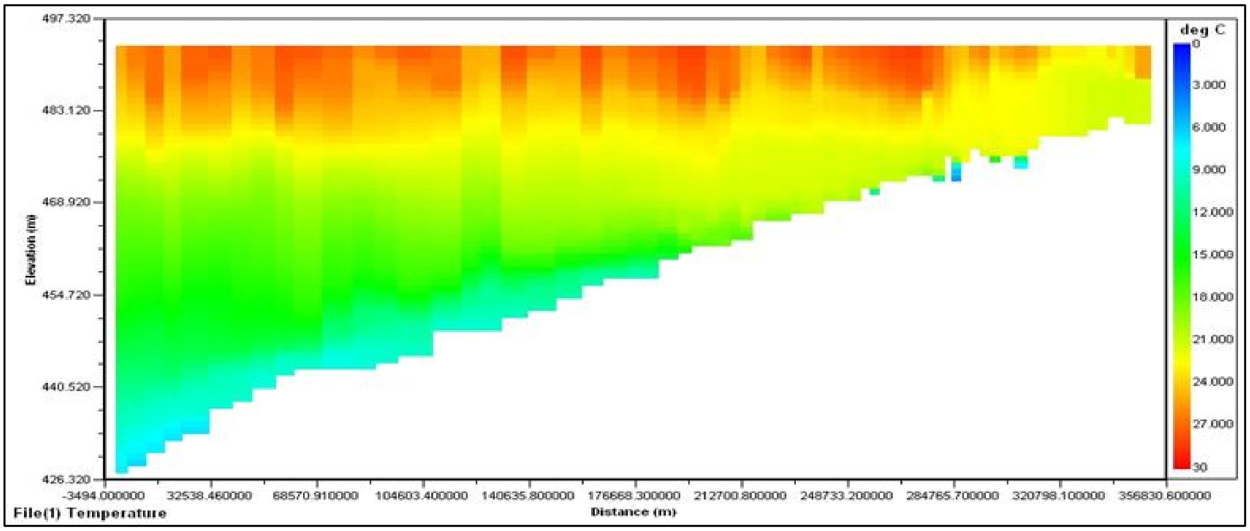
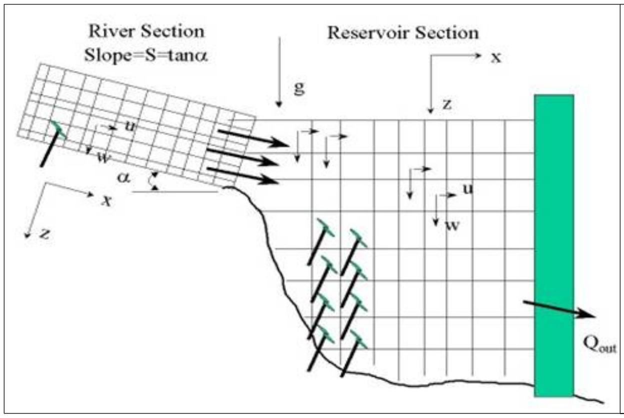
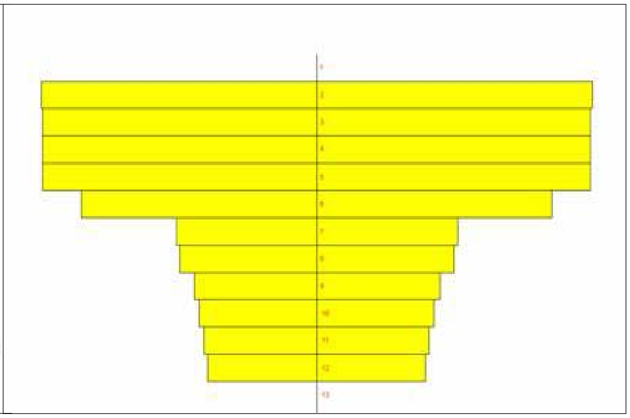
Water Quality Modeling Report

U.S. Army Corps of Engineers
Omaha District

Application of the CE-QUAL-W2 Hydrodynamic and Water Quality Model to Oahe Reservoir, North and South Dakota







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For Information Regarding This Document Please Contact:

John Hargrave
U.S. Army Corps of Engineers, Omaha District
1616 Capitol Avenue
Omaha, Nebraska 68102-9000
(402) 995-2347

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1 INTRODUCTION

1.1 APPLICATION OF THE CE-QUAL-W2 HYDRODYNAMIC AND WATER QUALITY MODEL TO THE MISSOURI RIVER MAINSTEM SYSTEM RESERVOIRS

1.1.1 WATER QUALITY MODELING NEED

A priority water quality management need identified by the Omaha District (District) is the capability to quantifiably assess, with acceptable uncertainty, the affects that operation and regulation of the six Missouri River Mainstem System (Mainstem System) projects have on water quality of the Missouri River and the impounded reservoirs (USACE, 2013). To meet this need, the District developed a plan to apply the CE-QUAL-W2 Hydrodynamic and Water Quality Model (W2) to the six Mainstem System reservoirs: Fort Peck (Montana), Garrison (North Dakota), Oahe (North and South Dakota), Big Bend (South Dakota), Fort Randall (South Dakota), and Gavins Point (South Dakota and Nebraska). The District is approaching application of the W2 model to the Mainstem System reservoirs as an ongoing, iterative process. Water quality data is collected at the reservoirs and the model is applied and calibrated. The goal is to have linked, fully-functioning water quality models in place for all the Mainstem System reservoirs that meets the uncertainty requirements of appropriate decision-makers.

W2 is a "state-of-the-art" model that can greatly facilitate addressing water quality management issues at the Mainstem System projects. W2 mechanistically models basic physical, chemical, and biological processes such as temperature, nutrient, algae, dissolved oxygen, organic matter, and sediment relationships. Once applied and calibrated, the model can reliably predict reservoir water quality conditions based on changes in environmental conditions or project operations and regulation. The ability to reliably predict reservoir water quality conditions under different environmental, operational, and regulation situations will allow the District to determine if water quality at specific projects may be impacted by project operations and regulation. As such, the model will allow the District to proactively assess how proposed project operations and regulation may affect water quality, and allow appropriate water quality management measures to be identified and implemented.

1.1.2 PRIOR APPLICATION OF THE CE-QUAL-W2 MODEL TO THE MAINSTEM SYSTEM RESERVOIRS

An early version of the W2 model was applied to four of the Mainstem System reservoirs in the early 1990's (i.e., Ft. Peck, Garrison, Oahe, and Fort Randall). The application of the model was part of the supporting technical documentation of the Environmental Impact Statement (EIS) that was prepared for the Missouri River Master Water Control Manual Review and Update Study. The results of the model application were included as an Appendix to the Review and Update Study – "Volume 7B: Environmental Studies, Reservoir Fisheries, Appendix C – Coldwater Habitat Model, Temperature and Dissolved Oxygen Simulations for the Upper Missouri River Reservoirs" (Cole et. al., 1994). The report (Cole et. al, 1994) provided results of applying the model to the four reservoirs regarding the effects of operational changes on coldwater fish habitat in the reservoir. This early application of the model represents the best results that could be obtained based on the model version and water quality data available at that time, and provided predictive capability for two system operational variables of concern; end-of-month stages and monthly average releases.

Although application of the early W2 model met its intended purpose at the time, a lack of available water quality data placed limitations on its full utilization. These limitations were discussed in the Master Water Control Review and Update Study report (Cole et. al, 1994). The following excerpt is taken from that report:

> *"Steps should be taken to obtain a suitable database that can be used to calibrate the entire suite of water quality algorithms in the model. It is almost a certainty that water quality issues will remain important in the future."*

The current version of the W2 model has incorporated numerous enhancements over the earlier version that was applied to the four Mainstem System reservoirs in the early 1990's. These enhancements, among other things, include improvements to the numerical solution scheme, water quality algorithms, two-dimensional modeling of the water basin, code efficiencies, and user-model interface. Communication with the author of the earlier version of the W2 model applied to the Mainstem System reservoirs and current model support personnel indicated that the District should pursue implementing the current version of the model.

1.1.3 CURRENT APPLICATION OF THE CE-QUAL-W2 MODEL TO THE MAINSTEM SYSTEM RESERVOIRS

The plan for applying the current W2 model to a single Mainstem System reservoir encompasses a 5-year period. During years 1 through 3 an intensive water quality survey is conducted on the reservoir to collect the water quality data needed to fully apply the model. Application and calibration of the model occurs in years 4 and 5 or beyond, as resources allow. Resource limitations required that the initiation of intensive water quality surveys at the Mainstem System reservoirs be staggered annually. The order and year of initiation of the intensive water quality surveys at the Mainstem System reservoirs are: 1) Garrison (2003), 2) Fort Peck (2004), 3) Oahe (2005), 4) Fort Randall (2006), 5) Big Bend (2008), and Gavins Point (2008). Once calibrated for a project, the model will be used to develop a water quality management report and objectives for each of the Mainstem System projects.

This report documents the application of the W2 model to Oahe Reservoir in North and South Dakota.

1.2 REGULATION OF THE MAINSTEM SYSTEM

The Mainstem System is a hydraulically and electrically integrated system that is regulated to obtain the optimum fulfillment of the multipurpose benefits for which the dams and reservoirs were authorized and constructed. The Congressionally authorized purposes of the Mainstem System are flood control, navigation, hydropower, water supply, water quality, irrigation, recreation, and fish and wildlife (including threatened and endangered species). The Mainstem System is operated under the guidelines described in the Missouri River Mainstem System Master Water Control Manual, (Master Manual) (USACE-RCC, 2004). The Master Manual details reservoir regulation for all authorized purposes as well as emergency regulation procedures in accordance with the authorized purposes.

Mainstem System regulation is, in many ways, a repetitive annual cycle that begins in late winter with the onset of snowmelt. The annual melting of mountain and plains snow packs along with spring and summer rainfall produces the annual runoff into the Mainstem System. In a typical year, mountain snow pack, plains snow pack, and rainfall events respectively contribute 50, 25, and 25 percent of the annual runoff to the Mainstem System. After reaching a peak, usually during July, the amount of water stored in the Mainstem System declines until late in the winter when the cycle begins anew. A similar pattern may be found in rates of releases from the Mainstem System, with the higher levels of flow from mid-March to late November, followed by low rates of winter discharge from late November until mid-March, after which the cycle repeats.

To maximize the service to all the authorized purposes, given the physical and authorization limitations of the Mainstem System, the total storage available in the Mainstem System is divided into four regulation zones that are applied to the individual reservoirs. These four regulation zones are: 1)

Exclusive Flood Control Zone, 2) Annual Flood Control and Multiple Use Zone, 3) Carryover Multiple Use Zone, and 4) Permanent Pool Zone.

1.2.1 EXCLUSIVE FLOOD CONTROL ZONE

Flood control is the only authorized purpose that requires empty space in the reservoirs to achieve the objective. A top zone in each Mainstem System reservoir is reserved for use to meet the flood control requirements. This storage space is used only for detention of extreme or unpredictable flood flows and is evacuated as rapidly as downstream conditions permit, while still serving the overall flood control objective of protecting life and property. The Exclusive Flood Control Zone encompasses 4.7 MAF and represents the upper 6 percent of the total Mainstem System storage volume. This zone, from 72.4 MAF down to 67.7 MAF, is normally empty. The four largest reservoirs, Fort Peck, Garrison, Oahe, and Fort Randall, contain 97 percent of the total storage reserved for the Exclusive Flood Control Zone.

1.2.2 ANNUAL FLOOD CONTROL AND MULTIPLE USE ZONE

An upper “normal operating zone” is reserved annually for the capture and retention of runoff (normal and flood) and for annual multiple-purpose regulation of this impounded water. The Mainstem System storage capacity in this zone is 11.6 MAF and represents 16 percent of the total Mainstem System storage. This storage zone, which extends from 67.7 MAF down to 56.1 MAF, will normally be evacuated to the base of this zone by March 1 to provide adequate storage capacity for capturing runoff during the next flood season. On an annual basis, water will be impounded in this zone, as required to achieve the Mainstem System flood control purpose, and also be stored in the interest of general water conservation to serve all the other authorized purposes. The evacuation of water from the Annual Flood Control and Multiple Use Zone is scheduled to maximize service to the authorized purposes that depend on water from the Mainstem System. Scheduling releases from this zone is limited by the flood control objective in that the evacuation must be completed by the beginning of the next flood season. This is normally accomplished as long as the evacuation is possible without contributing to serious downstream flooding. Evacuation is, therefore, accomplished mainly during the summer and fall because Missouri River ice formation and the potential for flooding from higher release rates limit release rates during the December through March period.

1.2.3 CARRYOVER MULTIPLE USE ZONE

The Carryover Multiple Use Zone is the largest storage zone extending from 56.1 MAF down to 17.6 MAF and represents 53 percent of the total Mainstem System storage volume. Serving the authorized purposes during an extended drought is an important regulation objective of the Mainstem System. The Carryover Multiple Use Zone provides a storage reserve to support authorized purposes during drought conditions. Providing this storage is the primary reason the upper three reservoirs of the Mainstem System are so large compared to other Federal water resource projects. The Carryover Multiple Use Zone is often referred to as the “bank account” for water in the Mainstem System because of its role in supporting authorized purposes during critical dry periods when the storage in the Annual Flood Control and Multiple Use Zone is exhausted. Only the reservoirs at Fort Peck, Garrison, Oahe, and Fort Randall have this storage as a designated storage zone. The three larger reservoirs (Fort Peck, Garrison, and Oahe) provide water to the Mainstem System during drought periods to provide for authorized purposes. During drought periods, the three smaller projects (i.e., Fort Randall, Big Bend, and Gavins Point) reservoir levels are maintained at the same elevation they would be at if runoff conditions were normal.

1.2.4 PERMANENT POOL ZONE

The Permanent Pool Zone is the bottom zone that is intended to be permanently filled with water. The zone provides for future sediment storage capacity and maintenance of minimum pool levels for power heads, irrigation diversions, water supply, recreation, water quality, and fish and wildlife. A drawdown into this zone is generally not scheduled except in unusual conditions. The Mainstem System storage capacity in this storage zone is 17.6 MAF and represents 25 percent of the total storage volume. The Permanent Pool Zone extends from 17.6 MAF down to 0 MAF.

1.2.5 WATER CONTROL PLAN FOR THE MAINSTEM SYSTEM

Variations in runoff into the Mainstem System necessitates varied regulation plans to accommodate the multipurpose regulation objectives. The two primary high-risk flood seasons are the plains snowmelt and rainfall season extending from late February through April, and the mountain snowmelt and rainfall period extending from May through July. Also, the winter ice-jam flood period extends from mid-December through February. The highest average power generation period extends from mid-April to mid-October, with high peaking loads during the winter heating season (mid-December to mid-February) and the summer air conditioning season (mid-June to mid-August). The power needs during the winter are supplied primarily with Fort Peck and Garrison Dam releases and the peaking capacity of Oahe and Big Bend Dams. During the spring and summer period, releases are normally geared to navigation and flood control requirements, and primary power loads are supplied using the four lower dams. The normal 8-month navigation season extends from April 1 through November 30, during which time Mainstem System releases are increased to meet downstream target flows in combination with downstream tributary inflows. Winter releases after the close of the navigation season are much lower and vary depending on the need to conserve or evacuate storage volumes, downstream ice conditions permitting. Releases and pool fluctuations for fish spawning management generally occur from April 1 through June. Two threatened and endangered bird species, piping plover (*Charadrius melodus*) and least tern (*Sterna antillarum*), nest on “sandbar” areas from early May through mid-August. Other factors may vary widely from year to year, such as the amount of water-in-storage and the magnitude and distribution of inflow received during the coming year. All these factors will affect the timing and magnitude of Mainstem System releases. The gain or loss in the water stored at each reservoir must also be considered in scheduling the amount of water transferred between reservoirs to achieve the desired storage levels and to generate power. These items are continually reviewed as they occur and are appraised with respect to the expected range of regulation.

