Long Lake HED Phase II Aeration Modeling Assessment of Alternatives

Prepared for Avista Corporation

July 2010

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1 Introduction

Avista is evaluating the best approach(s) to enhance dissolved oxygen concentrations (DO) in the turbine releases from Long Lake Hydroelectric Development (HED). A Phase I study (HDR, 2006) showed that the alternatives for enhancing DO at Long Lake HED included draft tube aeration, penstock aeration or oxygenation, tailrace aeration or oxygenation and forebay aeration or oxygenation.

Avista is now conducting a Phase II study of these alternatives. The first task is to apply modeling tools to determine the alternatives that are likely to be most effective. Modeling helps to determine the design and performance requirements for each alternative prior to field testing. The modeling approach also allows evaluating the comparative benefits of aeration versus oxygenation for feasible alternatives. The models predict the amount of air or oxygen that would be required to attain DO targets, the increase in DO, and nitrogen/TDG saturation levels. Modeling also identifies uncertainty so that field tests can be conducted to increase confidence in the design of full scale aeration systems. These tools were developed by the REMI team members and have been applied at over 20 hydropower projects (McGinnis and Ruane, 2007; Ruane and McGinnis, 2007; Mobley et al, 2000; Ruane et al, 2008).

The advantage of this approach is that by using models additional information and predictions will be developed to better understand which alternatives will likely be effective and those alternatives that are not likely to be effective. Field-testing is costly, and this approach can be used to eliminate alternatives that may not be effective. The modeling approach also allows evaluating the comparative benefits of aeration versus oxygenation for feasible alternatives.

Models Used for the Long Lake HED Assessments

WIZEGUY Model—Used to Compute Withdrawal Zone

WIZEGUY is a suite of modeling programs used to determine the withdrawal zone in the reservoir forebay and to predict the concentration of DO and temperature entering the penstock based on reservoir profile and unit flow data. The withdrawal zone is the area where water is actively moving into the penstock. The water quality in the withdrawal zone in the reservoir forebay controls the water quality in the releases from the turbines (the word "releases" as used in this report applies to water released from Long Lake HED when the turbine units are operating.) The withdrawal zone expands vertically with higher discharges and shrinks or is truncated vertically in the presence of density stratification. The withdrawal zone is also affected (truncated) by underwater barriers and by the geometry of the approach channel. It is necessary to determine the area where water is actively moving into the penstock for efficient design of the forebay aeration alternative. It is necessary to predict the temperature and dissolved oxygen concentration of water from the withdrawal zone entering into the reservoir penstock.

The one-dimensional withdrawal zone models, including TVA WITHDRAW (Wunderlich, W et al, 1969) and WES SELECT (Davis, J. E., et al., 1987 and 1992) , predict the vertical extent and distribution of layered withdrawals from a reservoir of known density distribution. This withdrawal zone is computed for a given discharge from a specified outlet. When discharge is from multiple outlets, superposition and boundary adjustments are performed to provide the combined withdrawal zone. The quality of water entering the penstock is then computed as a mixed concentration based on computed layer withdrawals and known vertical profiles of water quality in the forebay. Constituent mass is assumed to be conserved between the location of the vertical quality profile and the intake (i.e., no sources or sinks for the constituent are included). WIZEGUY displays results of the TVA, WES, and adjusted WES (as ADJ) models for comparison.

WIZEGUY computes withdrawal zones and reservoir release quality for user-supplied reservoir forebay thermal and water quality conditions and release flows. Withdrawal zone models are not reservoir water quality models. Their purpose is to compute withdrawal and release quality characteristics; they do not simulate far-field hydrodynamic and biochemical processes in a reservoir.

Minimum data inputs include: intake characteristics for each outlet; forebay profiles of temperature and DO; release flow for each outlet; and release temperature and DO.

Bubble Plume Model—Used for Forebay and Tailrace Aeration Modeling

A bubble plume model (BPi and BUBBLEP) was used to evaluate aeration/oxygenation of the reservoir forebay within the withdrawal zone and the tailrace.

BPi is the interface for BUBBLEP, a FORTRAN bubble plume model that has been incorporated into CE-QUAL-W2 v3. BPi was developed by Gary Hauser (Loginetics, Inc.). The BUBBLEP routine was originally developed for the TVA BETTER model by Dr. Ming Shiao (TVA Engineering Laboratory). This version of BUBBLEP was later debugged, updated, expanded to handle circular and rectangular plumes and incorporated into W2 v3 by Hauser, G. E. (2004).

BUBBLEP calculates hydrodynamic and water quality variables for a bubble plume that consists of a bubble-water inner core and an annulus of entrained water from the ambient reservoir. The model is based on integration of the governing equations for 7 fluxes (water, momentum, heat, dissolved oxygen, dissolved nitrogen, gaseous oxygen, and gaseous nitrogen) and 5 equations of state (pressure, water density, bubble-water mixture density, gas volume, bubble radius) based on Wuest, et. al. (1992). BUBBLEP simulates upwelling associated with air or oxygen plumes in a stratified ambient based on time-variant gas flow inputs and an initial bubble size. It includes bubble size changes that result from decompression and gas transfer as the bubbles rise and exchange gases with ambient water. Bubble slip velocity is related to bubble size.

Discrete Bubble Model (DBM)—Used for Penstock and Turbine Aeration Analysis

Air can be introduced into the turbine discharges from some projects at the entrance to the draft tube, immediately below or through the turbine. In these cases, the water is under a negative pressure (i.e., vacuum) as it exits the turbine and flows into the draft tube. At Long Lake HED ports in the draft tube would be opened and the negative pressure would draw air into the water as it enters the draft tube. The air-water mixture consists of bubbles that diffuse into the water as it flows through the draft tube and into the tailrace. Turbine venting has commonly been used to increase DO in the releases from hydropower projects. It is estimated that some form of turbine venting is currently used or is being planned at over 70 hydropower projects. It is usually the preferred aeration method wherever it is applicable because other alternatives are usually more costly (Mobley et al., 1995; Hauser (1996); Johnson et al., 1993; Harshbarger, 1997), and maintenance is simpler than for other options.

The discrete bubble model (DBM) for turbine aeration is a tool that assists in understanding and quantifying the major factors that affect aeration in draft tubes and their associated tailraces. It accounts for the effects of draft tube geometry, tailrace elevation, unit water flow, air flow, first-order gas transfer processes including mass transfer, and the derived bubble size for the air-water mixture in the draft tube.

The DBM includes a mechanistic description of the factors affecting gas transfer as described below which allows for a good prediction of DO increases for conditions beyond those for which data can be obtained (i.e., DO uptake at higher airflows when increasing venting on current turbines or considering new aerating wheels; for new draft tubes at proposed power houses.) The DBM also offers the capability to test sensitivity of mass-transfer and initial bubble size to predicted conditions.

The DFM is the foundation of the turbine aeration model and predicts gas transfer (both dissolution and stripping) across the surface of individual bubbles and simultaneously tracks both gaseous (bubble) and dissolved nitrogen and oxygen, but can easily include more gases (e.g., methane). The basic model equation has been described by the following publications; McGinnis and Little, 2002; Wüest et al., 1992; McGinnis, D.F., et al., 2004.

Overview of Modeling Approach

1. **Analyzed Water Quality Data to Develop Design Inputs for Aeration Systems.** The available data were analyzed to determine flow rates and levels of DO, TDG, DN, and temperature. These data were then used to assemble input datasets for modeling each of the alternatives.
2. **Determined the Forebay Withdrawal Zone.** The withdrawal zone model (WIZEGUY) was used to determine the forebay withdrawal zone (the area in the forebay where water actively flows into the turbines).
3. **Evaluated the Forebay Aeration/Oxygenation Alternative.** The bubble plume model (BPi) was used to evaluate aerating/oxygenating the forebay withdrawal zone. This option involves dissolving air or oxygen into the withdrawal zone of the reservoir to increase DO.
4. **Evaluated the Penstock Aeration/Oxygenation Alternative.** DBM was used to evaluate aeration/oxygenation in the penstock system. Under this option air or oxygen is injected into the penstock and allowed to diffuse into the solution as water flows through the penstock, turbine, draft tube, and tailrace. The penstock geometry

data and the water flow rates through the penstock and turbine were used to develop time-pressure curves for input to the DBM. The bubble size for the penstock aeration system was estimated assuming a typical diffuser system.

5. **Evaluated Turbine Aeration.** The model DBM was set up to evaluate aeration of the draft tube of the turbine units. The draft tube drawings were used to generate the draft tube geometry and time-pressure input. Experience at other hydropower projects that had similar draft tubes was considered for developing settings for bubble size as input to the DBM. A draft tube airflow model was used to estimate the amount of air flow that can be expected into the draft tube. DBM was then used to determine the rate of DO, DN, and TDG uptake.
6. **Evaluated Tailrace Diffuser Oxygenation/Aeration.** BPi was used with temperature and DO data, as well as tailrace geometry and tailrace elevation data, to evaluate the effectiveness of a tailrace aeration and oxygenation diffuser system.

2 Water Quality Analyses for Aeration Designs

Water quality data were collected during the periods of low DO at Lake Spokane Reservoir and the Long Lake HED discharge during 1991, 1999-2001, and 2007.

Physical Characteristics of Long Lake HED and Lake Spokane

A summary of the physical and water quality characteristics of Lake Spokane and Long Lake HED is presented below.

- Volume of reservoir: 148,500 ac-ft; useable storage is above elevation 1,512 ft NAVD 88 datum and is 105,000 ac-ft.
- Surface area of reservoir: 5,060 acres at normal full pool (elevation 1,536 ft).
- Spokane River drainage area above Long Lake HED: 6,020 square miles.
- Maximum reservoir depth in forebay: about 180 ft.
- Elevation of penstock intake: Ranges from 1491 to 1507 ft (16-ft diameter penstock) and centerline is at elevation 1499, about 37 feet below the surface of the lake.
- Period when DO at Long Lake HED discharge is usually less than the regulatory standard of 8 mg/l: August through September (also October in some years).
- Lowest DO concentration at Long Lake HED discharge: 5-6 mg/l based on 1999-2001 and 2007 monitoring data.
- Average flow downstream from Long Lake HED during the period when DO can be less than 8 mg/L: 1833 cfs (based on August-September data for the years 1999-2001 and 2007)
- Nominal residence time through the reservoir during the low DO period (August–September): 35 days
- Peak turbine discharge: Normal peak operating level is 1,575 cfs for each unit (1,850 cfs max).
- Total turbine discharge from the power plant: about 6,300 cfs.
- Peak power capacity for individual units: 17.46 MW for units 1-3 and 19.21 MW for unit 4.

- Spring, summer, and autumn reservoir operations: The water in the reservoir is generally held within 1 foot of full pool (1,536') for the months of May through December.
- Winter operations: Water is passed through turbines up to the full capacity and excess flow is spilled.
- Tailrace water surface elevation (TWE): minimum elevation is 1,362 ft; during generation TWE is 1,363 ft for the turbine flows up to 4,000 cfs (i.e., for one-two unit operations) and 1,364 ft for turbine flows up 6,600 cfs (i.e., for three-four unit operations).

Regulatory Standards for DO, Temperature and TDG in Long Lake HED Discharge

The following are the Washington State water quality regulatory standards for DO, temperature and TDG for the discharge from Long Lake HED as per WAC 173-201A:

- ***Dissolved Oxygen*** 8.0 mg/l minimum
- ***Temperature*** Less than 20 degrees C and no increase more than 0.3 degrees C above background in addition to anti-degradation criteria cited in WAC 173-201A
- ***Total Dissolved Gas*** Not greater than 110 percent of saturation concentration.

The following are the Spokane Tribe water quality regulatory standards for DO and temperature. These apply from the upstream Spokane Indian Reservation boundary at RM 32.7 and downstream to the mouth of the Spokane River.

- ***Dissolved Oxygen*** greater than 8.0 mg/l
- ***Temperature*** **June 1–September 1:**

  < 18.5^{o} C 7-day average of daily max. temp.,

  September 1–October 1 and April 1–June 1:

  < 13.5^{o} C 7-day average of daily maximum temperature, < 18.5^{o} C daily maximum temperature

  October 1–April 1:

< 11° C 7-day average of daily maximum temperature, < 18.5 C° daily maximum temperature

- ***Total Dissolved Gas*** Not greater than 110 percent of saturation concentration.

Overview of Flow Conditions at Long Lake HED, 1985-2009

Figure 2-1 shows the average annual flow below Long Lake HED for January through December and July through September time periods from 1985 through 2009. Figure 2-2 shows these same years plotted in order of highest to lowest July through September average flow below the dam..

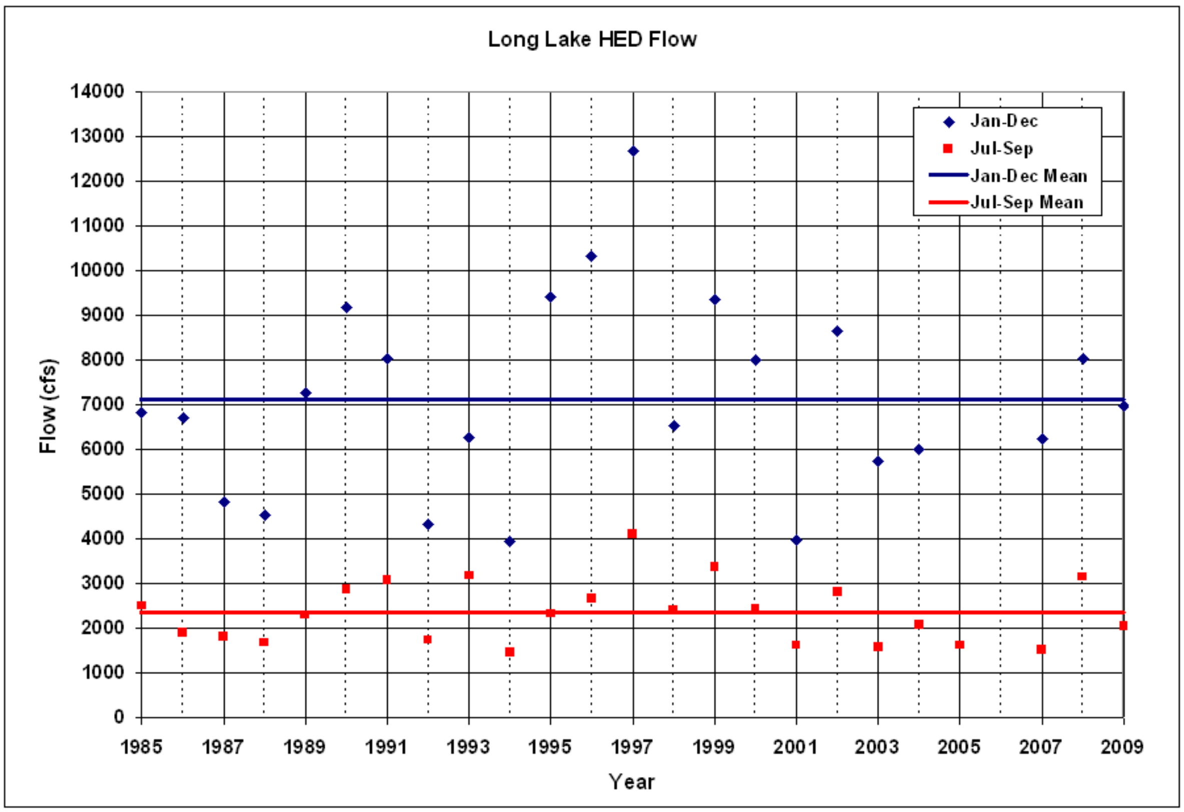


Figure 2-1 Average Annual flow and July-September flow downstream from Long Lake HED

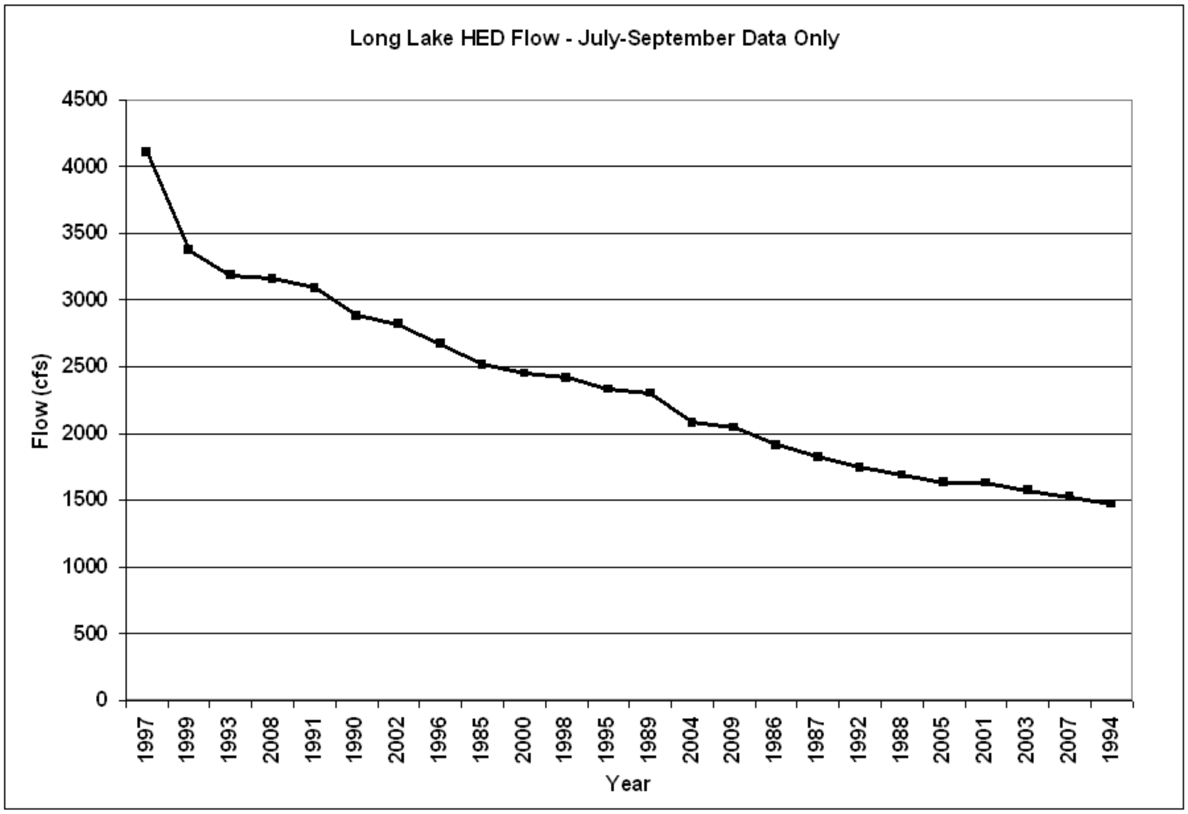


Figure 2-2 Annual Rankings of July-September flows downstream from Long Lake HED

Overview of Flow Conditions at Long Lake HED

Figure 2-3 provides an overview of daily average flow conditions downstream from Long Lake HED for the years 1999 through 2001 and 2007, the years that continuous water quality instruments were placed on the tailwater. Figure 2-4 shows plots of flow frequency for each of these years based on hourly flow data for the tailwater. This figure shows that hourly flows in 1999 had a greater frequency of high generation flows (e.g., exceeding the capacity of three turbine units), i.e., in 1999 20 percent of hourly flows exceeded 5,500 cfs; in 2000, 5-10 percent of hourly flows exceeded 5,500 cfs; and in 2001 and 2007, less than 5 percent of hourly flows exceeded 5,500 cfs. It is also apparent from Figure 2-4 that Long Lake HED is usually operated for generation using two to three units.

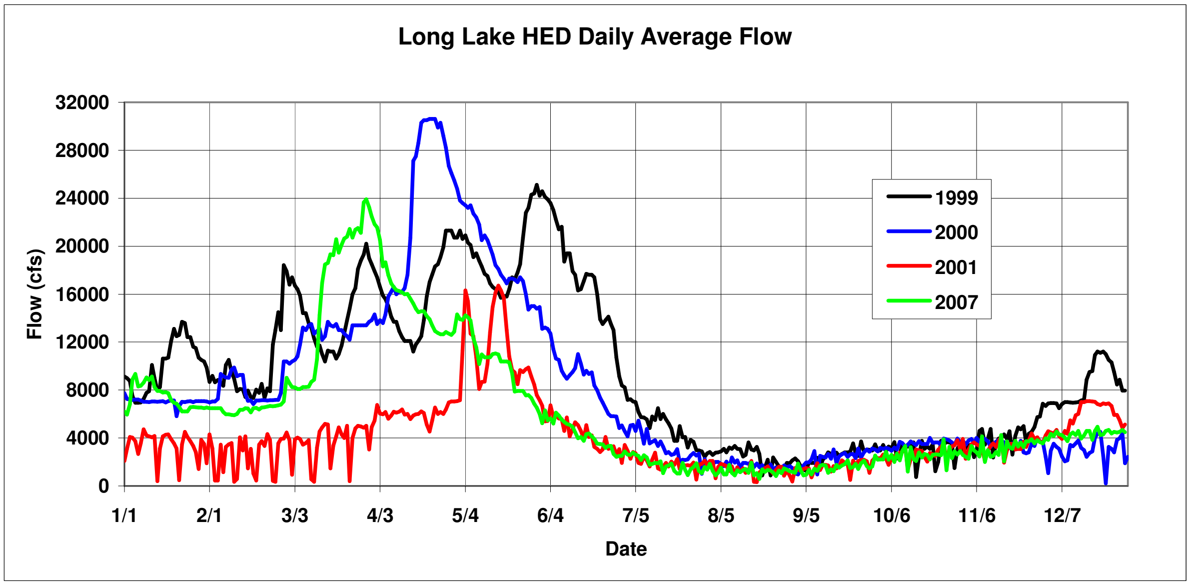


Figure 2-3. **Daily average flow (cfs) conditions downstream from Long Lake HED for the years 1999 through 2001 and 2007**

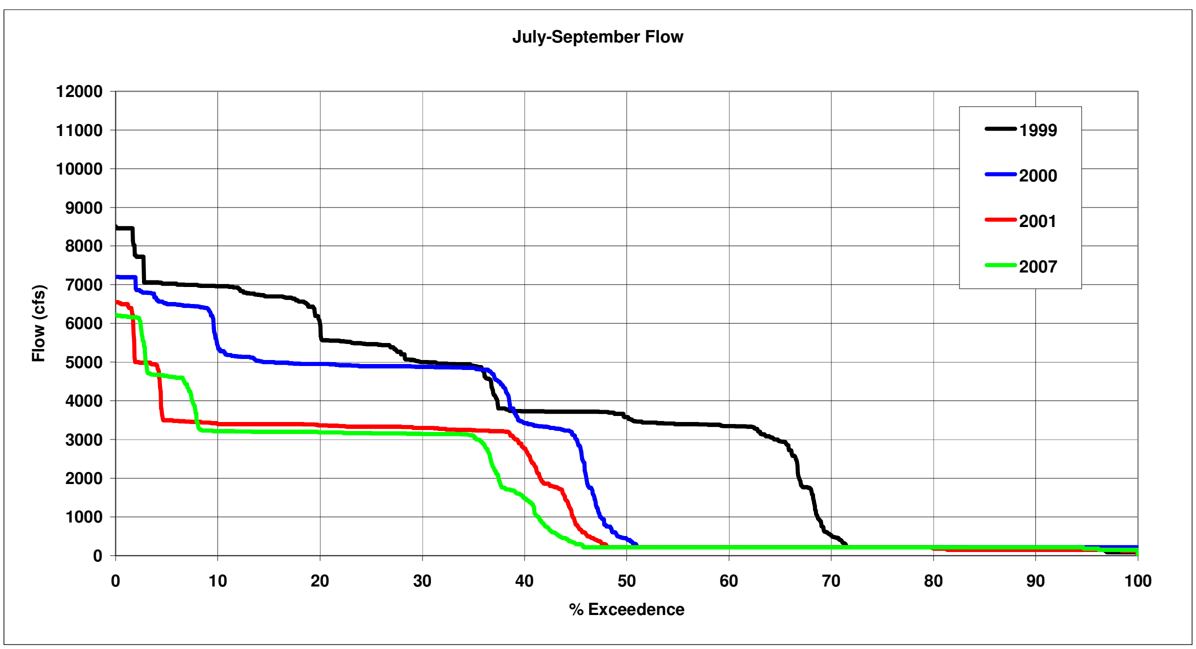


Figure 2-4. **Frequency of Exceedance for Hourly Flows Downstream From Long Lake HED During the Months July-September for the Years 1999-2001 and 2007**

Water Quality in the Forebay

Figures 2-5 through 2-7 show the available profiles of DO and temperature data collected in 1991 (a high flow year), 2000 (a normal flow year) and 2001 (a low flow year). These plots show how temperature and DO varied vertically in the forebay of Long Lake for these years. A typical withdrawal zone for water drawn from the lake during generation during the period of summer stratification when DO is low is depicted in Figure 2-8. This figure shows that water is withdrawn from the forebay to a lower depth of about elevation 1,450 ft based on velocity profiles for the WES and ADJ models, and perhaps deeper based on the TVA model, in August and September. As a point of reference, the centerline of the penstock intakes is at elevation 1,499 ft. The results of all the WIZGUY model runs are more fully presented in the Appendix A. Two observations discussed in the Appendix include 1) the WES and ADJ models are apparently more representative for the Long Lake application, and 2) the WIZEGUY results indicate that DO currently increases by about 1 mg/L as water passes from the forebay to the downstream DO monitor when DO is low in the releases.

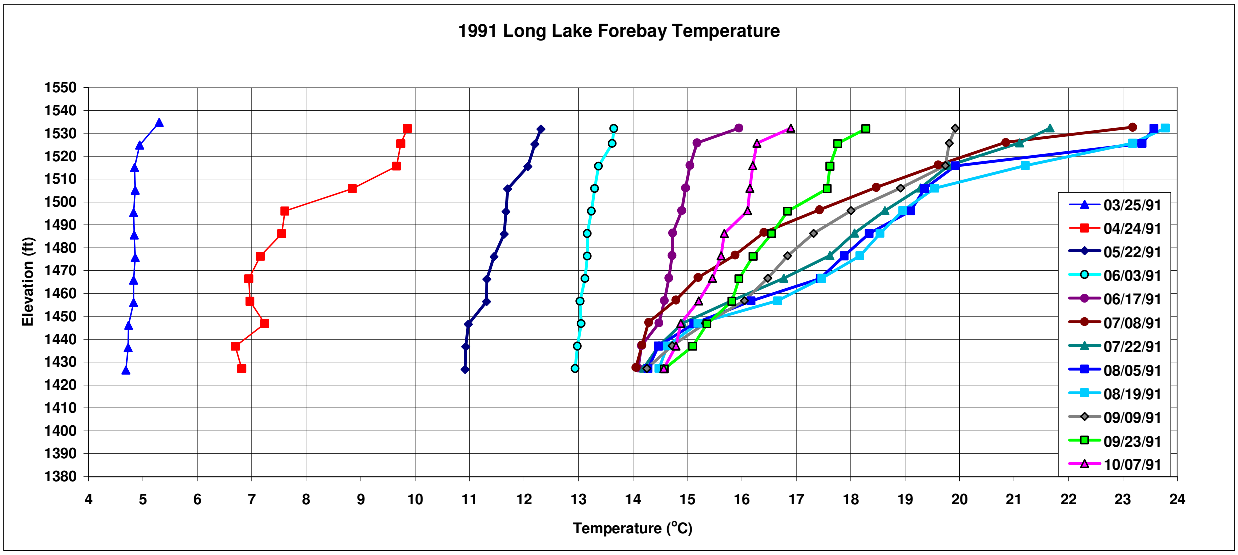
The following observations can be made about the available profiles of DO:

The available profile data indicate that minimum DO in the withdrawal zone (e.g., at elevations greater than 1450 ft) was about 3 mg/L in mid-September 1991, 4 mg/L in mid-August to mid-September 2000, and 3 mg/L in late August 2001.

Considering that the outlets at Long Lake HED are near the surface of the lake and the bottom temperatures in the lake at elevations less than 1450 ft increase between winter and mid-summer, it was important to examine why the temperature increased so as to rule out potential leakage of low DO water to the tailrace. The following reasoning is provided to show that leakage is not a likely concern.

1. In 1991, water temperature near the bottom of the forebay (Figure 2-5) increased at the rate of about 3C^{o} per month from March until about July and then increased less than 1 C^{o} per month in July through September. This change in rate of temperature increase was probably caused by the drop in total project flows between June and July (i.e., see Figure 2-3 and note that flows in 1991 were high like those shown for 1999 and 2008.)

2. In the low flow year 2001, the bottom temperatures were lower than in the other two years with profiles—this cooler water probably was caused by less water being withdrawn from the bottom of the lake compared to the amount of water released in 1991 and 2001.
3. These last two observations indicate that the warming of the bottom of the lake is not caused by leakage of cool water from the bottom



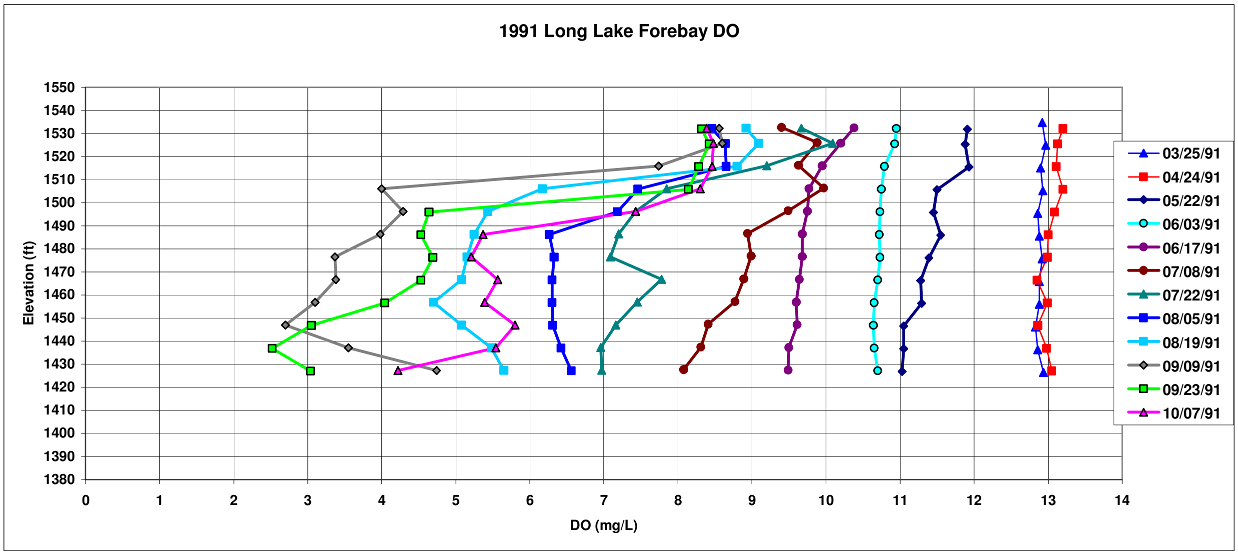
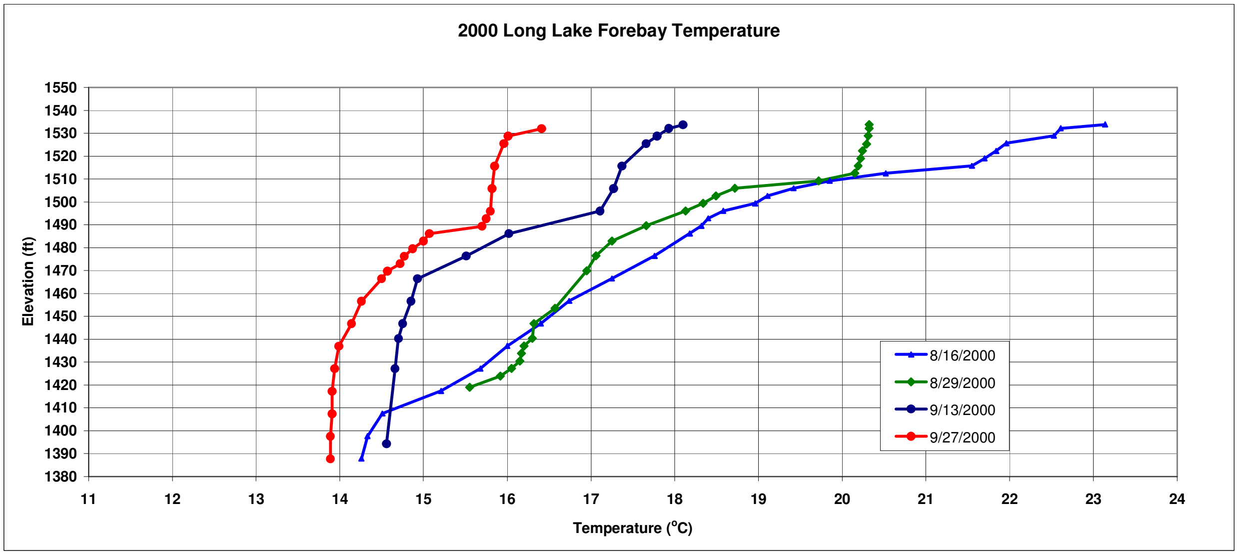


Figure 2-5. Forebay profiles of temperature and DO for 1991 at Long Lake HED (Note: the centerline for the intake is at elevation 1499 ft, and the water surface was near full pool elevation.)



