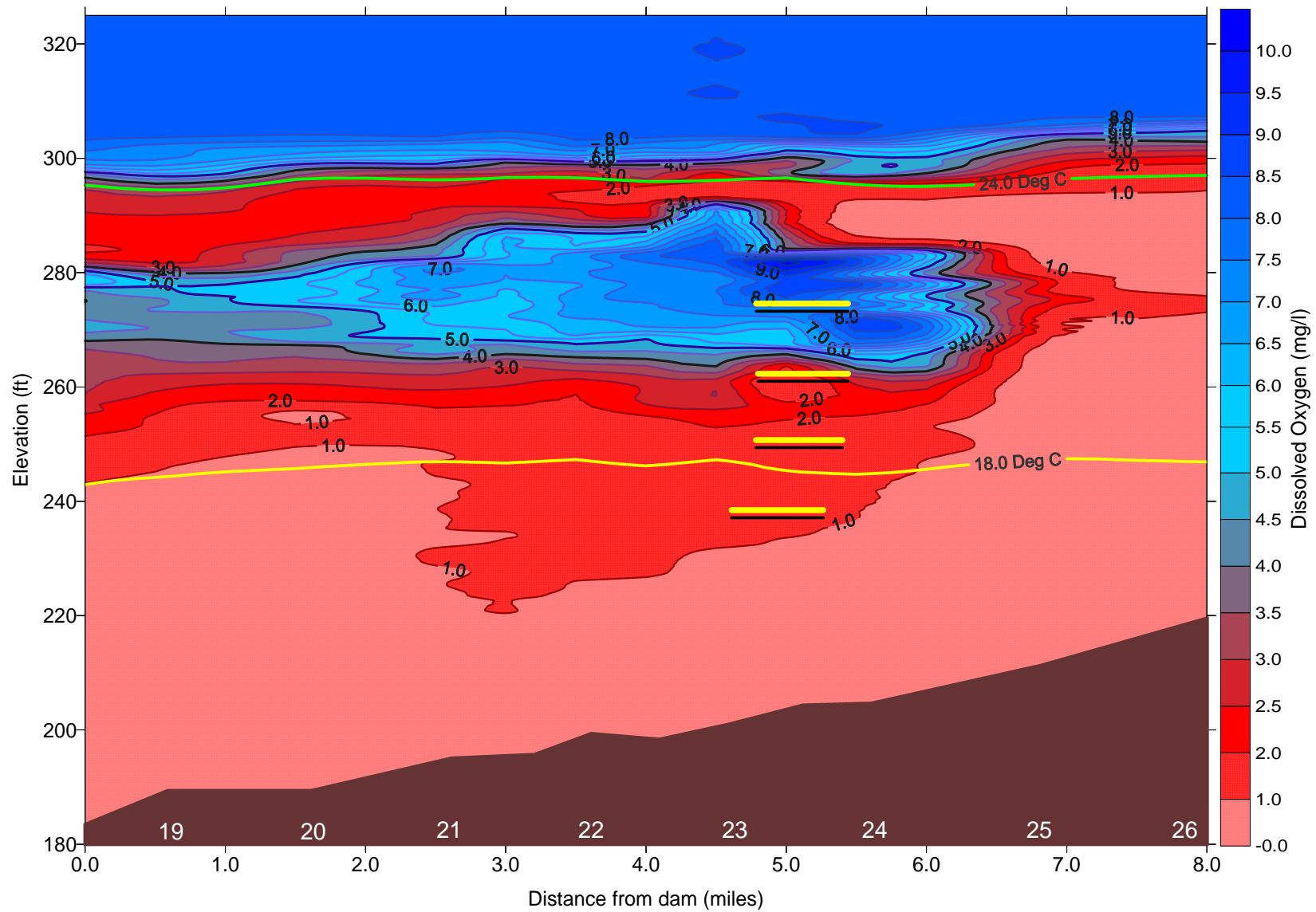


Figure 5.11: August 16, Diffuser #1 (100 SCFM, 274 ft.), Diffuser #2 (300 SCFM, 262 ft.) and #7 (300 SCFM, 262 ft.)