1.3 DESCRIPTION OF THE OAHE PROJECT

Oahe Dam is located on the Missouri River at RM 1072.3 in central South Dakota, 6 miles northwest of Pierre, SD. The closing of Oahe Dam in 1958 resulted in the formation of Oahe Reservoir (Lake Oahe). When full, the reservoir is 231 miles long, covers 374,000 acres, and has 2,250 miles of shoreline. Table 1-1 summarizes how the surface area, volume, mean depth, and retention time of Lake Oahe vary with pool elevations. The reservoir has recovered from recent drought conditions of the past decade and was at a pool elevation of 1593.5 at the end of December 2012. This is 14 feet below the top of the Carryover Multiple Use Zone (1607.5 ft-NGVD29). Major inflows to the reservoir are the Missouri and Cheyenne Rivers. Water discharged through Oahe Dam for power production is withdrawn from Lake Oahe at elevation 1524 ft-NGVD29, approximately 114 feet above the reservoir bottom. Figure 1-1 shows a schematic drawing and photo of Oahe Dam and the power intake structure.

Table 1-1. Surface area, volume, mean depth, and retention time of Lake Oahe at different pool elevations based on 2010 bathymetric survey.

Elevation (Feet-msl)	Surface Area (Acres)	Volume (Acre-Feet)	Mean Depth (Feet)*	Retention Time (Years)**
1620	385,585	22,982,900	59.6	1.30
1615	352,515	21,161,350	60.0	1.20
1610	325,930	19,463,330	59.7	1.10
1605	298,850	17,904,680	59.9	1.01
1600	279,520	16,461,230	58.9	0.93
1595	258,595	15,117,980	58.5	0.86
1590	244,405	13,863,320	56.7	0.79
1585	229,685	12,676,740	55.2	0.72
1580	212,675	11,569,960	54.4	0.66
1575	195,760	10,549,470	53.9	0.60
1570	179,831	9,610,441	53.4	0.54
1565	163,143	8,755,206	53.7	0.50
1560	152,181	7,968,796	52.4	0.45
1555	140,063	7,239,563	51.7	0.41
1550	132,594	6,559,882	49.5	0.37
1545	124,749	5,915,629	47.4	0.34
1540	115,352	5,314,664	46.1	0.30

Average Annual Inflow (1967 through 2012) = 18.47 Million Acre-Feet.

Average Annual Outflow: (1967 through 2012) = 17.65 Million Acre-Feet.

* Mean Depth = Volume ÷ Surface Area.

** Retention Time = Volume ÷ Average Annual Outflow.

Note: Exclusive Flood Control Zone (elev. 1620-1617 ft-NGVD29), Annual Flood Control and Multiple Use Zone (elev. 1617-1607.5 ft-NGVD29), Carryover Multiple Use Zone (elev. 1607.5-1540 ft-NGVD29), and Permanent Pool Zone (elev. 1540-1415 ft-NGVD29). All elevations are in the NGVD 29 datum.

Lake Oahe and Oahe Dam are authorized for the purposes of flood control, recreation, fish and wildlife, hydroelectric power production, water supply, water quality, navigation, and irrigation. Habitat for one endangered species, interior least tern, and one threatened species, piping plover, occurs within the project area. Lake Oahe is used as a water supply by the towns of Fort Yates, ND (RM1244); Wakpala, SD (RM1198); Mobridge, SD (RM1193), and Huron, SD (RM1074), SD. The intake for the WEB Water System is at RM 1184 (serves 45 towns and over 7,000 rural households), and the intake for the Cheyenne River Tribe Mni Water Company is at RM 1110 (Eagle Butte, LaPlante, Swiftbird, Whitehorse, Promise, Dupree, Iron Lightning, Thunder Butte, Faith, Howes, Isabel, Takina, Cherry Creek, Bridger, Lantry, Ridgeview, Red Elm, Red Scaffold, Blackfoot, and Parade, SD). Lake Oahe is an important recreational resource and a major visitor destination in South Dakota.

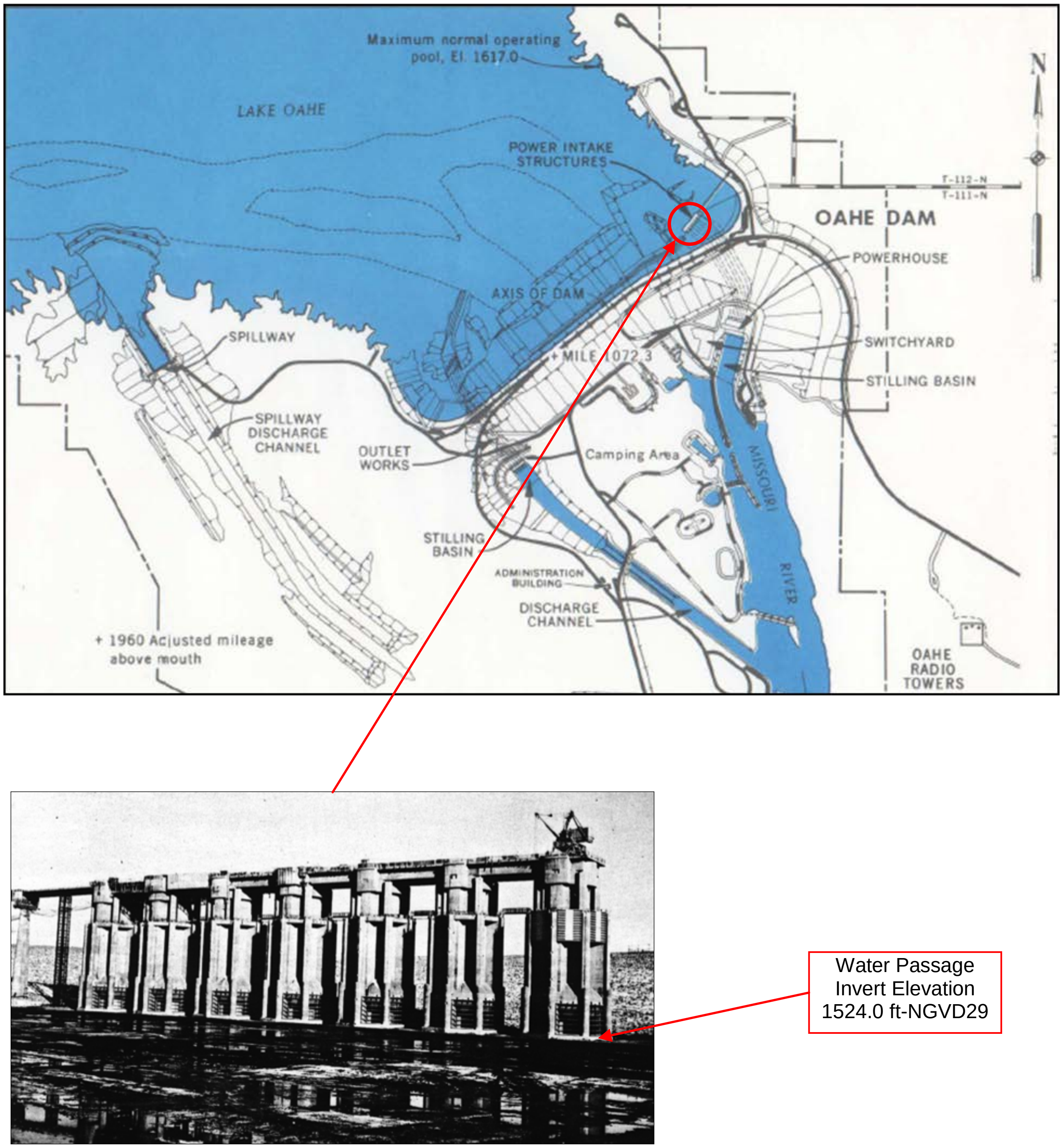

Figure 1-1. Location and photo of the power intake structure at Lake Oahe.

1.3.1.1 Water Quality Standards Classifications and Section 303(d) Listings

1.3.1.1.1 Lake Oahe

Under normal pool levels, Lake Oahe runs along the Missouri River from approximately RM1072 to RM1290, and crosses the North Dakota/South Dakota border which is at RM1232. Therefore under normal pools about 25 and 75 percent of the length of the reservoir is respectively in North Dakota and South Dakota. Water quality standards from each State respectively apply to the portion of the reservoir in each state.

The State of North Dakota has classified Lake Oahe as a Class 1 lake. As such, the reservoir is to be protected for a coldwater fishery; swimming, boating, and other water recreation; irrigation; stock watering; wildlife; and municipal or domestic use after appropriate treatment. Pursuant to Section 303(d) of the Federal CWA, North Dakota has not placed the Lake Oahe on the State's list of impaired waters. The State of North Dakota has issued a fish consumption advisory for Lake Oahe due to mercury concerns.

South Dakota has classified the Missouri River impoundments within the State as flowing streams and not reservoirs (South Dakota Administrative Rules 74:51:01:43). The following water quality-dependent beneficial uses have been designated for Lake Oahe in South Dakota's water quality standards: domestic water supply waters, coldwater permanent fish life propagation waters, immersion recreation waters, limited-contact recreation waters, commerce and industry waters, agricultural water supply (i.e., irrigation and stock watering), and fish and wildlife propagation. The State of South Dakota has not placed the reservoir on the State's Section 303(d) list of impaired waters and has not issued a fish consumption advisory for the reservoir. However, the Cheyenne River Sioux Tribe has issued a fish consumption advisory for Lake Oahe and the Cheyenne and Moreau Rivers. Tribal lands of the Cheyenne River Sioux are located along the west side of Lake Oahe between the Moreau and Cheyenne Rivers.

1.3.1.1.2 Missouri River Downstream of Oahe Dam

The following beneficial uses have been designated by South Dakota in their water quality standards for the Missouri River from Oahe Dam to Lake Sharpe: recreation (i.e., immersion and limited-contact), coldwater permanent fish life propagation, domestic water supply, agricultural water supply (i.e., irrigation and stock watering), commerce and industrial waters, and fish and wildlife propagation. The State of South Dakota has not placed the Missouri River on its Section 303(d) list of impaired waters and has not issued a fish consumption advisory for the river.

1.3.1.2 Ambient Water Quality Monitoring

The District has monitored water quality conditions at the Oahe Project since the late 1970's. Water quality monitoring locations have included sites on the reservoir and on the inflow to and outflow from the reservoir. A 3-year intensive water quality survey was completed at the Oahe Project in 2007, and the findings of the intensive survey are available in the separate report, "Water Quality Conditions Monitored at the Corps' Oahe Project in South Dakota during the 3-year period 2005 through 2007" (USACE, 2008). Figure 1-2 shows the location of sites at the Oahe Project that have been monitored by the District for water quality during the 8 year period 2005 through 2012. Water quality monitoring upstream of Mobridge, South Dakota (i.e., RM1196) was not conducted prior to 2009. Drought conditions and low pool levels during the mid-2000s resulted in the reservoir's upstream boundary receding to near the North Dakota/South Dakota border. The near-dam location (i.e., site OAHLK1073A) has been continuously monitored since 1980.

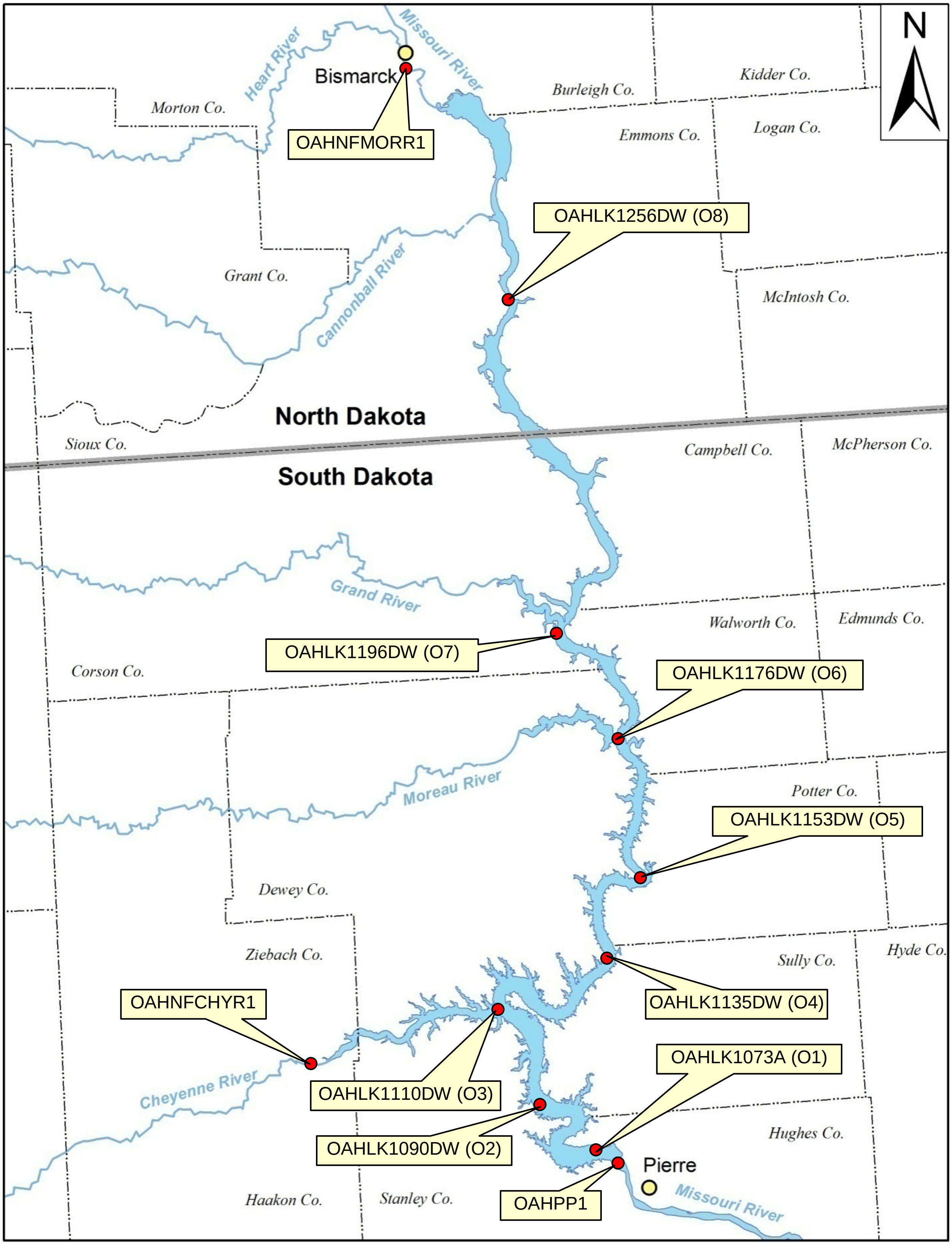

Figure 1-2. **Location of sites monitored by the District at the Oahe Project during the 8-year period 2005 through 2012.**

2 MODEL METHODS, SETUP & DATA

2.1 CE-QUAL-W2

CE-QUAL-W2 (W2) is a two-dimensional (longitudinal and vertical) water quality and hydrodynamic model for rivers, estuaries, lakes, reservoirs, and river basin systems. W2 simulates basic physical, chemical, and biological processes such as temperature, nutrient, algae, dissolved oxygen, organic matter, and sediment relationships. The model is supported by the Environmental Lab at the USACE Engineering Research and Development Center (ERDC) Waterways Experiment Station (WES) in Vicksburg, MS, and by the Civil Engineering Department at Portland State University in Portland, OR.