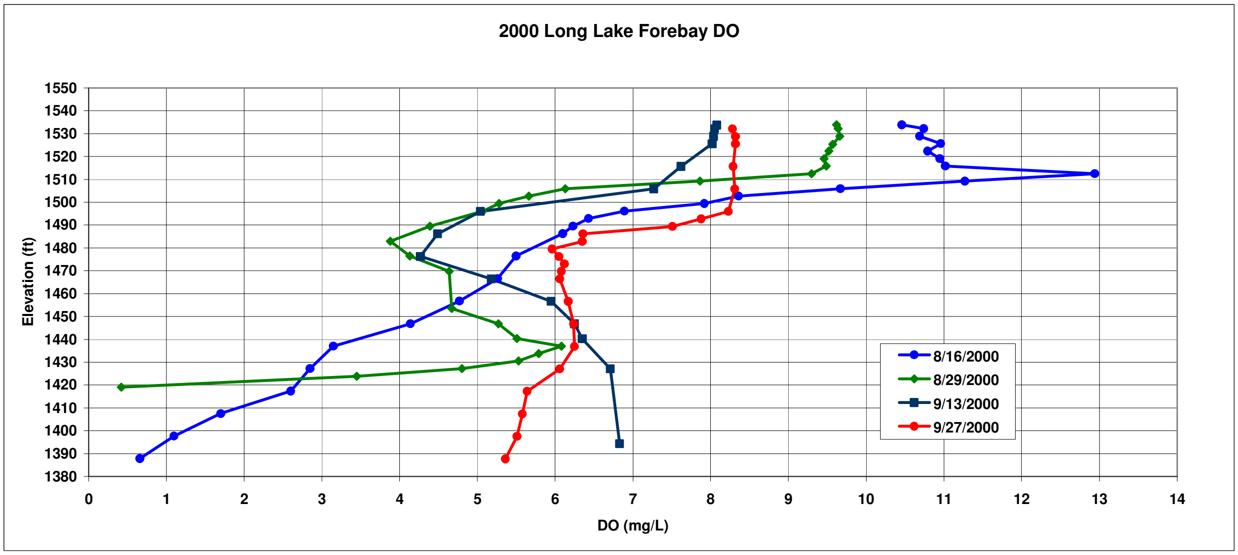
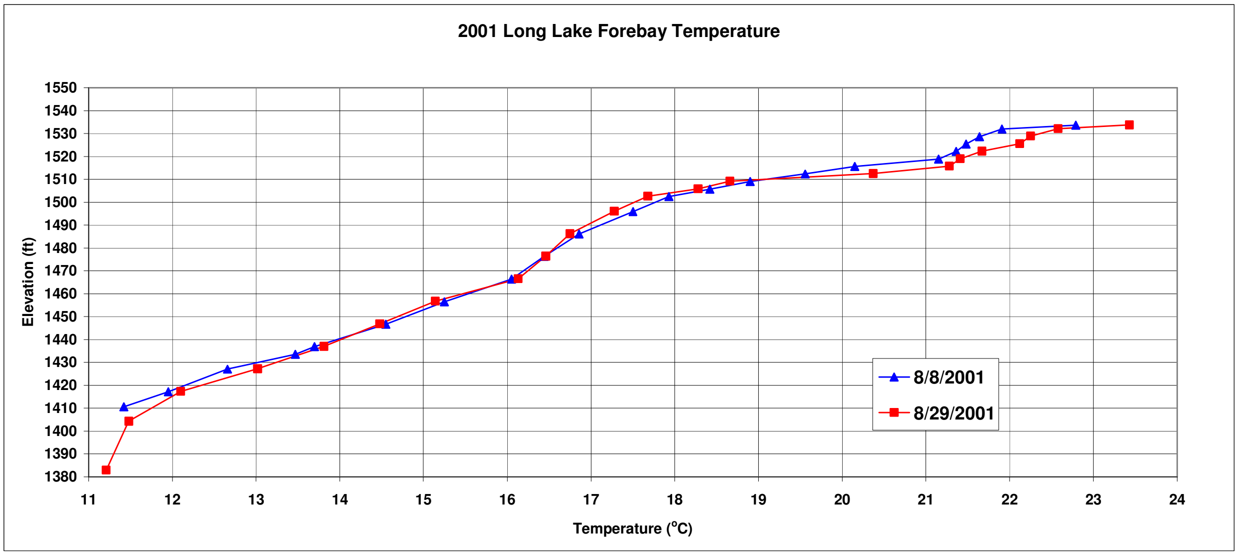


Figure 2-6. Forebay profiles of temperature and DO for 2000 at Long Lake HED (Note: the centerline for the intake is at elevation 1499 ft, and the water surface was near full pool elevation.)



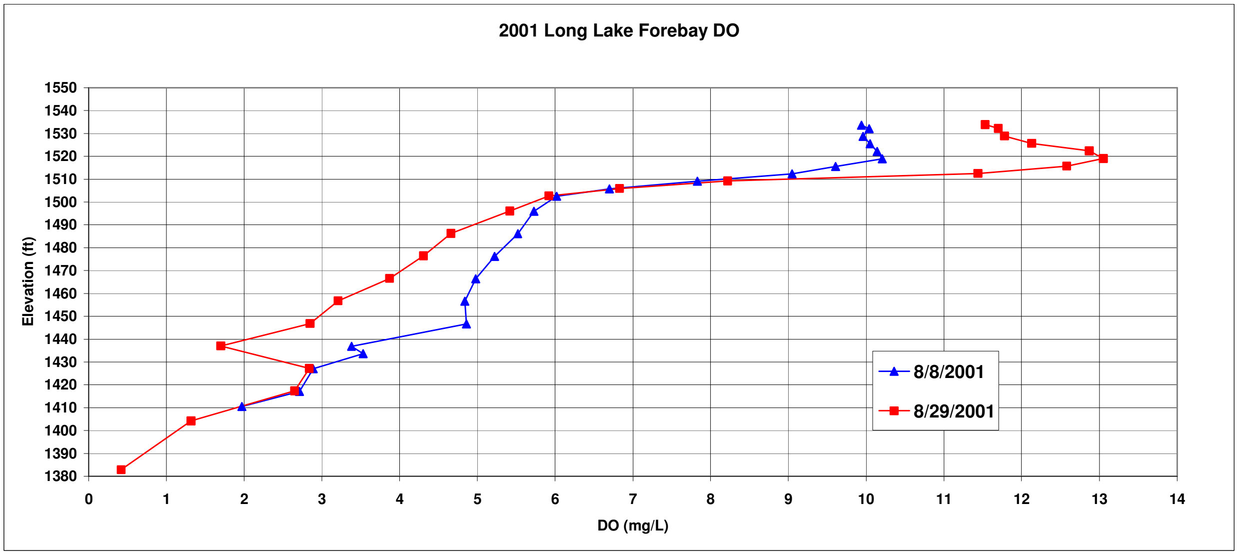


Figure 2-7. Forebay profiles of temperature and DO for 2001 at Long Lake HED (Note: the centerline for the intake is at elevation 1499 ft, and the water surface was near full pool elevation.)

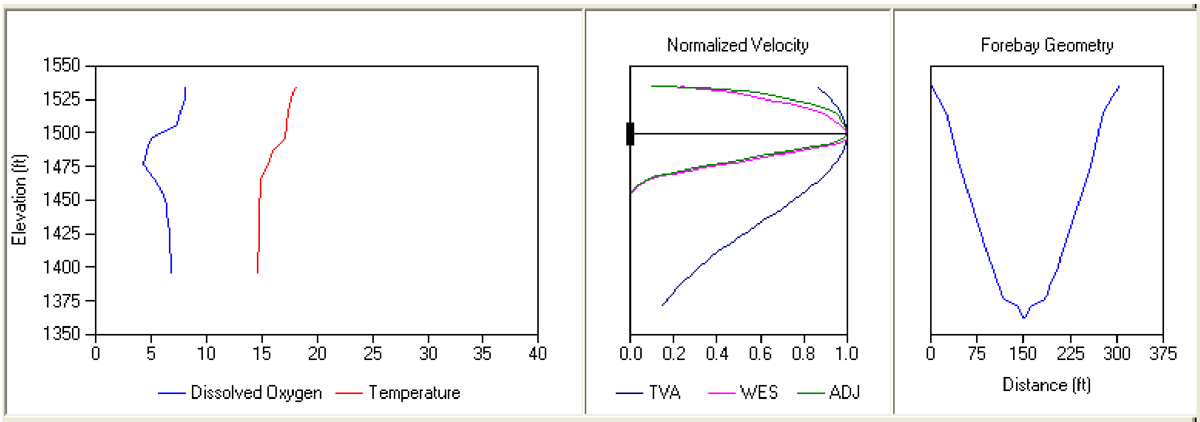


Figure 2-8 Modeled Withdrawal Zone for Long Lake HED with Total Releases of 4,900 cfs and September 13, 2000, Temperature (^{o}C) and DO (mg/L) Profiles

Water Quality in the Discharge from Long Lake, 1999 through 2001 and 2007

Figure 2-9 provides an overview of daily average temperature for the months (July through October) that include the low DO period in the years 1999 through 2001 and 2007. Figure 2-10 shows the daily average DO for the months that include the low DO period in the years 1999-2001 and 2007. Only the DO values observed during generation (Q > 1000 cfs) were included in the daily average calculation.

Figure 2-10 shows that minimum daily average low DO is about 5 to 6 mg/l. Figure 2-11 shows the hourly DO data for Long Lake HED discharges greater than 1500 cfs. These figures show DO is less than 8 mg/L during the period August through most of October.

Time series plots of hourly DO, temperature, and flow data recorded for the years 1999 through 2001 and 2007 in the Long Lake tailwater are presented in Figures 2-12 through 2-15, respectively. The second plot in each of these figures is zoomed in on a shorter time period when the DO was lowest each year so the relationship between DO, temperature and flow could be readily viewed for spotting relationships between these three variables.

Data collected during minimum flow in 1999 were not included in the plot because the O2 probe did not have a stirrer, and the data collected during these low flows were considered unreliable. Also all DO data collected between 8/17/99 and 9/9/99 were not included in the plot due to a problem with monitor calibration during this time period (CH2MHill, 2000).

Figure 2-16 presents a frequency of exceedance plot for DO in the releases from Long Lake HED. The plot includes data for only those years when data gaps were minimal. The plot indicates that DO was less than 5 mg/L only about 0.3% of the time during August-September, or 0.05% of the time on an annual basis, for the years 2000 and 2001.

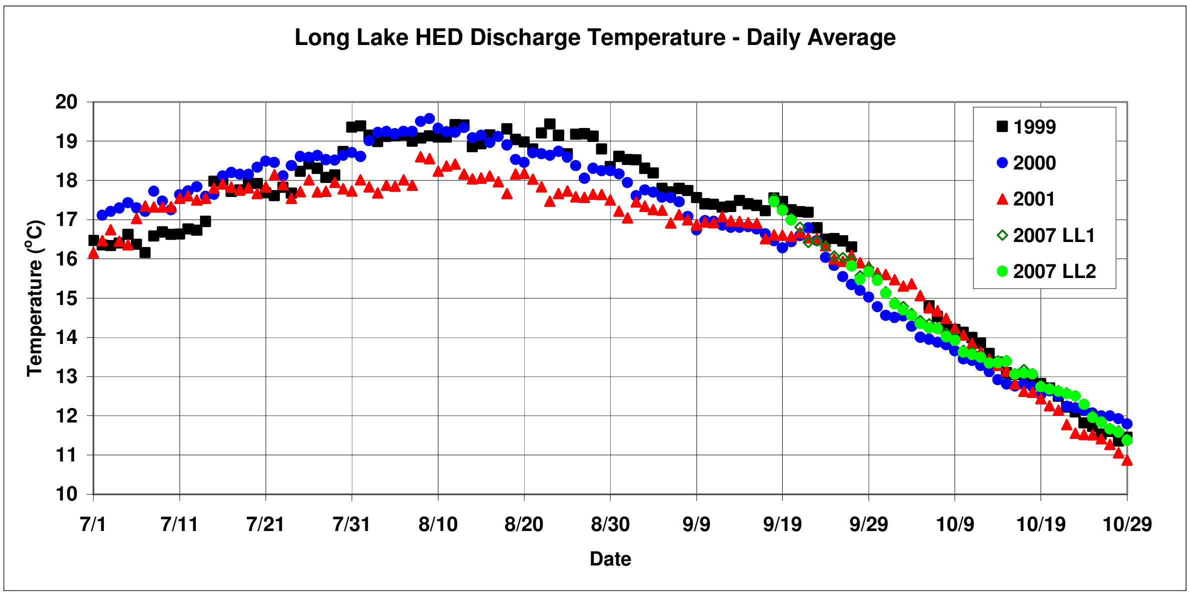


Figure 2-9. Daily average temperature (ºC) conditions in the releases from Long Lake HED for the years 1999 through 2001 and 2007

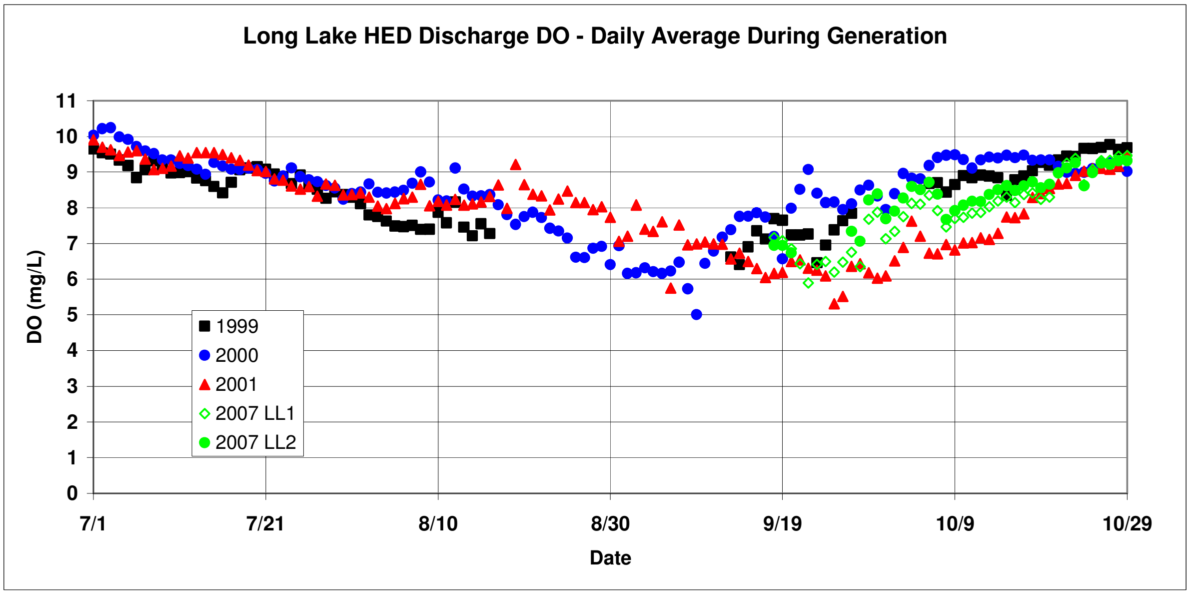


Figure 2-10. Daily average DO (mg/L) in Long Lake HED tailrace for releases during generation for 1999-2001 and 2007

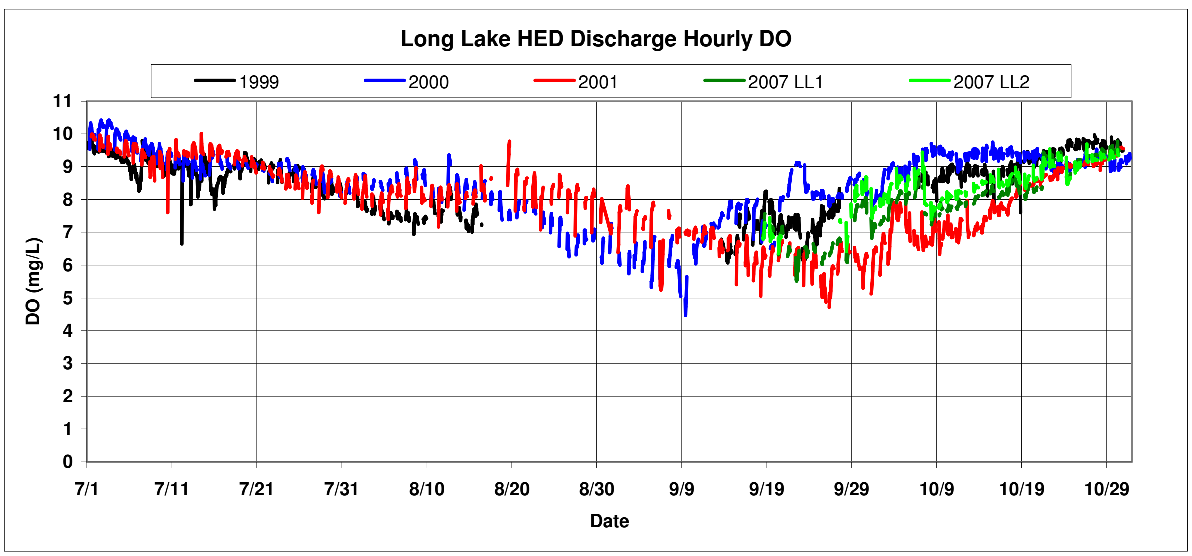
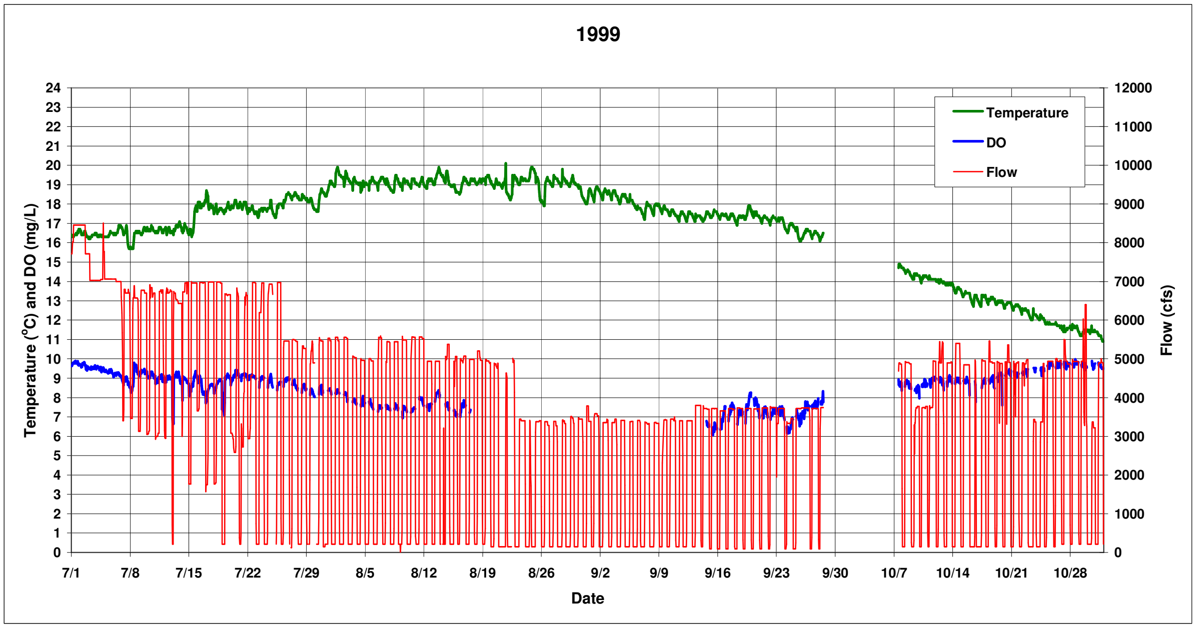


Figure 2-11. Hourly DO (mg/L) in Long Lake HED tailrace for releases during generation for 1999-2001 and 2007



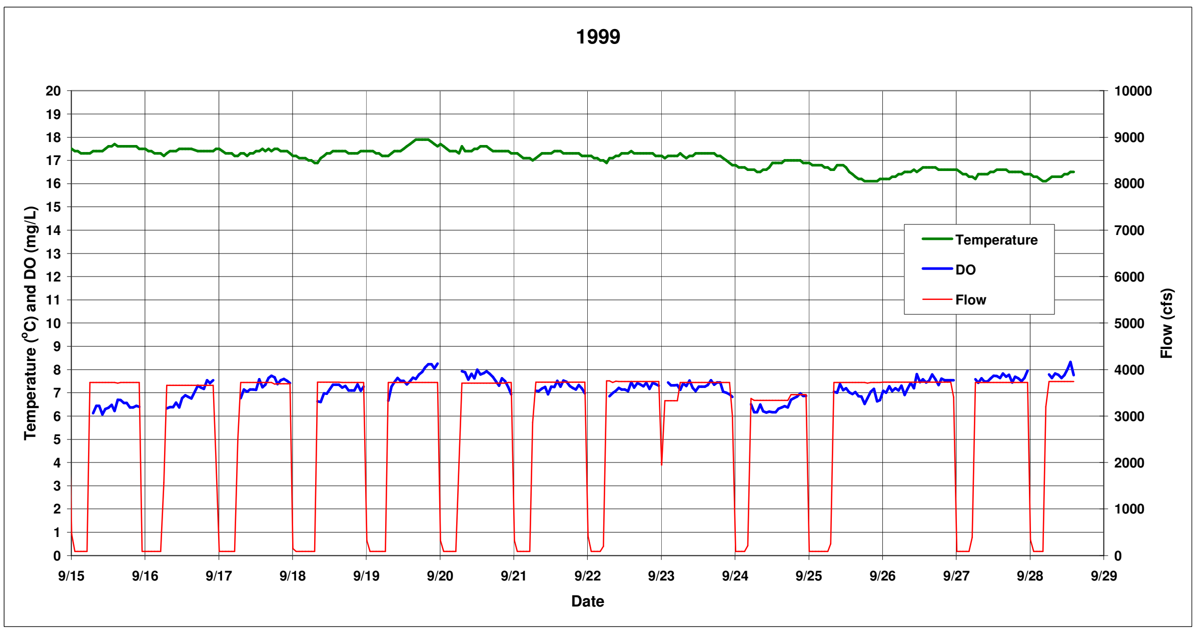
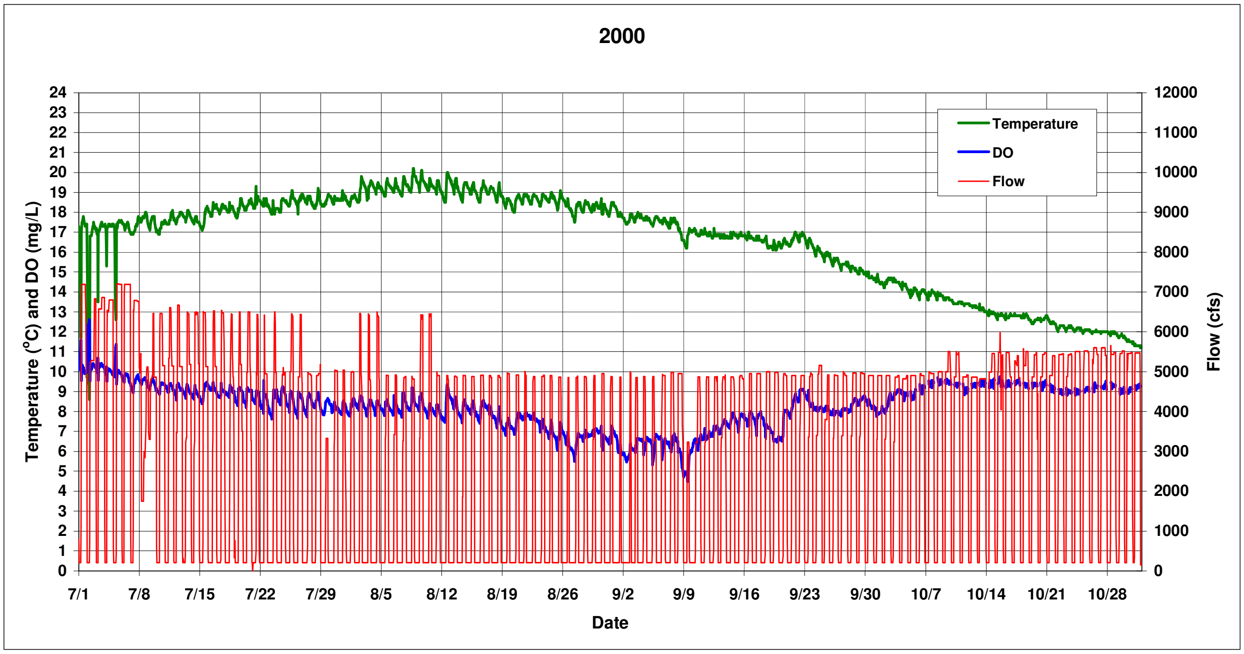


Figure 2-12. Long Lake HED Tailwater data – 1999 (The lower figure is zoomed-in on a low DO period.)



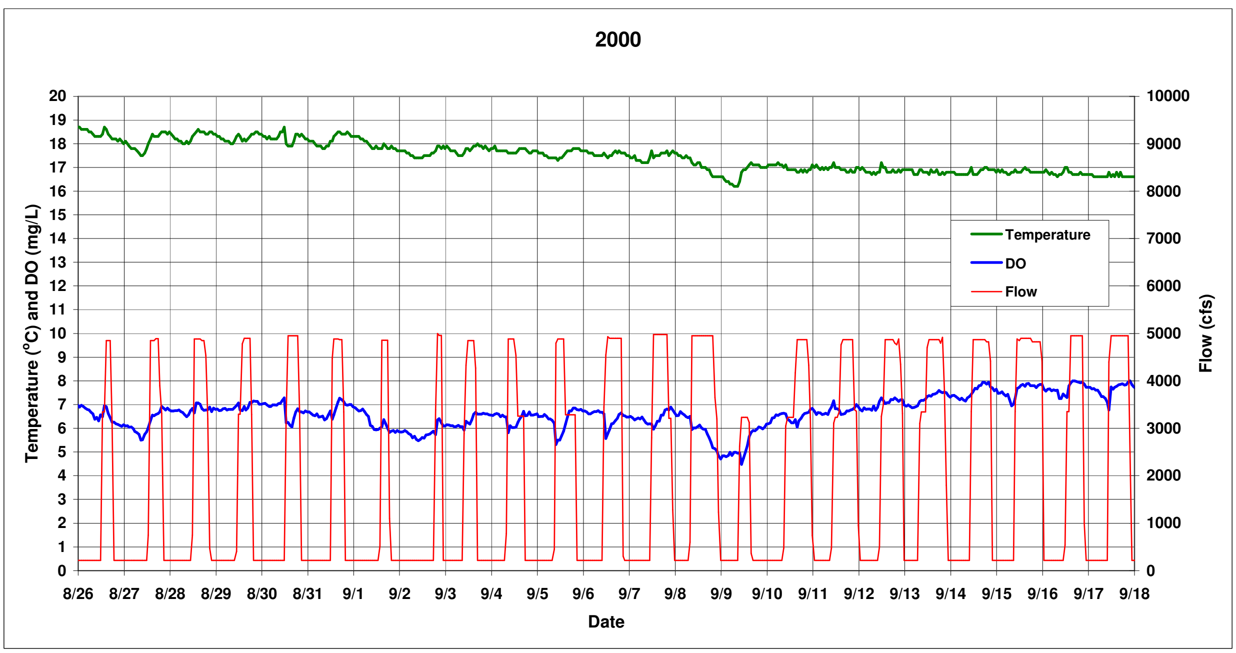
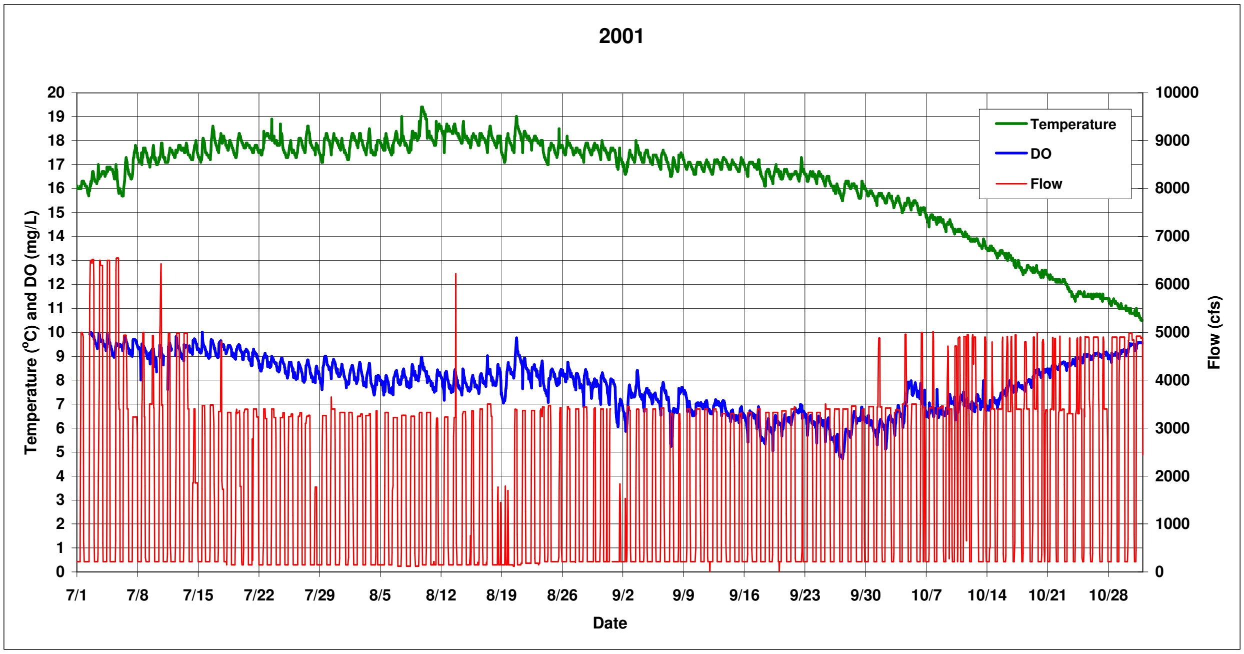


Figure 2-13. Long Lake HED Tailwater data – 2000 (The lower figure is zoomed-in on the lowest DO period.)



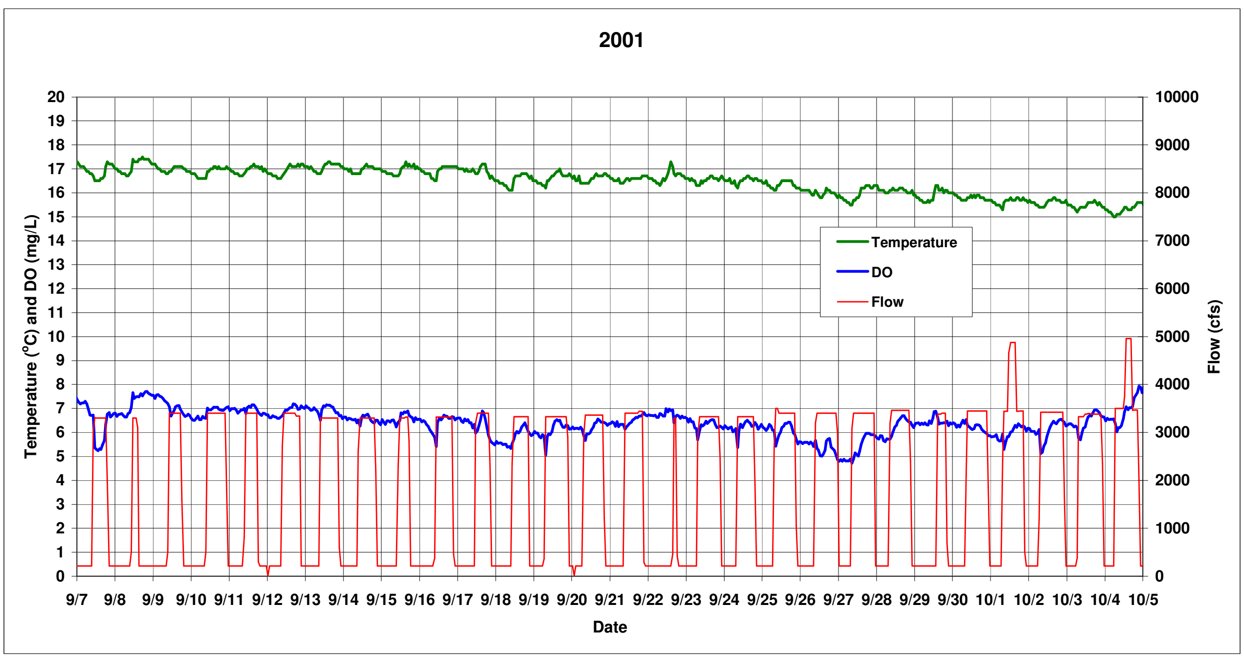
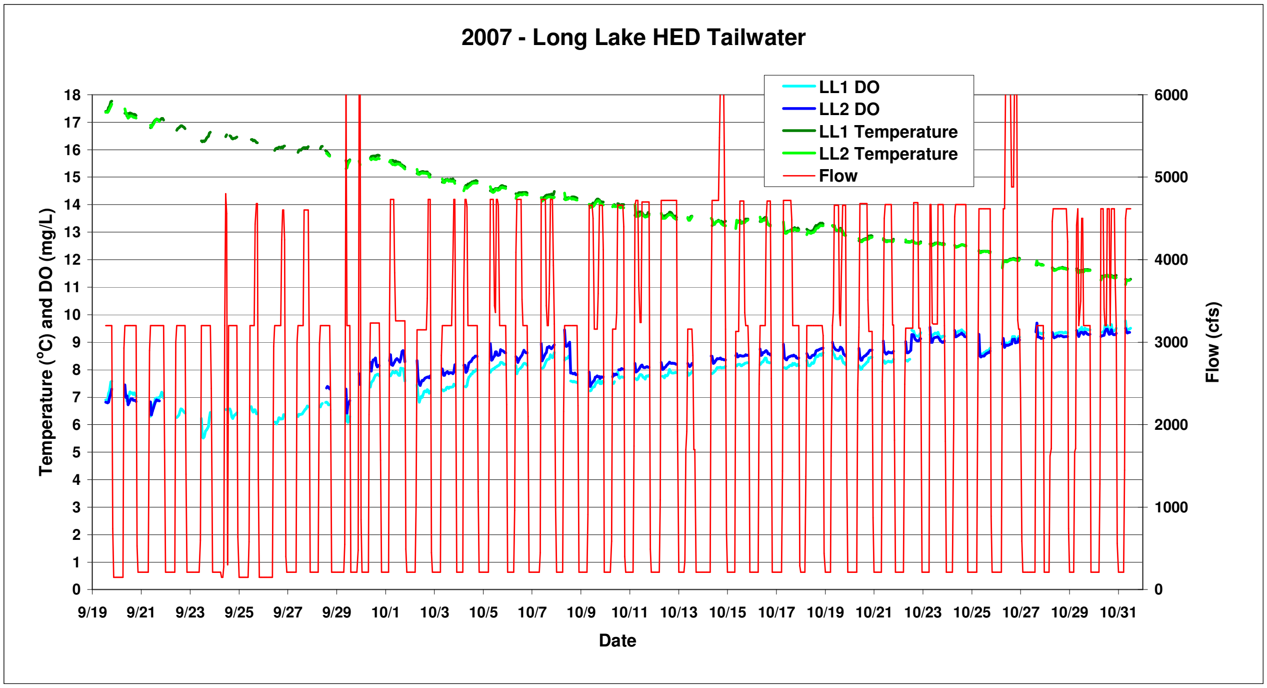


Figure 2-14. Long Lake HED Tailwater data – 2001 (The lower figure is zoomed-in on the lowest DO period.)