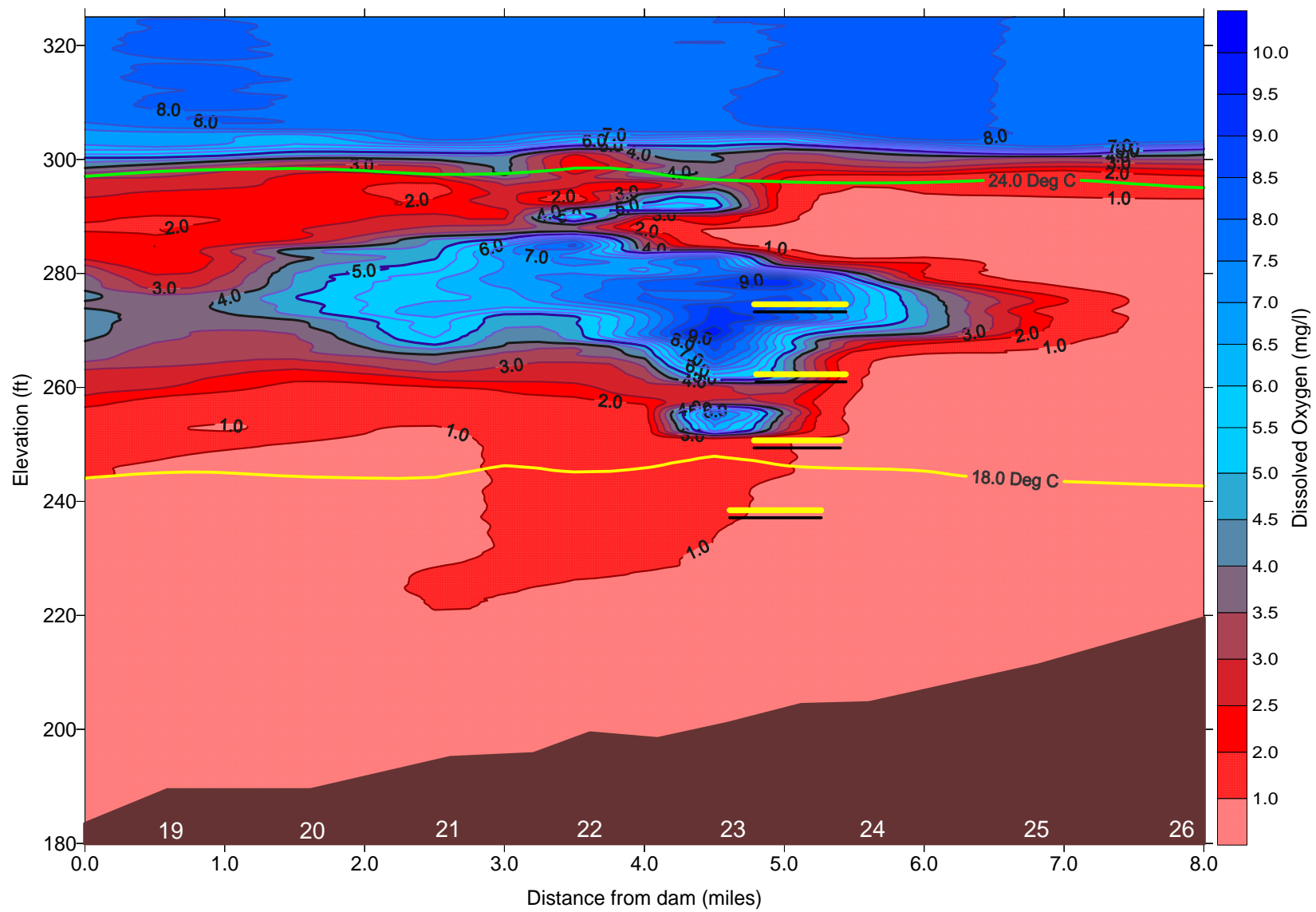


Figure 5.12: August 18, Diffuser #7 (200 SCFM, Elevation 262 ft.) and #8 (400 SCFM, Elevation 250 ft.)