Version 2.0 of the W2 model was applied to four of the upper Mainstem System Projects in the early 1990s (i.e., Ft. Peck Lake, Lake Sakakawea, Lake Oahe, and Lake Francis Case). The application of the model was part of the supporting technical documentation of the Environmental Impact Statement (EIS) that was prepared for the Missouri River Master Water Control Manual Review and Update Study. The results of the model application were included as an Appendix to the Review and Update Study – "Volume 7B: Environmental Studies, Reservoir Fisheries, Appendix C – Coldwater Habitat Model, Temperature and Dissolved Oxygen Simulations for the Upper Missouri River Reservoirs" (Cole et. al., 1994).

Version 3.7 of the W2 model was used in this report to model temperature, dissolved oxygen, and nutrients in Lake Oahe. Predicted temperatures in the lake will be influenced by reservoir inflow volumes and temperatures; environmental factors such as wind, air temperature, and solar radiation; and management factors such as reservoir release rates and outflow structure configurations.

All model calculations and outputs are performed in the International System (SI) of Units; therefore, all subsequent data and figures presented in this report are expressed in SI units with the exception of coldwater habitat which is expressed in traditional English units of acre feet.

2.2 HYDRODYNAMICS

The governing equations for hydrodynamics and transport are derived from the conservation of fluid mass and momentum equation. The model uses a hydrostatic approximation for vertical fluid movement rather than rely on the true conservation of momentum equation. Hydrodynamics and transport are laterally and layer averaged meaning lateral and layer variations in velocities, temperatures and constituents are negligible. The hydrodynamic behavior of the model is dependent largely on initial conditions, boundary conditions, and hydraulic conditions which are described with specific regard to the Lake Oahe model in the following paragraphs and later sections of this report.

2.2.1 INITIAL CONDITIONS

The simulation was performed from January 1 (jday = 1) to December 31 (jday = 365) for the years 2005 thru 2011. Each year was simulated separately with a minimum timestep of 1 minute. The initial water column temperature was set to 1.0 degrees C. An initial ice thickness of 0.1 meters (0.3 ft) covering the entire reservoir on January 1 was assumed each year.

2.2.2 HYDRAULIC COEFFICIENTS

CE-QUAL-W2 uses default values for a number of hydraulic parameters that influence the movement of momentum and heat exchange within a water body (Table 2-1). The horizontal dispersion of momentum and heat are determined by the horizontal eddy viscosity and diffusivity, while vertical diffusion of momentum is influenced by the method for computing the vertical eddy viscosity. A very important factor influencing momentum transfer and mixing near the bottom of a water body is the bottom friction expressed either as Manning's roughness or Chezy coefficients. In the Lake Oahe model, a Chezy coefficient of 70 was used for the entire water body.

Table 2-1. CE-QUAL-W2 hydraulic and heat exchange coefficients.

Hydraulic Coefficients	
Horizontal Eddy Viscosity & Diffusivity (m^2/s)	1.0
Vertical Eddy Viscosity Method	W2
Max. Vertical Eddy Viscosity (m^2/s)	0.001
Friction Type (Chezy)	70
Heat Exchange Coefficients	
Sediment Heat Exchange Coefficient ($W/\ m^2/s$)	0.3
Bottom Sediment Temperature (^oC)	5.5 to 8.1
Fraction Solar Radiation at Sediment to Water	0.25
Coefficient of water-ice heat exchange	10
Ice Albedo (Reflection/Incident)	0.25
Fraction of Radiation Absorbed by Ice	0.6
Solar Radiation Extinction Coefficient (m^{-1})	0.07
Temperature for ice formation (^oC)	3.0
Wind Measurement Height (m)	3
Fraction of solar radiation absorbed at WS	0.40

2.2.3 HEAT EXCHANGE

Water surface heat exchange is defined as the sum of incident short and long wave solar radiation, reflected short and long wave solar radiation, back radiation, evaporative heat loss, and heat conduction. Since some of these computed terms are temperature dependent, the Lake Oahe model uses an equilibrium temperature method in which the net rate of surface heat exchange is zero at the equilibrium temperature. Although this method is empirical in nature, it consistently gives better results than other theoretical methods. A number of heat exchange coefficients that affect ice formation and transfer of heat through ice are specified in Table 2-1.

Heat is transferred between the bottom sediment-water interface, and a heat exchange rate along with average sediment temperature must be specified. The fraction of solar radiation re-radiating from the lake bottom to the water column is specified as a fraction of radiation reaching the bottom. In Lake Oahe very limited shortwave solar radiation reaches the bottom.

The wind measurement height is particularly important because the model adjusts wind speed to the height of the wind speed formulation which drives surface mixing and evaporative heat losses. In addition the fraction of solar radiation absorbed by the water surface is specified.

2.3 WATER QUALITY

CE-QUAL-W2 computes numerous water quality constituents in their basic forms and derived forms based on a constituent mass balance. Within this mass balance constituents may undergo kinetic reactions that convert the nutrient to other organic or inorganic forms of the nutrient by algae utilization or other biological processes. While nutrients are important in many water quality applications, dissolved oxygen is a more important parameter concerning Lake Oahe.

2.3.1 NUTRIENTS

Lake nutrients undergo transport and kinetic reactions through biological or chemical transformation to nutrient sources or sinks. Water quality state variables used in the Lake Oahe simulations included total dissolved solids (TDS), suspended solids (SS), bio-available phosphorus, ammonium, nitrate-nitrite, labile and refractory forms of dissolved and particulate organic matter, algae, and dissolved oxygen (DO). Further discussion on how CE-QUAL-W2 handles nutrient kinetics may be found in the Appendix B of the W2 User Manual (Cole and Wells, 2011).

2.3.2 DISSOLVED OXYGEN

A use of the water quality constituent modeling is to compute cold water habitat as a function of dissolved oxygen (and temperature) throughout the reservoir. The most important components that serve as sources of dissolved oxygen in these simulations are aeration from the atmosphere and algae (phytoplankton) photosynthesis, depicted in Figure 2-1. Dissolved oxygen sinks include algal respiration and decay or decomposition of organic sediments and organic matter. Reaeration, organic matter oxygen demand, algal dynamics, and sediment oxygen demand are discussed in more detail.

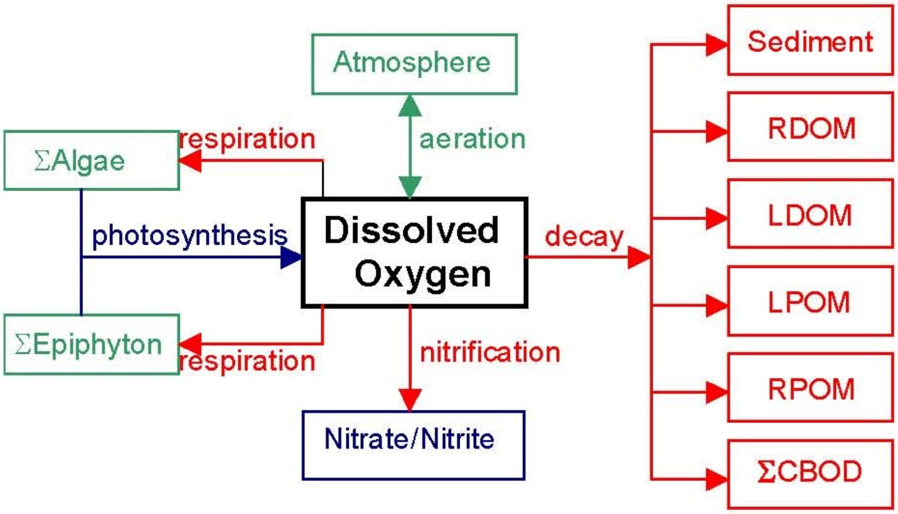

Figure 2-1. Dissolved oxygen dynamics in CE-QUAL-W2.

2.3.2.1 Reaeration

The reaeration of water with dissolved oxygen occurs in lakes as a function of turbulent mixing caused by surface winds. Reaeration by wind primarily effects dissolved oxygen concentrations in the mixed volume of the water column (e.g., epilimnion during summer thermal stratification, etc.). Model equations are written for 10-meter measured wind heights, but can be adjusted for alternate wind heights.

2.3.2.2 Organic Matter

The total oxygen demand exerted on a lake is often measured as biological oxygen demand (BOD); however, both decomposition and production of these materials occurs in the model so organic matter represented as BOD must be separated into its major components, which include labile dissolved organic matter (LDOM), refractory dissolved organic matter (RDOM), labile particulate organic matter (LPOM), and refractory particulate organic matter (RPOM). Dissolved organic matter (DOM) and particulate organic matter (POM) are important because they utilize DO during their decay process. Labile DOM and labile POM decay at a faster rate than refractory OM, which is product of labile OM decay. Settling POM contributes to the lake sediment oxygen demand. DOM and POM are produced by algal mortality and excretion. DO concentrations in the reservoir are greatly influenced by organic matter (OM) dynamics.

2.3.2.3 Algal Dynamics

Although CE-QUAL-W2 version 3.7 allows algal groups to be broken into several types of algae, one "generic" algal group was modeled. Algae are important in nutrient and DO dynamics by utilizing nutrients and producing DO during photosynthesis, and utilizing DO during respiration. Algal mortality and excretion produces DOM and POM which eventually decay and further utilize DO. Chlorophyll *a* (Chl *a*) is used as an indicator of algae present in the reservoir.

2.3.2.4 Sediment Oxygen Demand

Organic sediments resulting from algae and OM decay contribute to nutrients and DO demand in the reservoir using a constant (zero-order) release and demand method, and an organic sediment accumulative (first-order) method. The zero-order method specifies a sediment oxygen demand (SOD) and nutrient release rates that are temperature dependent. The first-order method accumulates organic sediment from settling of algae and POM, therefore it is more predictive in nature and attempts to accurately account for the SOD. The first-order SOD method was used in the water quality simulations.

2.3.3 INITIAL CONDITIONS

Initial constituent concentrations were derived from minimum constituent concentrations detected in the ambient water quality samples from the reservoir, with the exception of dissolved oxygen (DO), total dissolved solids (TDS), and organic matter (OM). DO was assumed saturated at the beginning of the simulation, TDS was estimated from the May surface sample taken near the dam. Initial and observed OM concentrations in the lake and inflows were estimated based on measured concentrations of total organic carbon (TOC).

2.4 MODEL SETUP

2.4.1 LAKE BATHYMETRY

The Lake Oahe bathymetry was modified from the bathymetry used in the Coldwater Habitat Model constructed by Cole et al. (1994). Modifications were based on 2010 field survey cross sections and input from the U.S. Army Corps of Engineers Waterways Experiment Station. The reservoir bathymetry consisted of one main branch with one minor branch, and it is shown in Figure 2-2. Branch 1 of the model is the main Missouri River branch, and it contains 70 active segments and 69 layers. Branch 2 represents the Cheyenne River confluence just to the South of Little Bend Recreation area. Bathymetry segments are all 5 km in length with 1 m vertical layer thicknesses. The length of the lake bathymetry from inlet to outlet is approximately 350 km and the lake model depth at the dam is 61 m. At the top of the flood control and multipurpose pool (1617 ft) segment widths ranged from 881 m to 9230 m. Chezy's bottom friction coefficients were set at 70 for all segments.

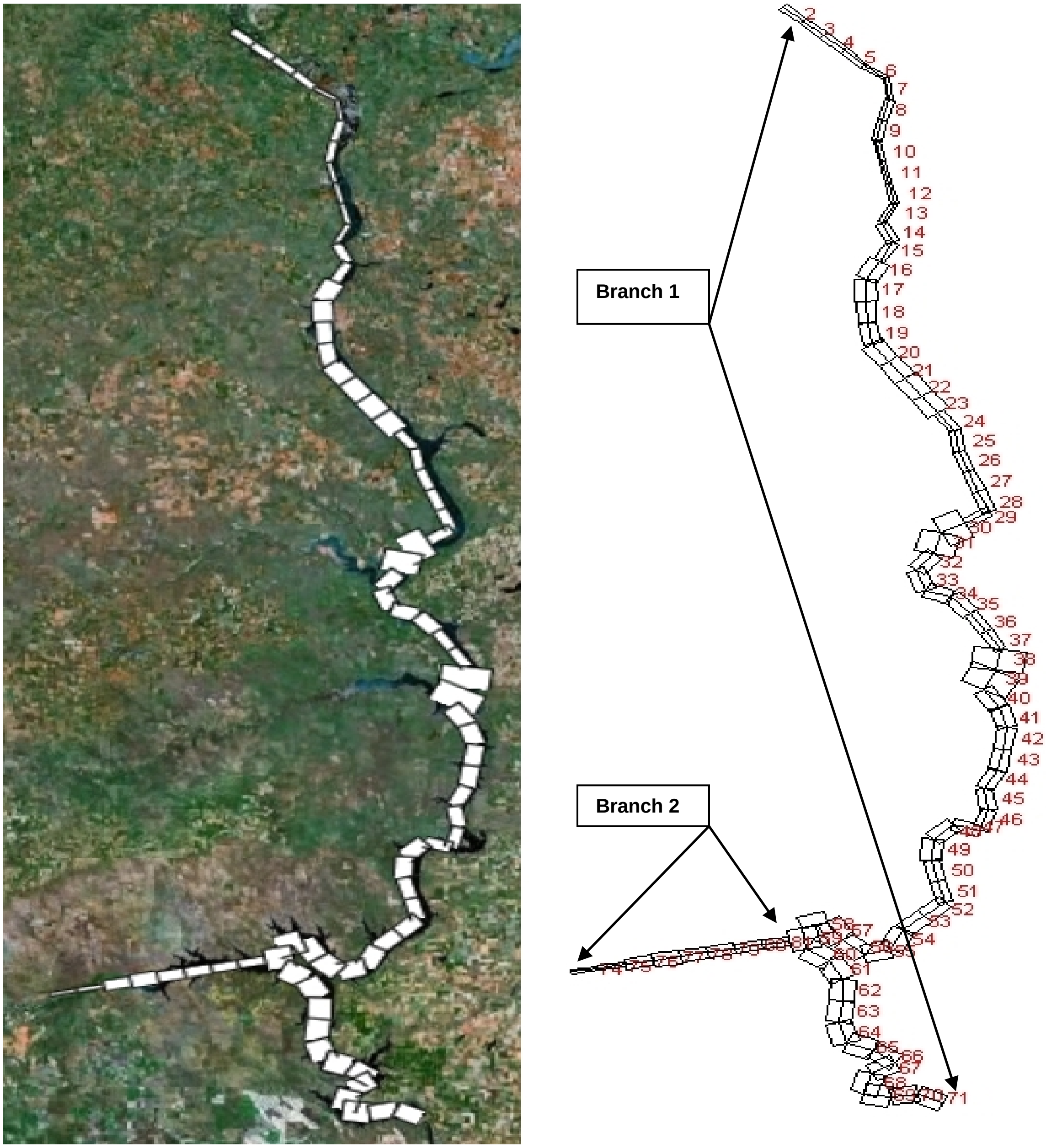

Figure 2-2. Overlay of plan view of Lake Oahe waterbody in Google Earth using 2013 aerial imagery and plan view of branches, segment layout, and orientation in space.