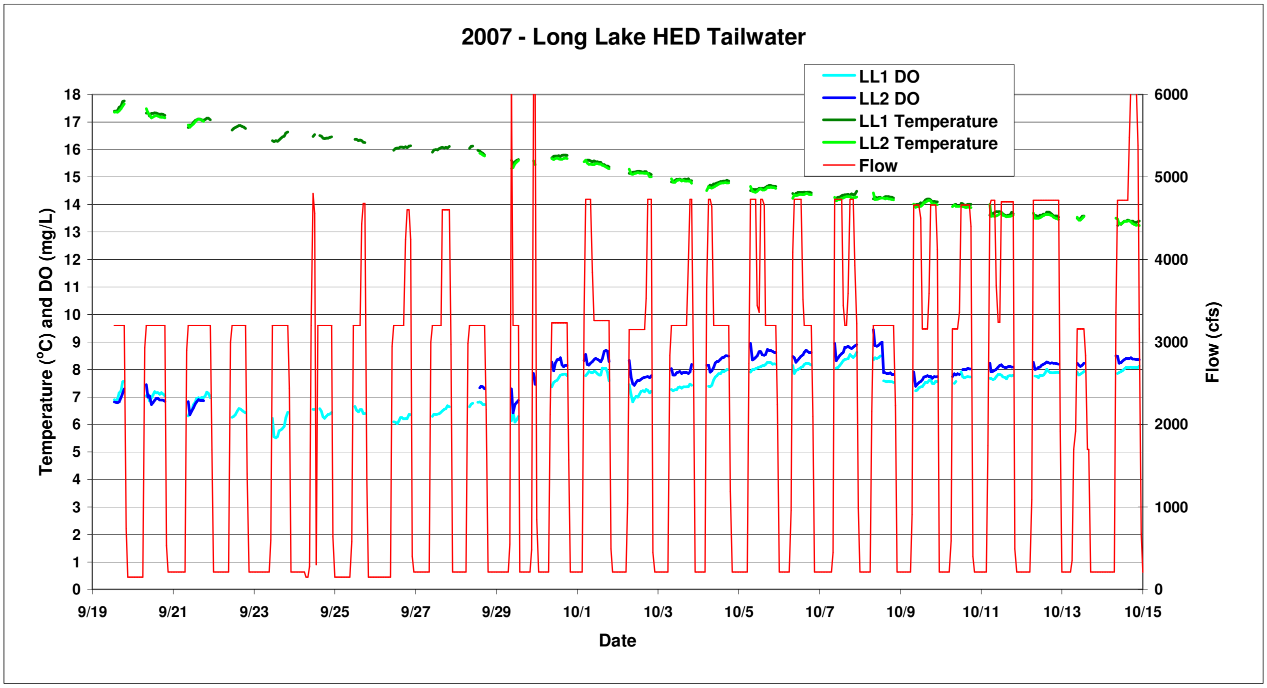


Figure 2-15. Long Lake HED tailwater data – 2007 (The lower figure is zoomed-in on the lowest DO period.)

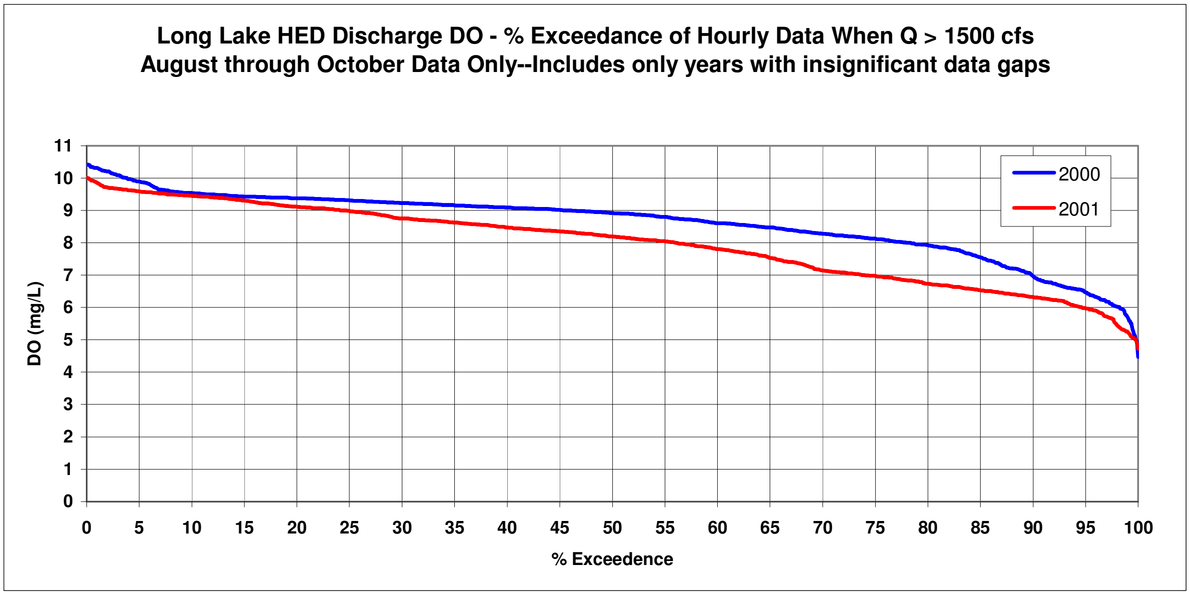


Figure 2-16. Frequency of exceedance plots for DO in the tailwater of Long Lake HED

Water Quality Observations Regarding Minimum DO to Use for Design of Aeration Systems

The available DO data collected on behalf of Avista Corporation will be considered for developing preliminary designs and comparing alternative aeration systems. To determine this baseline level of minimum DO, the water quality data collected over the periods 1999-2001 and 2007 were considered. However, emphasis was placed on using the 2000-2001 data considering the availability of sufficient data to develop frequency of exceedance analyses for DO levels during these low DO periods. In addition, the DO data collected in 2007 were within the range of DO levels reported for the years 2000 and 2001.

The available Avista monitoring data from the Long Lake HED tailrace for the period 1999 through 2001 and for 2007 indicate that DO ranges from 5 to 10 mg/L over the period August through mid-October. Minimum DO occurrences below 5 mg/l were short-lived and were only marginally less than 5 mg/L, occurring only for a day or a few days like on September 8-9, 2000, and September 7 and 26-27, 2001. Based on the available data on the releases in 2000 and 2001, the average frequency of DO dropping below 5 mg/L was less than 0.03% on an annual basis (or, 5 hours over 2 years; or, 0.11% for 5 hours over 3 months each year) and dropping below 6 mg/L was less than 0.5% on an annual basis (or,. 79 hours over 2 years; or, 1.8% for 79 hours over 3 months each year).

Aeration/oxygenation systems for reservoir releases are generally designed to maximize DO improvement and to meet the regulatory standard most of the time. Meeting the regulatory standard most of the time, but not all of the time, avoids building a system with excess capacity that would remain unused during most periods. For preliminary design purposes of determining the capacity of the various alternative DO enhancement methods, the minimum DO is 5 or 6 mg/L, and that an increase in DO of 3 or 2 mg/L is desired to achieve the 8 mg/L DO standard. Both these cases will be evaluated for the aeration alternatives considering the uncertainty in establishing baseline conditions due to the limited amount of data that are available.

TDG Monitoring Data

Avista monitored total dissolved gas (TDG) in the Long Lake HED tailrace during the summer in 2000 and 2001 (CH2M Hill, 1999, 2000, 2001). The more-recent TDG monitoring by Avista focused on measuring TDG during peak-flow periods in the winter. Since low DO is only an issue in the summer, the wintertime monitoring data for TDG is less relevant for this project.

Figures 2-17 and 2-18 present the results of DO and TDG monitoring by Avista in 2000 and 2001 at the Long Lake HED tailrace. Documenting background TDG and DN in the reservoir releases is important for aeration assessments and modeling so that TDG can be evaluated for the effects of aeration systems on TDG. The TDG regulatory standard is 110 percent of saturation. Figures 2-17 and 2-18 show that summer TDG in the Long Lake HED tailrace is less than 100% when DO is less than 8 mg/L. However, %DN usually ranges between 100 to 110 percent saturation when DO is less than 8 mg/L. DN values greater than 100% are not unusual (i.e., elevated DN values can be caused by natural processes such as spilling processes upstream from the reservoir, normal warming processes of water, dissolved gas products from sediments, etc), but they need to be considered when designing and operating aeration systems. TDG and DN levels will be considered in the design of the aeration alternatives. Other TDG data have been collected more recently by Avista- but these data focus on the spring reservoir spills and do not include data during the late summer low-DO period.

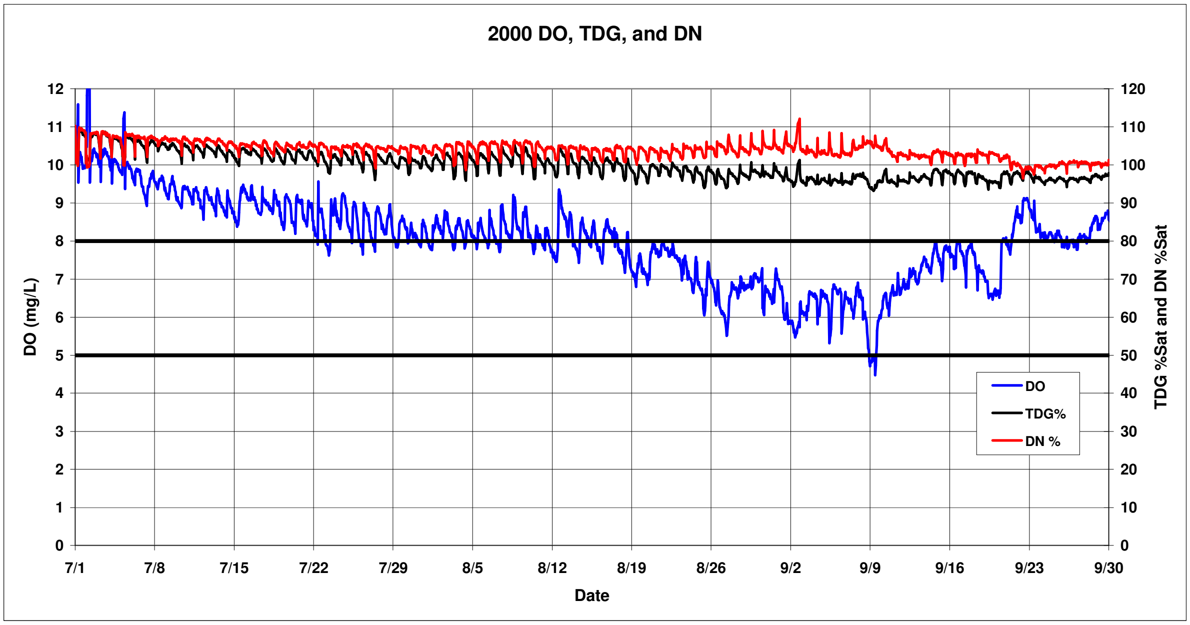


Figure 2-17. Percent dissolved nitrogen in the tailrace (% DN), DO, and TDG for 2000

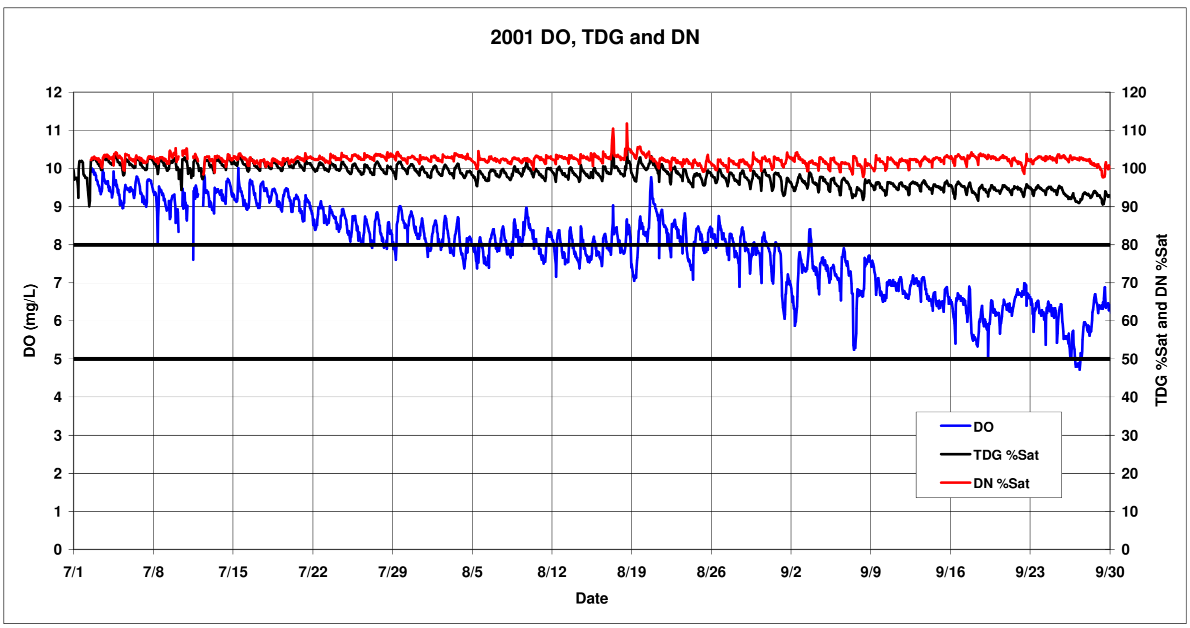


Figure 2-18. Percent dissolved nitrogen in the tailrace (% DN), DO, and TDG for 2001

3 Draft Tube Aeration

Estimation of Draft Tube Air Flow Rate

Objective and Scope

The objective of this analysis is to estimate the rate of air that can be introduced into the draft tubes of the Long Lake HED generating units using the natural negative pressure existing in the draft tube as the water leaves the turbines. The method used to estimate the draft tube inflow rate is based on a one-dimensional analytical model, using standard fluid flow, head loss, and nozzle discharge relationships. Because the real flow patterns existing in a draft tube can be quite complex and very difficult to model, even numerically, the results presented here are estimates, not predictions. The model has previously been validated against a limited set of field data. If turbine venting is selected for field testing, actual airflow measurements likely would be conducted to either validate these estimates or to adjust the model as needed for further assessments.

Description of Unit and Draft Tube

The Long Lake HED powerhouse contains four horizontal double-runner Francis wheels rated for 27,800 hp and 1,575 cfs at 168 feet of net head. Maximum unit discharge is about 1,850 cfs. The draft tube for each unit is a horizontal discharge elbow-type, with a draft tube chest combining the discharges from the two runners into a single draft tube throat. The draft tube chest is shown in Figure 3-1 and the elbow draft tube is shown in Figure 3-2. The unit centerline is at elevation 1,377 ft and the centerline of the draft tube discharge is at 1,342.25 ft. Normal tail-water surface elevation is 1,362 ft during the low DO period.

The draft tube transitions from an oval shape at the entrance to a horseshoe shape at the exit, as shown in the design drawing in Figure 3-2. Draft tube elevation and area along the draft tube centerline are shown in Figure 3-3. Figure 3-4 shows the average velocity and residence time at 1,575 cfs as functions of centerline distance. The data are summarized in tabular form in Table 3-1. The draft tube centerline is taken to be at the plane tangential to the mean flow which bisects the draft tube area.

Air Admission

Air admission to the draft tube chest is considered for two locations, as shown in Figure 3-1:

1. At the four existing four-inch flanged openings (ports) used for installation of draft tube platform supports
2. On the two 20-inch ID manhole covers on either side of the draft tube chest.

The centerlines of the four-inch flanged openings are at elevation 1,372.75. The man door centerlines are at elevation 1,374.5.

It is assumed that bellmouth inlets are used to admit air to the admission locations. Four-inch ID bellmouths are assumed for the flanged openings. At the man doors, bellmouth inlets with 6 and 8 inch IDs were evaluated. In all cases, it is assumed that a flow-deflecting baffle is installed just upstream of the air admission ports to induce supplemental negative pressure to draw more air into the draft tube.

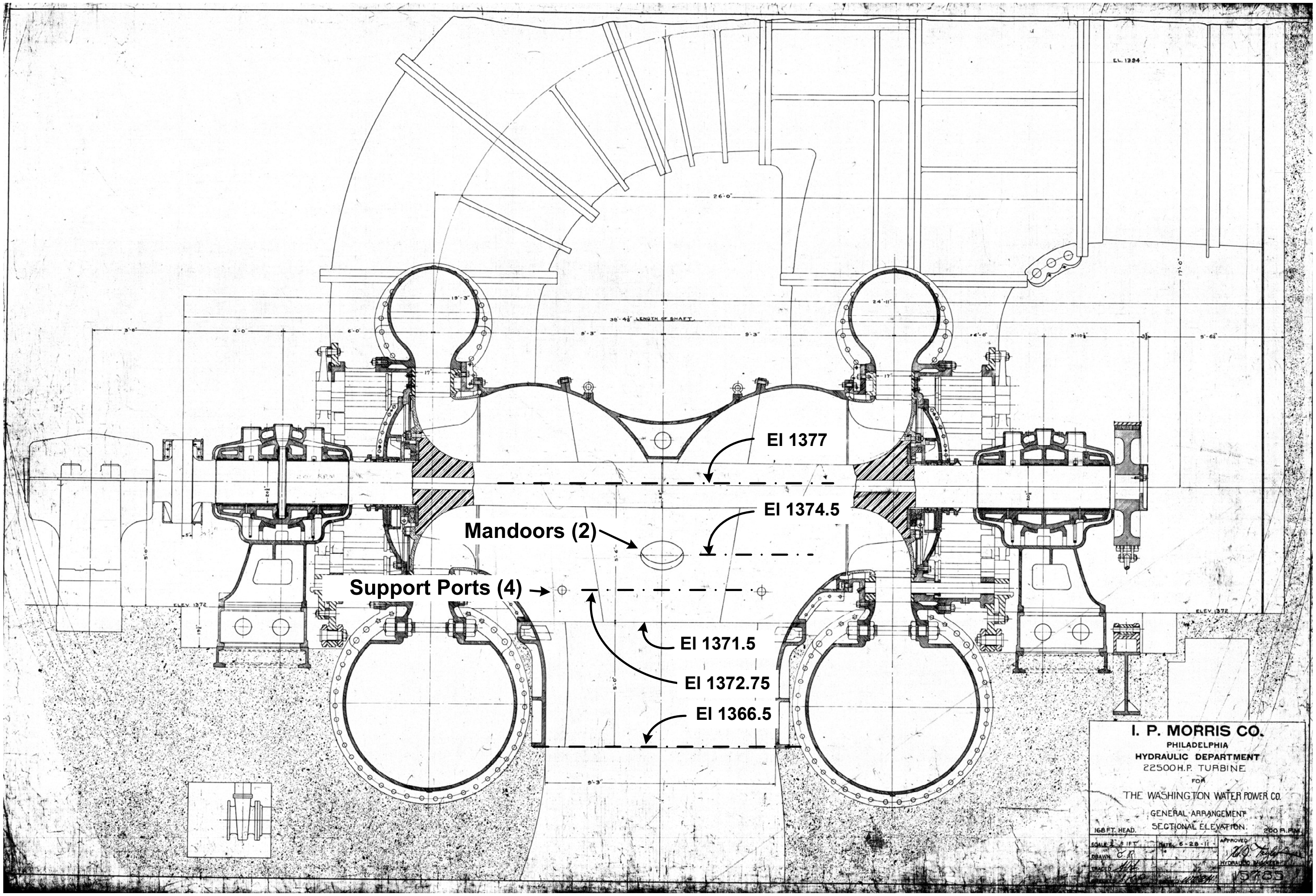


Figure 3-1. Horizontally-opposed runners and draft tube chest and air inlets

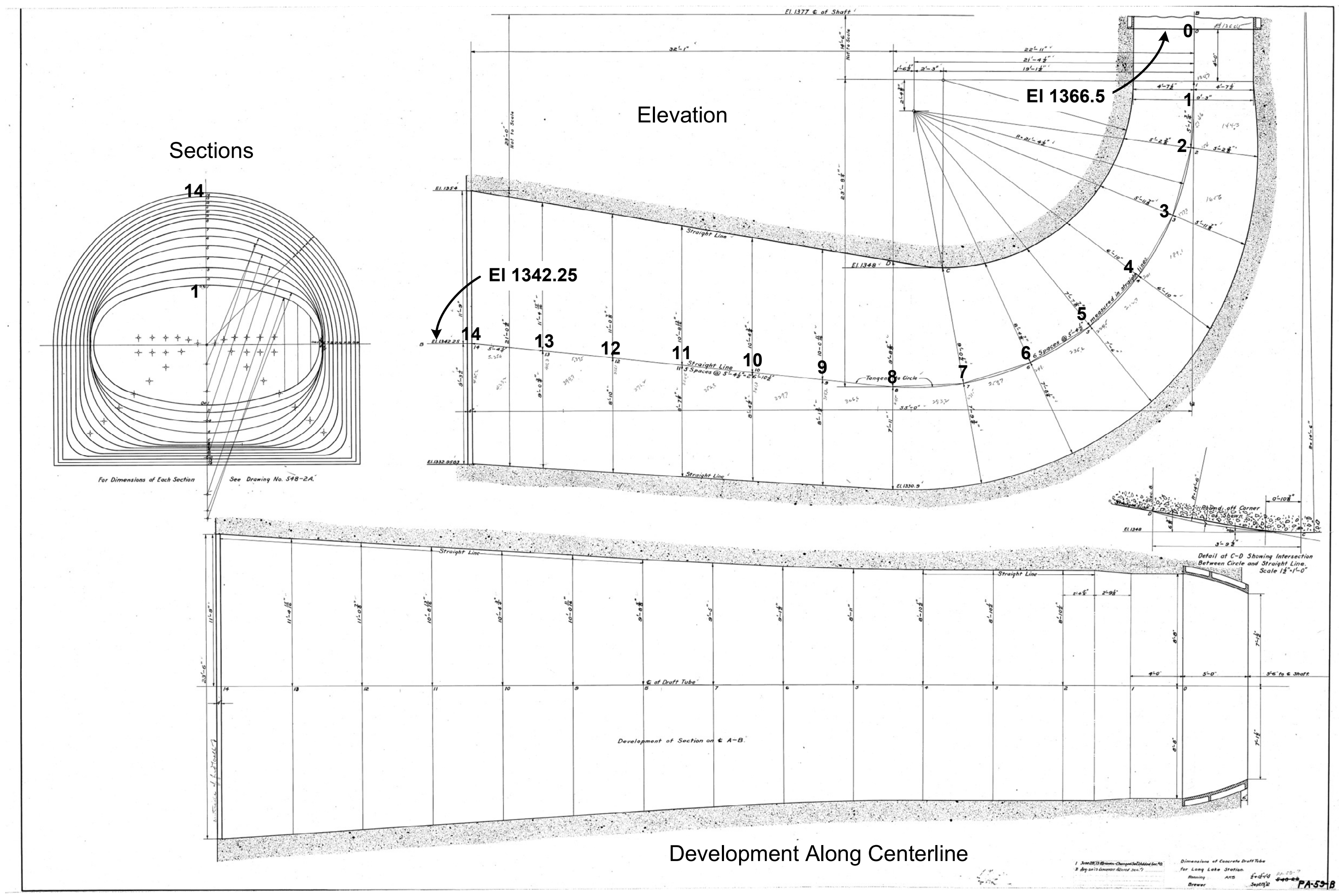


Figure 3-2. Elbow draft tube geometry

Table 3-1. Draft Tube Characteristics

Section	Centerline Distance	Elevation of Centerline	Area	Velocity at Section	Section Average Velocity	Section Residence Time	Total Residence Time
	ft	ft	ft^2	ft/s	ft/s	s	s
Inlet	0	1371.50	134.7	11.69			0
0	5.00	1366.50	134.7	11.69	11.69	0.428	0.43
1	9.00	1362.50	134.7	11.69	11.69	0.342	0.77
Throat	11.36	1360.14	143.6	10.97	11.32	0.209	0.98
2	14.14	1357.37	154.0	10.23	10.58	0.262	1.24
3	19.53	1352.17	177.3	8.88	9.51	0.567	1.81
4	24.92	1347.47	201.0	7.84	8.33	0.647	2.46
5	30.31	1343.58	224.5	7.02	7.40	0.728	3.18
6	35.70	1340.73	248.0	6.35	6.67	0.809	3.99
7	41.09	1339.11	271.5	5.80	6.06	0.889	4.88
8	46.48	1338.82	295.0	5.34	5.56	0.969	5.85
9	51.86	1339.39	318.2	4.95	5.14	1.046	6.90
10	57.23	1339.96	341.3	4.61	4.78	1.125	8.02
11	62.61	1340.53	364.4	4.32	4.46	1.204	9.23
12	67.98	1341.11	388.1	4.06	4.19	1.284	10.51
13	73.36	1341.68	411.3	3.83	3.94	1.364	11.87
14	78.71	1342.25	435.2	3.62	3.72	1.439	13.31

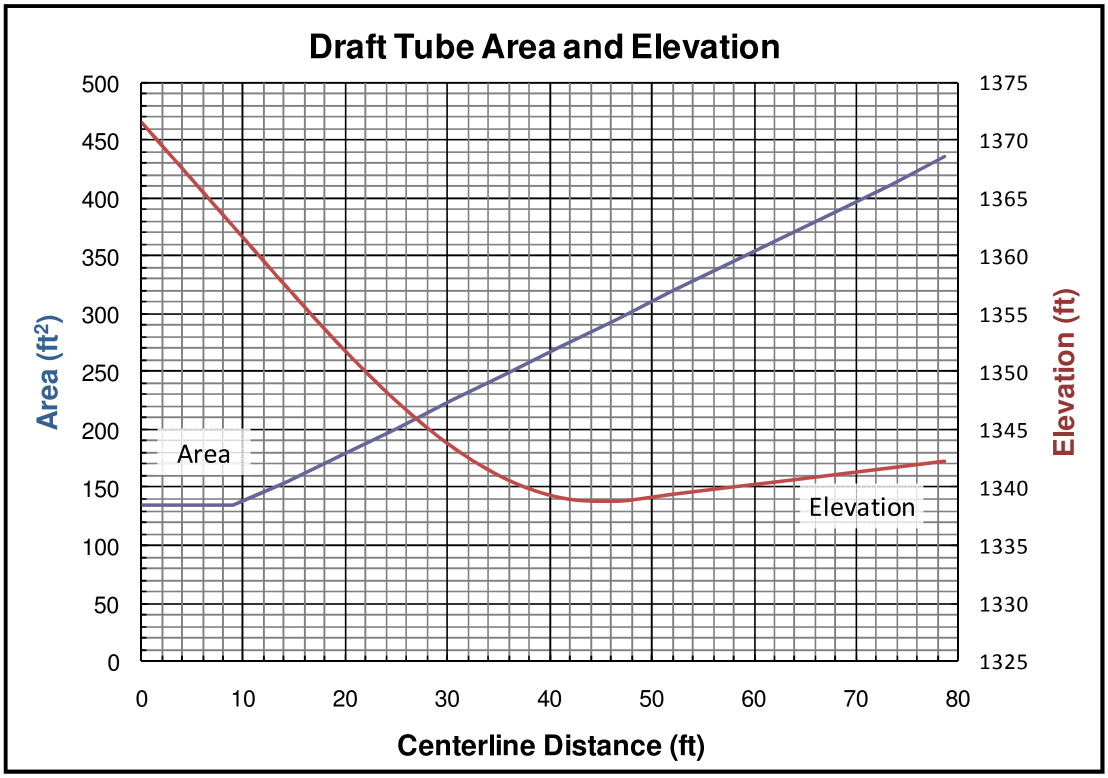


Figure 3-3. Draft tube area and elevation

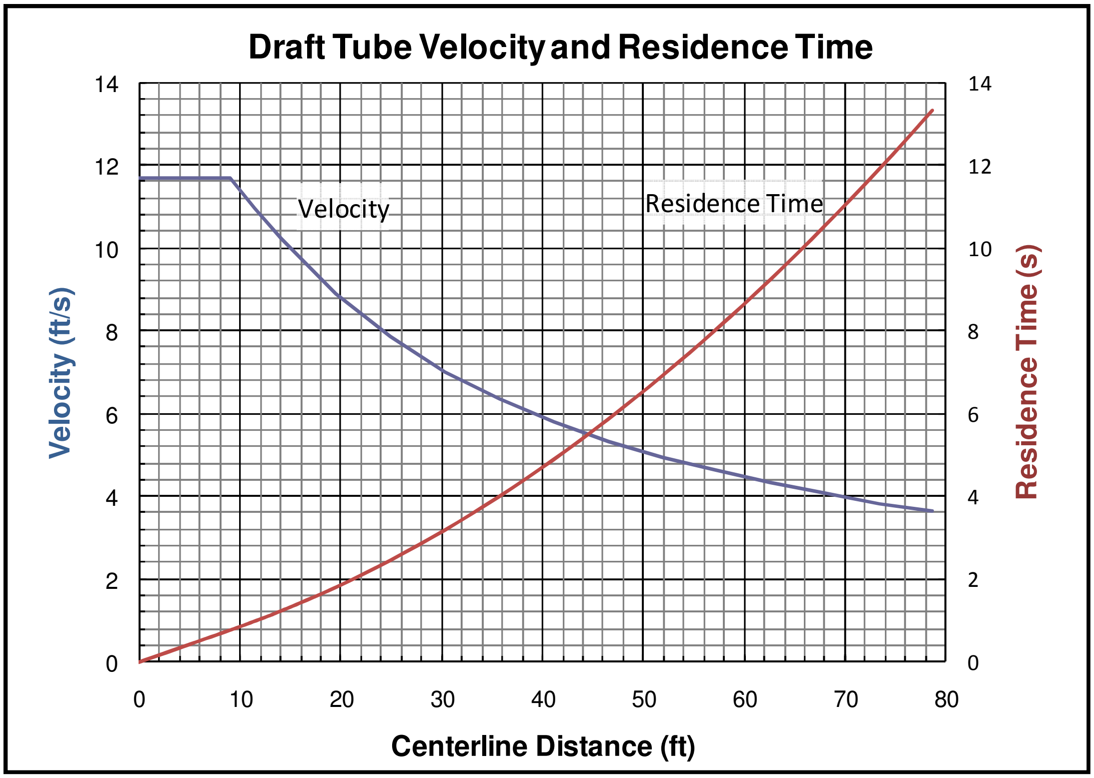


Figure 3-4. Draft tube velocities and residence times at 1,575 cfs

Description of the Analytical Model

The two main components of the model are:

1. Determination of the pressure difference between the inside and the outside of the draft tube chest at the air inlet locations; this pressure difference drives the air flow;
2. Determination of the air flow induced by the pressure difference.

The basis for the pressure difference calculation is shown schematically in Figure 3-5. The Bernoulli equation is used to determine the pressure recovery generated by the draft tube. The full calculation takes into account unit flow rate, air inlet elevation, tailwater elevation, friction losses in the draft tube, and the draft tube exit loss. In addition, the effect of pressure-reducing baffles upstream of the air inlet ports is included. Although the figure schematizes the draft tube as a vertical cone, this one-dimensional analysis also applies to an elbow-type draft tube.

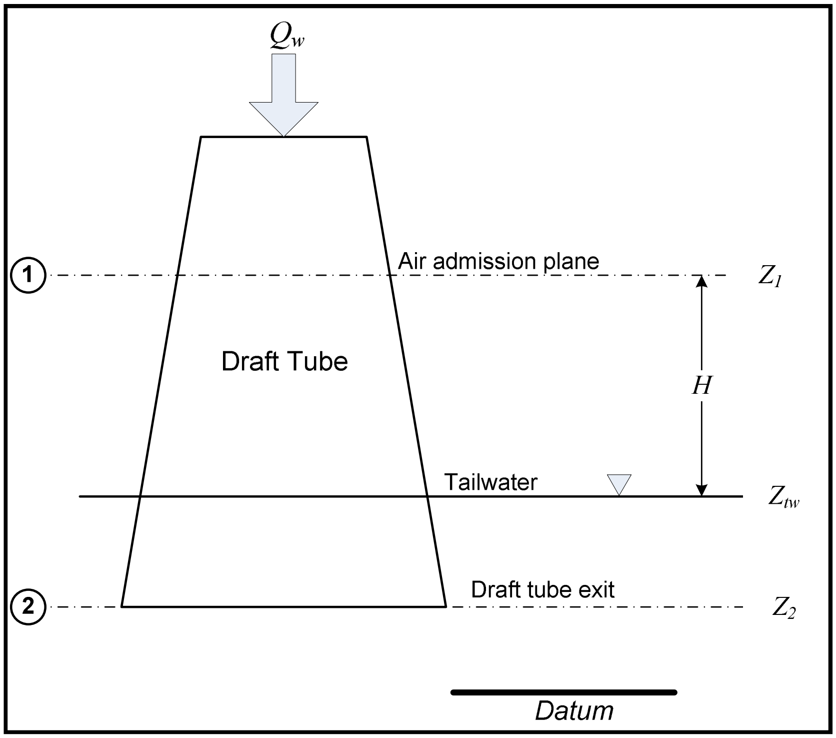


Figure 3-5. Definition Sketch for Draft Tube Pressure Recovery Analysis

The pressure drop h across the air inlet ports is given by:

$$h = C_{dt}\left(\frac{V_1^{\,2}}{2g} - \frac{V_2^{\,2}}{2g}\right) + (Z_1 - Z_{TW}) + C_b\,\frac{V_1^{\,2}}{2g}$$

where

V_1 = water velocity at the air admission point (ft/s)
V_2 = water velocity at the draft tube exit (ft/s)
Z_1 = elevation of the air admission point (ft)
Z_{TW} = tailwater elevation (ft)
C_{dt} = Draft tube efficiency coefficient
C_b = Baffle pressure reduction coefficient

The induced air velocity is computed by a simplified version of the full compressible flow equations found in Reference 1:

$$V_1 = C_d \cdot Y \cdot \left(2gh\frac{\rho_w}{\rho_a}\right)^{1/2}$$

where

V_1= air velocity (ft/s)
C_d = discharge coefficient
Y = air expansion factor
g = acceleration of gravity (ft/s^2)
h = pressure difference across the inlet port (ft H_2O)

$\rho_w =$ water density at test conditions (lbm/ft^3)
$\rho_a =$ air density at test conditions (lbm/ft^3)

The full model calculation accounts for energy losses associated with air flow into and though the delivery piping and exit losses from the inlet ports.

Model Limitations

Although this model of air admission to a draft tube captures the main mechanisms for air flow in an ideal flow situation, it does not address details of the air flow in the bellmouth inlets and the air delivery system, and it does not address conditions for which air velocities are near sonic values. Near-sonic values are possible in parts of the air delivery piping at the Long Lake HED.

The model does not address the complexities of the water flow patterns and pressure distributions existing in the draft tube. These conditions are generally quite complex, and are known to affect the air intake rate. For instance, the pressure at the air admission point can be affected by vortex action in the draft tube, a phenomenon which is not accounted for in the simple Bernoulli equation used in this analysis. However, the closer to best efficiency (i.e., "best flow conditions") that the unit is operated, the better the approximations become. The fact that the air admission points are in a part of the flow passage where the discharges from two opposed runners meet is a further complication beyond the scope of an analytical model. The model does not explicitly account for the effect of very large air flows, i.e., about 10% above the water flow rate. The model has been verified against a limited set of field data for relatively small units, with good results.