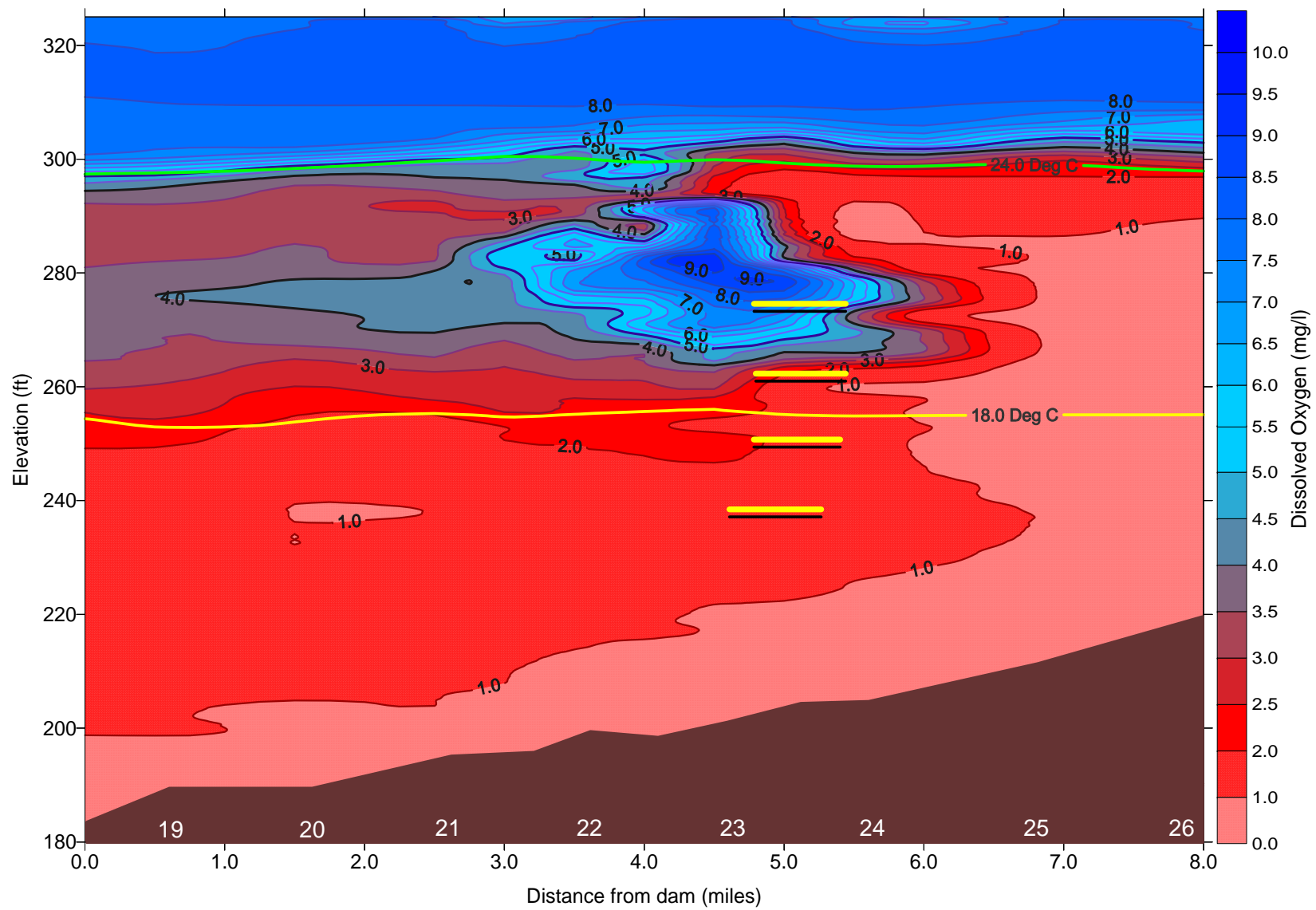


Figure 5.13: August 2, Diffuser #1 (100 SCFM), #2 (100 SCFM) and #7 (400 SCFM). Box Indicates the Region of Towed Array Data.