Volume-area-elevation curves constructed from the 2010 Corps of Engineers field survey and computed from model bathymetry are compared in Figures 2-3 and 2-4. Adjustments may still need to be made to the bathymetry in order to further improve the accuracy of the model. The model and COE surveyed lake areas and volumes deviate some, yet the provided inflows and outflows yielded good water surface elevations. At the top of the annual flood control and multipurpose pool elevation (1617.0 ft) the model lake volume is 25,249 million m^3 (20.5 MAF), and at the bottom of the annual flood control and multipurpose pool elevation (1607.5 ft) the model lake volume is 21,413 million m^3 (17.4 MAF).

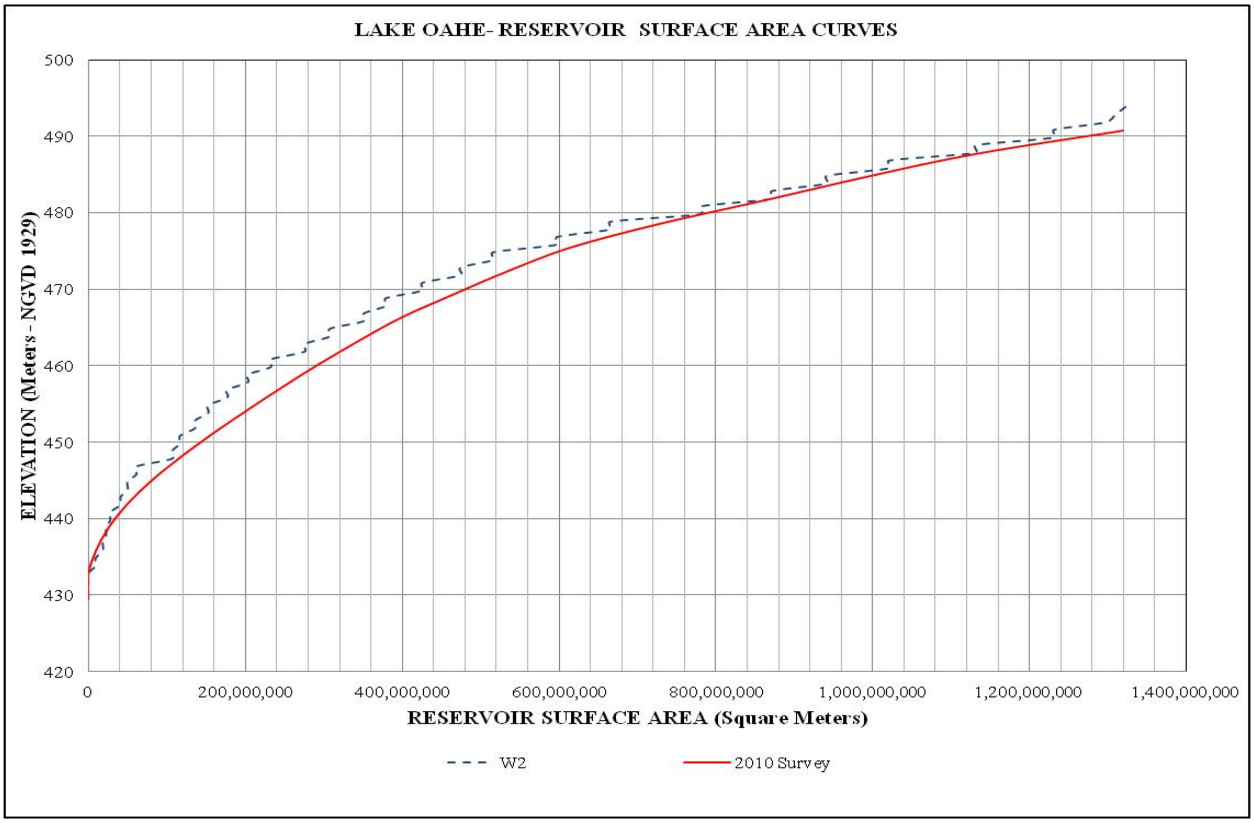

Figure 2-3. Area-elevation curves computed from the W2 model bathymetry and the 2010 COE lake survey.

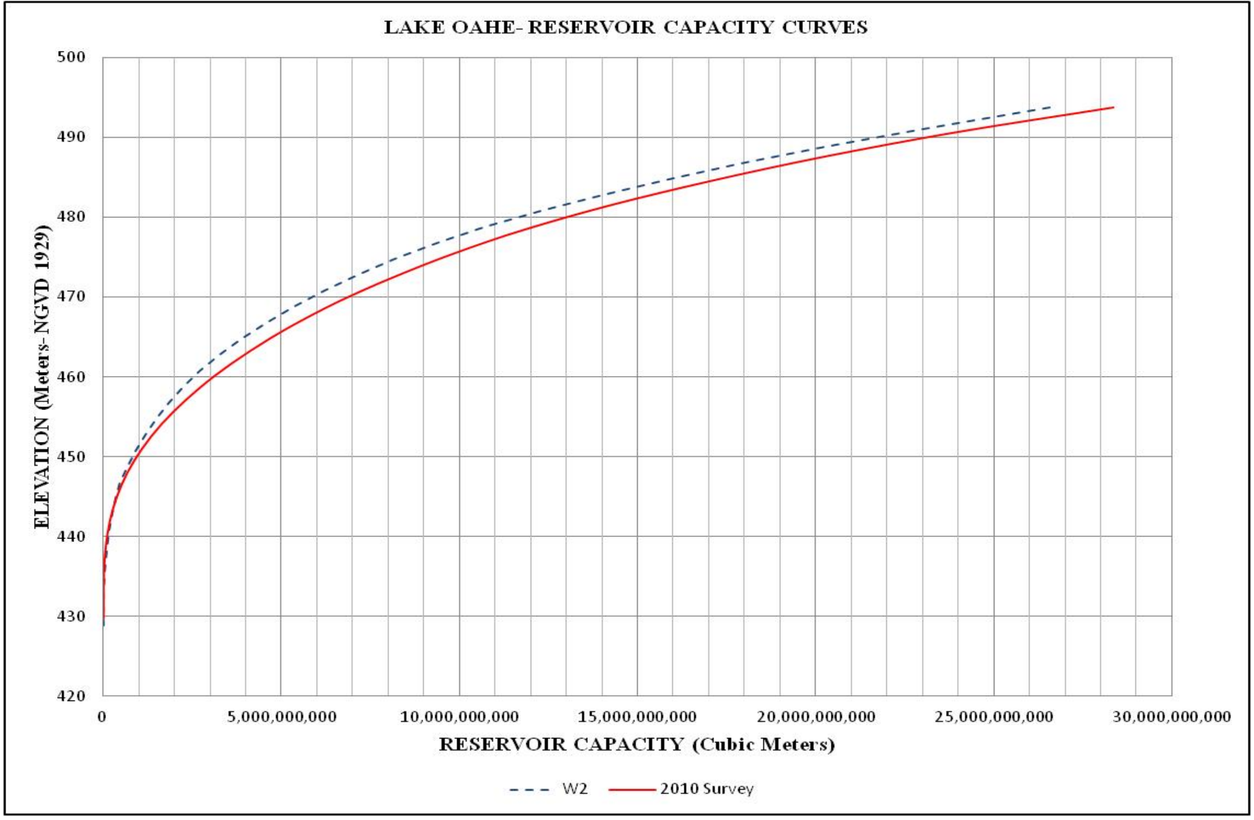

Figure 2-4. Volume-elevation curves computed from the W2 model bathymetry and the 2010 COE lake survey.

2.4.2 POWER STRUCTURES

The intake structure for power generation is located on the left (east) abutment of the dam. The structure consists of seven separate intake towers. The seven intakes are evenly spaced and house a 10 ft high by 32 ft diameter cylinder gate. The cylinder gates regulate flow to a 30 ft diameter drop inlet. The gate invert elevation is at 1524.0 ft. The drop inlets then converge from a diameter of 30 ft through a 90 degree elbow to 24 ft diameter tunnels at an invert elevation of 1390.0 ft.

2.4.3 OUTLET WORKS

The Oahe outlet works are located on the right (west) bank of the river and consist of an approach channel and six tunnels with individual submerged intake structures. Leading southerly from the river channel to the tunnel intakes, the outlet works approach channel is approximately 2,000 ft in length. The upstream portion of the channel next to the river is 1300 ft long and is made up of two levels. The lower level channel is at elevation 1425 ft with a 100 ft bottom width. The upper level channel, a berm 60 ft wide, parallels the lower level channel on the west at elevation 1455 ft. The remaining length of the approach channel is curved toward the intakes with a transition zone to the intake invert elevation. The individual intake structures are staggered in position and elevation. The first is set furthest upstream with the lowest invert elevation of 1425 ft. Each subsequent intake is set back approximately 70 ft with the invert elevation raised in 6 ft increments.

2.4.4 SPILLWAY STRUCTURE

Located approximately 1.5 miles west of the outlet works, the Oahe spillway is located in the right abutment. Spillway discharge is regulated by eight tainter gates. The spillway is constructed of reinforced concrete. The tainter gates and bridge are constructed of structural steel. The spillway proper is 456 feet wide between abutment faces. The weir crest is at elevation 1596.5 ft. The spillway at the Oahe project has never been used; however it is planned to undergo repairs that may make future use a viable option.

2.5 MODEL INPUTS

2.5.1 METEOROLOGICAL DATA

CE-QUAL-W2 requires meteorological inputs including air temperature, dew point temperature, wind speed, wind direction, cloud cover, and shortwave solar radiation. Cloud cover is used to estimate the amount of shortwave solar radiation reaching the water surface; however, it may be measured directly. Hourly weather data that included all parameters were obtained from the Mobridge Municipal Airport Weather Station near Mobridge, SD and the Bismarck, ND Municipal Airport Weather Station. The station coordinates are 45^{o}32’46” N latitude, 100^{o}24’29” W longitude, at a ground elevation of 507.2 m (1664 ft) and 45^{o}46’59” N latitude, 100^{o}45’25” W longitude, at a ground elevation of 506.0 m (1660 ft), respectfully.

Initially the meteorological dataset from the Mobridge Weather Station was used in each simulation year, after further review of model output it was decided to use data from the Bismarck Weather Station in years where there was difficulty calibrating model temperature with the Mobridge dataset. The Bismarck dataset was used in 2005, 2006, and 2008, which corresponds well with model years of low water surface elevation.

2.5.1.1 Temperature

Temperature data from the Mobridge Municipal Airport Weather Station and the Bismarck Municipal Airport Weather Station were used in the model. The Pierre Airport Weather Station was also examined as a possible source of temperature data, but was not used in the model because of poor initial fit to observed temperature profiles. Ambient air and dew point temperatures from 2005 through 2011 are plotted in Figures 2-6 and 2-7.

2.5.1.2 Wind Data

Wind data is a major driving factor of temperature calibration, thus weather data recorded at the Mobridge, Bismarck, and Pierre stations were examined during temperature model calibration. Mobridge and Bismarck wind data was used in the 2005 through 2011 simulations, and average daily and maximum daily wind speeds are plotted in Figure 2-8.

2.5.1.3 Cloud Cover

Cloud cover data was obtained from the Bismarck and Mobridge weather stations and converted to a cloud cover value on a 0 to 10 scale. If shortwave solar radiation is omitted from the meteorological data the cloud cover value is used to limit the amount of estimated incident shortwave radiation on the surface layer of the reservoir. Shortwave solar radiation was utilized in the model; however it was still necessary to include the cloud cover data in the meteorology file. Average daily cloud cover values are plotted in Figure 2-9.

2.5.1.4 Solar Radiation

Rather than allow the model to estimate incoming solar radiation from cloud cover, shortwave solar radiation, which represents mainly the visible spectrum, was included in the meteorological input file. Shortwave solar radiation data was estimated using the output from Response temperature: a simple model of water temperature (rTemp) from the Washington State Department of Ecology (WSDE) (WSDE, 2011). Response temperature can be defined as the temperature a completely mixed water column would have if it were only responding to heat fluxes across the waters surface. The estimate of shortwave solar radiation is provided in the model output along with the reservoir inflow water temperatures. The estimate from the rTemp model was was further adjusted during model temperature calibration. Short-wave solar radiation from the rTemp model is plotted in Figure 2-10.

2.5.1.5 Wind Sheltering Coefficients

Wind sheltering coefficients are the ratio of transferred wind energy to actual wind energy present in the meteorological data. Wind sheltering coefficients are one of the most important calibration parameters because they directly influence the amount of mixing that occurs in the surface layer of the reservoir and therefore the transfer of heat energy from the water surface to deeper layers in the reservoir. Wind sheltering coefficients were adjusted to 0.9 from the default value of 1.0 for some segments during model calibration. This is likely due to topographic differences between the model surface layer and the location of the weather station.

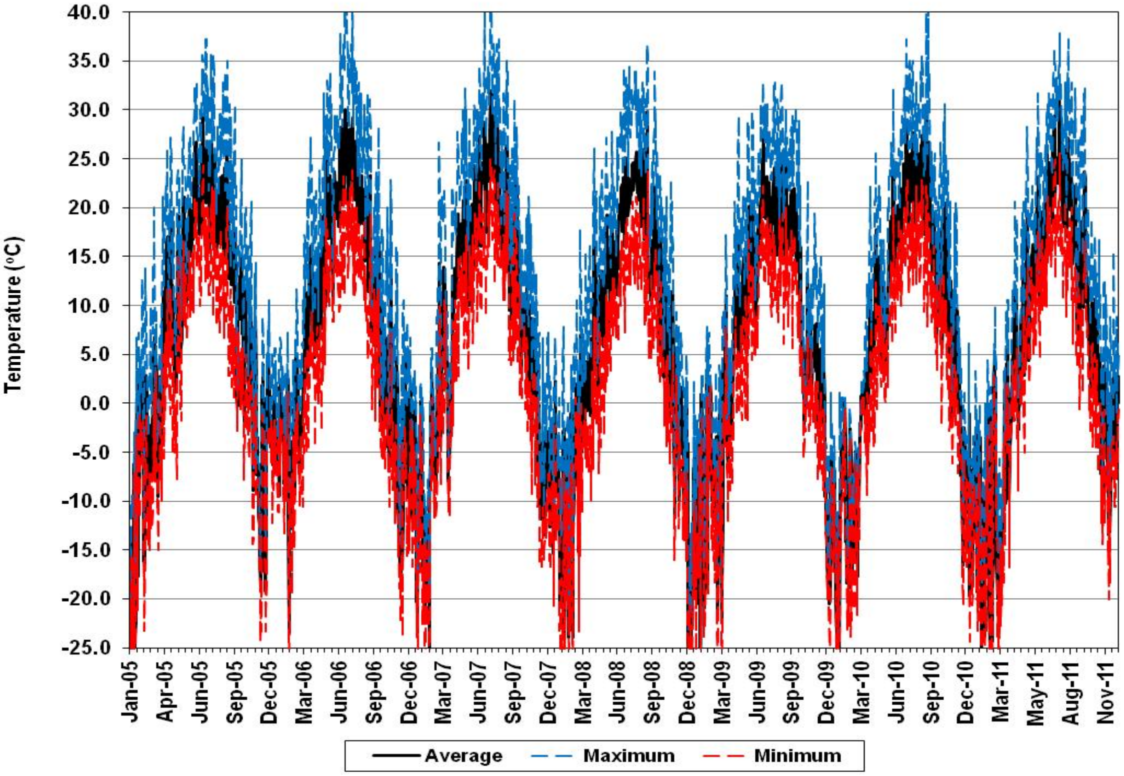

Figure 2-6. Daily average, maximum, and minimum air temperatures at Mobridge, SD.