Analysis Conditions

The following conditions and parameters were assumed for all model results presented in Table 3-2, and the model runs and the parameters associated with them are summarized in Table 3-3.

Table 3-2. Conditions and Parameters Used in Analysis

Tailwater elevation	1,362	ft
Elevation of air inlet at man door	1,374.5	ft
Elevation of air inlet at draft tube ports	1,372.75	ft
Draft tube area at air inlets	134.7	ft^2
Draft tube area at exit	435.2	ft^2
Air pressure	14.0	psia
Air temperature	70	deg F
Outside air density	0.071	lbm/ft^3
Relative humidity	0	%
Water temperature	60	deg_F
Water density	62.37	lbm/ft^3
Exit loss coeff	1	-
Inlet loss coeff	0.2	-
Draft tube coeff	0.8	-
Air delivery piping loss coeff	2	-
Baffle coefficient	0.5	-
Overall bellmouth discharge coeff	0.575	-

Table 3-3. Model Runs

Run	Discharge (cfs)	Inlet Location	Inlet Diameter (in)	Number of Inlets
1	1,575	DT Ports	4	2
2	1,575	DT Ports	4	4
3	1,575	Man door	6	1
4	1,575	Man door	6	2
5	1,575	Man door	8	1
6	1,575	Man door	8	2
7	1,850	DT Ports	4	2
8	1,850	DT Ports	4	4
9	1,850	Man door	6	1
10	1,850	Man door	6	2
11	1,850	Man door	8	1
12	1,850	Man door	8	2

Air Admission Results

The results of the air admission modeling, including some of the intermediate calculation results are summarized in Table 3-4. The air flow results are summarized graphically in Figure 3-6. Air:water ratio results are summarized in Figure 3-7.

Table 3-4. Model Results

Water Flow	Location	Inlet Diam.	Number of Inlets	Total Pressure Drop	Bellmouth Pressure Drop	Air Flow	Air:Water Ratio
cfs	-	in	-	ft H_2O	ft H_2O	scfs	%
1575	DT Ports	4	2	13.3	2.6	61.8	3.9
1575	DT Ports	4	4	13.3	2.6	123.6	7.8
1575	Mandoor	6	1	15.1	2.7	70.1	4.4
1575	Mandoor	6	2	15.1	2.7	140.1	8.9
1575	Mandoor	8	1	15.1	2.7	124.5	7.9
1575	Mandoor	8	2	15.1	2.7	249.1	15.8
1850	DT Ports	4	2	14.3	2.7	62.2	3.4
1850	DT Ports	4	4	14.3	2.7	124.3	6.7
1850	Mandoor	6	1	16.1	2.7	70.0	3.8
1850	Mandoor	6	2	16.1	2.7	139.9	7.6
1850	Mandoor	8	1	16.1	2.7	124.4	6.7
1850	Mandoor	8	2	16.1	2.7	248.8	13.4

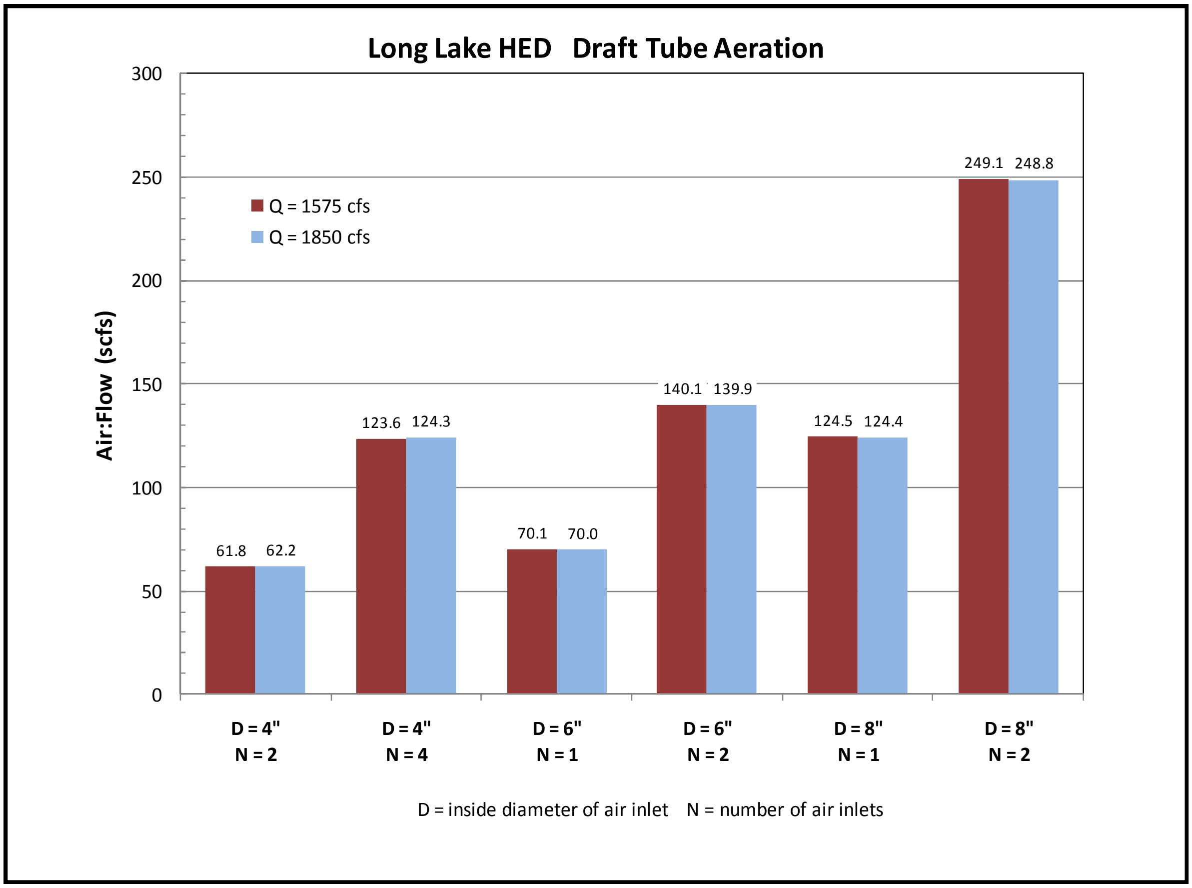


Figure 3-6. Air flow results for draft tube aeration analysis

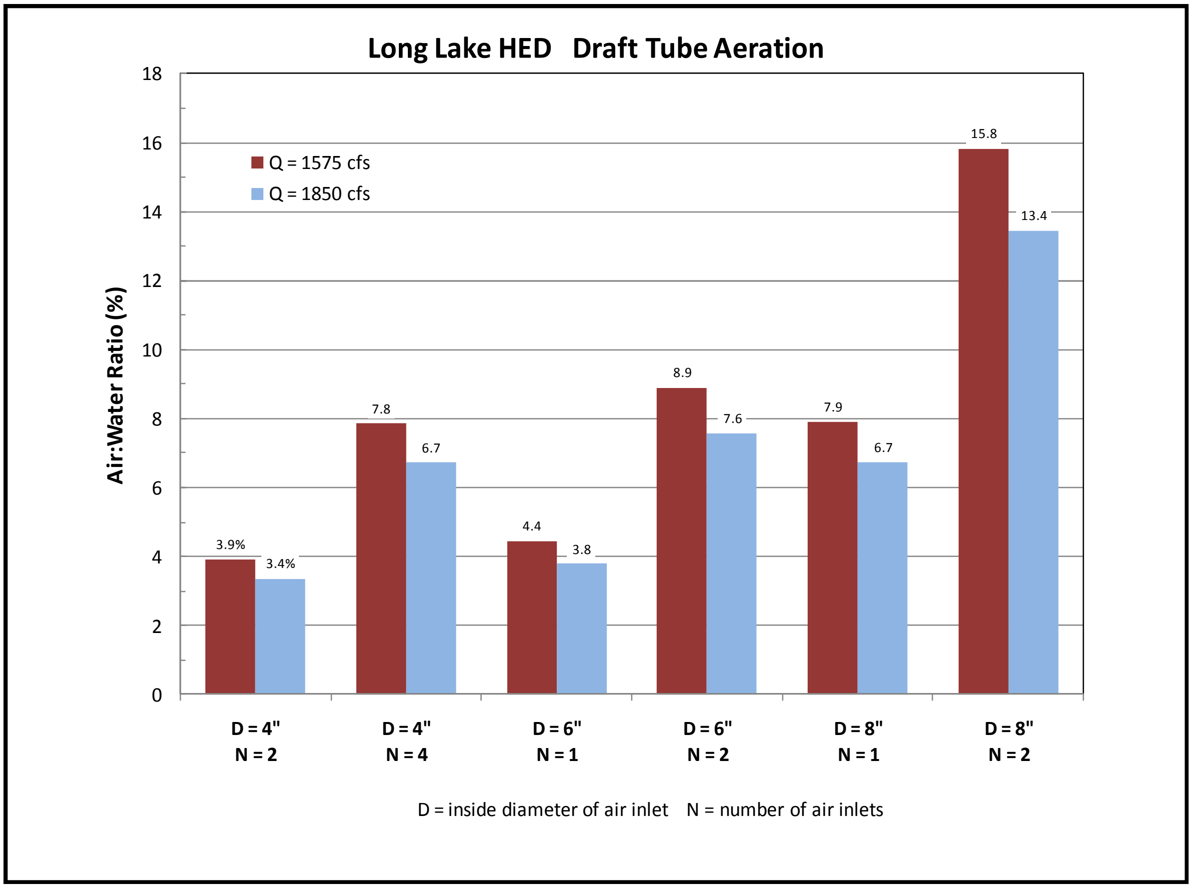


Figure 3-7. Air:water ratio results for draft tube aeration analysis

The air flow results presented in Figure 3-6 show that turbine discharge has little effect on the air flow. This is because most of the vacuum created at the elevation of the air inlets is due to the elevation difference between the inlet and the tailwater (10.75 ft for the draft tube ports, 12.25 ft for the man doors). Additionally, at these relatively large vacuums, compressibility effects have a choking influence on the air flow, with the results that increases in vacuum at the inlet locations produce diminishing increases in air flow rate.

Air water ratios shown in Figure 3-7 range from 3.9% to 15.8% at 1,575 cfs, and from 3.4% to 13.4% at 1,850 cfs. Because the absolute air flow rate depends only weakly on water flow rate, air:water ratios decrease with increasing water flow.

Discrete Bubble Model Application for Turbine Aeration at Long Lake HED

The DBM was used to determine the potential for using turbine venting to enhance DO in the releases from Long Lake HED. Within this section, turbine aeration using turbine venting was modeled using the discrete bubble model (DBM). The model accounted for DO and TDG changes in the water flow through the turbine system as air was drawn into the units by the venting system described in the previous section. Turbine venting systems were first used in the 1940s on the Fox River in Wisconsin, and this approach continues to be studied and advanced (Raney and Arnold, 1973; Sheppard and Miller, 1982; Carter, 1995; Harshbarger et al., 1999; Thompson and Gulliver, 1997; Hopping et al., 1997 and 1999) to increase effectiveness and address current environmental issues.

Background

The DBM has been applied to over 20 hydropower projects, and has been rigorously tested both practically and scientifically. See McGinnis and Ruane, 2007, and Ruane and McGinnis, 2007, for model background, development, assumptions, and application. The model tracks bubbles from the time that they are formed as air is released through the vent pipes, as they travel through the draft tube, until they exit to the surface of the tailwater. The model accounts for oxygen and nitrogen that dissolves (leaves the bubble) in the water or is stripped (enters the bubble) from the water, and considers hydrostatic pressure changes, temperature, dissolved oxygen and nitrogen. The DBM can then be utilized to investigate DO and TDG concentration changes resulting from introducing air at different points along the draft tube.

Development for Long Lake

The DBM is most sensitive to the initial bubble size. Data from prior similar projects using DBM calibrations was used to estimate the likely initial bubble size; however, this largely depends on turbulence at the point of bubble introduction, the type of aerating turbines, and water velocity. Figure 3-8 shows the initial bubble size as a function of unit flow rate. For turbine aeration sensitivity analysis a range of bubble sizes was considered with +/- 50% of the initial bubble diameter.

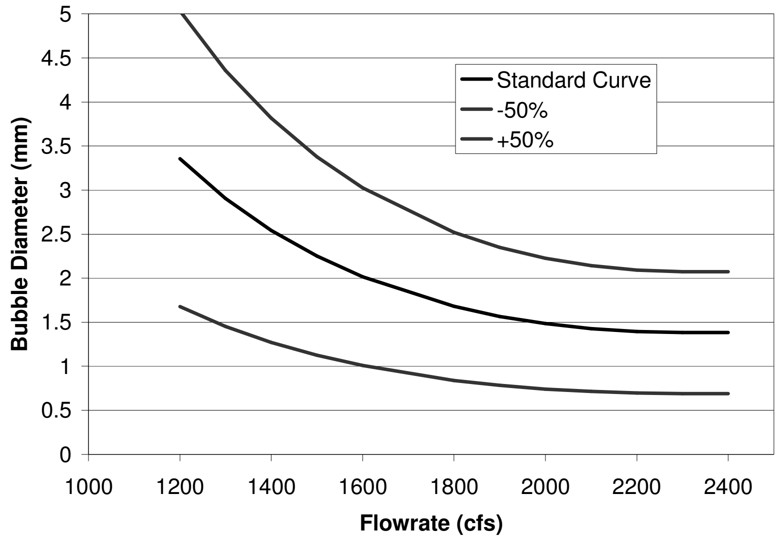


Figure 3-8. Initial bubble diameter for turbine aeration option as a function of unit flow rate. Gray bands show range of sensitivity analysis.

The draft tube geometry was discretized as described in the previous section and input into the DBM as in input file. Pressures are solved hydrostatically, with pressure above the turbine defined by the lake level and downstream of the turbine by the tailrace elevation. Turbine geometries were determined by Almquist as presented in the previous section.

TDG and DN Influence

To develop DBM predictions of DO and TDG in the releases over a range of background conditions for DO and DN, it was necessary to estimate the influent TDG and back calculate the dissolved nitrogen (DN). Because TDG is the sum of dissolved gases (mainly DO and DN), TDGin was estimated as a function of DOin (see Figure 3-9). Relationships were developed to estimate background TDG using the 2000 and 2001 data (see Figures 2-17 and 2-18) for input into the DBM. While TDGin/DOin values in 2001 showed a consistent trend over the low DO period, the TDGs in 2000 were higher and there was a distinct shift in the TDG/DO data between August and September that was consistent with lower DN values in September, yielding lower values of TDG% in September.

For analyses of the TDG/DO trend lines, only data with DO < 8 mg/L collected during generation (Q > 1000 cfs) were used. Figure 3-9 shows that the relationship between

DO and TDG is highly variable and suggests that air addition to the units may need to be controlled to avoid exceeding the TDG standard.

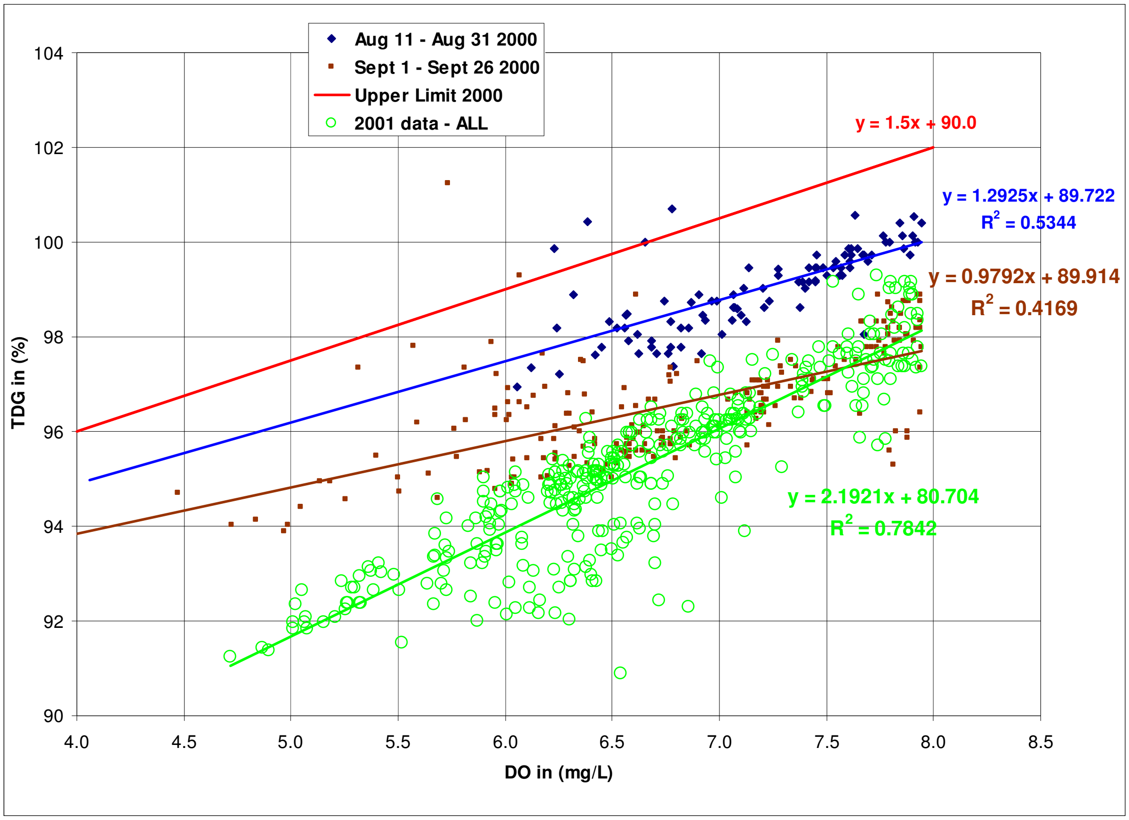


Figure 3-9. TDGin values versus DOin values observed in 2000 and 2001

Results – Turbine Aeration

Modeling results suggest that turbine aeration could supply enough air to meet the DO goal of 8 mg/L when DOin values are as low as 4 mg/L; however, when DOin values are less than about 7 mg/L TDG values could exceed the 110% regulatory criteria (see Figure 3-10 and Table 3-5). However, a second analysis showed that when TDG was maintained within 110 percent an increase in DO of 1.5 to almost 2 mg/l would be possible when DOin was 6 mg/L (see Figure 3-11 and Table 3-6). In other words if TDG was limited to 110% in the releases, the DO in the releases could be increased to 7.5 to 8 mg/L over 95% of the time for the months of August through October (see Figure 2-16.)

About 50 scfs of natural air per unit should be adequate over the full range of possible aeration scenarios considering the TDG and DO standards, and the draft tube vents should be able to supply this amount of air (see the previous section and Table 3-5). However, the TDG limit of 110% will be exceeded unless airflow is controlled so as to avoid the TDG limit.

In summary, a draft tube aeration system could be operated in a manner that allowed real-time peak aeration operations considering inflow DO and DN values as well as temperature conditions and unit flows to achieve significant increases in DO. If the TDG standard was maintained at 110%, draft tube aeration would attain 8 mg/L DO a high percentage of the time, i.e., about 75 to 90% in the months of August through October when DOin values were about 7 mg/L based on 2000 and 2001 data (see Figure 2-16); and would attain 7.5 to 8 mg/L over 95% of the time when DOin values were about 6 mg/L; and the minimum DO that would occur would be about 6.5 mg/L.

Cost and Power Loss Considerations

The cost for retrofit turbine aeration systems at Long Lake HED is difficult to derive at this point prior to a site visit. At this time, use of the 4 – four inch ports in the turbine draft chest is envisioned for air admission. This will provide multiple entry points for the air which will enable better dispersion of the air bubbles in the turbine draft tube and improve the resulting DO uptake. These ports combined should meet the needed air flow rate predicted by the DMB.

Typically each port would be fitted with an “eyelid” type air baffle, butterfly type air valve, air silencer, entrance bellmouth with differential pressure taps and an inlet screen. The required air flow would be approximately 10 cfs per air port for a total air flow of 40 cfs maximum. Depending upon a number of factors, the installed cost for field testing would be in the $50k to $100k range. This number would be refined after the site visit and follow-on engineering.

This scheme should perform like a combination between central type aeration, where air is admitted from one point down through the runner nose cone, and peripheral type aeration, where air is admitted at the top of the turbine draft tube from many ports equally spaced around the draft tube perimeter. This aeration approach is usually considerably less expensive than other aeration alternatives as discussed further in this report.

The effect of turbine discharge aeration on power loss is estimated to be 1.5-2 % considering that airflows would be about 2% of the water flow (Rohland et al, 2010) as predicted by the DBM. The decease in efficiency should not vary throughout the anticipated operational range of 1,500 cfs to 1,900 cfs. Field tests should be conducted to determine the actual power losses at Long Lake HED.

A water quality monitor would need to be installed to measure DO, TDG, and temperature at a representative location in the tailwater. To control TDG and avoid excursions of the water quality standard, a real-time airflow control system would be needed. A similar control system was installed at Osage Hydro to maintain the DO standard and to minimize the TDG levels such that the 110% standard was maintained to the extent possible. For Long Lake HED the operation procedure could limit TDG to 110% while improving the DO as much as possible.

Sensitivity of DO Improvements to Operational TDG Limits

Considering an airflow control system would likely be needed at Long Lake HED to limit the TDG level, DBM model runs were made to predict DO increases over a range of DOin and DNin values for TDG% limited to 109, 105, and 100. The results of these model runs are presented in Figure 3-12. The results show that a TDG limit at 109% would yield DO levels in the releases that would be similar to the DO levels with the TDG limit set at 110%. For the case with TDG limited to105%, the DO increase would drop about 0.5 mg/L (or 42%) for DOin at 7 mg/L compared to the case for TDG limit set at 109%. For the case with TDG limited to100%, the DO increase would drop about 1.1 mg/L (or 92%) for DOin at 7 mg/L compared to the case for TDG limit set at 109%.

The case with TDG limited to 100% shows that there would be essentially no benefit of turbine aeration. If TDG is limited to 110% with no allowance for marginal excursions, Avista may want to consider setting an operational goal for TDG at 107% to 108% to see if the 110% level can be maintained. For this latter case the DO in the tailrace would be near 8 mg/L when DOin was 7 mg/L and would be near 7.5 mg/L when DOin was 6 mg/L.

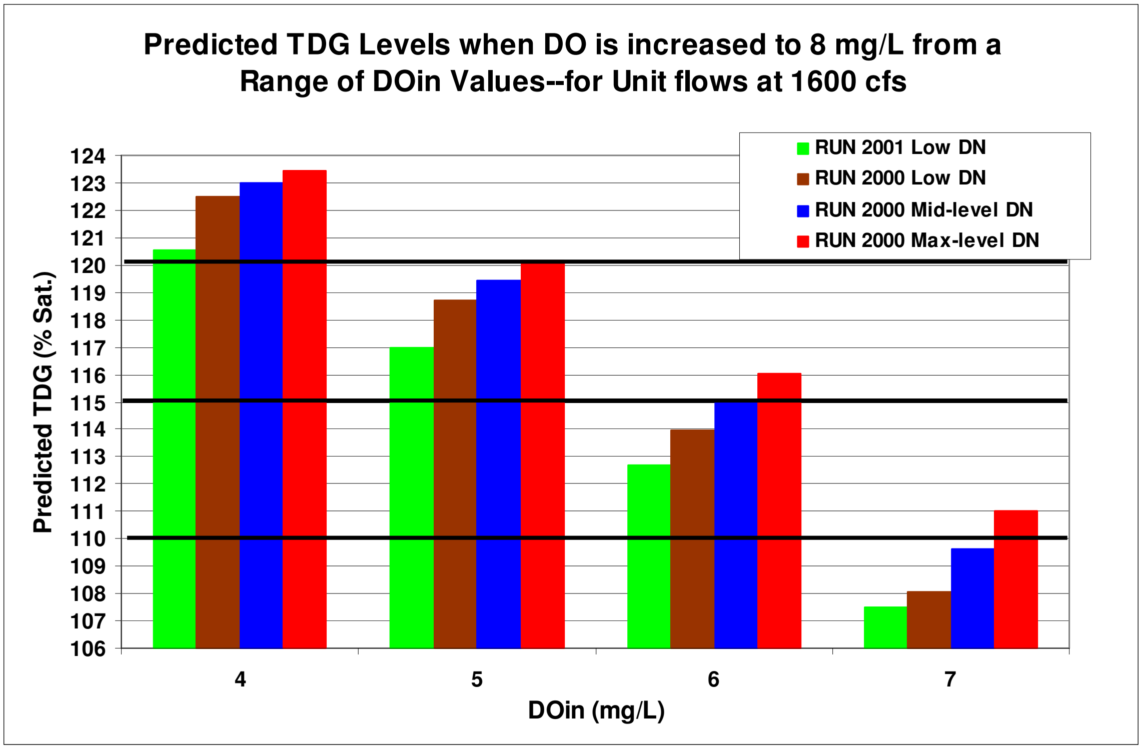


Figure 3-10. Predicted TDG values for the case where turbine releases are aerated to 8 mg/L without TDG limits, considering a range of DOin and DN levels

Table 3-5. Results of DBM runs to determine airflows required for turbine aeration with the objective of attaining 8 mg/L in the releases from Long Lake HED for 2000 and 2001 operating conditions and a range of model inputs for DOin, unit flows, DNin, and bubble size.

RUN 2001 **TDGin = 2.1921*CO2 + 80.704** **Green Line**
Tin 19 °C
Target DO 8 mg/L

Unit Flowrate cfs	Initial Velocity m/s	DOin mg/L	OTE %	Initial bubble Radius (mm) mm	DNin estimated %	TDG predicted %	Airflow Required scfs	- 50% bubble size scfs	+50% bubble size scfs
1600	3.6	**4**	37	1	**102.2**	**121**	**65**	60	80
1850	4.2	**4**	38	0.8	**102.2**	**120**	**73**	73	88
1600	3.6	**5**	37	1	**102.2**	**117**	**50**	45	65
1850	4.2	**5**	37	0.8	**102.2**	**116**	**55**	53	68
1600	3.6	**6**	36	1	**102.2**	**113**	**35**	30	45
1850	4.2	**6**	37	0.8	**102.2**	**112**	**38**	38	48
1600	3.6	**7**	35	1	**102.2**	**108**	**20**	15	25
1850	4.2	**7**	36	0.8	**102.2**	**106**	**20**	20	25

RUN 2000 Low TDG **TDGin = 0.98*CO2 + 89.9** **Brown Line**
Tin 18 °C **Sept 1-26, 2000**
Target DO 8 mg/L

Unit Flowrate cfs	Initial Velocity m/s	DOin mg/L	OTE %	Initial bubble Radius (mm) mm	DNin estimated %	TDG predicted %	Airflow Required scfs	- 50% bubble size scfs	+50% bubble size scfs
1600	3.6	**4**	37	1	**107.7**	**123**	**65**	60	80
1850	4.2	**4**	37	0.8	**107.7**	**122**	**73**	73	88
1600	3.6	**5**	36	1	**106.2**	**119**	**50**	45	65
1850	4.2	**5**	37	0.8	**106.2**	**119**	**58**	55	68
1600	3.6	**6**	36	1	**104.6**	**114**	**35**	30	45
1850	4.2	**6**	36	0.8	**104.6**	**113**	**38**	38	48
1600	3.6	**7**	35	1	**103.1**	**108**	**20**	15	25
1850	4.2	**7**	36	0.8	**103.1**	**107**	**20**	20	25

RUN 2000 High-level TDG **TDGin = 1.3DO +89.7** **High-level TDG--Blue Line**
Tin 18 °C **Aug 11-31, 2000**
Target DO 8 mg/L

Unit Flowrate cfs	Initial Velocity m/s	DOin mg/L	OTE %	Initial bubble Radius (mm) mm	DNin estimated %	TDG predicted %	Airflow Required scfs	- 50% bubble size scfs	+50% bubble size scfs
1600	3.6	**4**	37	1	**109**	**123**	**65**	60	80
1850	4.2	**4**	37	0.8	**109**	**122**	**73**	73	88
1600	3.6	**5**	36	1	**107.9**	**119**	**50**	45	65
1850	4.2	**5**	36	0.8	**107.9**	**119**	**58**	55	68
1600	3.6	**6**	36	1	**106.8**	**115**	**35**	30	45
1850	4.2	**6**	36	0.8	**106.8**	**114**	**38**	38	48
1600	3.6	**7**	35	1	**105.6**	**110**	**20**	15	25
1850	4.2	**7**	36	0.8	**105.6**	**108**	**20**	20	25

RUN 2000 Max-level TDG **TDGin = 1.5DO +90** **Maximum Level--** **Red Line**
Tin 19 °C
Target DO 8 mg/L

Unit Flowrate cfs	Initial Velocity m/s	DOin mg/L	OTE %	Initial bubble Radius (mm) mm	DNin estimated %	TDG predicted %	Airflow Required scfs	- 50% bubble size scfs	+50% bubble size scfs
1600	3.6	**4**	37	1	**110.4**	**123**	**65**	60	80
1850	4.2	**4**	37	0.8	**110.4**	**123**	**73**	73	88
1600	3.6	**5**	36	1	**109.6**	**120**	**50**	45	65
1850	4.2	**5**	36	0.8	**109.6**	**120**	**58**	55	68
1600	3.6	**6**	35	1	**108.7**	**116**	**35**	30	45
1850	4.2	**6**	36	0.8	**108.7**	**115**	**38**	38	48
1600	3.6	**7**	34	1	**107.8**	**111**	**20**	15	25
1850	4.2	**7**	35	0.8	**107.8**	**110**	**20**	20	25

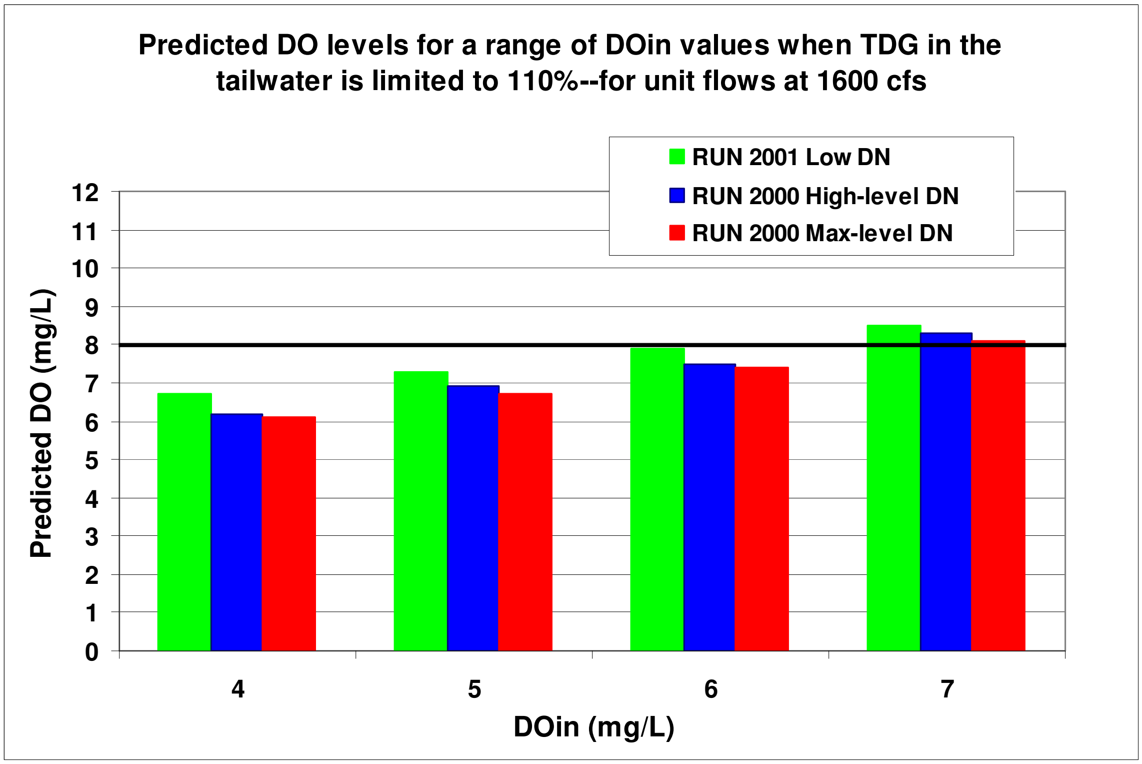


Figure 3-11. Predicted DO values for the case where turbine releases are limited to a TDG level of 110%, considering a range of DOin and DN levels

Table 3-6. Results of DBM runs to predict DO in the releases from Long Lake HED for 2000 and 2001 operating conditions with TDG limited to 110% and a range of model inputs for DOin, unit flows, and DNin.