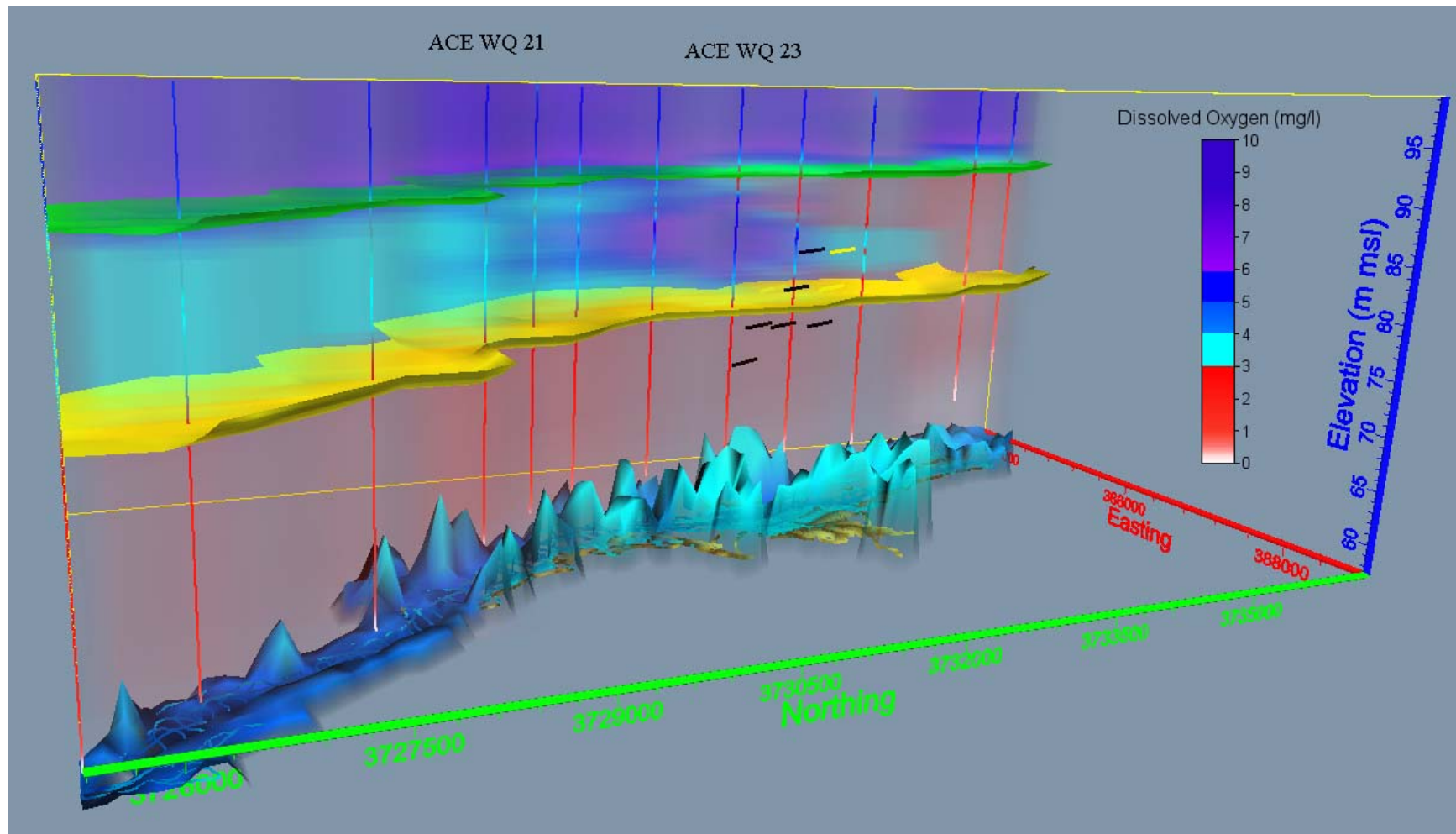


Figure 5.14: August 2 Data with the 18°C and 24°C Temperatures Represented as Yellow and Green.  
Diffusers #1, #4 and #7 at 100, 100 and 400 SCFM, Respectively. View Perspective Is Looking West.