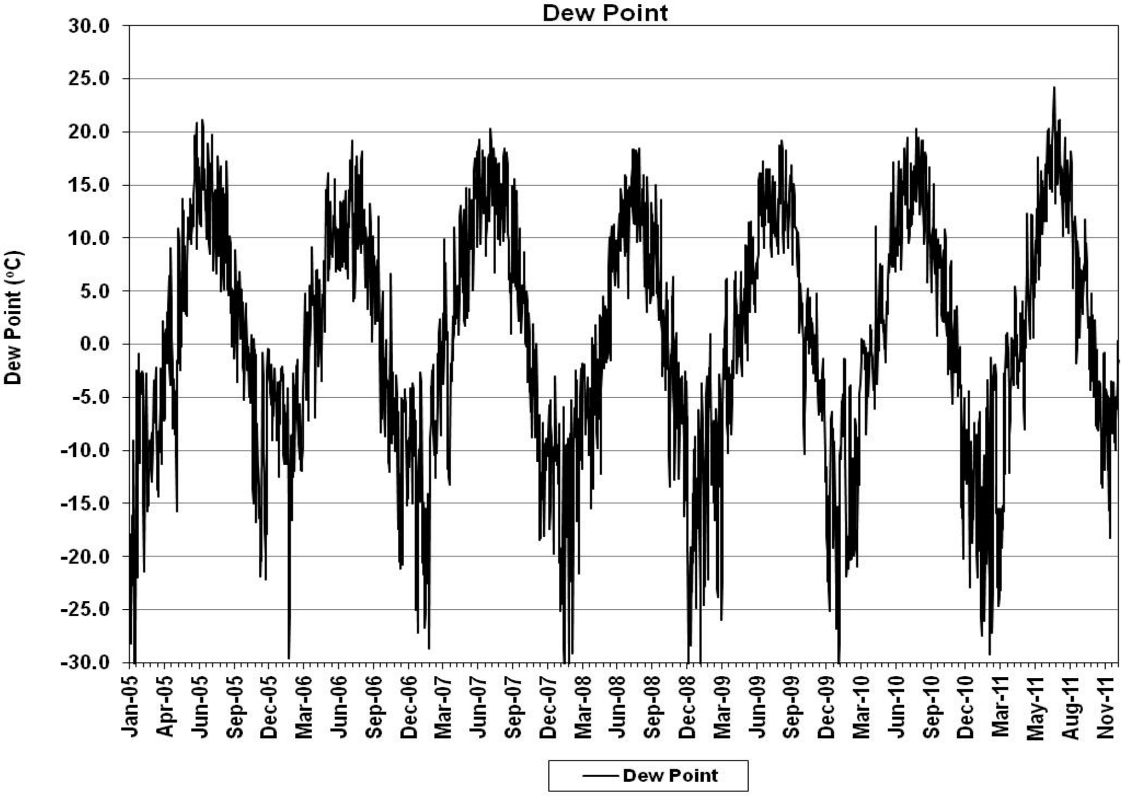

Figure 2-7. Daily average dew point temperature at Mobridge, SD.

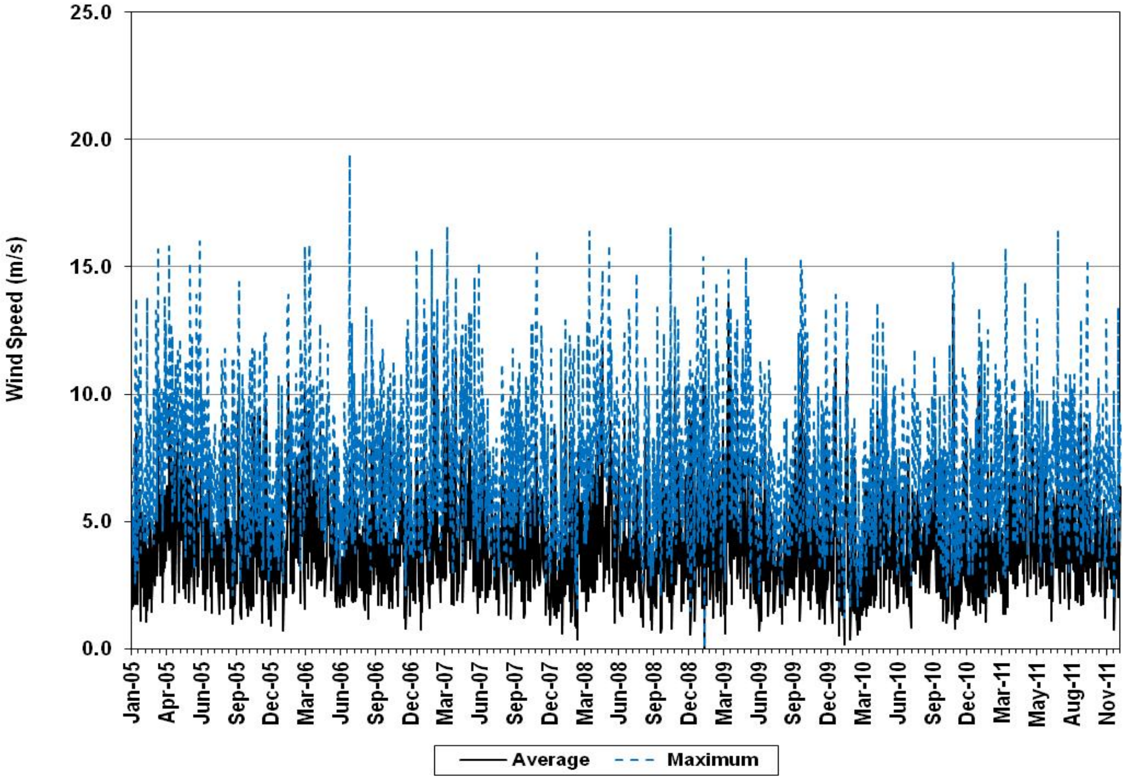

Figure 2-8. Daily average and maximum wind speed at Mobridge, SD.

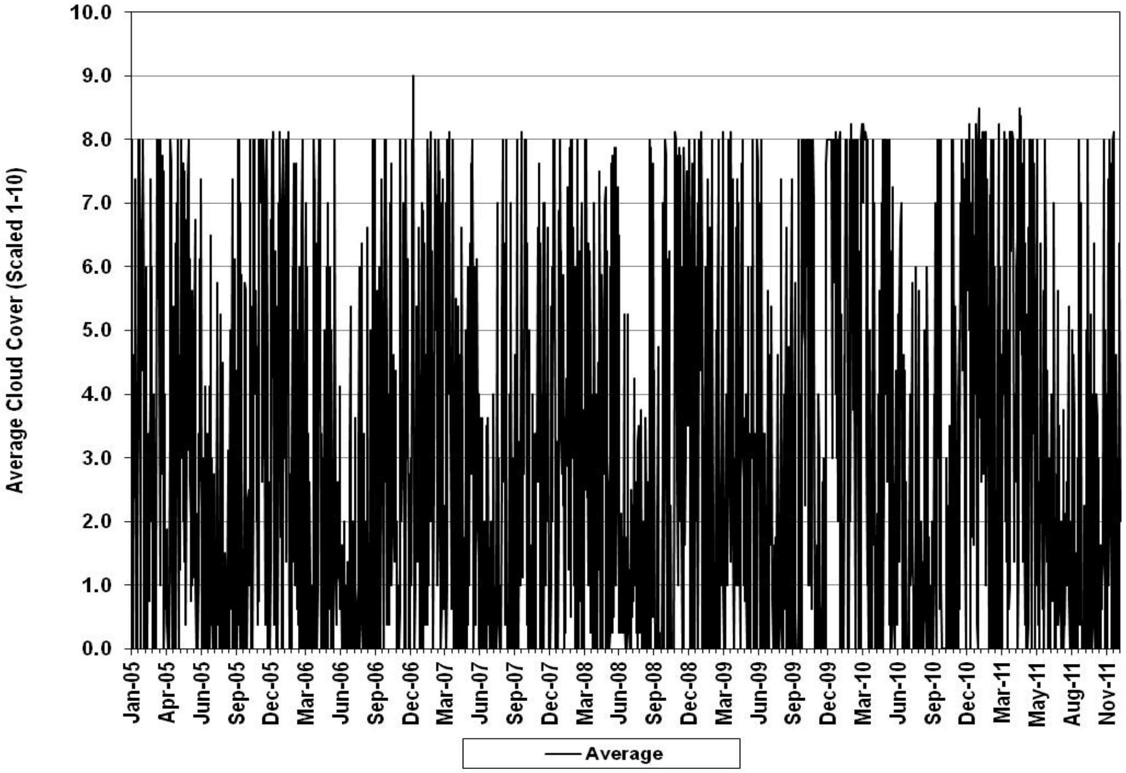

Figure 2-9. Daily average cloud cover at Mobridge, SD.

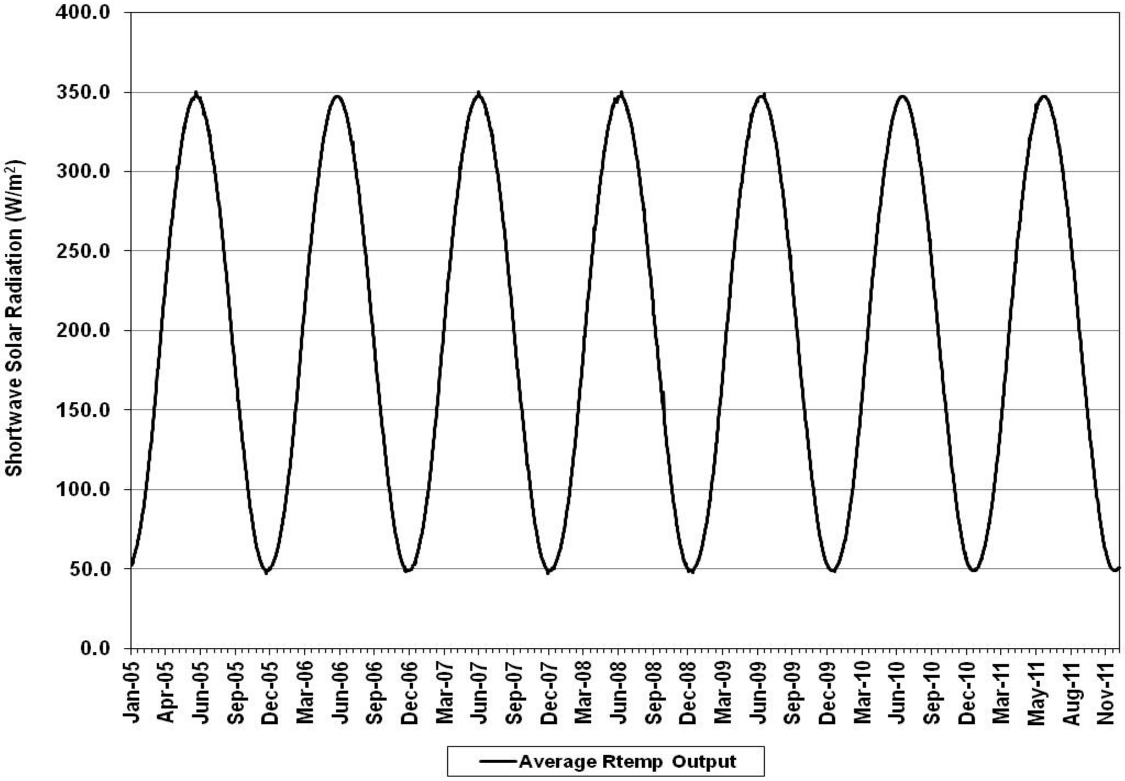

Figure 2-10. Daily average shortwave solar radiation at Bismarck, ND.

2.5.2 RESERVOIR INFLOW AND OUTFLOW

Daily inflow from the Missouri and Cheyenne Rivers were input as reservoir branch inflows while several minor tributaries were excluded from the model. Daily Missouri and Cheyenne River inflows were obtained from the Corps Water Management System (CWMS) managed by the Omaha District. Data was collected by the USGS at both the Missouri River (USGS 06342500) and the Cheyenne River (USGS 06438500) stations. Daily inflows are plotted in Figure 2-11.

Daily and hourly reservoir outflow data was recorded by the USACE. The outflow data were retrieved from the Oahe Project Power Plant Control System (PPCS). The combined daily outflows are plotted in Figure 2-12. Hourly reservoir outflow was used during all simulations.

2.5.3 INFLOW TEMPERATURE

Missouri River temperatures measured at 15-minute intervals at the USGS stream gage in Bismarck, ND (06342500) were used to generate inflow temperatures for the model for the majority of 2010 and 2011; however, temperatures in 2005 thru 2009 were not measured or only partially available due to equipment problems at the gage site. Inflow temperatures for 2005 thru 2008 and most of 2009 were estimated using a program called Response temperature: a simple model of water temperature (rTemp) from the Washington State Department of Ecology (WSDE) (WSDE, 2011). The meteorological data required by the rTemp program was obtained from the Bismarck Airport Weather Station. Inflow temperatures are plotted in Figure 2-13. Estimated temperatures were compared to measured water temperature in the Missouri River at Bismarck, ND (N=37). Computed values compared favorably to the observed data (absolue error (ABSE) = 1.5°C, root-mean square error (RMSE) = 2.3°C).

Cheyenne River temperature measurements were available from the USGS station at Howes, SD; however, the collected data was incomplete and error laden. In all years except 2009 the dataset from the Missouri River was used for the Cheyenne River, actual temperatures would likely have been warmer because of shallower water depth. During 2009 model temperature calibration the simulated water surface temperature below the Cheyenne River branch inflow was too low. To correct this, the rTemp program was used to generate inflow temperatures for the Cheyenne River. The rTemp generated temperatures compared favorably with observed Cheyenne River data obtained from the South Dakota Department of Environment and Natural Resources (SDDENR) station number 460133 (N=12, ABSE = 1.0°C, RMSE = 1.4°C).