RUN 2001- Low DN	**TDGin = 2.1921*CO2 + 80.704**			**Green Line**			
	Tin	18	℃				
	TargetTDG	110	%				
Unit Flowrate cfs	DOin mg/L	DOpred mg/L	OTE %	Initial bubble Radius (mm) mm	TDN in estimated %	TDGpredicted %	Airflow Required scfs
1500	4	6.7	42	1.1	102.2	110	35
1600	4	6.7	43	1	102.2	110	36
1800	4	6.7	44	0.8	102.2	110	39
1900	4	6.7	43	0.8	102.2	110	43
1500	5	7.3	39	1.1	102.2	110	32
1600	5	7.3	40	1	102.2	110	33
1800	5	7.3	41	0.8	102.2	110	36
1900	5	7.3	40	0.8	102.2	110	39
1500	6	7.9	36	1.1	102.2	110	29
1600	6	7.9	37	1	102.2	110	29
1800	6	7.9	38	0.8	102.2	110	32
1900	6	7.9	37	0.8	102.2	110	35
1500	7	8.5	33	1.1	102.2	110	25
1600	7	8.5	34	1	102.2	110	26
1800	7	8.5	34	0.8	102.2	110	28
1900	7	8.5	33	0.8	102.2	110	31

RUN 2000 High-level DN	**TDGin = 1.3x + 89.7**			**High-level TDG--Blue Line Aug 11-31, 2000**			
	Tin	18	℃				
	TargetTDG	110	%				
Unit Flowrate cfs	DOin mg/L	DOpred mg/L	OTE %	Initial bubble Radius (mm) mm	TDN in estimated %	TDGpredicted %	Airflow Required scfs
1500	4	6.2	44	1.1	109	110	27
1600	4	6.2	45	1	109	110	28
1800	4	6.2	46	0.8	109	110	30
1900	4	6.2	45	0.8	109	110	33
1500	5	6.9	40	1.1	107.9	110	25
1600	5	6.9	41	1	107.9	110	26
1800	5	6.9	43	0.8	107.9	110	28
1900	5	6.9	41	0.8	107.9	110	31
1500	6	7.6	37	1.1	106.8	110	23
1600	6	7.5	38	1	106.8	110	23
1800	6	7.6	39	0.8	106.8	110	26
1900	6	7.6	38	0.8	106.8	110	28
1500	7	8.3	33	1.1	105.6	110	21
1600	7	8.3	34	1	105.6	110	21
1800	7	8.3	35	0.8	105.6	110	23
1900	7	8.3	34	0.8	105.6	110	25

RUN 2000 Max-level DN	**TDGin = 1.5DO +90**			**Maximum Level-- 2000 data - Red line**		**Red Line**	
	Tin	19	℃				
	TargetTDG	110	%				
Unit Flowrate cfs	DOin mg/L	DOpred mg/L	OTE %	Initial bubble Radius (mm) mm	TDN in estimated %	TDGpredicted %	Airflow Required scfs
1500	4	6.1	44	1.1	110.4	110	25
1600	4	6.1	45	1	110.4	110	26
1800	4	6	47	0.8	110.4	110	28
1900	4	6.1	45	0.8	110.4	110	31
1500	5	6.7	41	1.1	109.6	110	23
1600	5	6.7	42	1	109.6	110	23
1800	5	6.7	43	0.8	109.6	110	26
1900	5	6.7	42	0.8	109.6	110	28
1500	6	7.5	37	1.1	108.7	110	21
1600	6	7.4	38	1	108.7	110	21
1800	6	7.4	39	0.8	108.7	110	23
1900	6	7.4	38	0.8	108.7	110	25
1500	7	8.1	34	1.1	107.8	110	18
1600	7	8.1	35	1	107.8	110	18
1800	7	8.1	36	0.8	107.8	110	20
1900	7	8.1	35	0.8	107.8	110	22

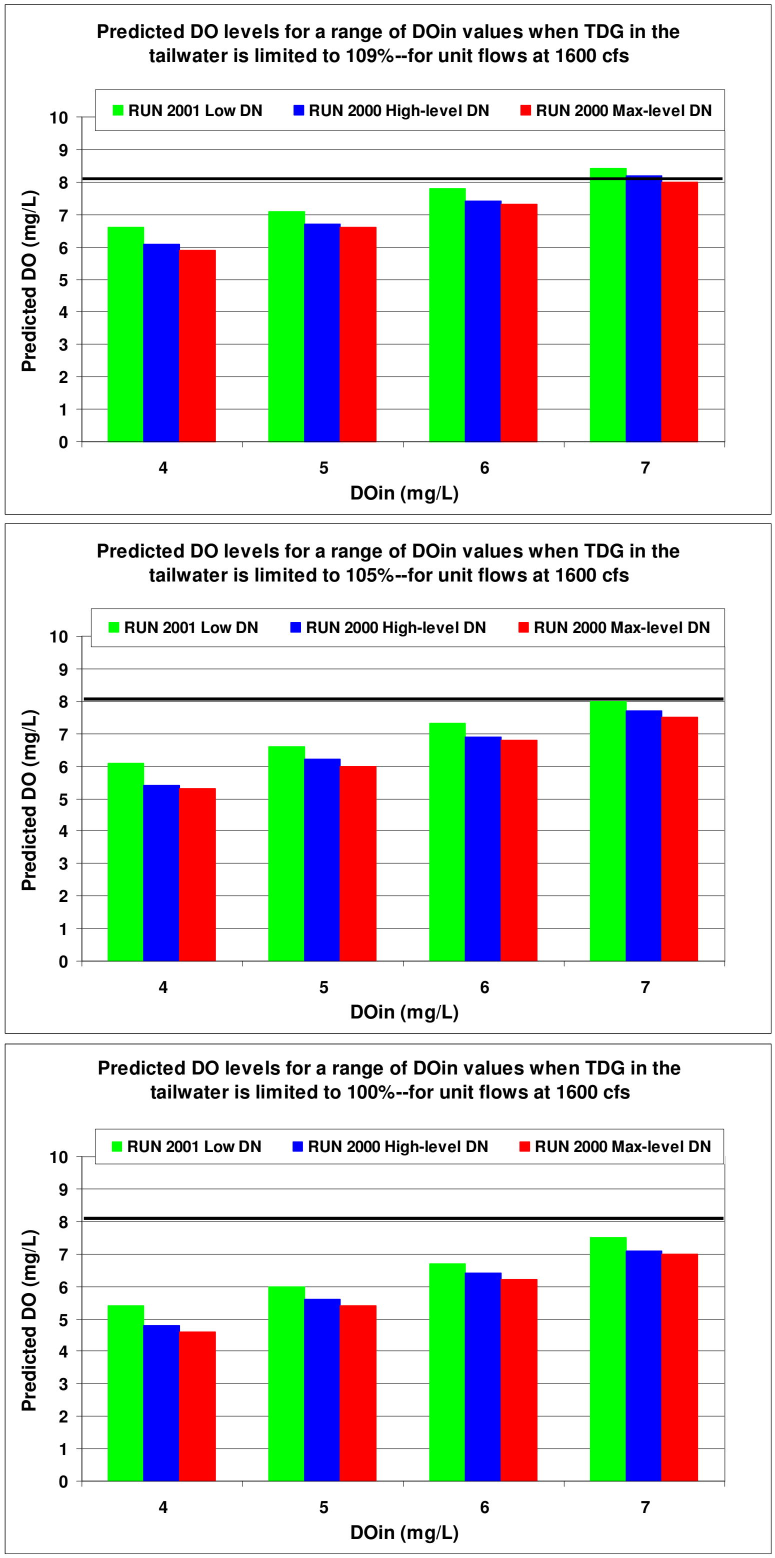


Figure 3-12. Predicted DO values for TDG levels in turbine releases limited to 109%, 105%, and 100% considering a range of DOin and DN levels

4 Penstock Oxygenation

Penstock oxygenation and, possibly, aeration are alternatives that have potential for application at Long Lake HED, especially considering the long length of the penstock and the high pressure on the water as it passes through the penstock and into the turbine. Also, additional aeration occurs as oxygenated/aerated water passes through the turbine system, the draft tube, and the tailrace. Figure 4-1 shows a side view of the penstock, turbine system, draft tube, and the tailrace.

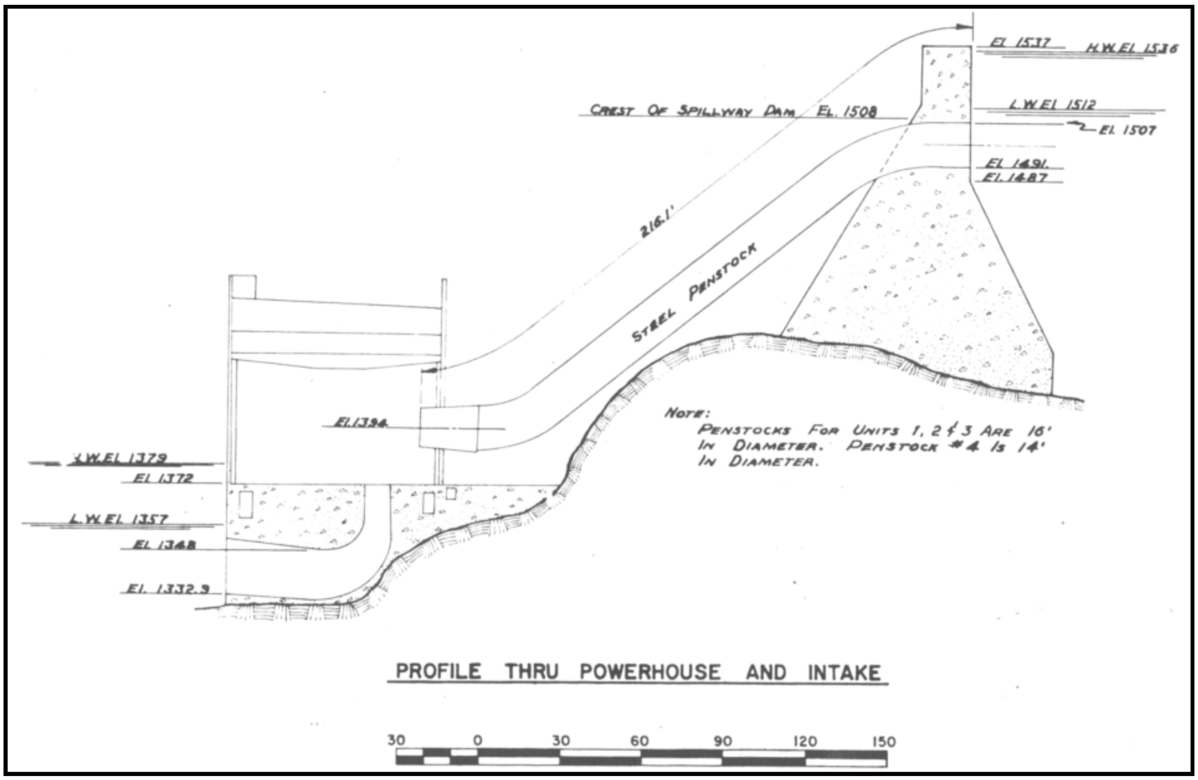


Figure 4-1. Side View of Long Lake HED

A penstock oxygenation system would inject gaseous oxygen or air into the penstock of each unit to increase DO in the discharge. The oxygen is injected at point sources (such as piezometer line locations) or through diffusers installed along the floor of an accessible, most-upstream end in the penstock. The resulting bubbles are swept along the penstock and are dissolved into the water flow as the bubbles rise to the top of the penstock. Bubbles that collect on the roof will seek an outlet such as a surge tank, or other raw water piping – even upstream to the intake if there is sufficient gradient in the penstock. Small bubbles introduced through a diffuser system is the best injection method to obtain high oxygen transfer efficiency and minimize uncontrolled two-phase flow problems because large bubbles have less diffusion surface area and overall efficiency and end up coalescing on the penstock roof. Penstock oxygenation systems are best applied to dams with long, deep penstocks to provide time and a strong driving force for efficient oxygen transfer. Penstock systems have additional advantages—water velocity mixing and turbulence in a closed environment—that also improve oxygen transfer. The small amount of gas in the water flow does not have a significant effect on turbine efficiency. Penstock systems are operated only during hydropower operation and must obtain all of the required DO increase in the time that the bubbles are in contact with the water as it passes through the system.

Modeling

The DBM was used to predict the DO uptake as well as the DN changes as water passes through the penstock, draft tube, and tailrace. Penstock modeling was less sensitive to initial bubble size and bubble size was more definitive considering that data are available on bubble size versus flux for the porous hose that would be used to diffuse oxygen into the penstock. Bubbles have a much longer contact time with the penstock option, and the initial bubble diameter from the diffuser is relatively well established (McGinnis and Little, 2002).

The penstock geometry was discretized as described in the previous section and input into the DBM as in input file. Pressures are solved hydrostatically, with pressure above the turbine defined by the lake level and downstream of the turbine by the tailrace elevation (Figure 4-2). Turbine geometries were determined by Almquist as presented in the previous section.

Both air and oxygen were investigated for being diffused at the entrance to the penstock. Initial bubble diameters of 2 and 4 mm were used as boundary conditions. Due to the length of the penstock and draft tube, the bubbles have a high residence time, allowing them to achieve high oxygen transfer efficiencies of over 60% for oxygen bubbles 4 mm in diameter and over 84% for the oxygen bubbles 2 mm in diameter (see Table 4-1). For all initial DO values of 5 mg/l and above, the DO goal of 8 mg/L was met, and TDG did not exceed 110%. About 5 scfs (0.75 tons/hr) of oxygen would be required for the 2 mm bubbles for a DOin value of 5 mg/L, without consideration of a factor of safety.

Injecting air instead of oxygen, however, resulted in high TDG values greater than 110% TDG when adding 1 mg/L DO and above 120% TDG when adding 2 mg/L DO to the releases. This is due to the long contact times and high pressures (especially in the penstock) that allow a large amount of the nitrogen within the air bubbles to be dissolved.

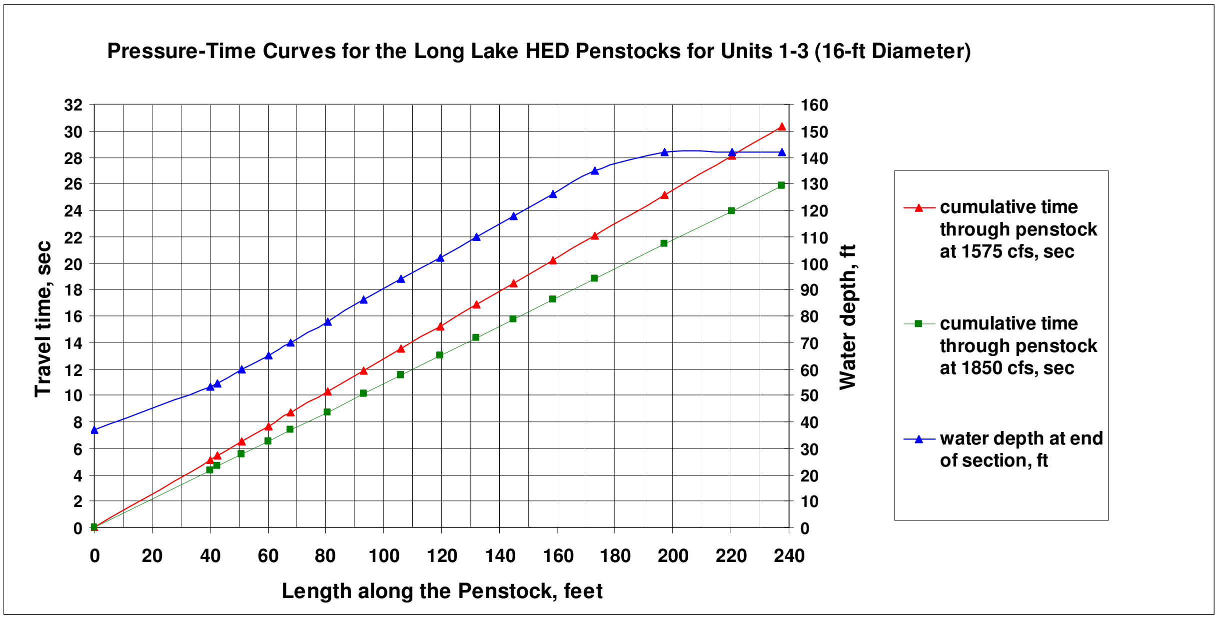


Figure 4-2. Pressure-Time Curves for Long Lake HED Penstocks for Units 1-3 (16-ft diameter)

Previous Experience

Penstock systems have been operated at two hydro projects for more than 10 years (Tims Ford, TVA and Table Rock, USACE). Both systems use pure oxygen to maximize oxygen transfer and avoid total dissolved gas problems.

TVA installed a penstock oxygen system at Tims Ford Dam (Figures 4-3 and 4-4) in 1993, with several design iterations through 1995. Tims Ford is a single unit hydroproject rated at 45 MW at 4,800 cfs and 120 feet of head. The Tims Ford penstock is 22 feet in diameter, 700 feet long and approximately 120 feet deep resulting in good oxygen transfer. Oxygen piping was routed up through the penstock to the diffuser headers. The steel lining of the penstock allowed attachment of the oxygen piping and diffusers using spot welding techniques. Operation of the Tims Ford penstock oxygenation system resulted in several problems in the powerhouse that were addressed by operational changes or system modifications:

Table 4-1. Results of DBM runs to predict the amount of oxygen and air needed for diffusers at the entrance to the penstock to increase DO to 8 mg/L for a range of DOin values and the resulting TDG levels in the tailrace—Based on Long Lake HED conditions for 2000 and 2001

Results of DBM Runs for Penstock Diffusers						
	TDGin = 100%		Temperature = 20C			
OXYGEN--2mm diameter bubbles						
Q, cfs	**DOin, mg/L**	**DOpred**	**OTE, %**	**TDGpred, %**	**Q O2 (scfs)**	**Q O2 (scfm)**
1500	3	8.6	90.6	110	7	420
1600	3	8.1	89.2	109	7	420
1800	3	8.0	86	108	8	480
1900	3	8.3	84.3	109	9	540
1500	4	8.8	90.6	107	5	300
1600	4	8.4	89.2	108	6	360
1800	4	8.4	85.9	107	7	420
1900	4	8.1	84.4	107	7	420
1500	5	8.2	90.9	106	4	240
1600	5	8.7	89.1	106	5	300
1800	5	8.2	86	105	5	300
1900	5	8.5	84.2	106	6	360
1500	6	8.4	90.9	104	3	180
1600	6	8.2	89.4	104	3	180
1800	6	8.5	85.9	104	4	240
1900	6	8.3	84.3	104	4	240
1500	7	8.6	90.9	103	2	120
1600	7	8.5	89.3	103	2	120
1800	7	8.3	86.1	102	2	120
1900	7	8.2	84.4	102	2	120
OXYGEN--4mm diameter bubbles						
1500	3	8.4	67.8	108	9	540
1600	3	8.4	65.2	108	10	600
1800	3	8.3	60.5	108	12	720
1900	3	8.3	58.4	108	13	780
1500	4	8.2	67.8	106	7	420
1600	4	8.3	65.2	107	8	480
1800	4	8.4	60.4	106	9	540
1900	4	8.0	58.4	106	10	600
1500	5	8.6	67.6	106	6	360
1600	5	8.2	65.1	105	6	360
1800	5	8.1	60.4	105	7	420
1900	5	8.2	58.2	105	8	480
1500	6	8.4	67.6	104	4	240
1600	6	8.1	65.1	103	4	240
1800	6	8.2	60.3	103	5	300
1900	6	8.0	58.2	103	5	300
1500	7	8.2	67.6	102	2	120
1600	7	8.1	65	102	2	120
1800	7	8.3	60.2	102	3	180
1900	7	8.2	58.1	102	3	180
AIR--2mm diameter bubbles						
1500	3	8.0	63	155	42	2520
1600	3	8.1	61.6	154	46	2760
1800	3	8.1	59.2	152	54	3240
1900	3	8.0	58	151	58	3480
1500	4	8.0	63.9	147	33	1980
1600	4	8.0	62.5	146	36	2160
1800	4	8.0	59.9	145	43	2580
1900	4	8.0	58.5	144	46	2760
1500	5	8.0	64.9	138	25	1500
1600	5	8.1	63.1	137	27	1620
1800	5	8.0	60.5	136	32	1920
1900	5	8.0	58.9	135	35	2100
1500	6	8.1	65.5	128	17	1020
1600	6	8.0	64.1	126	18	1080
1800	6	8.1	60.7	125	21	1260
1900	6	8.0	59.4	125	23	1380
1500	7	8.1	66.2	114	8	480
1600	7	8.0	64.8	114	9	540
1800	7	8.0	61.3	114	11	660
1900	7	8.1	59.7	114	12	720
AIR--4mm diameter bubbles						
1500	3	8.1	46.7	145	57	3420
1600	3	8.0	45	145	63	3780
1800	3	8.0	41.9	144	77	4620
1900	3	8.0	40.3	143	84	5040
1500	4	8.0	46.8	139	46	2760
1600	4	8.0	44.9	138	51	3060
1800	4	8.0	41.6	137	62	3720
1900	4	8.0	40.1	137	68	4080
1500	5	8.0	46.5	131	35	2100
1600	5	8.0	44.7	131	39	2340
1800	5	8.0	41.4	130	47	2820
1900	5	8.0	39.8	129	51	3060
1500	6	8.1	46.3	122	23	1380
1600	6	8.0	44.5	122	26	1560
1800	6	8.0	41.1	122	32	1920
1900	6	8.0	39.6	121	35	2100
1500	7	8.0	46.2	112	12	720
1600	7	8.0	44.4	112	13	780
1800	7	8.0	40.9	111	16	960
1900	7	8.0	39.3	112	18	1080

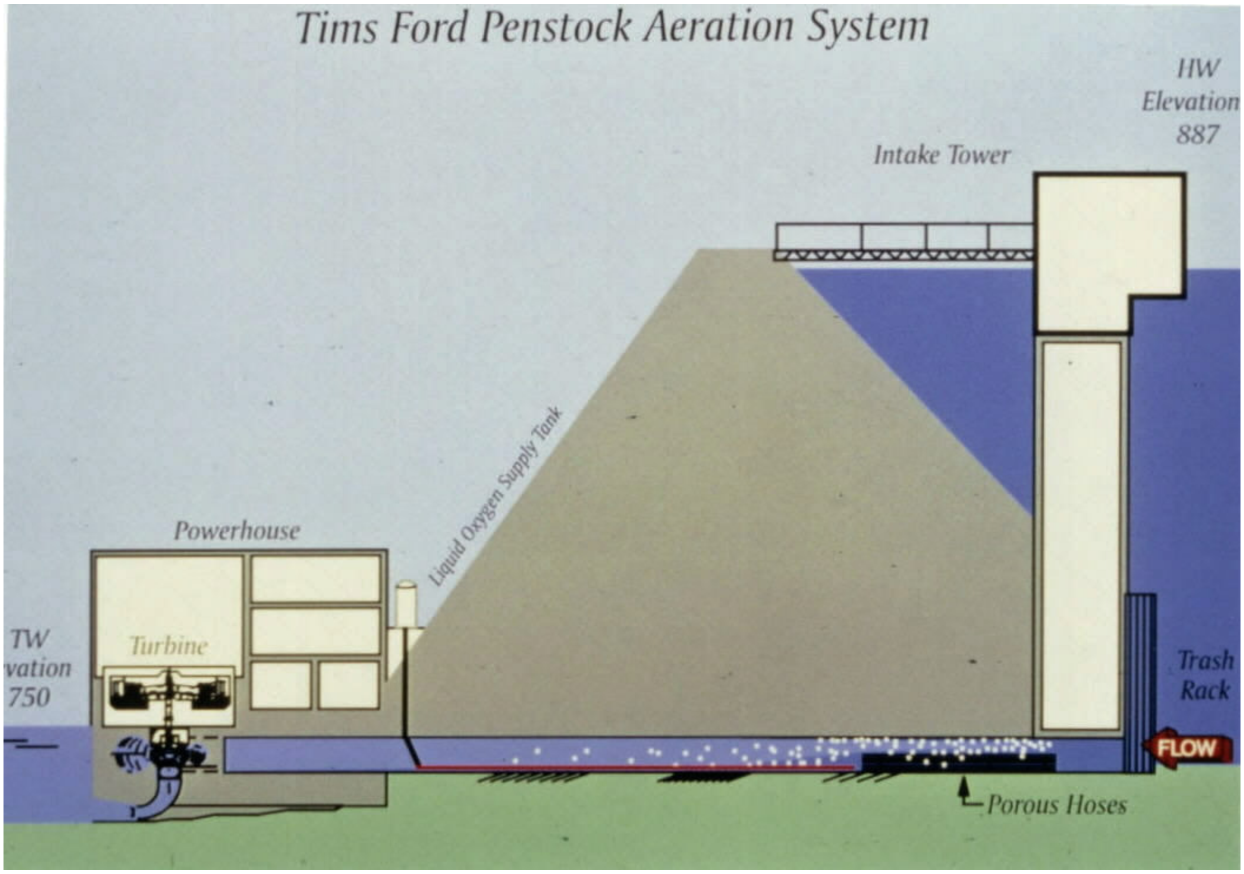


Figure 4-3. Tims Ford Penstock Oxygenation System (Tennessee Valley Authority)

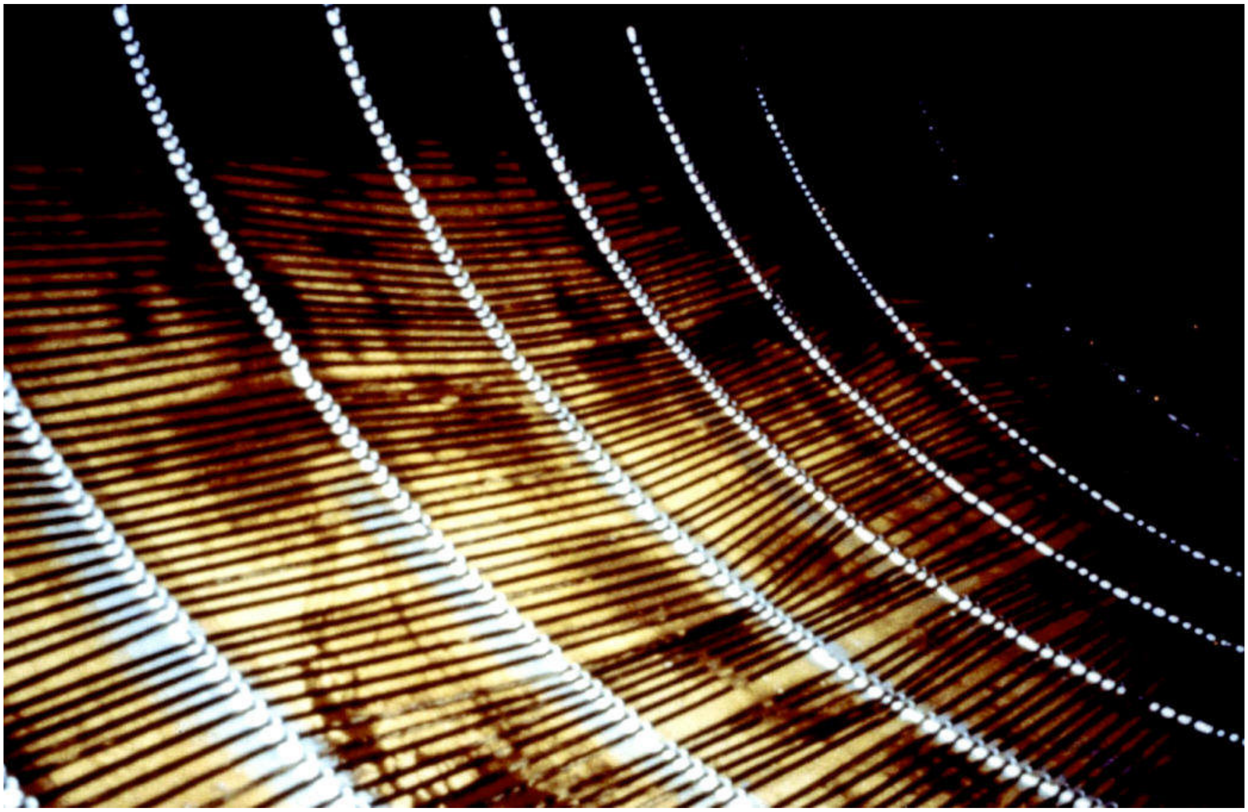


Figure 4-4. Porous Hose Diffuser in Tims Ford Penstock

- Flow Meter Disruption: Gaseous oxygen bubbles in the water flow through the penstock disrupted the use of the acoustic flow meter system at Tims Ford and will disrupt the use of Winter - Kennedy tap flow measurements, due to gas trapped in the lines.
- Cooling Water Disruption: Gaseous oxygen bubbles collected in the powerhouse raw water cooling systems at Tims Ford and disrupted operation of the air conditioning system. The raw water system connection was at the top of the penstock at Tims Ford and required numerous iterations, including a shield over the penstock connection and several valve seal replacements, to solve the problem.
- Oxygen Enriched Environment in Intake Tower: Gaseous oxygen bubbles collected and moved upstream along the top of the penstock during a header break at Tims Ford causing an oxygen enriched environment as the bubbles vented into the enclosed intake structure. This problem does not occur unless major leaks are present in the diffuser system.

Results at Tims Ford:

- o 3 mg/L uptake
- o Flexible oxygen input rates
- o High OTE at Tims Ford
- o High operating costs
- o Backflow, venting problems with broken diffuser lines
- o Significant maintenance due to diffuser damage by
  - turbulent flows
  - debris

The Tims Ford Penstock Oxygen System was decommissioned and replaced by a reservoir oxygen diffuser system in 2005.

Table Rock is a four unit hydro project rated at 200 MW operated by the Little Rock District of the U. S. Army corps of Engineers. At Table Rock, oxygen was injected through piezometer lines that connected near the upstream end of the penstock. Operation of high oxygen flows at Table Rock caused surges of water and oxygen to be vented out of vertical ventilation piping at the dam. A monitoring system was installed to handle the risk of an oxygen-enriched environment where oxygen piping was routed through the enclosed areas around the penstocks and powerhouse.

Application to Long Lake Hydro Electric Development

<u>Conceptual Design for Penstock Oxygen at Long Lake</u>

Design Basis

The penstock system design capacity is sized to provide 20 tons of oxygen per day to the average summertime water flow. This equates to increasing the DO concentration by up to turbine water flow by 2.5 mg/L. Each of the four penstocks at Long Lake is operated at about 1,575 cfs as needed to meet the daily hydropower schedule. Up to three penstocks are utilized for several hours each during typical summertime operations. The oxygen supply to each penstock would account for predicted oxygen transfer efficiencies and a factor of safety of 1.3. The oxygen transfer efficiency was modeled for penstock length, depth and turbulence at the project using the DBM model. A prediction of 78% was used for the conditions of this study. The resulting design capacity for each penstock is 18 tons per day (300 scfm) or 72 tons per day for the project.

Description of Oxygen Diffuser Equipment

For Long Lake, the penstock system design includes porous hose diffusers mounted inside the upstream end of the penstock behind the head gates (Figure 4-5) similar to TVA's Tims Ford System. High flow, aeration specific, porous hoses would be utilized in a linear arrangement of 25 hoses at the bottom of the penstock near the head gate. Each hose would extend 40 feet into the penstock. This hose is expected to produce a 3 mm diameter bubble at the design flowrate (0.4 scfm/ft).

Description of Oxygen Supply Equipment

The penstock system would be supplied with oxygen delivered to the site in liquid form in truck and stored in a tank at an oxygen supply facility onsite (Figure 4-6). The supply facility would include ambient air vaporizers to convert liquid oxygen to gaseous form and utilize vaporization pressure build to maintain the pressure requirements for oxygen delivery. Oxygen flow control and monitoring would be included at the facility. The facility and piping would be designed for an oxygen supply rate of 72 tons per day to handle peak hydropower operations for the plant. Liquid oxygen storage facilities have numerous safety requirements regarding proximity to other structures and overhead power lines as detailed in NFPA 50. Potential liquid oxygen supply facility locations are assumed to be available near dam or powerhouse. A liquid oxygen storage tank capacity of at least 6,000 gallons would be required to allow offloading of a full truckload (4,500 gallons) on each delivery. Truck deliveries would be about 1 truck per day during maximum use. A 3" stainless steel supply pipe would be run up and across the dam to the penstock vents. A 1-1/2" oxygen supply pipe would be routed through each vent pipe to the upstream penstock end. Each pipe will be sized to comply with CGA G 4.4 requirements. Automated flow controls would be installed at each intake. A diffuser manifold and strapped porous hoses would be located at the upstream end of the penstock.

Construction Requirements

The construction of the penstock diffuser system would require an outage, penstock dewatering, scaffolding, lighting, and ventilation to provide access for crew, equipment and materials. Maintenance of the diffuser system would require similar costs and effort as initial construction.

Costs for Installation and Operations

See Table 4-2.

Environmental Effects

- DO uptake ~ 2.5 mg/L
- Temperature increase ~ none
- TDG ~ 105%
- Fish Entrainment ~ none
- Other Water Quality Effects ~ none

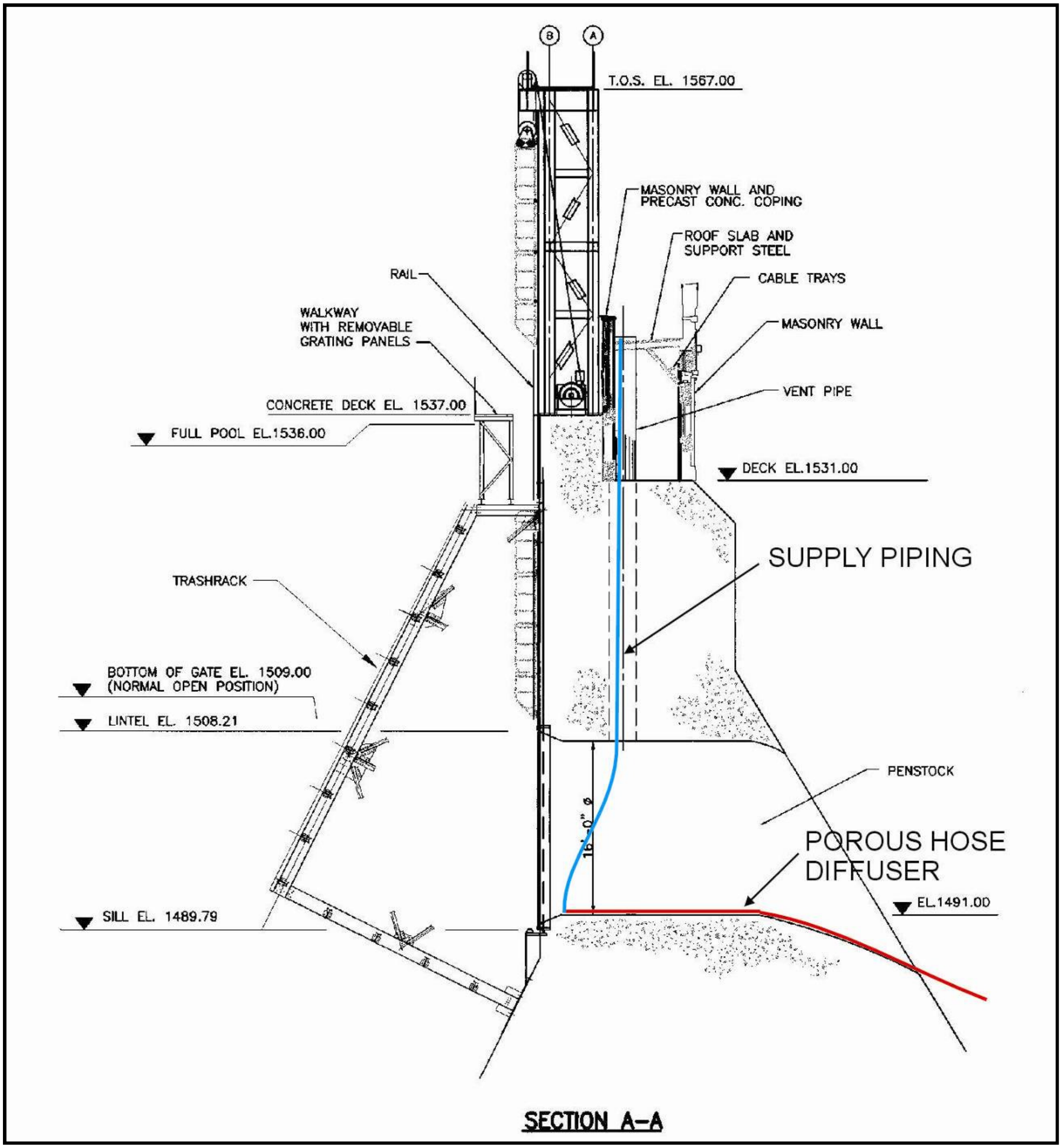


Figure 4-5. Penstock oxygen diffuser layout

Figure 4-6. Oxygen facility at TVA Tims Ford hydropower project

Table 4-2. Estimated Installation and Operating Costs

Avista Long Lake Penstock O2 System INSTALLATION COST BREAKDOWN						
PENSTOCK DIFFUSER:				**Labor**	**Material**	**Total**
Detailed design and drawings				$35,000	$2,500	$37,500
Diffuser hose and straps	4,000	feet total		$24,000	$23,000	$47,000
Penstock diffuser manifolds				$36,000	$32,000	$68,000
Penstock dewatering, scaffolding, ventilation				$60,000	$10,000	$70,000
Flow control valves, remote operation, power				$40,000	$33,000	$73,000
Supply piping on dam	500	feet total		$26,500	$26,500	$53,000
Supply piping to dam	1,000	feet total		$3,000	$50,000	$53,000
Travel expenses and shipping:				$6,000	$10,000	$16,000
O&M manual, startup testing and training				$27,500	$4,000	$31,500
		Diffuser System Total:		**$224,500**	**$187,000**	**$417,500**
OXYGEN SUPPLY FACILITY:				**Labor**	**Material**	**Total**
Facility layout design				$10,000	$1,000	$11,000
Grade and drainage				$12,000	$12,000	$24,000
Concrete foundations and pads				$55,000	$45,000	$100,000
Truck access and turnaround				$20,000	$25,000	$45,000
Electrical power supply				$10,000	$15,000	$25,000
LOx equipment and cryogenic piping installation				$15,000	$0	$15,000
Supply manifold, piping, control valves, pipe supports				$9,000	$25,000	$34,000
Fence and gate				$6,000	$6,000	$12,000
		Oxygen Facility Total:		**$137,000**	**$129,000**	**$266,000**
OPERATING COSTS:				**Labor**	**Material**	**Total**
Annual LOx Usage	325	tons	Add for oxygen demands?			
	78%	OTE				
	$144.00	per ton			$60,000	$60,000
Annual Diffuser Maintenance (10yr hose replacement)				$8,400	$3,300	$11,700
LOx Facility equipment lease, maintenance					$24,000	$24,000
		LOx Operating Costs Total:		**$8,400**	**$87,300**	**$95,700**

Installation estimate does not include outage costs. Oxygen facility costs are based on leased cryogenic oxygen equipment (storage tank, vaporizers, pressure control station and piping).