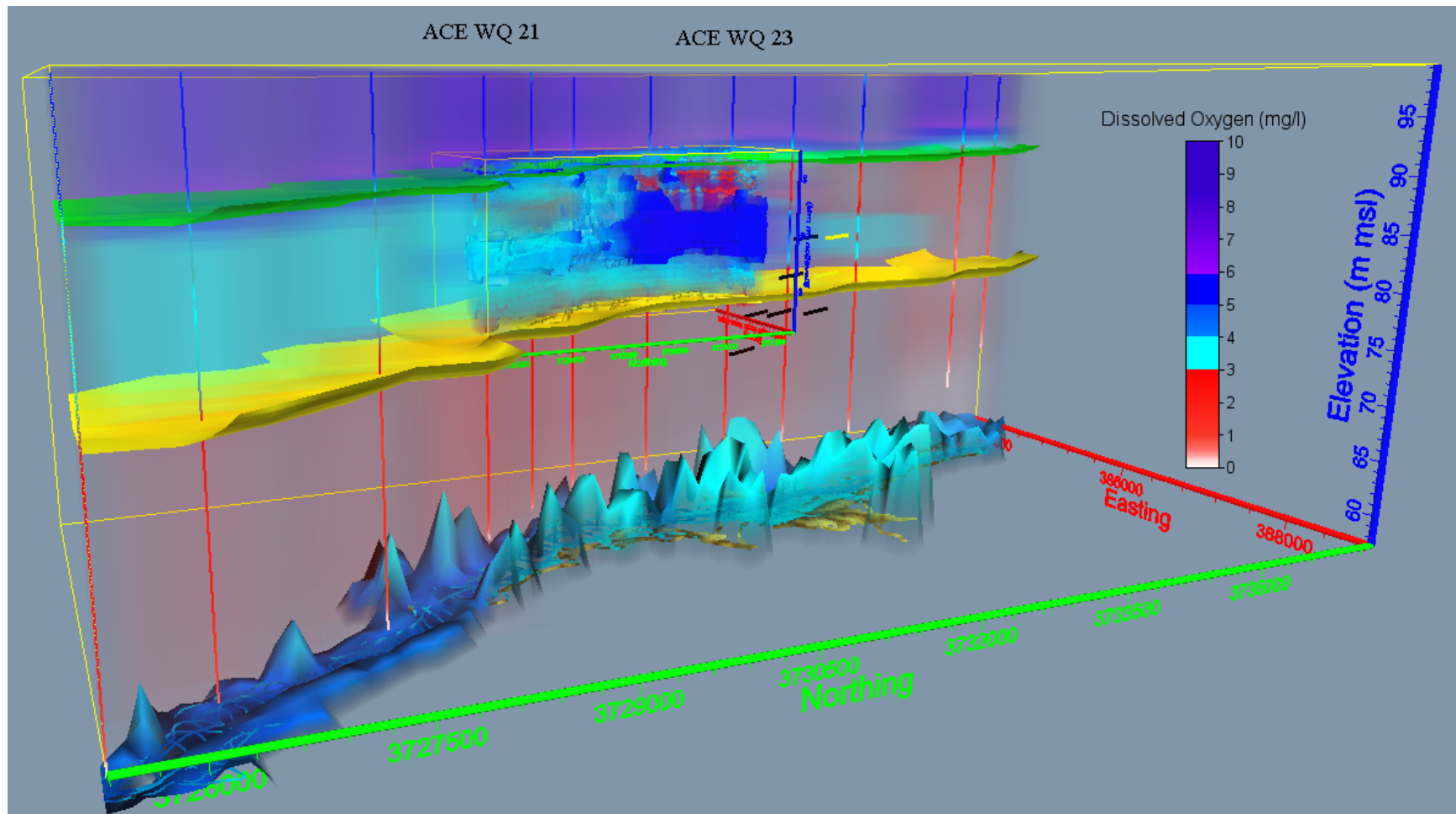


Figure 5.15: August 2 Towed Array Data Overlaid on Individual Profile Data.