2.5.4 INFLOW DISSOLVED OXYGEN

Dissolved oxygen measurements were made with samples taken at the inflow locations to the reservoir; however, since a continuous record of DO was needed at the modeled reservoir inlet, it was approximated as the saturated DO concentration using an empirical equation. The equation provided by the Environmental Laboratory of ERDC approximates DO concentrations in milligrams per liter of water (mg/L) as a function of water temperature (*T*) in Kelvin (K) and elevation (*z*) in kilometers (km). Measured and assumed water temperatures were used in the approximation, and the resulting DO concentrations are shown in Figure 2-14. Computed DO concentrations were compared to measured DO concentrations in the Missouri River at Bismarck, ND (N=38). Computed values compared favorably to the observed data (ABSE = 0.63 mg/l, RMSE = 0.76 mg/l).

$$DO = (1 - 0.1148z)\exp\left(-139.3441 + \frac{1.58x10^{5}}{T} - \frac{6.64x10^{7}}{T^{2}} + \frac{1.24x10^{10}}{T^{3}} - \frac{8.62x10^{11}}{T^{4}}\right)$$

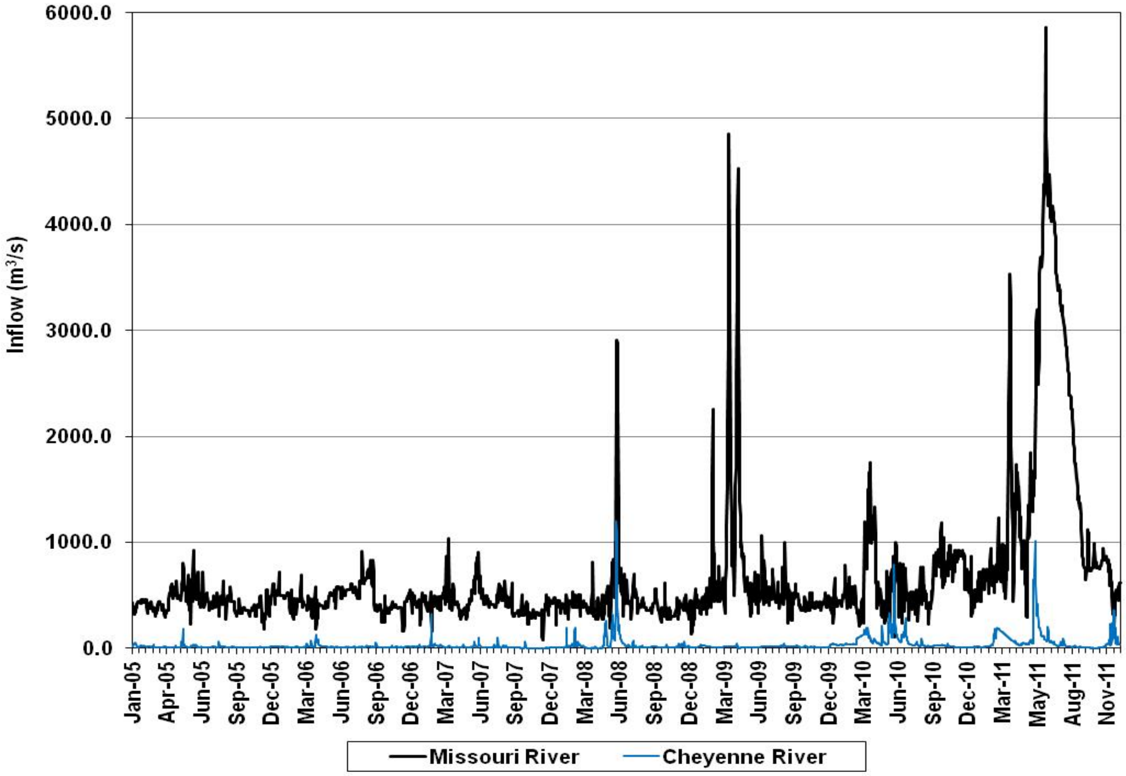

Figure 2-11. Missouri River and Cheyenne River inflows to Lake Oahe.

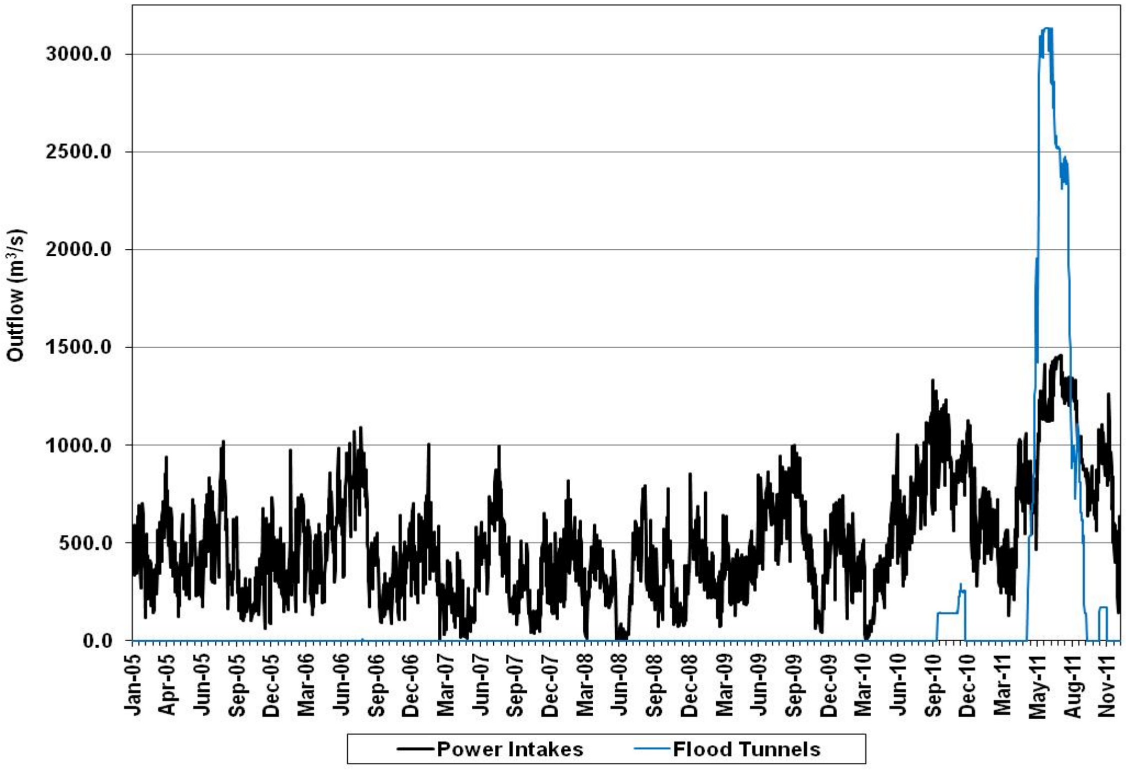

Figure 2-12. Oahe Dam average daily discharge.

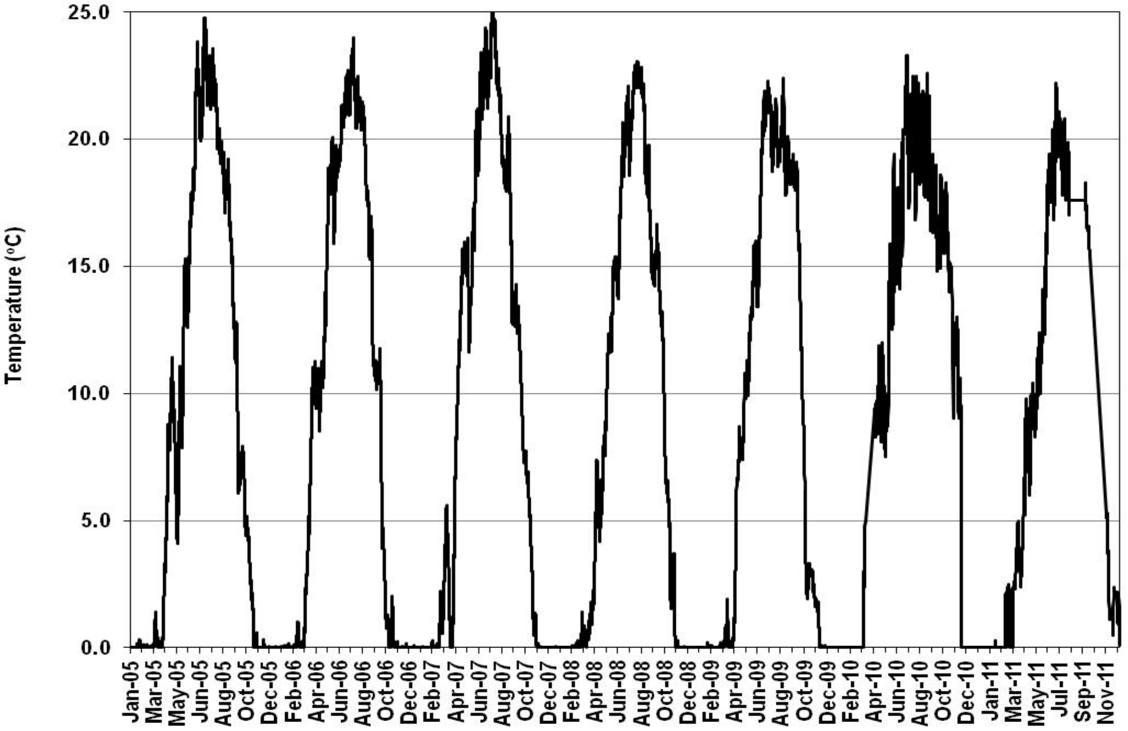

Figure 2-13. Missouri River and Cheyenne River inflow temperature.

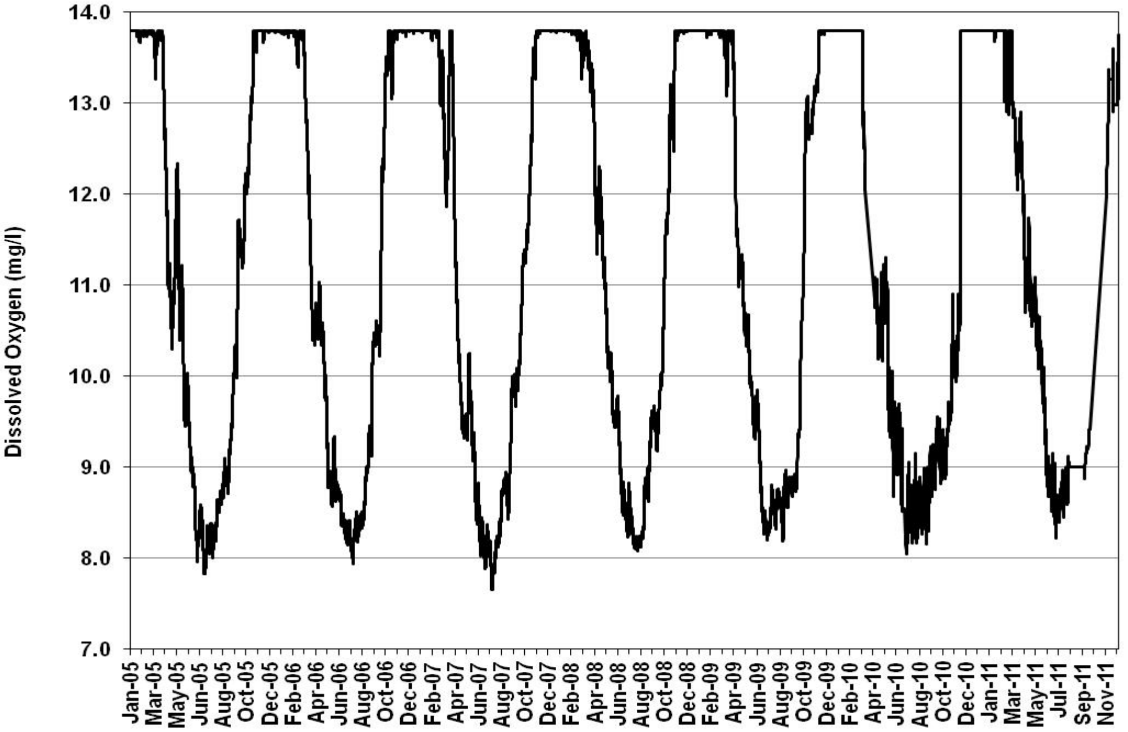

Figure 2-14. Dissolved oxygen concentration in the Missouri and Cheyenne Rivers.

2.5.5 INFLOW CONSTITUENT CONCENTRATIONS

2.5.5.1 Missouri River

Water quality samples were taken during the modeled period at one inflow location, the Missouri River near Bismarck, ND (OAHNFMORR1). Water samples were taken monthly from April thru September for each modeled year (n=39). Samples were analyzed for a number of water quality constituents including: suspended solids, alkalinity, total ammonia, dissolved solids, dissolved and total iron, dissolved and total manganese, nitrate/nitrate, total and ortho-phosphorus, sulfate, total Kjeldahl nitrogen, and total and dissolved organic carbon. In addition water temperature, DO, pH, specific conductance, turbidity and sometimes chlorophyll *a* were measured in the field. From the measured constituent concentrations the following constituent concentrations were input into the model: total dissolved solids, suspended solids, phosphate phosphorus, ammonium, nitrate/nitrite, labile and refractory dissolved organic matter, labile and refractory particulate organic matter, algae, and DO.

Dissolved and particulate organic matter was estimated from total organic carbon concentrations at an organic carbon to organic matter ratio of 0.45. Furthermore through model calibration, 90 percent of organic matter was assumed dissolved and 10 percent was assumed particulate, and 10 percent of organic matter was assumed labile and 90 percent was assumed refractory.

2.5.5.2 Cheyenne River

Water quality samples were collected monthly from April thru September at the Cheyenne River inflow site (OAHNFCHYR1) south of Eagle Butte, SD by the USACE from 2005 through 2007. Inflow data were also collected at the same location by the SDDENR from 2005 through 2011. These data were used to define inflow constituent concentrations. Since a continuous daily inflow constituent record was not possible, constituent concentrations were assumed at the beginning of each month in each simulation year along with the actual concentrations on the sampling dates. Total organic carbon concentrations were not measured by the SDDENR in any year, so to estimate organic matter concentrations, Missouri River inflow constituent data was used. It is recommended that for further model application that the Cheyenne River be sampled by the USACE in the same manner as it was in 2005 thru 2007. This will allow more accurate model calibration of the station where the Cheyenne River branch joins the main Lake Oahe model branch.

3 WATER TEMPERATURE & CONSTITUENT CALIBRATION

Reservoir hydrodynamics were calibrated by comparing the observed and modeled water surface elevation. Reservoir temperatures and dissolved oxygen were calibrated at eight locations in the reservoir where temperature profiles were measured throughout the observing years. In addition, powerhouse release temperatures and dissolved oxygen concentrations were compared to observations as an additional level of model calibration.

3.1 OBSERVED WATER QUALITY DATA

Locations where temperature measurements were taken are shown in Figure 1-1. Table 3-1 gives the site name, alternate name, and model segment of the locations monitored for model calibration. Temperature profiles and water quality samples for laboratory analysis were taken only on designated sampling dates that took place monthly from May to October. Oahe Dam release temperatures were measured with a Hydrolab instrument placed in a sampling chamber inside the dam. The water supply for the chamber is provided by water drawn through penstocks 1 through 7 (24-foot diameter), which vary in length from 3,280 feet to 4,005 feet. A common 10-inch header collects the raw water from each penstock where the water travels from 40 to 500 feet depending on which penstock it entered. The 10-inch pipe is reduced to a 6-inch pipe for 60 feet and finally to a 3/4-inch pipe for 60 feet before the water reaches the sampling chamber. For calibration purposes, hourly release temperatures were used.

Table 3-1. Sample points, CEQUAL-W2 segment numbers, and approximate lake kilometer.