Concerns and Considerations

Advantages

- Low capital costs
- Effective DO uptake for any operating conditions
- Not affected by reservoir oxygen demands
- Instantaneous application when needed
- Minimal maintenance requirements (unless diffusers get damaged)
- Can be operated at low levels to oxygenate leakage flows that originate from the penstock
- Could potentially be combined with turbine aeration to achieve a higher DO concentration during periods when turbine aeration alone could not meet the 8 mg/l regulatory water quality standard.
- Could potentially alleviate the TDG increases attributed to turbine aeration by stripping DN from the water in the draft tube

Disadvantages

- Operating costs for oxygen
- Oxygen flow rates must be operated to meet instantaneous DO mass deficits
- Oxygen system must be sized to meet peak hydro flows
- Higher operating costs due to less efficient OTE than reservoir diffusers
- Potential for causing oxygen enriched environments in dam or powerhouse
- Installation, maintenance and repair of diffusers requires an outage, dewatering and installation of scaffolding and ventilation.
- Safety concerns working on scaffolding in penstock and behind headgate.
- Possible gas blockage of raw water intakes from and water taps in the penstock
- Dependent on oxygen supplier and truck delivery

5 Forebay Aeration and Oxygenation

Reservoir Line Diffuser Utilizing Oxygen

Description

Dissolved oxygen can be increased using oxygen or aeration diffusers in the reservoir forebay. The deep water pressure in the reservoir can be used to achieve high gas transfer efficiency (Figures 5-1 and 5-2). The diffusers can be supplied with compressed air or oxygen from a liquid oxygen storage facility or other gas supply system. A properly designed forebay aeration system causes minimal adverse effects on hydro plant operation. Diffusers can be designed to place DO at strategic locations in the reservoir and the operation of the system can be tied to unit operation schedules, usually on a daily or weekly average basis.

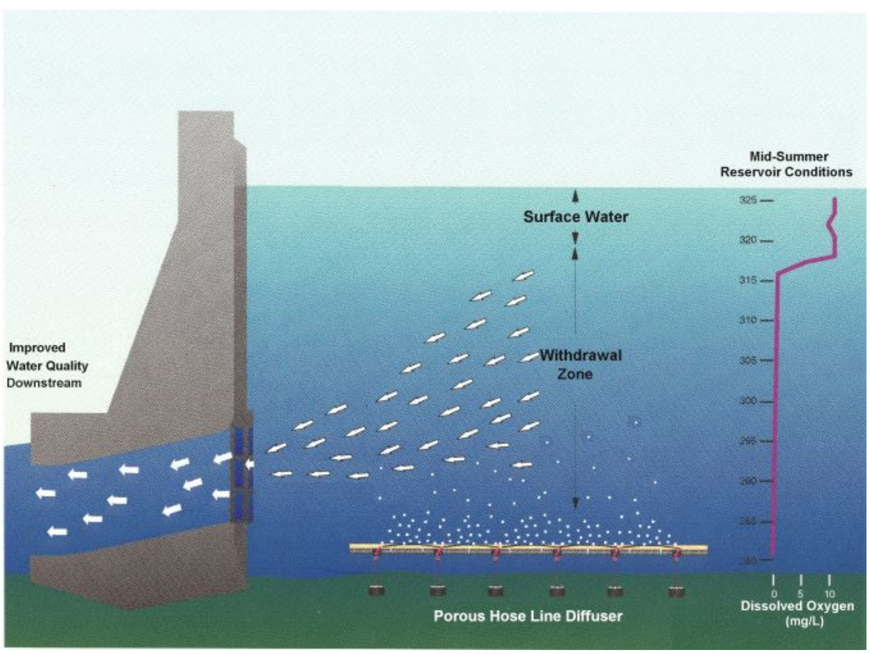


Figure 5-1. Reservoir Diffuser System

Figure 5-2. Installation of Diffusers at Richard B Russell (US Army Corps of Engineers, 2002)

Previous Experience

Reservoir diffuser systems have been applied to hydropower reservoirs since the 1970's. Almost all of these systems have utilized oxygen to reduce diffuser size and avoid TDG problems. A forebay diffuser system can be designed to aerate a large volume in the reservoir to handle peaking hydro turbine flows, or to change input oxygen flow rates as a function of turbine operation. TVA is operating oxygen diffuser systems at nine hydropower projects. These systems were installed from 1993 to 1996 with recent system upgrades and installations through 2005. The US Army Corps of Engineers has been operating an oxygen diffuser system at the Richard B Russell hydro project since 1985. This system uses up to $1M per year of oxygen and was upgraded in 2001 with new line diffusers and controls to improve operation.

The line diffuser system, originally developed for TVA, has emerged as the most widely applied and successful hydropower oxygen diffuser system. The line diffuser is a simple and economical design that spreads bubbles over a large area and is installed and retrieved for any required maintenance without divers. The system uses long lines of flexible porous hose to avoid clogging and other maintenance problems experienced by previous systems that used ceramic diffusers. The line diffuser has proven to transfer oxygen efficiently, and minimize temperature destratification and sediment disruption. A list of applications includes the following projects:

- NextEra Energy Resources, Gulf Island Pond
- First Light Power Resources, Shepaug
- TVA: Douglas, Cherokee, Blue Ridge, Watts Bar, Fort Loudoun, Hiwasee, Tims Ford, Norris, Nottely
- PPL: Lake Wallenpaupack
- Duke Energy: Buzzard Roost
- USACE: Richard B Russell
- Water supply reservoirs

Figure 5-3 presents profiles taken in Richard B Russell Reservoir during oxygen diffuser operation. The profiles upstream of the diffuser are shallower and show low DO that is indicative of background conditions. The profiles near the diffuser show marked DO increase over background.

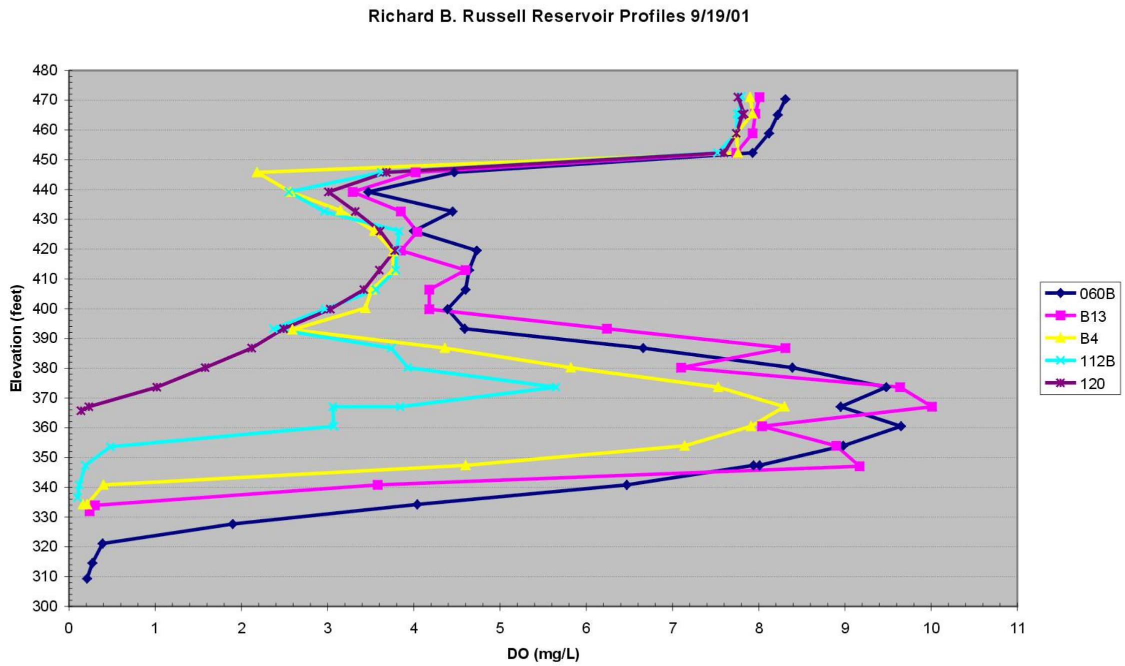


Figure 5-3. Richard B Russell Reservoir Profiles (9/19/01)
Stations 060b, B13 and B4 Are Near or Downstream of the Diffusers
Station 112b is Upstream but Near the Diffusers
Station 120 is Well Upstream of the Diffusers

Application to Long Lake Hydro Electric Development

Depending on the site specific requirements, reservoir diffuser systems can be applied near the penstock intake to oxygenate the water as it moves over the diffusers or over a large volume of the reservoir forebay to maintain oxygen content of a water volume that serves as a buffer for peak hydro flows, usually on a daily average basis. At Long Lake, either approach is applicable. The design concepts and advantages of each approach follow.

<u>Near-Field Reservoir Oxygenation Diffuser</u>

<u>Potential DO Enhancement Capability</u>

A near-field reservoir diffuser system could be sized to provide 2.5 mg/L uptake at the turbine flow of 4,725 cfs (a typical maximum hourly summer time flow). Oxygen flow rate would be controlled as a function of unit operations and reservoir conditions. The oxygen supply capacity would account for predicted oxygen transfer efficiencies and a factor of safety of 1.3. The oxygen flow rate per foot of diffuser was increased over normal design rates to achieve the compact layout and provide a strong plume to place the oxygen in the elevation of the withdrawal zone. The diffusers are positioned at elevation 1,460 well off the bottom to place oxygen near the centerline of the withdrawal zone. Due to this high flux, compact layout, the predicted oxygen transfer efficiency OTE is slightly less than that achieved with other designs. The oxygen transfer efficiency was modeled for diffusers in the intake channel using BPi, a state of the art bubble mass transfer model. A prediction of 85% OTE was used for the conditions of this study. The resulting design capacity is 49 tons per day or 800 scfm for the project. Capacity calculations are shown in Table 5-1.

Table 5-1. Near-Field reservoir design capacity calculations

FOREBAY OXYGEN DIFFUSER SYSTEM
Avista
Long Lake Near Field

SYSTEM DESIGN CALCULATIONS
Mobley Engineering
Norris, Tennessee
03/09/10

		Average Capacity		Design	
DESIGN Capacity		6,300	cfs	4,725	cfs
		3,000	cfs		
Oxygen Demands	Target	**2.5**	**mg/L**	**2.5**	**mg/L**
	BOD		mg/L	0.0	mg/L
	IOD		mg/L		mg/L
		2.5	mg/L	2.5	mg/L
DESIGN DO UPTAKE EFFICIENCY:		88%		85%	
DESIGN OXYGEN FLOW FOR 1MG/L DO UPTAKE		0.38	tons O2/ hr	0.62	tons O2/ hr
DESIGN SAFETY FACTOR:		1.00		1.30	
DESIGN OXYGEN SYSTEM CAPACITY		**23**	**tons O2/day**	**49**	**tons O2/day**
		0.95	tons O2/hr	2.02	tons O2/hr
		384	**SCFM**	**814**	**SCFM**
		4,807	gallons/day	10,189	gallons/day
		23,034	scfh	48,828	scfh

Conceptual Design of a Near-Field Reservoir Diffuser for Long Lake Hydroelectric Development

Design basis

For the near field design (Table 5-1), the diffusers are located in the intake channel near the dam at elevations approximately 70 feet above the bottom to place oxygen in turbine withdrawal zone. The turbine withdrawal zone was modeled to be above elevation 1,450 feet (443 meters) centered at 1,499 feet (457 meters). The turbine withdrawal is oxygenated as turbine intake water current flows over the diffusers. The diffuser location in the intake channel would permit a fairly quick adjustment to the DO content of the turbine water in response to changing conditions. A 2 hour reaction time to adjustments in the operation of the oxygen diffuser system is estimated for operation at 4,725 and 4 to 6 hours for operation at 1,575 cfs. During the summertime stratified conditions, this system would require a small oxygen flow to maintain an oxygenated volume of water for turbine startup.

Description of Near Field Reservoir Diffuser Equipment

The near-field diffuser system would consist of two 1,200 foot long diffusers positioned along the centerline and approximately 70 feet above the bottom of the intake channel. The near field diffuser layout is shown in Figure 5-4.

Recommendations

It is recommended that water currents in the withdrawal zone and in the intake channel be measured using acoustic Doppler current profiles before the final designs for diffuser placement are developed. Also, a diffuser plume study should be considered since this high flux diffuser has not yet been tested.

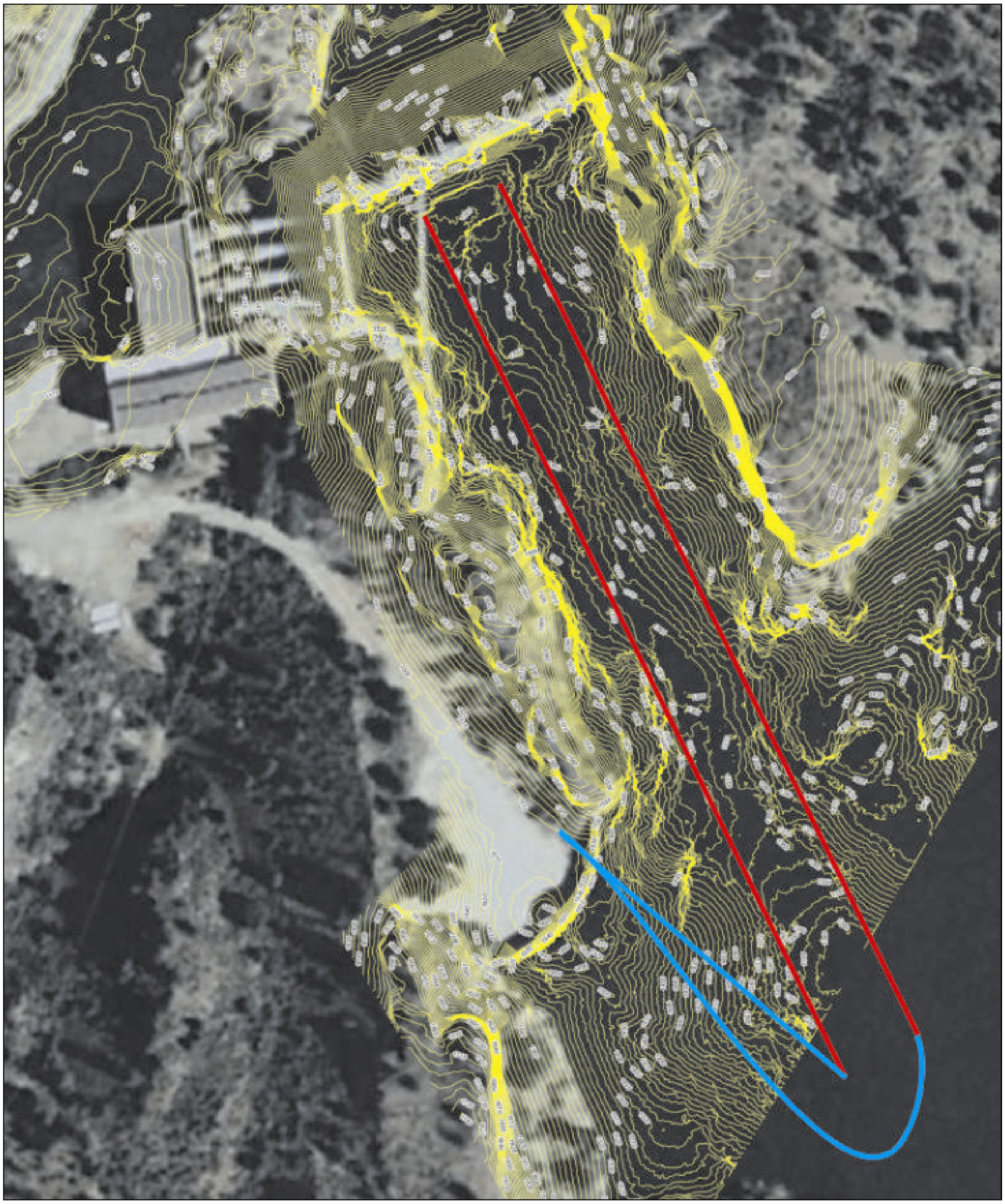


Figure 5-4. Conceptual Near-Field Diffuser Layout for Long Lake

Description of Oxygen Supply Equipment

The near-field reservoir oxygen diffuser system would be supplied with oxygen delivered to the site in liquid form in truck and stored in a tank at an oxygen supply facility onsite. The supply facility would include ambient air vaporizers to convert liquid oxygen to gaseous form and utilize vaporization pressure build to maintain the pressure requirements for oxygen delivery. Oxygen flow control, monitoring and remote control tied to turbine operation for each diffuser would be included at the facility. The facility and piping would be designed for an oxygen supply rate of 50 tons per day to handle typical summertime peak hydropower operations. Liquid oxygen storage facilities have numerous safety requirements regarding proximity to other structures and overhead power lines as detailed in NFPA 50. A potential liquid oxygen supply facility location is assumed to be available near the intake channel. A liquid oxygen storage tank capacity of at least 6,000 gallons would be required to allow offloading of a full truckload (4,500 gallons) on each delivery. Truck deliveries would be about 1 truck per day during maximum use. Polyethylene supply pipe would be run in a trench, sleeve pipe and underwater to each diffuser.

Construction Requirements

The construction of the reservoir diffuser system would require an assembly area with material laydown area and reservoir access such as a boat ramp. The diffuser system is deployed from the surface without the use of divers.

Maintenance Requirements

The maintenance of the reservoir diffuser system would require visual inspection of the bubble pattern to assure the porous hose has not been damaged. The entire diffuser system can be refloated to the surface for repair as needed. The oxygen supply facility maintenance is usually included in the contract with the bulk gas supplier.

<u>Environmental Effects</u>

- DO uptake ~ 2.5 mg/L
- Temperature increase ~ 0
- TDG ~ negligible
- Fish Entrainment, there is potential to attract more fish near intakes
- Other Water Quality Effects ~ some DO demands may be reduced in the reservoir

Cost Estimate

Potential installation and operation costs for the near-field reservoir diffuser are shown in Table 5-2:

Table 5-2. Installation and operating costs

Avista
Long Lake Near Field Reservoir Diffuser
INSTALLATION COST BREAKDOWN
Mobley Engineering High Flow Line Diffuser System

			Labor	**Material**	**Total**
MEI DIFFUSER:			**Labor**	**Material**	**Total**
Detailed design and drawings			$23,040	$4,204	$27,244
Shop assembly			$7,826	$16,518	$24,344
Diffuser lines and supply lines	4,100	feet total	$106,447	$29,417	$135,863
Travel expenses and shipping:			$9,504	$25,596	$35,100
Equipment rental, tools and fuel			$0	$32,117	$32,117
Startup training and O&M manual			$23,220	$4,298	$27,518
		Diffuser System Total:	**$146,800**	**$112,100**	**$282,200**
OXYGEN SUPPLY FACILITY:			**Labor**	**Material**	**Total**
Facility layout design			$10,000	$1,000	$11,000
Grade and drainage			$12,000	$12,000	$24,000
Concrete foundations and pads			$55,000	$45,000	$100,000
Truck access and turnaround			$20,000	$25,000	$45,000
Electrical power supply			$10,000	$15,000	$25,000
LOx equipment and cryogenic piping installation 50 tons/day capacity			$12,000	$0	$12,000
Supply manifold, control valves, supports, flow control and remote operati			$30,000	$35,000	$65,000
Fence and gate			$6,000	$6,000	$12,000
		Oxygen Facility Total:	**$155,000**	**$139,000**	**$294,000**
OPERATING COSTS:			**Labor**	**Material**	**Total**
Annual LOx Usage	325	tons			
	85%	OTE			
	$144.00	per ton		$55,059	$55,059
Annual Diffuser Maintenance (10yr hose replacement)				$20,500	$20,500
50 t/d LOx Facility equipment lease, maintenance				$18,000	$18,000
		LOx Operating Costs Total:	**$0**	**$93,559**	**$93,559**

Oxygen facility costs are based on leased cryogenic oxygen equipment (storage tank, vaporizers, pressure control station and piping).

Concerns and Considerations for Near-Field Reservoir Diffuser:

Advantages

- Low capital costs
- Effective DO uptake for any operating conditions
- Minimal maintenance requirements
- No outage required for installation or maintenance
- Oxygen piping located away from powerhouse eliminates oxygen enriched environment safety hazards.
- Quick response time to changes in hydro operations or reservoir conditions
- Negligible effect on TDG levels
- Increased DO content near intakes will eliminate low DO of leakage flows from the intakes.

Disadvantages

- Operating costs
- Oxygen flow rates must be operated to meet hourly DO mass deficits
- Oxygen system must be sized to meet peak hydro flows
- Dependent on oxygen supplier and truck delivery
- Increased DO content near intakes may increase fish entrainment

Volumetric Reservoir Diffuser

Potential DO Enhancement Capability

In a volumetric diffuser design, a large volume of the reservoir forebay maintained in an oxygenated condition to handle peaking hydropower flows. Utilizing this approach, a 2.5 mg/L uptake can be provided at average daily flows of 3,000 cfs including several hour peaks of full turbine flow of 6,300 cfs. The 90% percentile average daily summertime flow is approximately 5,000 cfs at Long lake for June through September. The volumetric approach would provide 1.2 mg/L uptake at continuous full turbine flow of 6,300 cfs. Larger DO uptakes would be possible at lower daily flows. The volumetric diffuser design achieves high oxygen transfer efficiencies by spreading low levels of oxygen input over a wide area in the reservoir. The large volume of oxygenated water can handle peaking operations for a limited time until the volume is depleted. Oxygen flow rate can be turned down as a function of unit operations and reservoir conditions.

Volumetric design will oxygenate a large volume of the forebay and will require capacity to counteract any reservoir oxygen demands in that volume and in the water moving through. For this evaluation the oxygen demands were conservatively estimated at 0.85 mg/L. The diffuser layout over a large area in the reservoir will require some time to react to changing conditions. A reaction time of 1 to 2 days would be expected, depending on turbine flows.

Table 5-3. Capacity calculations for volumetric diffuser system

FOREBAY OXYGEN DIFFUSER SYSTEM
Avista
Long Lake Volumetric Diffuser System

SYSTEM DESIGN CALCULATIONS

Mobley Engineering
Norris, Tennessee
03/10/10

		Average Capacity		**Design**	
DESIGN Capacity		1,575	cfs	3,000	cfs
Oxygen Demands	Target	**2.5**	**mg/L**	**2.5**	**mg/L**
	BOD		mg/L	0.0	mg/L
	IOD	0.85	mg/L	0.85	mg/L
		3.4	mg/L	3.4	mg/L
DESIGN DO UPTAKE EFFICIENCY:		90%		90%	
DESIGN OXYGEN FLOW FOR 1MG/L DO UPTAKE		0.20	tons O2/ hr	0.37	tons O2/ hr
DESIGN SAFETY FACTOR:		1.00		1.30	
DESIGN OXYGEN SYSTEM CAPACITY		**16**	**tons O2/day**	**39**	**tons O2/day**
		0.66	tons O2/hr	1.63	tons O2/hr
		264	**SCFM**	**654**	**SCFM**
		3,307	gallons/day	8,188	gallons/day
		15,845	scfh	39,234	scfh

Conceptual Design for Long Lake Hydro Electric Development

Design basis

For a volumetric diffuser design, the diffusers are spread over a large area several thousand feet upstream of the dam to oxygenate a large volume of the reservoir. The turbine withdrawal is from this volume previously oxygenated by diffuser operation. If that volume is completely removed (during high turbine flows) the withdrawal is oxygenated as turbine intake water flows over the diffusers. The diffuser location in the reservoir oxygenates a large volume of water that can be removed as needed for hydropower operations. Response time to adjustments to the operation of the oxygen diffuser system would 1-2 days, maybe several days. Volumetric diffuser systems are often operated with a manual oxygen flow setting to eliminate need for remote operation. During the summertime stratified conditions, this system would require a small continuous oxygen flow to counteract oxygen demands in the reservoir and maintain the oxygenated volume.

Description of Volumetric Reservoir Diffuser Equipment

The volumetric diffuser system would consist of two 4,000 foot long diffusers positioned along the centerline of the reservoir upstream of the intake channel. The diffusers would be deployed approximately 70 feet above the bottom to elevate oxygen placement into the turbine withdrawal zone. The volumetric diffuser layout is shown in Figure 5-5.

Figure 5-5. Conceptual volumetric Diffuser Layout for Long Lake

Description of Oxygen Supply Equipment

The volumetric reservoir oxygen diffuser system would be supplied with oxygen delivered to the site in liquid form in truck and stored in a tank at an oxygen supply facility onsite. The supply facility would include ambient air vaporizers to convert liquid oxygen to gaseous form and utilize vaporization pressure build to maintain the pressure requirements for oxygen delivery. Oxygen flow control, monitoring and remote control tied to turbine operation for each diffuser would be included at the facility. The facility and piping would be designed to for an oxygen supply rate of 40 tons per day to handle summertime reservoir conditions. Liquid oxygen storage facilities have numerous safety requirements regarding proximity to other structures and overhead power lines as detailed in NFPA 50. A potential liquid oxygen supply facility location is assumed to be available near the intake channel. A liquid oxygen storage tank capacity of at least 6,000 gallons would be required to allow offloading of a full truckload (4,500 gallons) on each delivery. Truck deliveries would be about 1 truck per day during maximum use. Polyethylene supply pipe would be run in a trench, sleeve pipe and underwater to each diffuser.

Construction Requirements

The construction of the reservoir diffuser system would require an assembly area with material laydown area and reservoir access such as a boat ramp. The diffuser system is deployed from the surface without the use of divers.

Maintenance Requirements

The maintenance of the reservoir diffuser system would require visual inspection of the bubble pattern to assure the porous hose has not been damaged. The entire diffuser system can be refloated to the surface for repair as needed. The oxygen supply facility maintenance is usually included in the contract with the bulk gas supplier.

<u>Environmental Effects</u>

- DO uptake ~ 2.5 mg/L
- Reservoir oxygen demands met ~ 0.85 mg/L
- Temperature increase ~ 0
- TDG ~ negligible
- Fishery ~ potential new fish habitat in reservoir
- Other Water Quality Effects ~ some DO demand products may be reduced in the reservoir

<u>Cost Estimate</u>

Potential installation and operation costs for the volumetric reservoir diffuser are shown in Table 5-4.

Table 5-4 Installation and operating costs

Avista
Long Lake Far Field Reservoir Oxygen Diffuser
INSTALLATION COST BREAKDOWN
Mobley Line Diffuser System

MEI DIFFUSER:			**Labor**	**Material**	**Total**
Detailed design and drawings			$27,936	$4,204	$32,140
Shop assembly			$12,719	$20,781	$33,500
Diffuser lines and supply lines	9,700	feet total	$139,113	$55,122	$194,235
Travel expenses and shipping:			$9,504	$30,556	$40,060
Equipment rental, tools, fuel			$0	$34,454	$34,454
Startup, Testing, Training and O&M Manual			$23,220	$4,298	$27,518
		Diffuser System Total:	**$189,300**	**$149,400**	**$361,900**

OXYGEN SUPPLY FACILITY:		**Labor**	**Material**	**Total**
Facility layout design		$10,000	$1,000	$11,000
Grade and drainage		$12,000	$12,000	$24,000
Concrete foundations and pads		$55,000	$45,000	$100,000
Truck access and turnaround		$20,000	$25,000	$45,000
Electrical power supply		$10,000	$15,000	$25,000
LOx equipment and cryogenic piping installation		$12,000	$0	$12,000
Supply manifold, control valves, supports, flow control and manual operat		$15,000	$25,000	$40,000
Fence and gate		$6,000	$6,000	$12,000
	Oxygen Facility Total:	**$140,000**	**$129,000**	**$269,000**

OPERATING COSTS:			**Labor**	**Material**	**Total**
Annual LOx Usage	423	tons			
	90%	OTE			
	$144.00	per ton		$67,680	$67,680
Annual Diffuser Maintenance (10yr hose replacement)				$19,400	$19,400
40 tpd LOx Facility equipment lease, maintenance				$18,000	$18,000
		LOx Operating Costs Total:	**$0**	**$105,080**	**$105,080**

Oxygen facility costs are based on leased cryogenic oxygen equipment (storage tank, vaporizers, pressure control station and piping).

Concerns and Considerations

Advantages

- Low capital costs
- Effective DO uptake for any operating conditions
- Minimal maintenance requirements
- No outage required for installation or maintenance

- Oxygen piping located away from powerhouse eliminates oxygen enriched environment safety hazards.
- Negligible effect on TDG levels
- Increased DO content in the reservoir and near intakes will eliminate low DO of leakage flows from the intakes.
- Oxygen system can be sized to meet daily average hydro flow rates
- Increased DO content in the reservoir may create new fish habitat
- System can be operated with simplified manual flow controls and bi-weekly settings

Disadvantages

- Operating costs
- Oxygen costs for meeting DO demands in the reservoir
- Dependent on oxygen supplier and truck delivery

Reservoir Aeration Diffuser System

Description:

- Diffusers mounted in the reservoir in similar manner as the volumetric diffuser system above, but using the high flux diffuser design proposed for the near-field diffuser system
- Supplied with compressed air from facility onshore

Previous Experience at Hydro Projects:

- Successful installation for small DO increases, i.e., 1-2 mg/L
  - Wallenpaupack (PPL)
- The amount of DO increase is limited by TDG limits
- Cost of compressors for larger projects has been found to be higher than cost of using oxygenation diffuser systems

Construction Requirements:

- Large construction area required with reservoir access and material laydown area

Design Basis:

- OTE ~ 50% at 70 feet of depth (compared to 90% OTE for the volumetric diffuser system)
- High flow diffuser 1 scfm/meter (like JST)
- 5,600 scfm compressed air supply facility
- Sized to add 2.5 mg/L to 3,000 cfs plus .85 mg/L oxygen demands

- Total length of diffuser system, excluding air supply hose: 18,500 feet (air supply hoses are estimated to be 3500 feet)

Advantages:
- Operation costs less than liquid oxygen (??)
- No outage required for installation or maintenance
- No safety concerns from handling of oxygen or cryogenic temperatures
- Increased DO content in the reservoir and near intakes will eliminate low DO of leakage flows from the intakes.
- Oxygen system can be sized to meet daily average hydro flow rates
- Increased DO content in the reservoir may create new fish habitat
- System can be operated with manual O2 flow controls and bi-weekly settings

Disadvantages:
- Low OTE (50%)
- High capital cost for compressors and a diffuser system that is much larger than that required for an oxygenation system
- High operating costs (electric power costs)
- High maintenance costs (compressor maintenance, 10-yr replacement costs for diffusers) Effective DO uptake for any operating conditions
- DO added to turbine releases would be limited by TDG limits
    - Adds twice as much N as DO
- Cost for an air diffuser system in the forebay is likely to cost as much or more than an oxygenation diffuser system and the DO uptake would be limited by %TDG limits

6 Tailrace Aeration Diffusers

Tailrace Diffuser Systems

There are no known successful diffuser systems that have been used in tailraces. Tailrace aeration and oxygenation have been considered before for TVA projects as well as other hydropower projects, but they have not been feasible considering other alternatives. The main reasons have been the oxygen transfer efficiency (OTE) values for tailrace locations compared to other available locations, i.e., forebay locations, penstocks, and draft tubes. OTE values for tailrace locations are typically 10% for air diffusers and 20-30% for oxygen diffusers while other locations have been found to have OTE values ranging from 20-40% for air in draft tubes, 60-90% for oxygen in penstocks, and 70-90% for oxygen in forebays.

Other challenges for diffuser systems in tailraces include having to be designed to accommodate spill flows and the need for restriction of flows during construction and installation of these systems.

Tailrace Oxygenation for Long Lake Tailrace

An oxygenation system was considered for Long Lake tailrace. Figure 6-1 shows a conceptual deployment where the diffusers are located in the deepest area of the tailrace (i.e., about 20 feet deep) so as to maximize oxygen transfer efficiency (OTE). The OTE was estimated using BPi to be about 30%. To accommodate the available area in the tailrace and to aerate the release flow within a reasonable area of the tailrace, Mobley Engineering recommended a high flux diffuser at 5.5 scfm/meter that is five times the flux designed previously using the porous hose diffuser. It was sized to add 2.5 mg/L DO to 4,725 cfs flow in the tailrace. The capacity of the oxygenation system was 138 ton/day, considerably larger than the oxygenation systems sized for the other locations, i.e., for the penstock and forebay systems.

In summary, the advantages and disadvantages include

Advantages:

- Direct oxygenation of tailrace

Disadvantages:

- Very low OTE
- High operating costs
- High probability of damage during high project flows
- High maintenance costs
- Hydro restriction during construction
- No known successful installations
- Must be sized to enhance DO of peak hydro flows

Tailrace Aeration for Long Lake Tailrace

To use air instead of oxygen in a tailrace diffuser system, it was estimated that about 30,000 scfm of air would be required to increase DO by 2.5 mg/L. The OTE would be about 10%. It was decided that such a system would be impractical, costly, and contribute to a TDG issue in the tailrace.