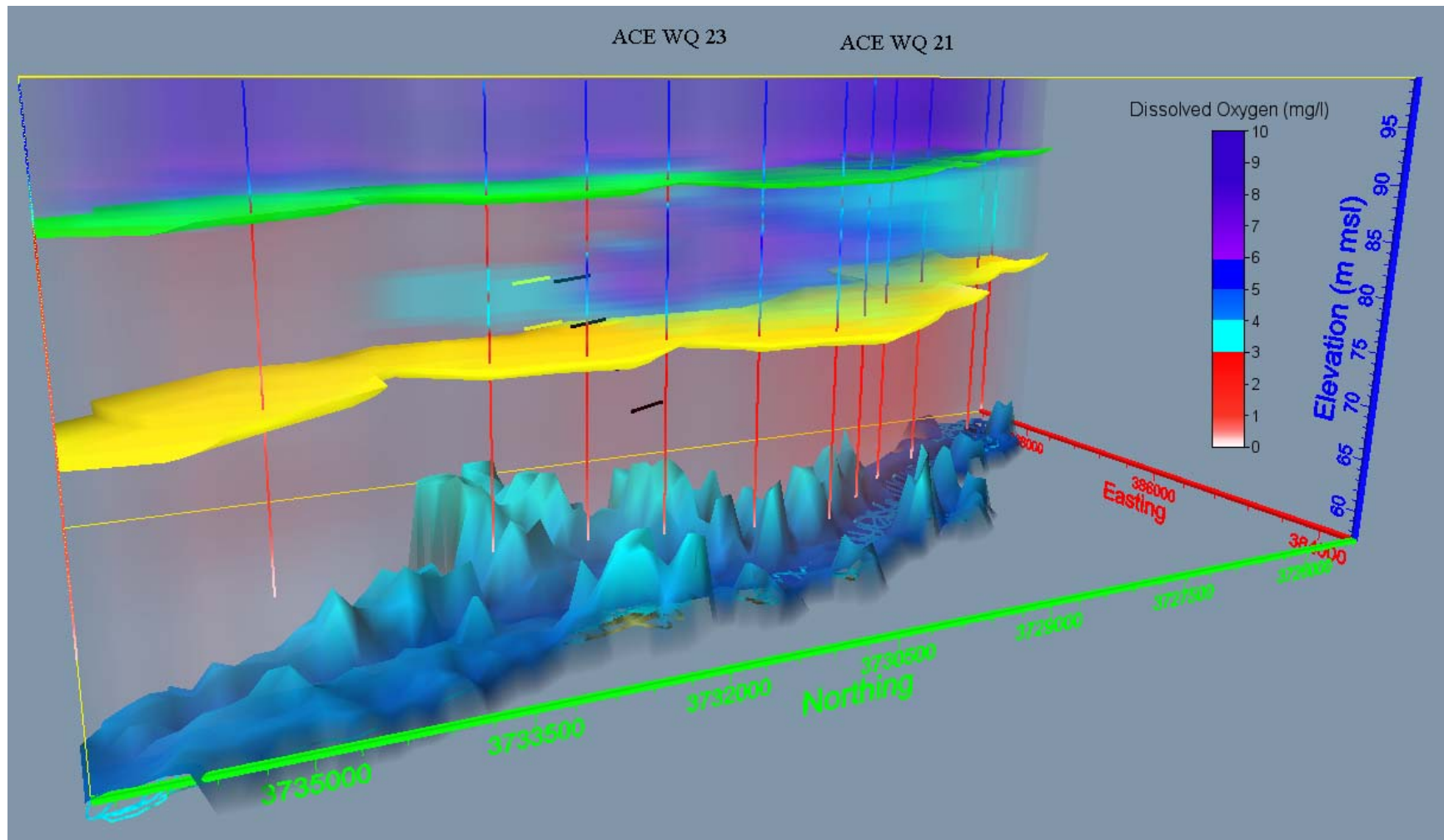


Figure 5.16: August 2 Data View Perspective is Looking East.