Site Name	Alternate Name	Model Segment Number	Distance from Dam (m)
OAHLK1073A	O1	71	1
OAHLK1090DW	O2	66	27353
OAHLK1110DW	O3	60	59533
OAHLK1135DW	O4	52	99758
OAHLK1153DW	O5	46	128720
OAHLK1176DW	O6	38	165727
OAHLK1196DW	O7	32	197907
OAHLK1256DW	O8	13	294447

3.1.1 TEMPERATURE

Depth-discrete lake temperatures were measured in the field at one-meter depth increments with Hydrolab instruments at eight different locations along the old Missouri River channel in Lake Oahe. Temperature profiles were constructed from the measurements for comparison to simulated CE-QUAL-W2 temperatures.

Dam release temperatures through the Oahe powerhouse were monitored on an hourly basis with Hydrolab instruments in water drawn from the raw water loop.

3.1.2 WATER QUALITY

Water quality samples were collected from the eight in-pool locations at near-surface and near bottom water column depths. Samples were collected with a Kemmerer sampler. A list of water quality constituents analyzed by the Omaha Districts contract laboratory (Midwest Laboratories) is provided in the Water Quality Special Study Report for the Oahe Project (USACE, 2008). A modified version of this list is presented in Table 3-2.

Dissolved oxygen was measured directly with Hydrolab instruments simultaneously with lake temperature and dam release temperature measurements. Dissolved oxygen was the primary water quality constituent used in the calibration process, and dissolved solids was used to a limited degree.

Table 3-2. Parameters measured and analyzed at the various monitoring stations.

Parameter	O1, O3, O5, O7	O2, O4, O6	NF1, NF2	OF1
Dissolved Solids, Total	✓		✓	✓
Organic Carbon, Total (TOC)	✓		✓	✓
Orthophosphorus, Dissolved	✓		✓	✓
Phosphorus, Total	✓		✓	✓
Dissolved Phosphorus, Total	✓		✓	✓
Nitrate-Nitrite as N, Total	✓		✓	✓
Ammonia as N, Total	✓		✓	✓
Kjeldahl Nitrogen, Total	✓		✓	✓
Suspended Solids, Total	✓		✓	✓
Alkalinity	✓		✓	✓
Sulfate	✓		✓	✓
Chlorophyll a	✓			
Phytoplankton Biomass and Taxa Identification	✓			
Iron, Total and Dissolved	✓		✓	✓
Manganese, Total and Dissolved	✓		✓	✓
Metals and Hardness			✓ (NF1)	✓
Pesticide Scan			✓ (NF1)	✓
Microcystins	✓			
Secchi Depth/Transparency	✓	✓		
Field Measurements (Hydrolab)**	✓ (Depth Profile)	✓ (Depth Profile)	✓ (Near Surface)	✓ (Grab Sample)
Continuous Monitoring ("Hydrolab")***				✓

Note: Not all parameters were monitored at all the sites indicated.

** Hydrolab field measurements included: water temperature, dissolved oxygen (mg/l and % saturation), pH, conductivity, ORP, turbidity, and chlorophyll *a*. Depth profile measurements taken at 1-meter intervals from the reservoir surface to the bottom.

*** Continuous monitored parameters include temperature, dissolved oxygen (mg/l and % saturation), and conductivity.

3.2 RESERVOIR ELEVATION

The water balance routine which is included with the W2 model was not used. Oahe reservoir has many inflows which are not measured when computing reservoir inflows. Because these inflows were omitted from the model and assumed minor relative to the Missouri river inflow, the reservoir bathymetry was modified in order to match observed water surface elevations. The variation in water surface elevation over the modeled time frame required multiple reviews of the reservoir bathymetry. The resulting pool elevations are shown in Figure 3-1.

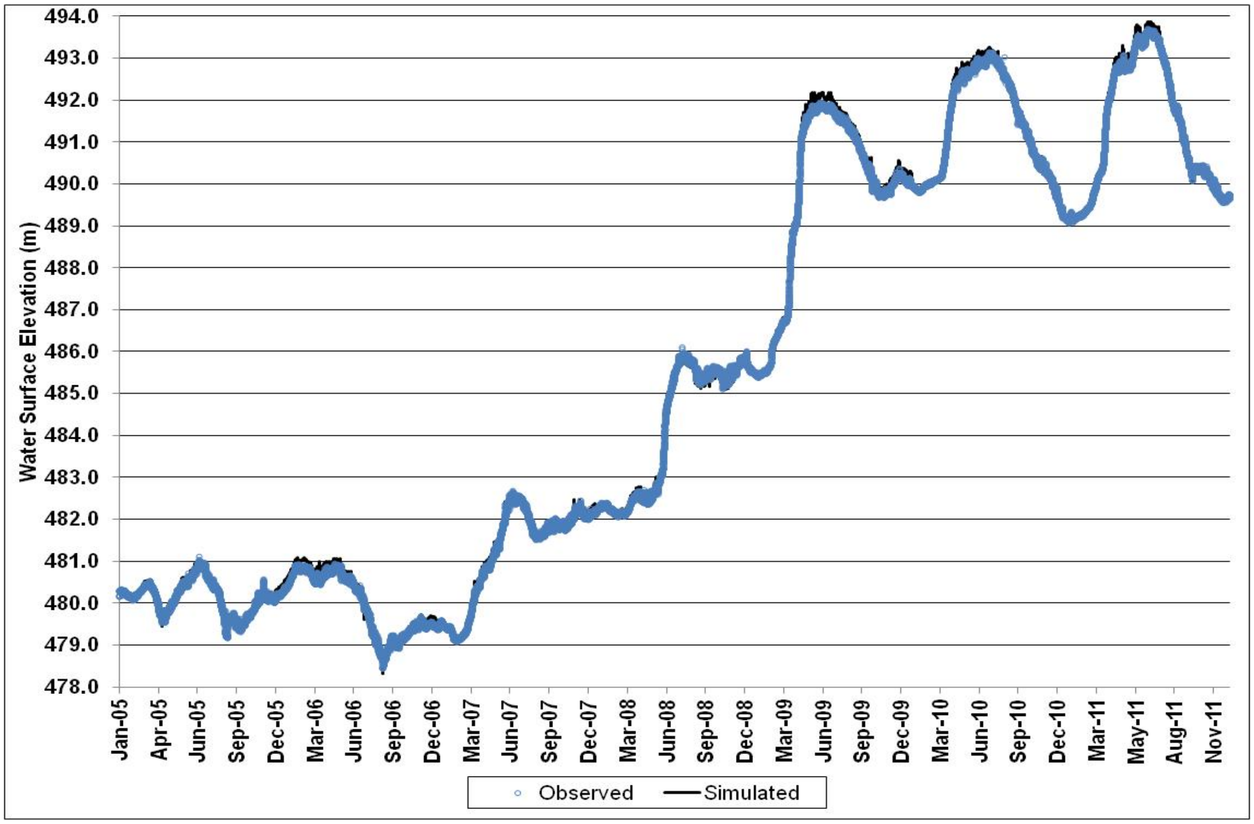

Figure 3-1. Observed and simulated Lake Oahe pool elevation for 2006 through 2011.

3.3 RESERVOIR TEMPERATURES

Simulated reservoir temperatures were calibrated to temperature profiles measured at eight locations in the reservoir. Factors that affected temperature calibration included incident shortwave solar radiation and wind. Because Lake Oahe and the applied model are very long (350 km), using one meteorological site to represent conditions for the entire reservoir is subject to error. During temperature calibration it was found that modifying the meteorological input file for each simulation year would yield acceptable calibration results more efficiently than direct changes to the model.

All changes made to the meteorological input file were tracked and followed a similar pattern. Shortwave solar radiation output from the rTemp model was reduced in all simulation years, with the greatest reductions occurring in January through May (up to 40% in 2005). This is likely due to snow on top of ice cover on the reservoir during the winter and topographic differences between the model surface layer and the location of the weather station. Wind was also reduced; it was found that in low water years (2005-2008) less adjustment was necessary. During June and July of 2006, August of 2007, and September of 2008, wind was reduced by 10-30%. In the high water years (2009-2011) wind was reduced by 20% in July through September of 2009 and January through July of 2010. Wind was also reduced by 10% in January through July of 2011. This may be due to inaccuracies in the model bathymetry and the topographic differences between the model surface layer and the location of the weather station.

Statistically the best temperature calibrations were achieved in 2006 (Table 3-3). Over the 7-year period monthly profile absolute error ranged from 0.05 to 2.31°C. Plots showing simulated versus observed temperature profiles are provided in the supplemental Figures 7-1 to 7-26 at the end of the report.

Table 3-3. Average annual absolute and root mean square error (RMSE) between measured and simulated reservoir temperatures and dissolved oxygen concentrations at all eight stations in Lake Oahe.

Year	Temperature (^oC)		Dissolved Oxygen (mg/L)	
	Absolute	Root-Mean Square[1]	Absolute	Root-Mean Square[1]
2005	0.88	1.00	0.83	0.90
2006	0.79	0.96	0.60	0.66
2007	0.95	1.04	0.77	0.81
2008	0.84	0.95	0.87	0.92
2009	0.87	0.99	0.93	1.05
2010	0.86	0.98	0.78	0.91
2011	0.83	0.95	0.59	0.69
Average	0.86	0.98	0.76	0.85

[1] RMSE calculated using monthly absolute error for profiles at each location.

3.4 RESERVOIR DISSOLVED OXYGEN

Factors that affected DO calibrations the most included initial reservoir concentrations of labile dissolved and particulate organic matter and inflow concentrations of labile dissolved and particulate organic matter. The inflow of organic matter from the Cheyenne River does have an observable impact on the DO concentrations at location O3. If future modeling efforts are made these data should be collected. Labile and refractory percentages of total organic matter are described previously in section 2.5.5 of this report.

Statistically the best DO calibrations were achieved in 2006 (Table 3-2). Over the 7 year period the absolute error ranged from 0.08 to 2.31mg/L. Plots showing simulated versus observed DO profiles are provided in the supplemental Figures 7-27 to 7-52 at the end of the report.

3.5 RESERVOIR OUTFLOW

Hydrolab instruments were installed in the powerhouse to record temperature and DO concentrations of power releases as indicated by conditions in the raw water loop. The W2 model produces simulated output for powerhouse, flood tunnel, and spillway releases; this output includes temperatures and constituent concentrations. Simulated and observed temperatures and dissolved oxygen concentrations are compared as an additional means of calibration.

3.5.1 OUTFLOW TEMPERATURES

Combined simulated outflow temperatures on a 3-hour time step are plotted against hourly observed temperatures in Figure 3-2. Absolute and root-mean square errors between observed and simulated outflow temperatures are provided in Table 3-4. In general the model had difficulty reproducing the extent of seasonal variability in release temperatures that was exhibited in temperatures recorded in the raw-water loop. This can be attributed to the model calibration, the frequency at which the modeled temperatures are output, and possibly the temperature difference between water pulled through the intakes and water passing through the Hydrolab sample chamber.

Table 3-4. Average annual absolute and root mean square errors between measured and simulated outflow temperatures and dissolved oxygen concentrations.

Year	Temperature (^oC)		Dissolved Oxygen (mg/L)	
	Absolute	Root-Mean Square	Absolute	Root-Mean Square
2005	1.66	1.96	1.44	1.64
2006	1.40	1.93	0.48	0.61
2007	1.10	1.39	0.97	1.10
2008	0.98	1.36	0.66	0.87
2009	1.32	2.05	0.77	0.90
2010	1.42	2.16	0.92	1.11
2011	1.22	1.55	1.03	1.19
Average	1.29	1.79	0.87	1.07

3.5.2 OUTFLOW DISSOLVED OXYGEN

Combined simulated outflow DO concentrations on a 3 hour time step are plotted against hourly observed DO concentrations in Figure 3-3. Absolute and root-mean square errors between observed and simulated outflow dissolved oxygen concentrations are provided in Table 3-4. In general the model release concentrations did not reproduce the peak seasonal variability in release concentrations exhibited in the raw-water loop. This is likely due to aeration of water passing through the system during the winter, and the need to further refine model oxygen dynamics and output frequencies if greater accuracy is desired.

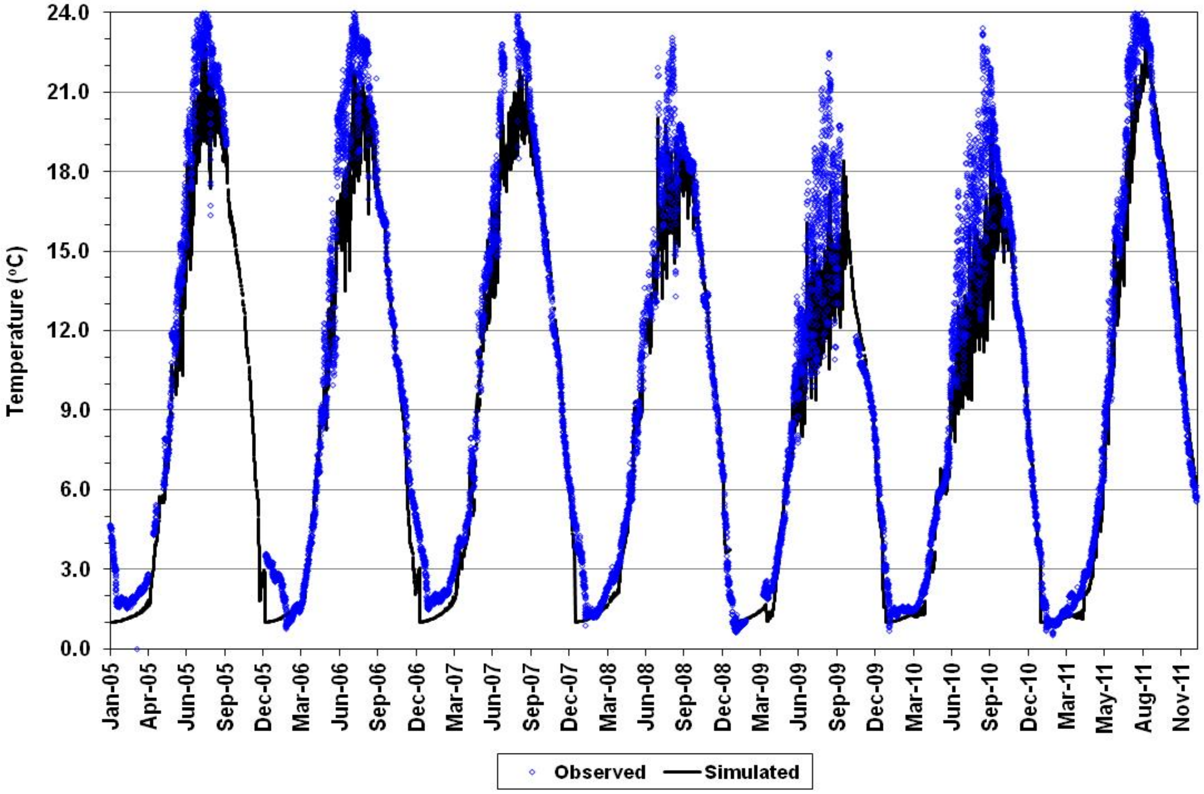

Figure 3-2. Simulated and observed Oahe powerhouse release temperatures.