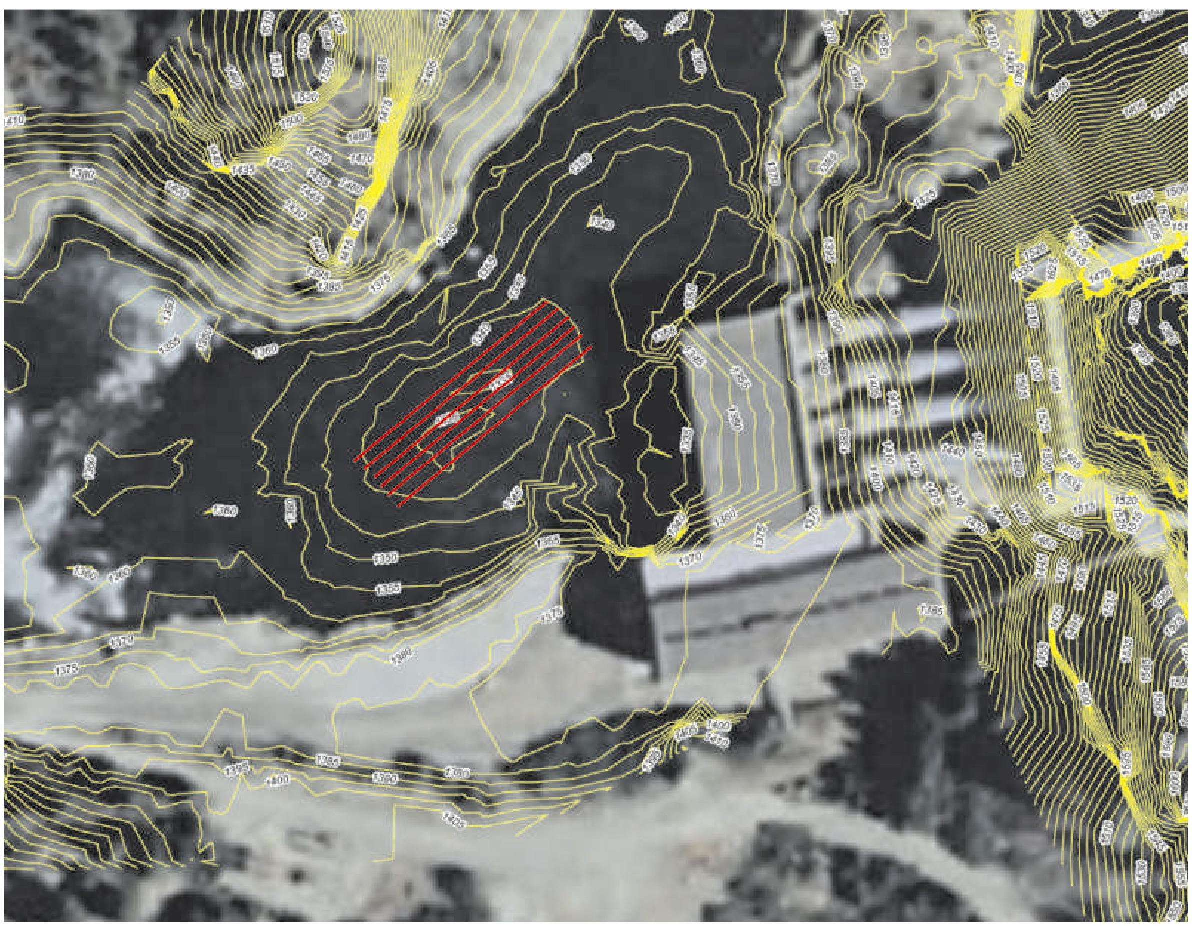


Figure 6-1. Plan view of diffuser deployment in the tailrace of Long Lake HED

7 Conclusions and Recommendations

The following aeration alternatives were determined to be promising for further consideration and testing:

1 draft tube aeration;
2 penstock oxygenation,
3 near-field oxygenation, and
4 forebay volumetric oxygenation

Turbine Aeration

- Turbine aeration and draft tube venting is the least cost alternative. The DBM model (calibrated based on data from other projects and based on airflow predictions using an airflow model) showed that a draft tube aeration system can attain the DO goal of 8 mg/L for the full range of observed DOin values based on the 2000 and 2001 tailrace DO data; however, the amount of DO increase that could be attained is limited by the TDG level that is allowed for the tailrace.
- The DBM modeling showed that a turbine aeration system could be operated in a manner that allows real-time optimal aeration operations considering inflow DO and DN values as well as temperature conditions and unit flows. If the TDG standard was maintained at 110%, draft tube aeration would attain 8 mg/L DO a high percentage of the time, based on 2000 and 2001 data; would normally attain between 7 and 8 mg/L when 8 mg/L was not attained; and the minimum DO that would occur would be about 6.5 mg/L,
- Installation of air supply vents and testing is recommended for turbine aeration to determine the actual performance of the venting system and to calibrate the DBM model for the Long Lake HED units.

Penstock and Forebay Oxygenation to Supplement Turbine/Draft Tube Aeration

- If additional aeration is needed beyond the turbine/draft tube aeration system, it is recommended that one of the oxygenation alternatives be selected to supplement the aeration that could be provided by the venting system. If the penstock diffuser system is deemed more desirable than the in-lake oxygenation systems, testing would be needed to address design issues.

Other Alternatives Infeasible

- Other alternatives considered were determined to have significant disadvantages for application at Long Lake HED. These other methods included penstock aeration, forebay aeration, and tailrace oxygenation and aeration. The main disadvantages included increased TDG levels and costs.

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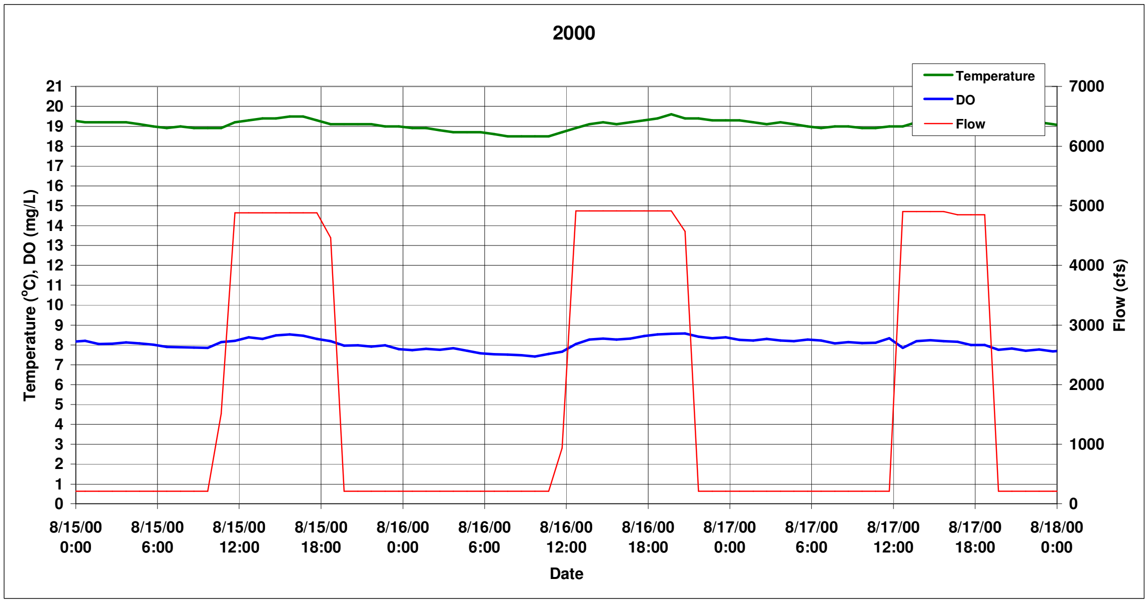
Appendix A. Withdrawal Zone Modeling

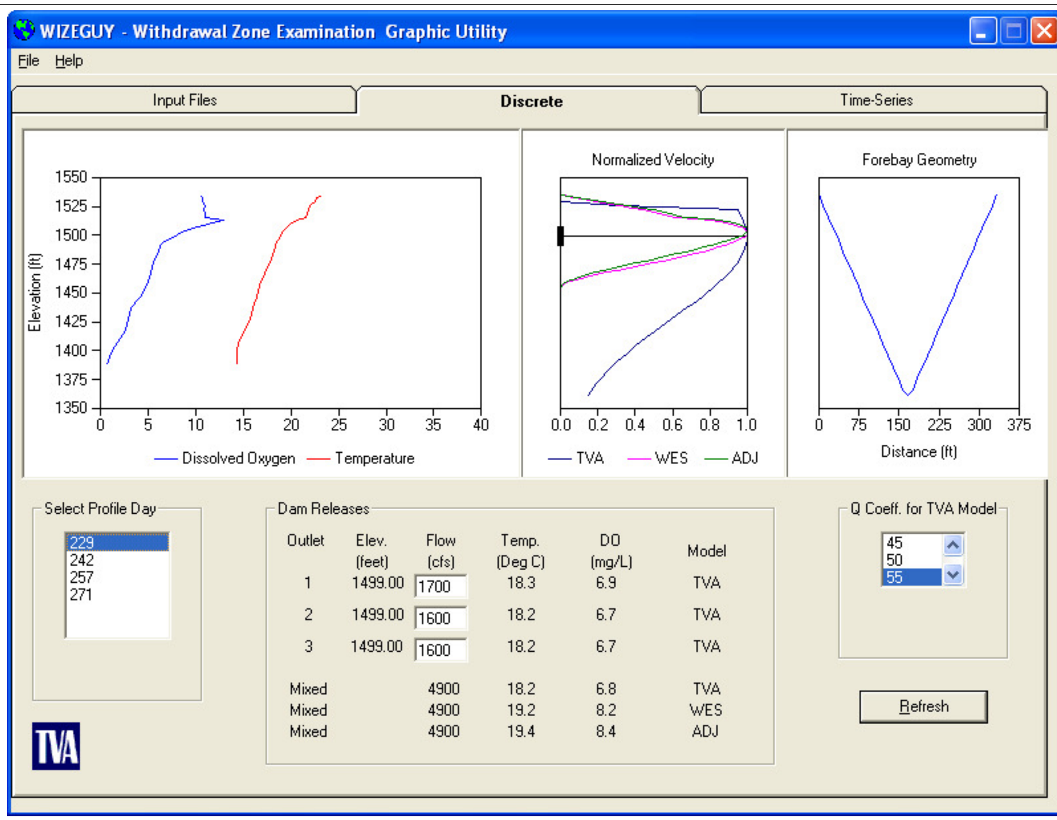
WIZEGUY runs were conducted on all dates when in-lake temperature and DO profiles and release data were collected at the same time, i.e., August 16 and 29, and September 13 and 27, 2000; and August 8 and 29, 2001. Such data sets allow calibration of the withdrawal zone models using available physical data, i.e., unit flow and temperature, so that withdrawal zones can be estimated and DO predictions for the releases can be compared with data collected from the tailrace to assess consistent deviations or patterns between the predicted and observed DO levels in the tailrace.

The WES and ADJ models provided the best results for calibration with temperature in the tailrace. The TVA model was consistently low for temperature predictions by as much as about 1 C^o compared to actual data as well as compared to the other models.

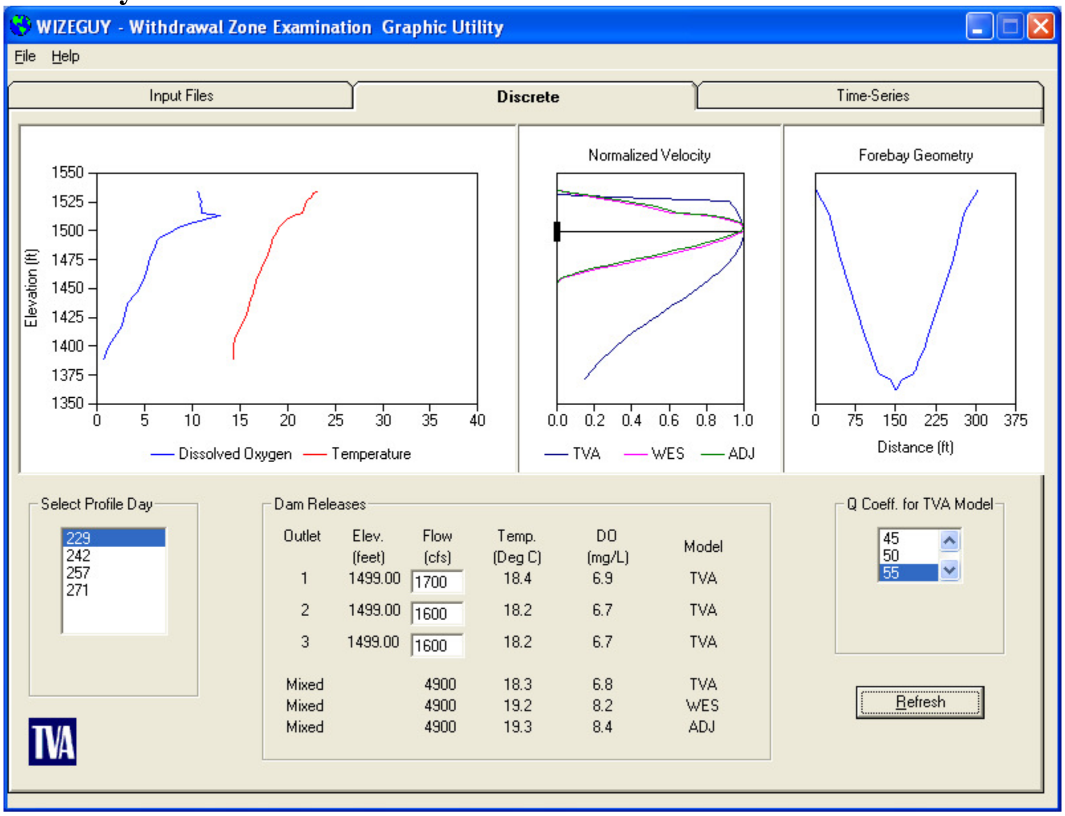
Minimum DO values in the modeled withdrawal zone from the lake were about 6 mg/L in 2000 (see WIZEGUY results in the following part of this Appendix for August 29 and September 13); however, the DO in the releases on the same dates was about 1 mg/L higher, i.e., about 7 mg/L. Minimum DO values in the modeled withdrawal zone were almost 7 mg/L in 2001 (see WIZEGUY results in the following part of this Appendix for August 29 and September 13); however, the DO in the releases on the same dates was about 8 mg/L. It appears that there was an increase in DO of about 1 mg/L in the releases through some form of aeration in the turbine system or the placement of the DO monitor was sufficiently downstream that DO increased by the time the releases arrived at the monitoring location.

8/16/00 (Day 229) – Profiles were collected at 17:20
TW Observations at 17:42 – T=19.3, DO=8.5

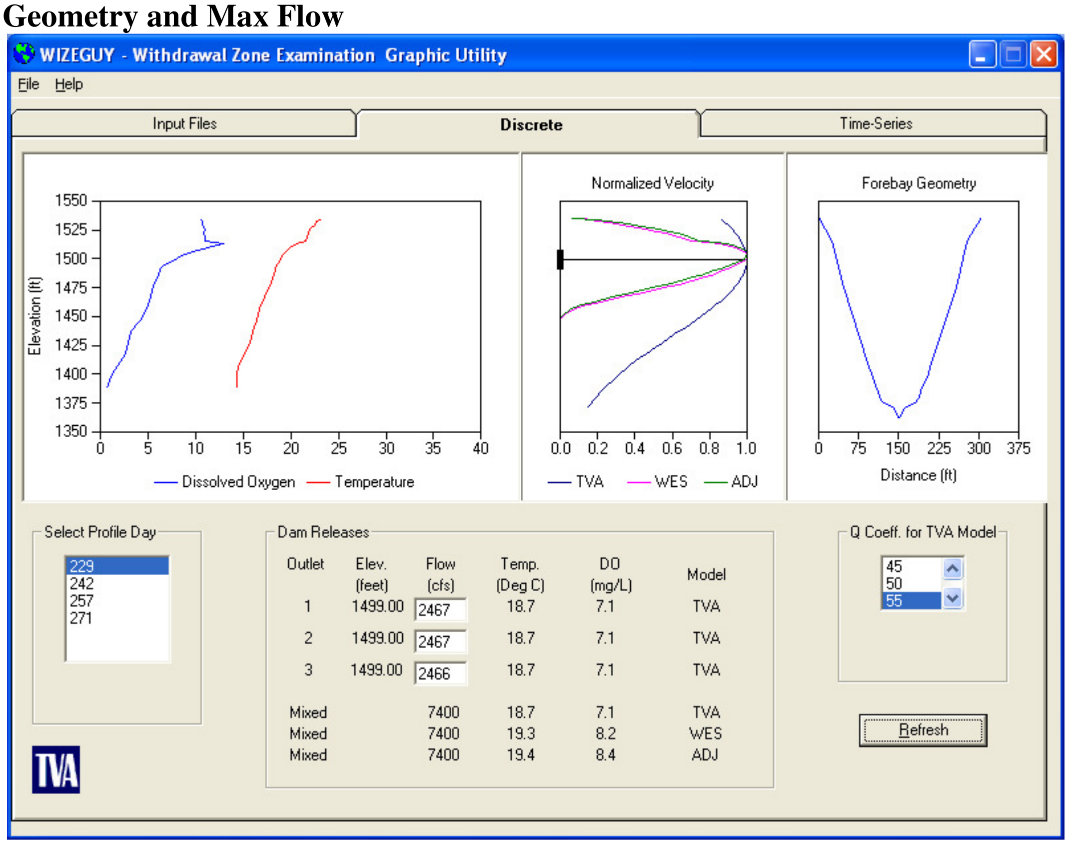




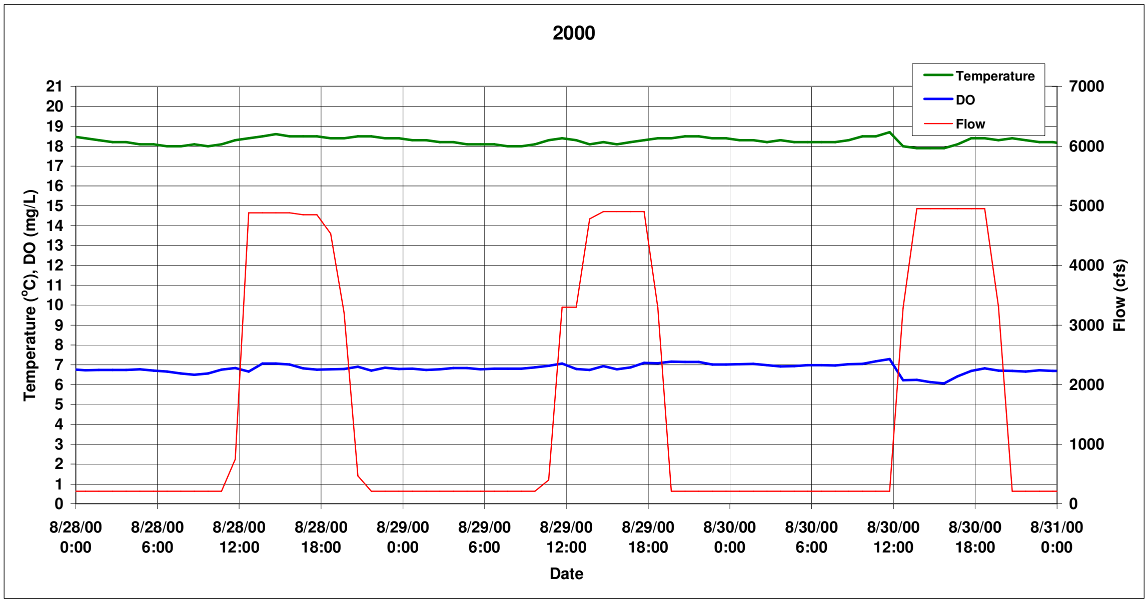
New Geometry

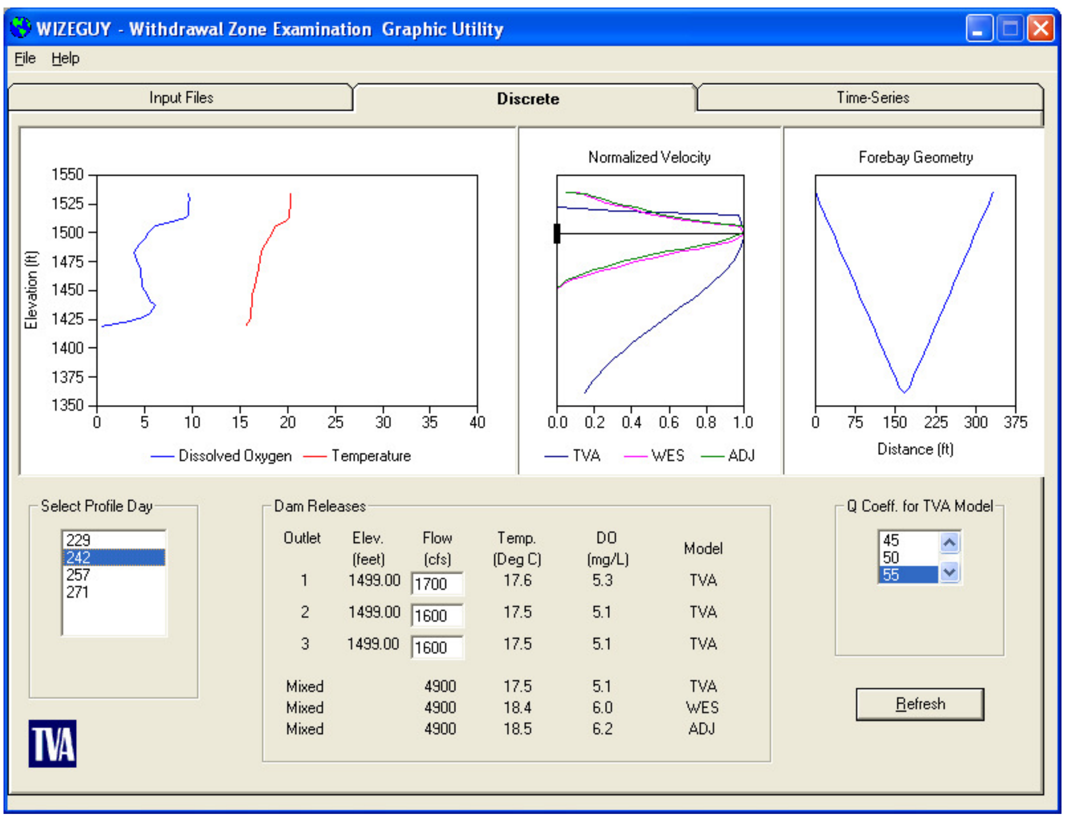


New Geometry and Max Flow

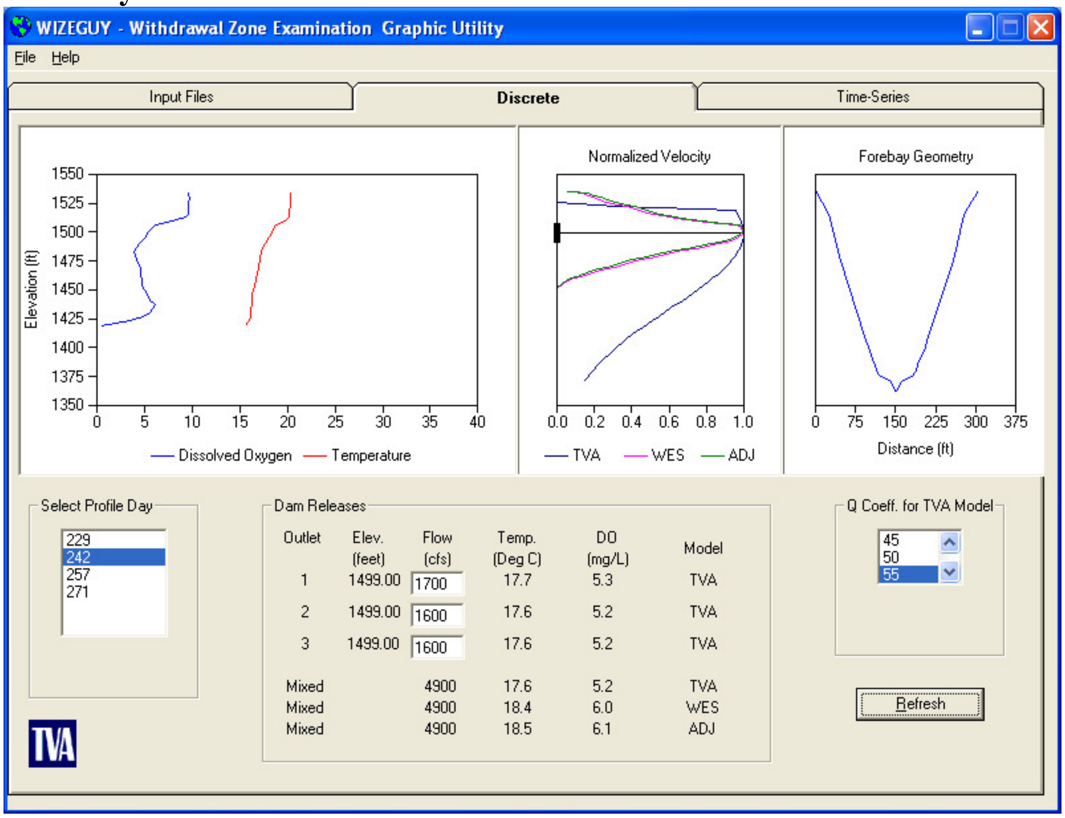


8/29/00 (Day 242) – Profiles were collected at 10:11
TW Observations at 10:42 – T=18.3, DO=7.0

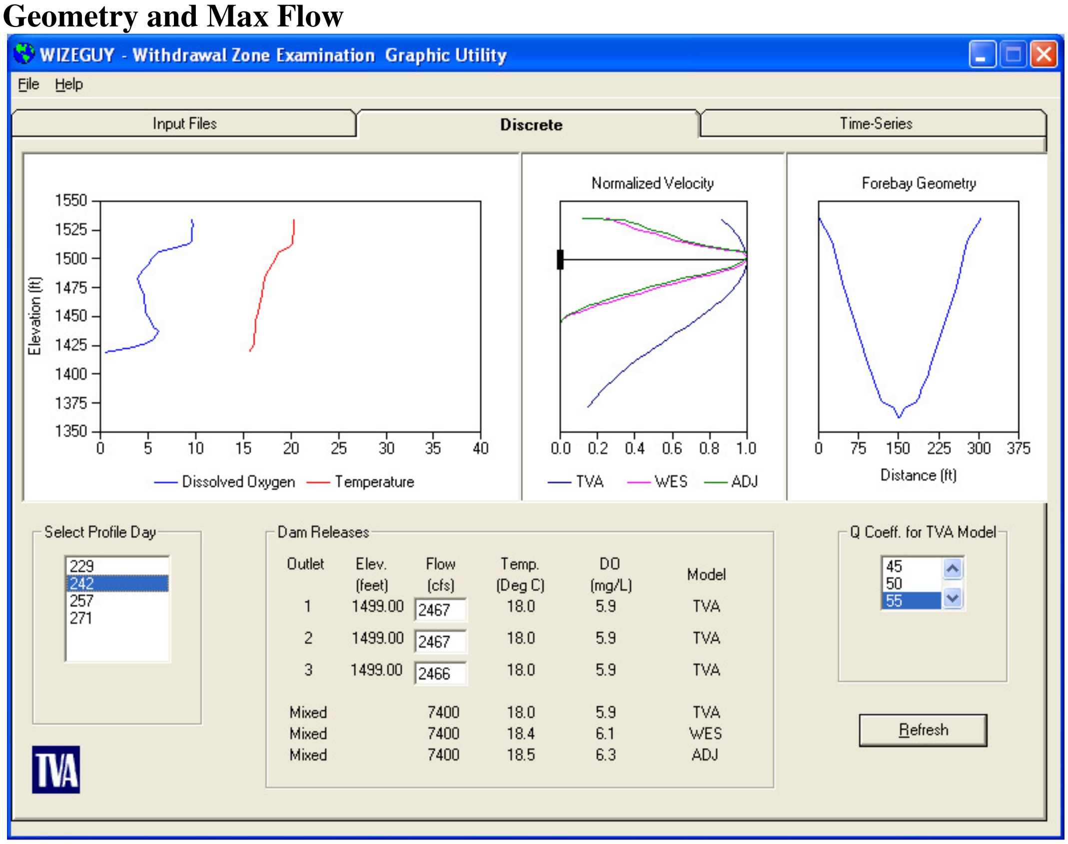




New Geometry

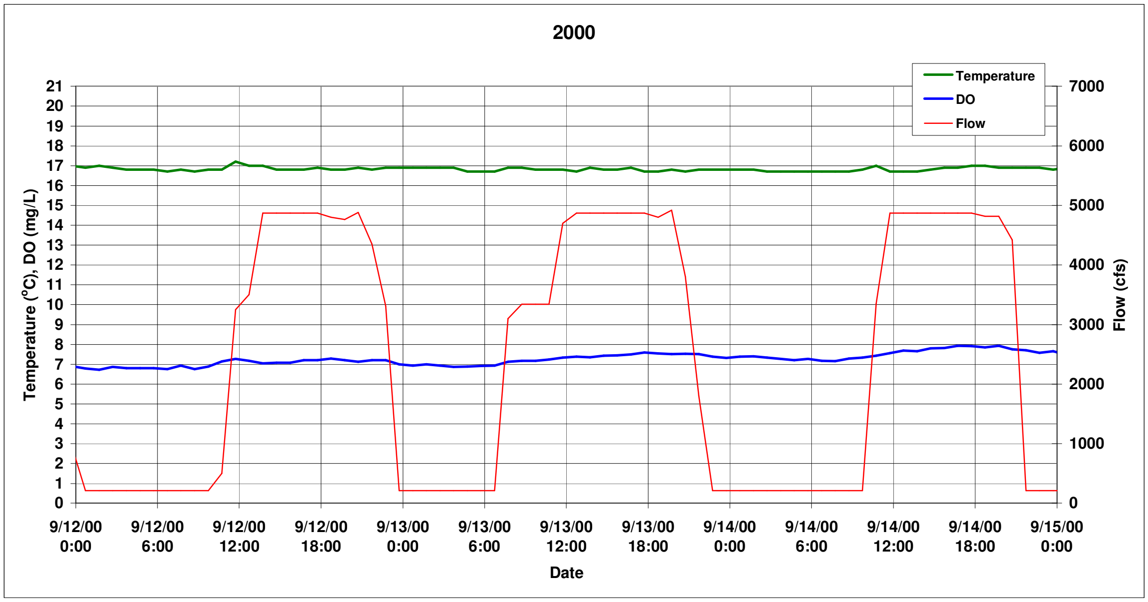


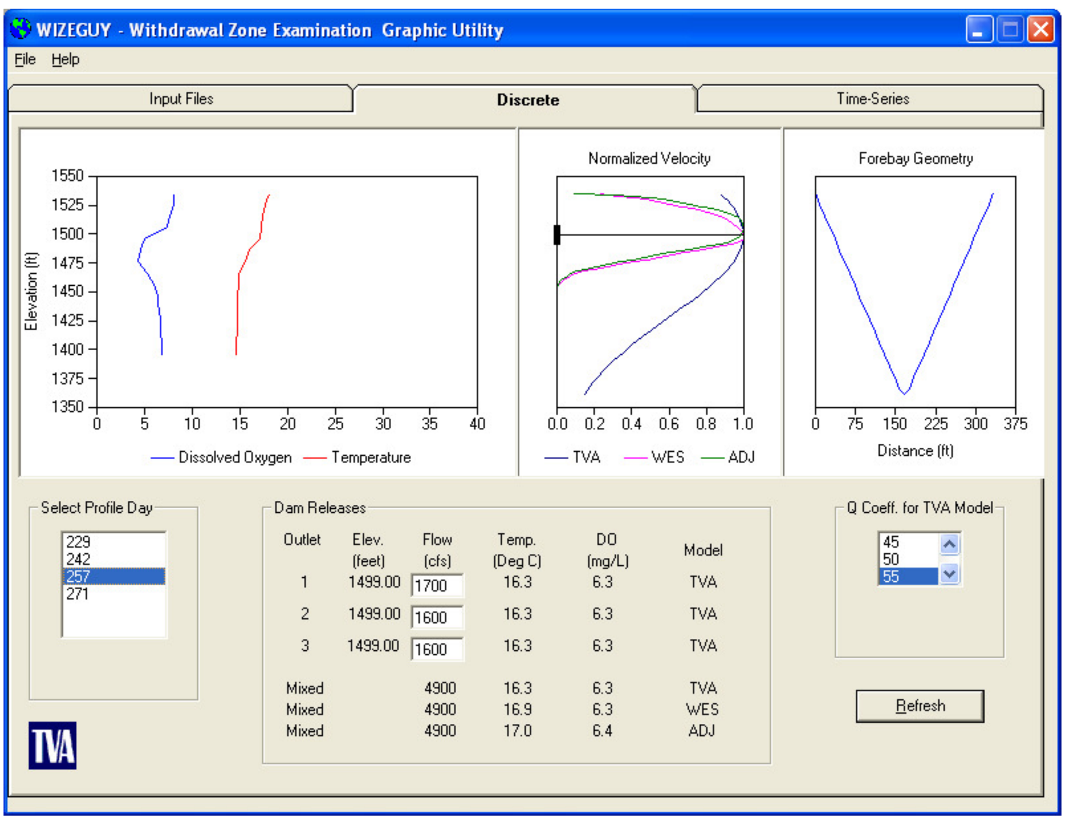
New Geometry and Max Flow



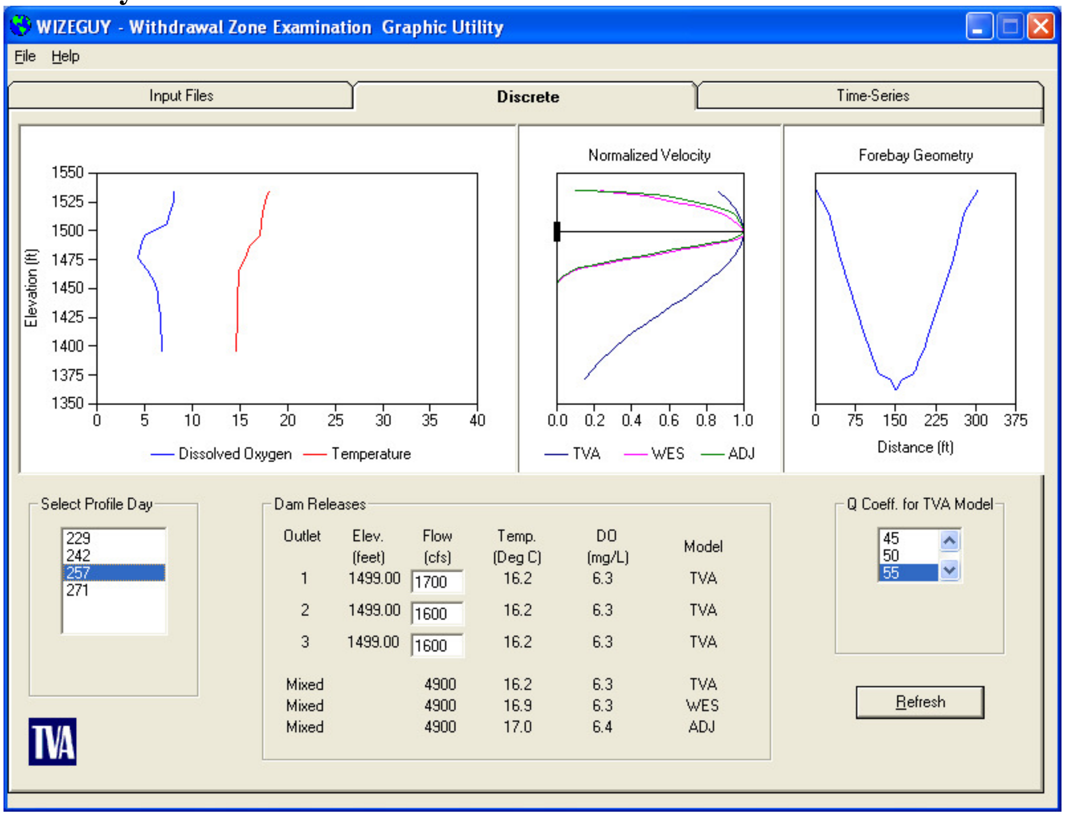
9/13/00 (Day 257) – Profiles were collected at 11:39