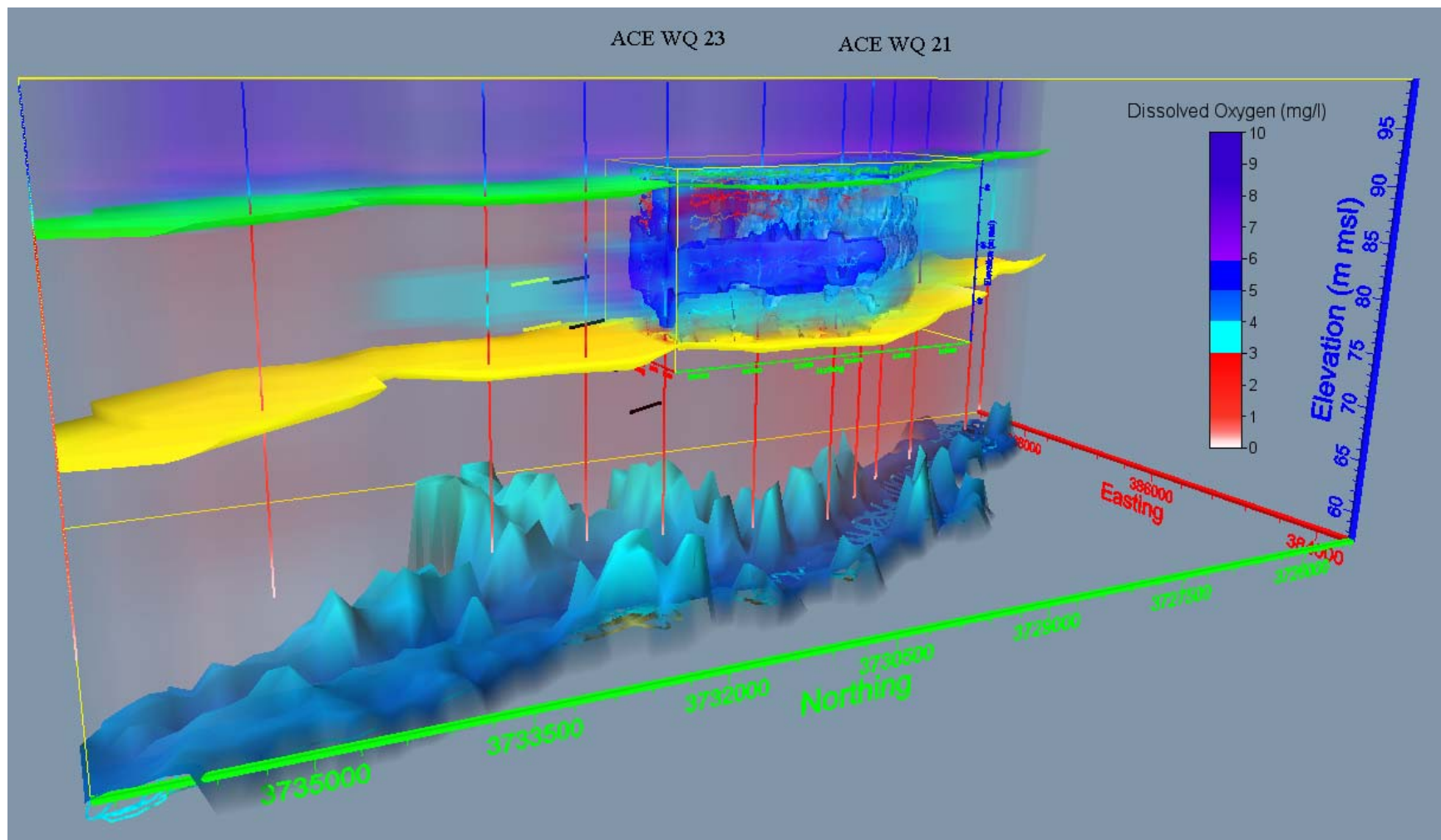


Figure 5.17: August 2 Towed Array Data Overlaid on Individual Profile Data. Perspective is Looking East

## **Author Biographical Sketches**

**Mark H. Mobley** is Vice-President of Mobley Engineering, Inc., providing design and installation services for reservoir diffuser systems for enhancement of hydropower and water supply reservoirs. Mr. Mobley received a B.S. degree in Mechanical Engineering in 1983 from Georgia Tech. He has over 25 years of experience designing, installing and testing reservoir and hydropower release enhancement systems, with 15 years at the Tennessee Valley Authority Engineering Laboratory and after founding Mobley Engineering in 1999.

**Paul A. Gantzer** received a Ph.D. in Civil Engineering and an M.S. in Environmental Engineering from Virginia Tech. He is the President of Gantzer Water Resources Engineering, LLC and specializes in water quality monitoring and oxygenation system modeling and design. He has over 13 years of experience mapping oxygen distribution and providing operational assistance following oxygen enhancement system installation.

**Gary Hauser** received a B.S. in Civil Engineering and M.S. in Water Resources Engineering from the University of Kansas, worked at the TVA Engineering Laboratory for 22 years, and founded Loginetics, Inc. in 1994. He developed mathematical models to solve problems related to hydrodynamics and water quality of rivers/reservoirs and conducted research and testing of release improvement approaches for hydroprojects. He is co-owner of two patents on aerating weir technology and author of EPRI's design guidance for aerating weirs.

**Jim Ruane** received a B.S. in Civil Engineering and an M.S. in Environmental Health Engineering from the University of Texas, worked in the TVA Water Quality Branch for 28 years, and formed Reservoir Environmental Management, Inc., in 1995. He specializes in water quality assessments, modeling, and management of major rivers and reservoirs. He has worked on over 130 large hydropower and water supply reservoirs.

**Jamie Sykes** received a B.S. in Aquaculture, Fisheries and Wildlife Biology from Clemson University and a Masters of Earth Resource Management from the University of South Carolina. He has worked 20 years with the Savannah District of the U.S. Army Corps of Engineers, including serving as the District Fisheries Biologist for the last eight years. His work often involves the interactions between reservoir fisheries and hydropower operations.