TW Observations at 11:44 – T=16.8, DO=7.3

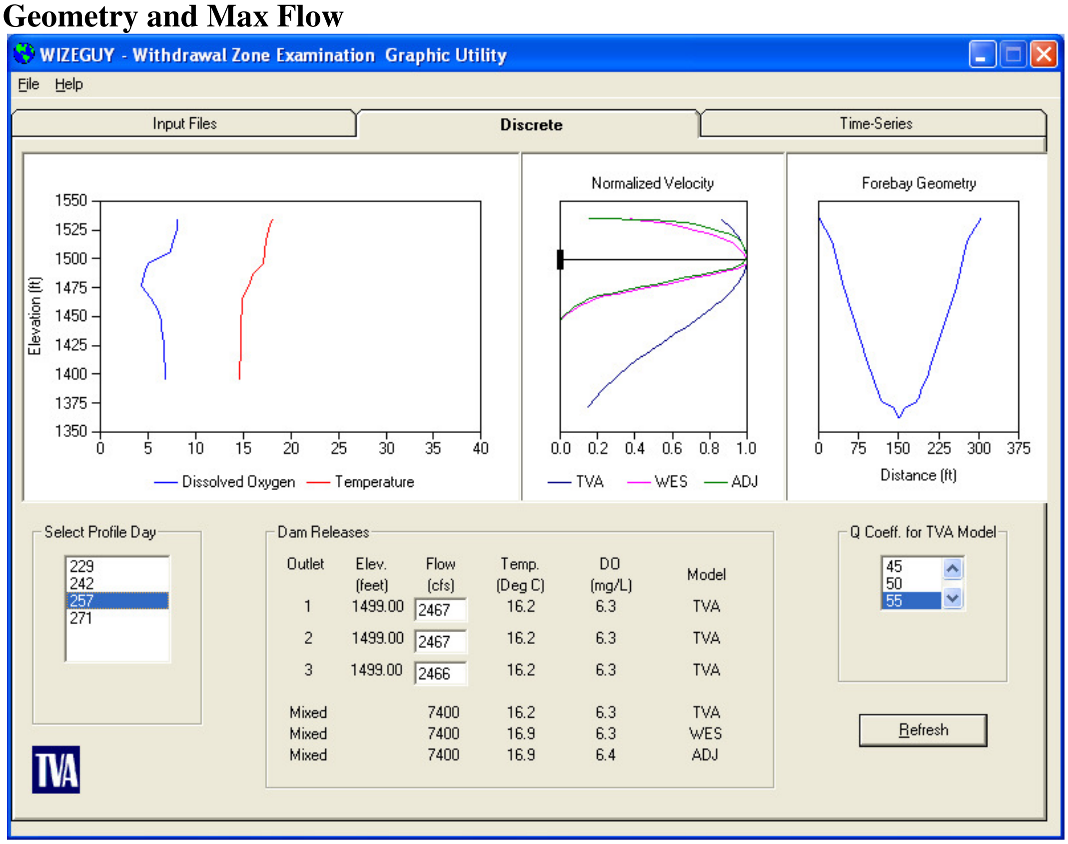




New Geometry

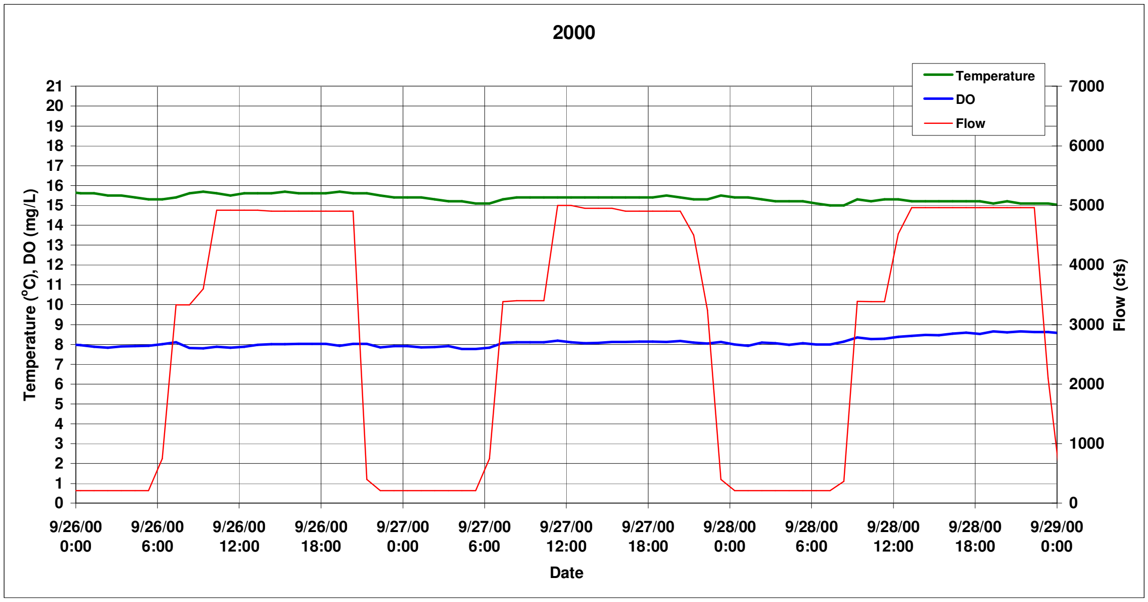


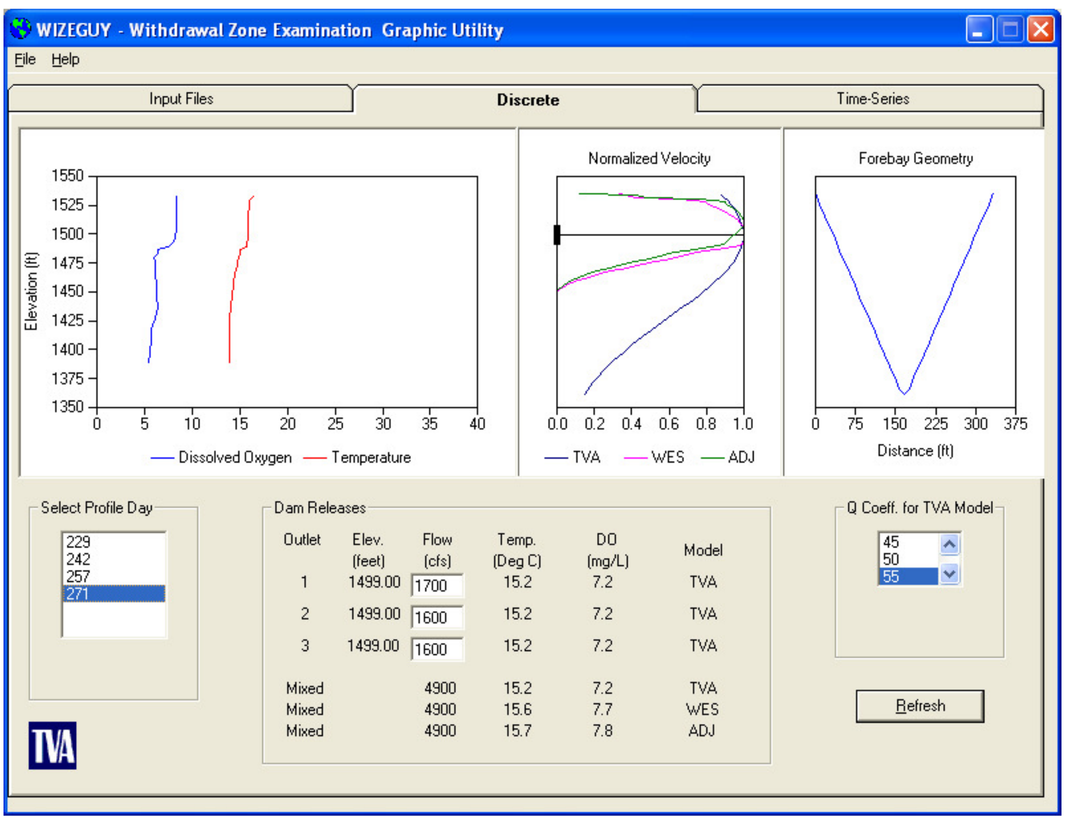
New Geometry and Max Flow



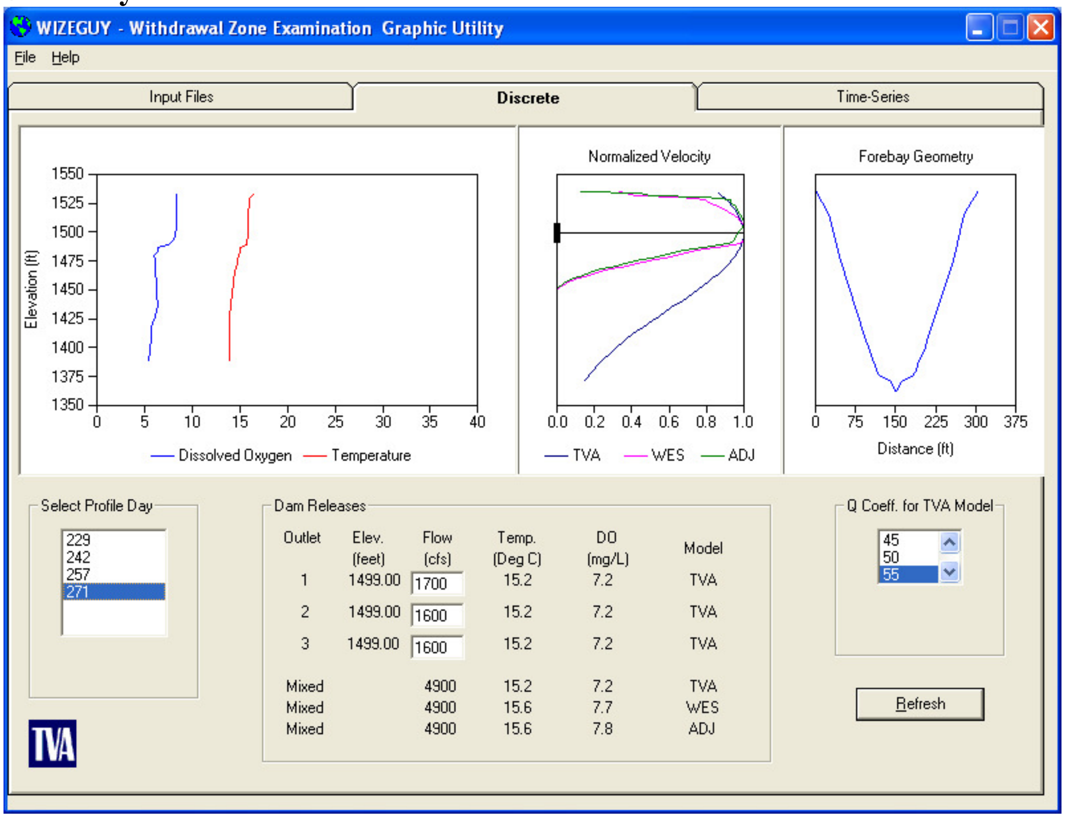
9/27/00 (Day 271) – Profiles were collected at 13:55

TW Observations at 14:21 – T=15.5, DO=8.1

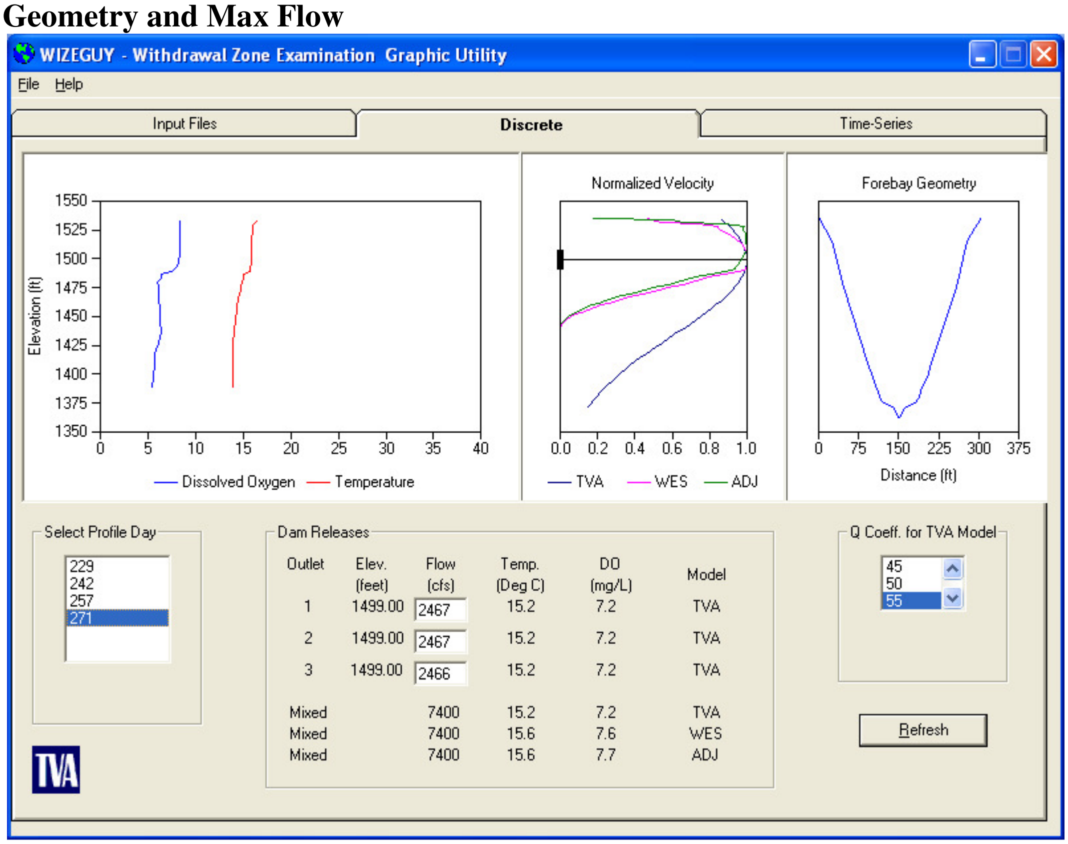




New Geometry

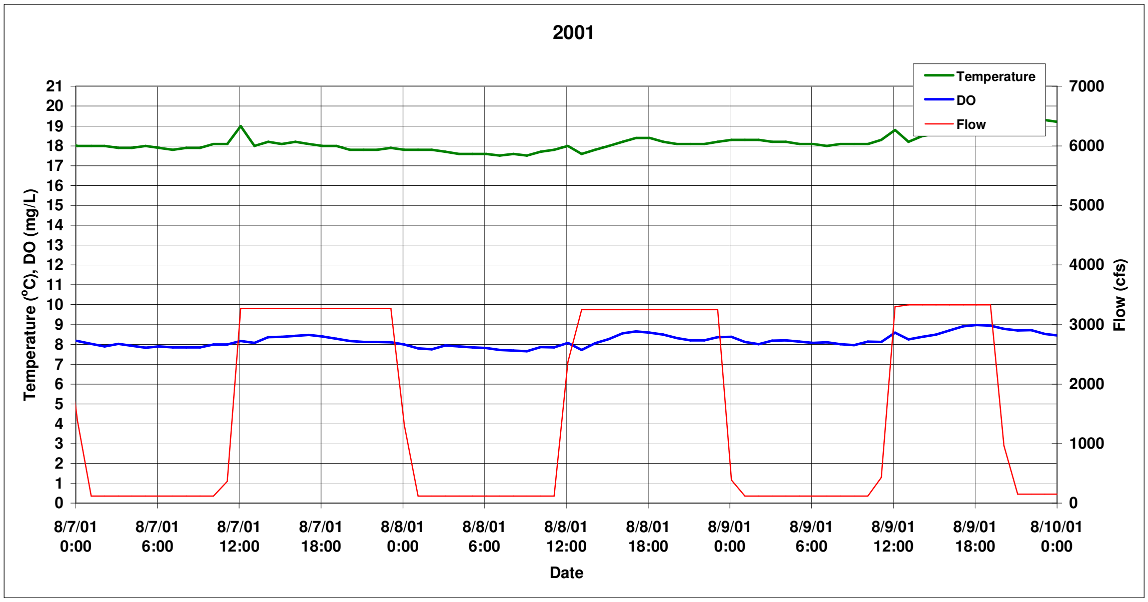


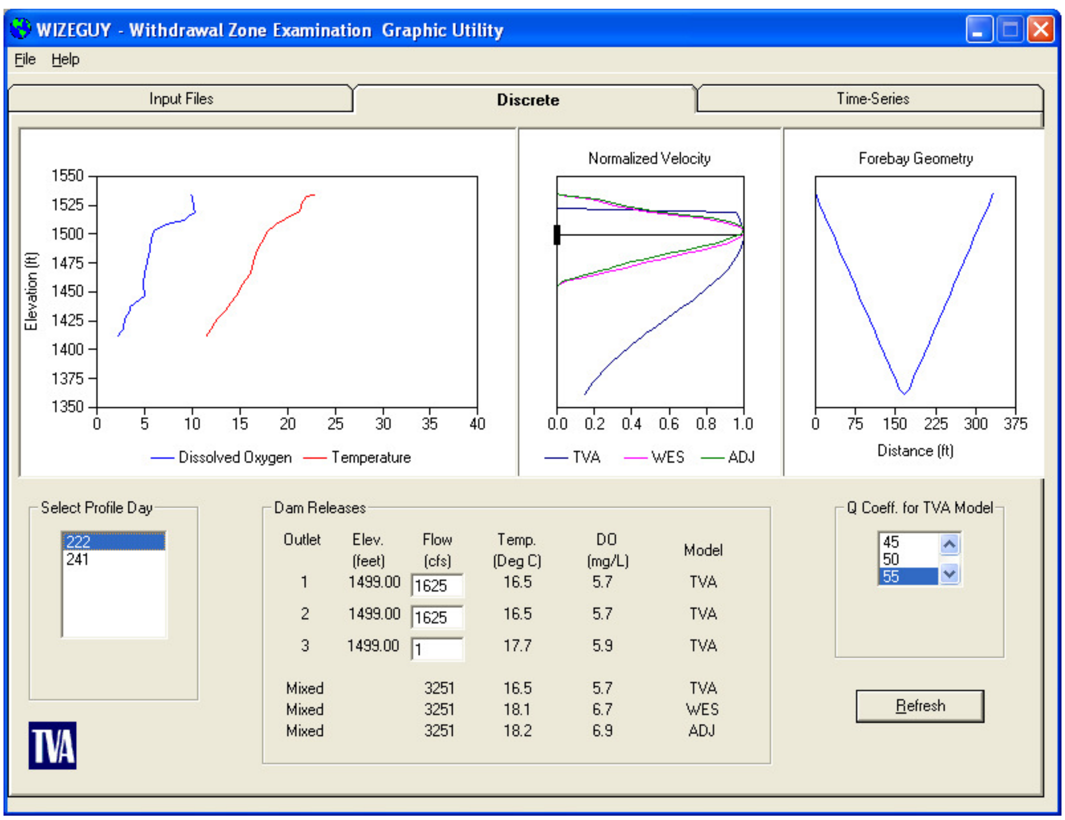
New Geometry and Max Flow



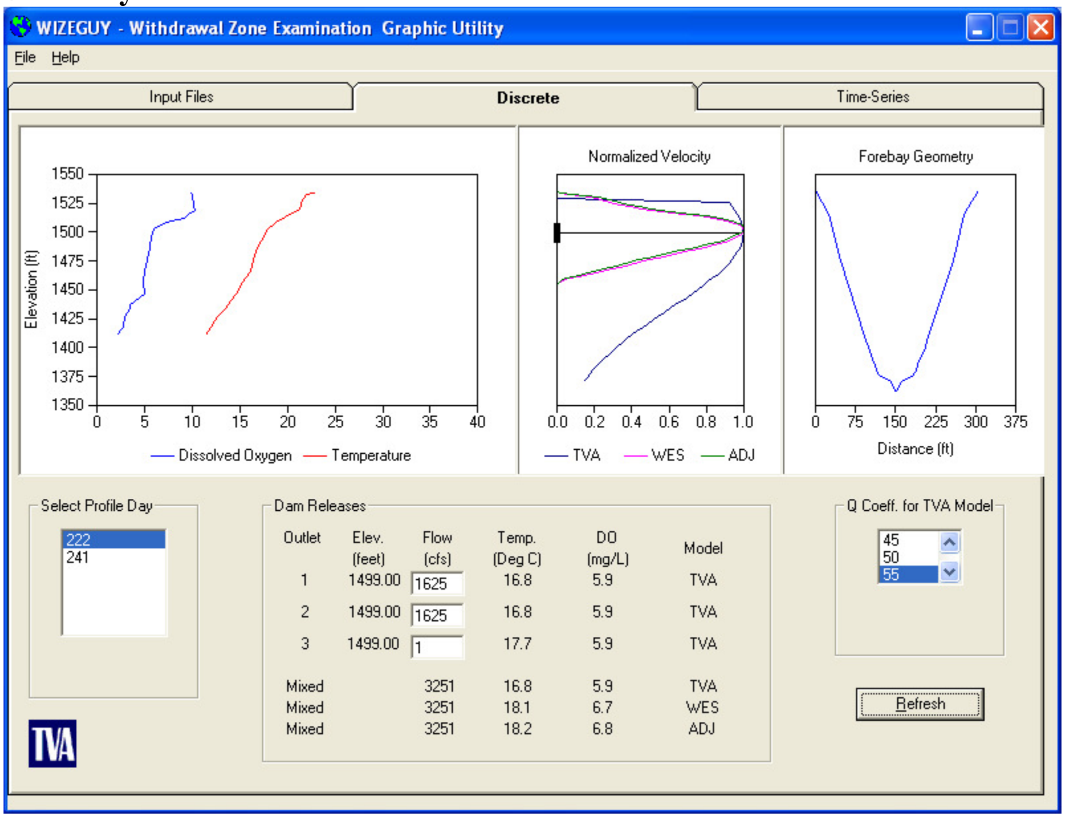
8/8/01 (Day 220) – Profiles were collected at 14:04

TW Observations at 14:07 – T=17.8, DO=8.1

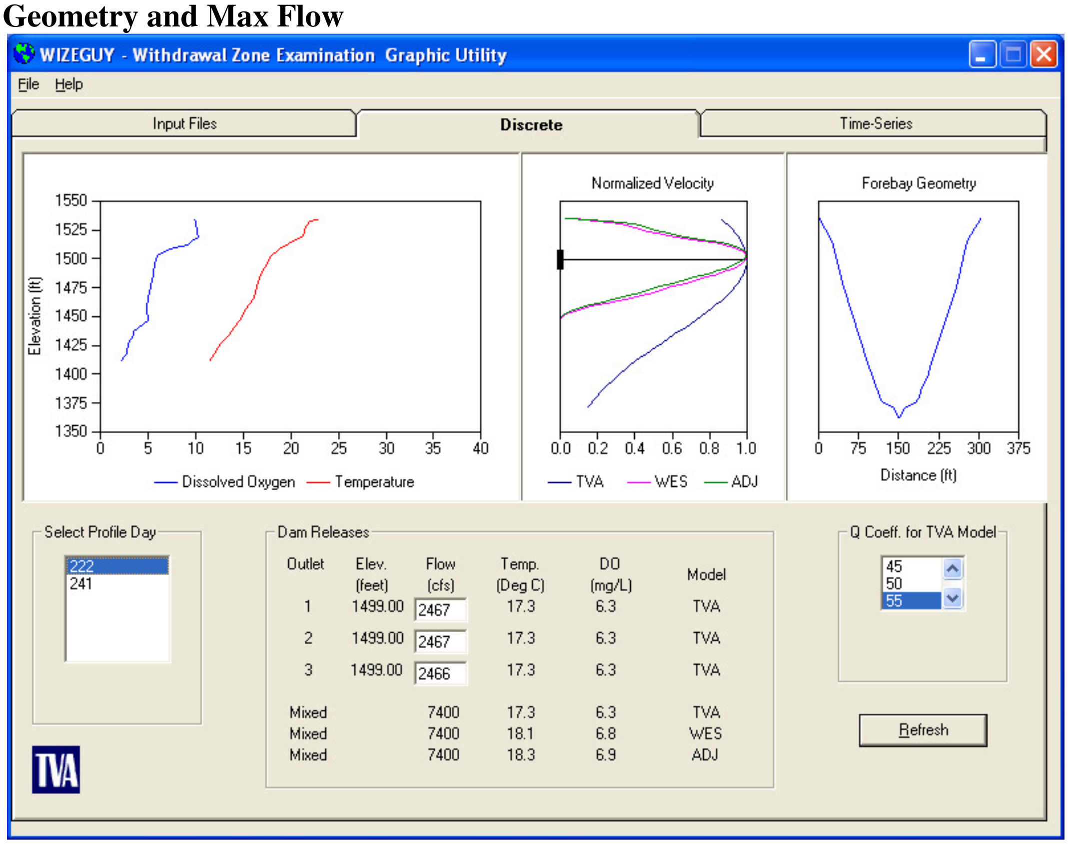




New Geometry

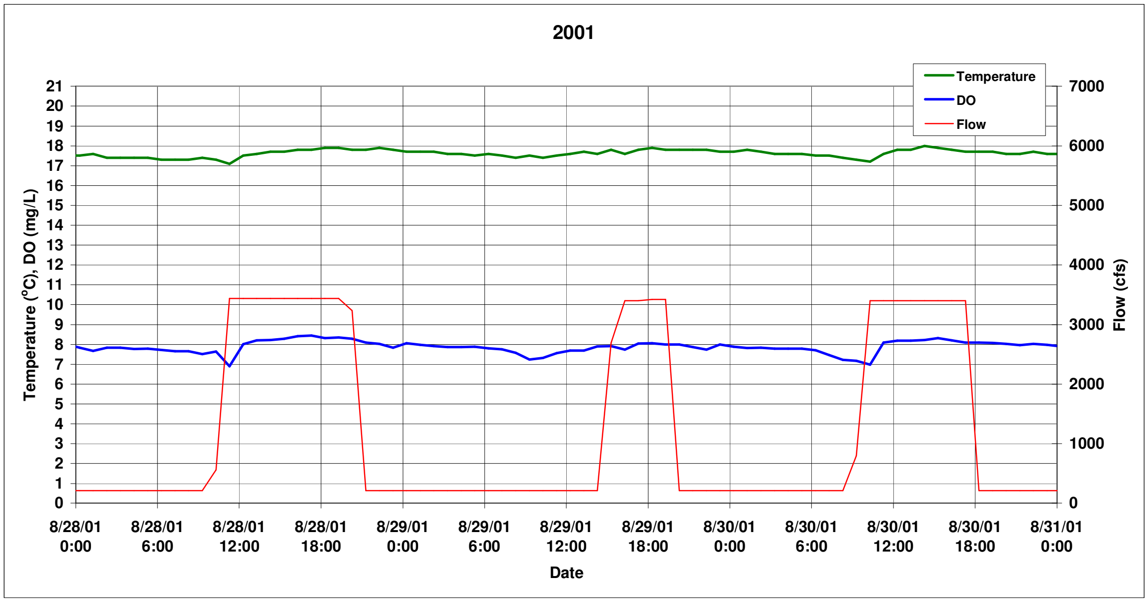


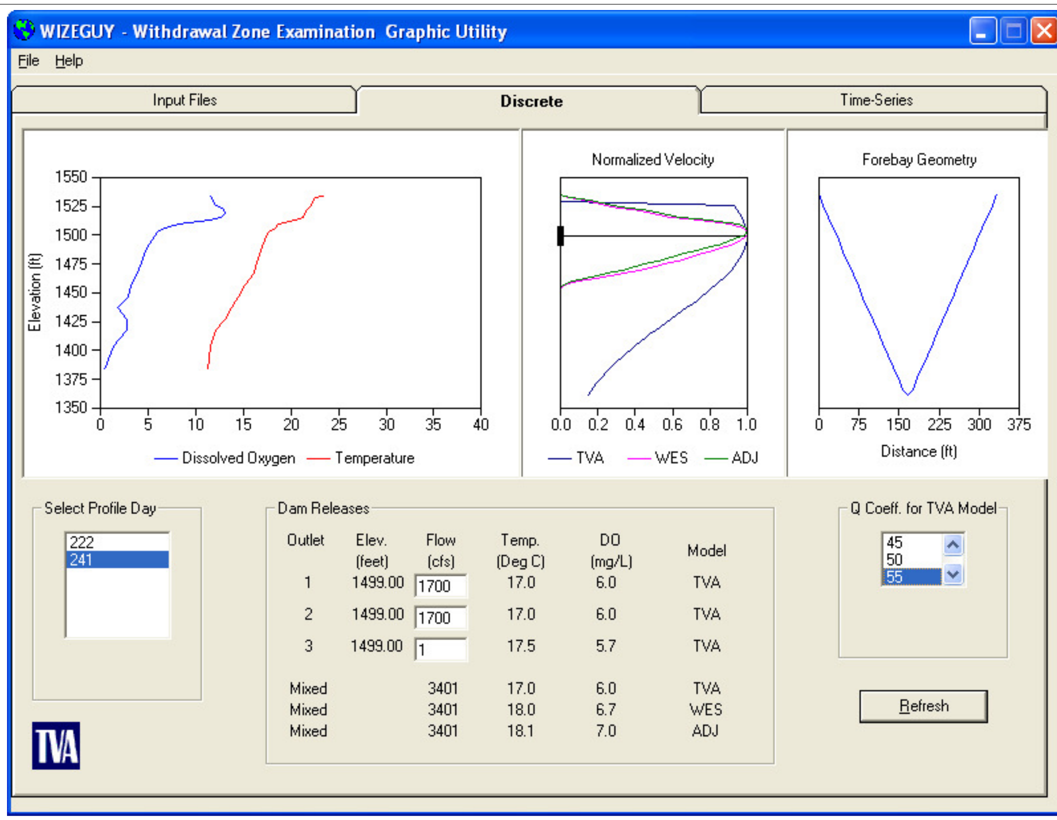
New Geometry and Max Flow



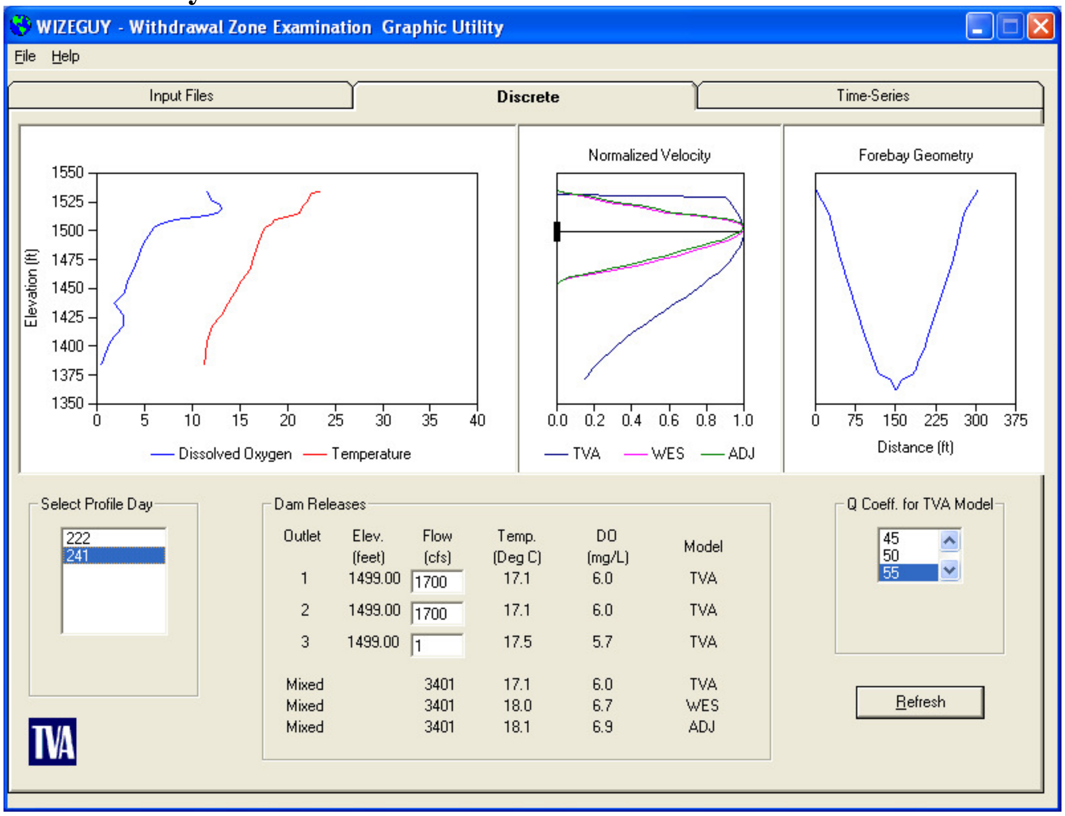
8/29/01 (Day 242) – Profiles were collected at 14:20

TW Observations at 14:17 – T=17.6, DO=7.9





New Geometry



New Geometry and Max Flow