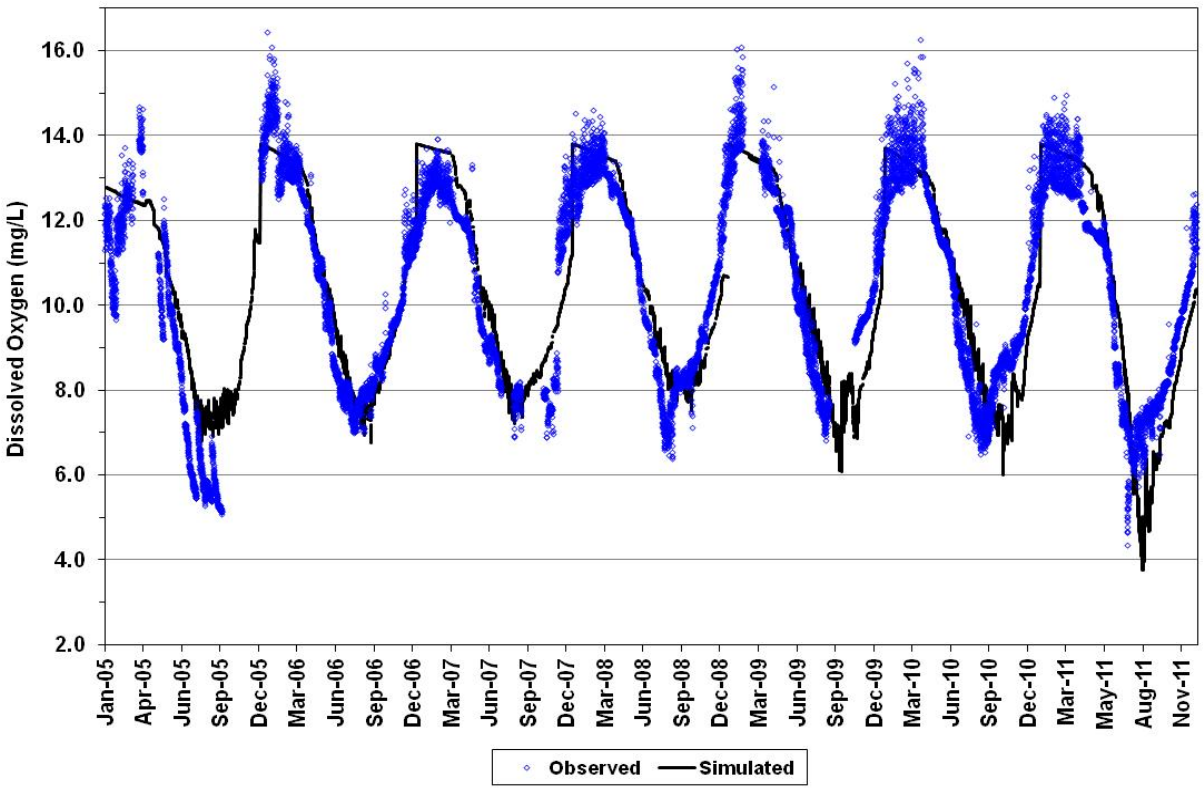

Figure 3-3. Simulated and observed Powerhouse powerhouse dissolved oxygen concentrations.

3.6 RESERVOIR WATER QUALITY CONSTITUENTS

Water quality constituents other than DO included in the model were total dissolved solids (TDS), total suspended solids (TSS), phosphate (PO4), ammonia (NH3), nitrate/nitrite (NO3/NO2), labile and refractory dissolved organic matter, labile and refractory particulate organic matter, and algae. These constituents play an important role in the timing and duration of hypolimnetic oxygen depletion as well as the extent of algal growth in the surface waters of the reservoir. The W2 model gives the user the option of calculating many derived constituents which can then be compared to observed data. In the Oahe model chlorophyll *a* was selected to be calculated and output by the model.

All laboratory data for the selected constituents collected at the eight monitoring locations during the seven year period were used for comparison. Laboratory non-detect samples were set to their detection limits for error analysis. Results of the error analysis are presented in Table 3-5.

The best year for constituent calibration was 2006; however, it may be more appropriate to divide the model years into high and low water years. From 2005 to 2007 water surface elevations and inflows were low and the intensive survey of Lake Oahe provided more frequent data for model input. During 2008 the reservoir water surface elevations and inflows grew, which resulted in an intermediate water quality constituent calibration. In 2009 the reservoir experienced a significant increase in algal growth which could be attributed to nutrient cycling of the influx of organic matter in 2008 and 2009. In 2011 there were record high flows and the model likely lacked sufficient constituent data to accurately characterize nutrients entering the reservoir.

Table 3-5. Average annual absolute and root mean square errors between measured and simulated constituent concentrations.

Year	TDS (mg/L)		PO4 (mg/L)[1]		NO2/NO3 (mg/L)[1]		NH3 (mg/L)[1]		Chlorophyll *a* (ug/L)[1]	
	Absolute	Root-Mean Square[2]	Absolute	Root-Mean Square[2]	Absolute	Root-Mean Square[2]	Absolute	Root-Mean Square[2]	Absolute	Root-Mean Square[2]
2005	20.80	24.85	0.03	0.04	0.04	0.05	0.07	0.11	4.17	4.73
2006	19.97	22.63	0.01*	0.01*	0.04	0.05	0.03	0.04	4.54	5.13
2007	28.60	32.22	0.01*	0.01*	0.05	0.06	0.02*	0.03	2.37	3.15
2008	43.84	58.55	0.00*	0.00*	0.03	0.04	0.08	0.11	3.72	4.68
2009	93.77	122.88	0.01*	0.01*	0.13	0.16	0.05	0.10	10.32	16.07
2010	69.82	85.37	0.01*	0.01*	0.05	0.06	0.02*	0.03	4.79	5.79
2011	45.88	64.49	0.12	0.21	0.06	0.07	0.03	0.04	2.55	3.20
Average	49.79	72.31	0.03	0.09	0.06	0.08	0.04	0.07	4.79	7.80

[1] PO4;NO2/NO3;NH3 detection limit = 0.02 mg/L, Chlorophyll *a* detection limit = 1 ug/L.

[2] RMSE calculated using monthly absolute error for each location.

* Calculated error ≤ constituent detection limit.

4 WATER QUALITY ASSESSMENT UNDER EXISTING CONDITIONS

Water quality was assessed based on reservoir temperatures and dissolved oxygen concentrations with respect to South Dakota cold water habitat (CWH) criteria. Existing condition simulations were performed from 2005 to 2011 using the calibrated temperature and water quality model. To aid the interpretation of the temperature and dissolved oxygen plots, pool elevations are shown in Figure 4-1.

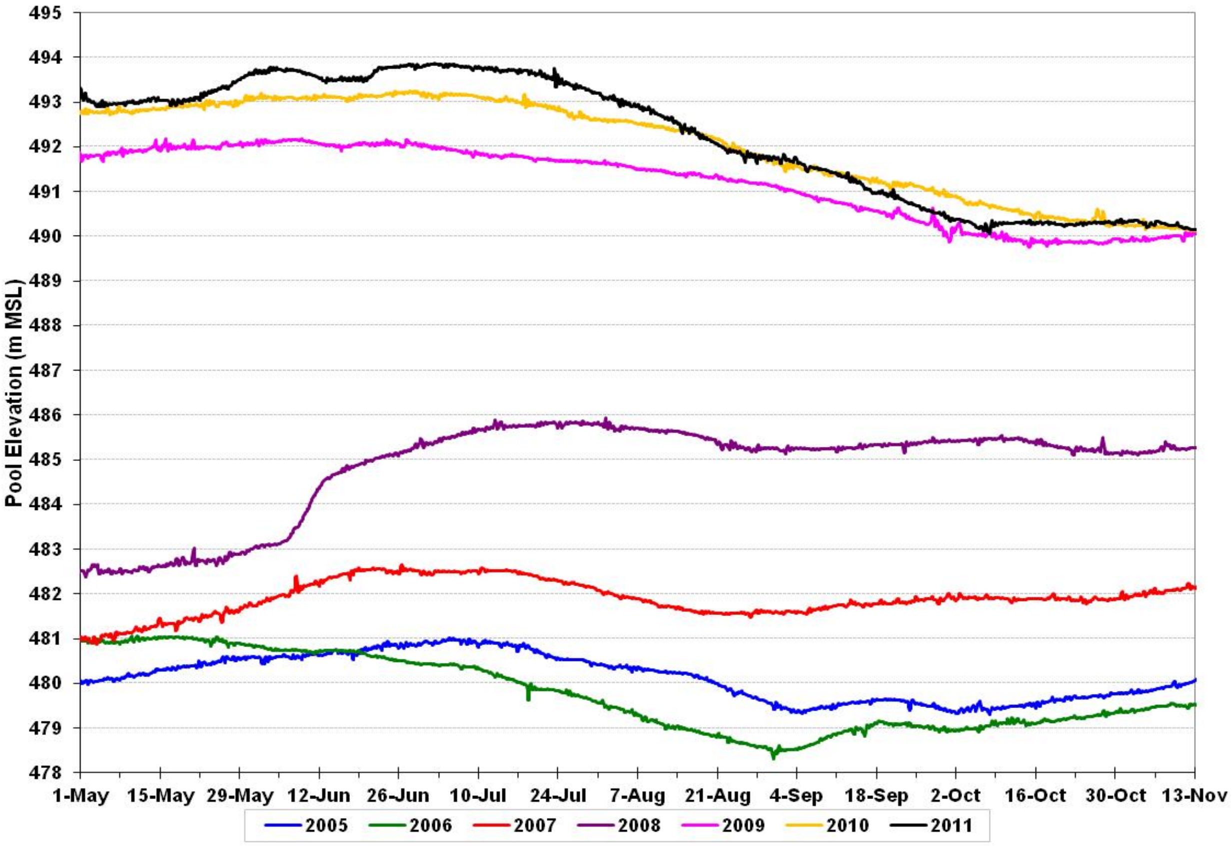

Figure 4-1. Simulated pool elevation of the existing Lake Oahe reservoir operating conditions from May 1 to November 13.

4.1 TEMPERATURE TRENDS

The presence of water that meets the maximum CWH temperature requirement of 18.3 degrees C is the greatest temperature water quality concern in Lake Oahe. The simulated temperature time series near the bottom of the reservoir at the centerline of the six flood tunnel centerline elevation of 438.9 m (1440.0 ft) was plotted from May 1 to November 13 for 2005 through 2011 (Figure 4-2). These time series indicate that the 18.3 degrees C CWH criterion was met with the exception of a 30 day period in the fall of 2011.

Simulation years 2009 and 2010 exhibited the lowest temperatures while 2005 was higher by 2.5 to 3 degrees C from early June to early October, and 2006 through 2008 were higher by about 1.5 to 2 degrees C. Greater reservoir volume indicated by higher pool elevations of roughly 4 to 13 m (13 to 43 ft) contributed to lower bottom temperatures in 2009 and 2010. The impact of high flood tunnel outflows during 2011 is shown; the warmer temperatures indicate that warm water is likely being pulled down from higher elevations near the reservoirs surface.

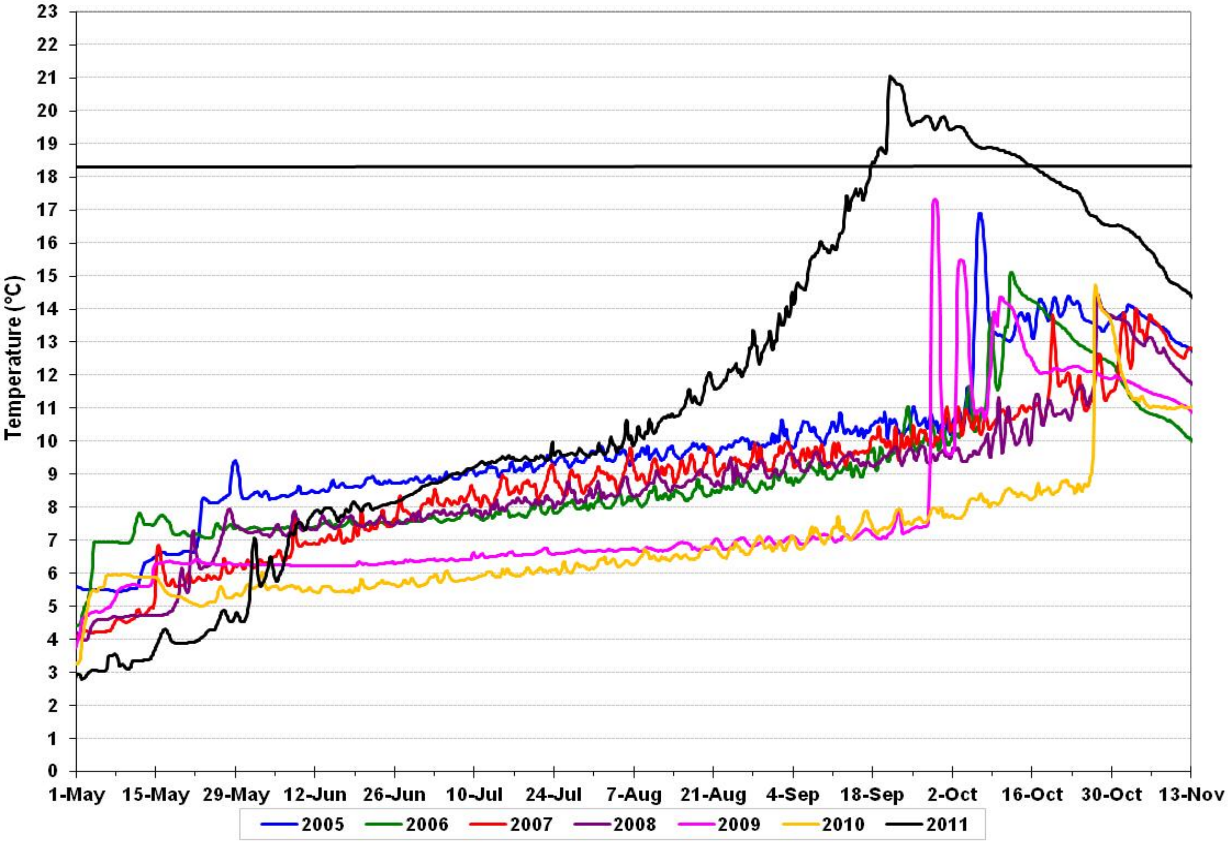

Figure 4-2. Simulated water temperatures near the flood tunnel centerline elevation 438.9 m (1440.0 ft) at site O1 – Near the Dam at Lake Oahe, from May 1 to November 13.

Temperatures near the reservoir bottom did not exceed 18.3 degrees C in any year except 2011. In September to October of all years stratification has broken down and turnover has started to occur. During 2010 lake turnover occurred later than in all other simulation years. This could be due to numerous factors such as weather and reservoir volume.

4.2 DISSOLVED OXYGEN TRENDS

Water must maintain a minimum of 6 mg/L dissolved oxygen (DO) concentration in order to meet the CWH DO criteria in Lake Oahe. The DO concentration time series near the reservoir bottom at the centerline of the six flood tunnel centerline elevation of 438.9 m (1440.0 ft) was plotted from May 1 to November 13 in 2005 through 2011 (Figure 4-3). These time series represent the DO concentration of water that persists near the reservoir bottom and indicate if conditions meet the 6 mg/L CWH criterion.

Simulation year 2007 exhibits higher DO concentrations through October while other simulations years are 0.25 to 3 mg/L lower than 2007. The impact of record high inflows and subsequent reservoir flushing during 2011 is evident in the in the near bottom DO concentrations; however, DO concentrations also fell below 6 mg/L at dates during 2009 and 2010. It is likely that increased hypolimnetic volume in 2009 and 2010 extended the time to fall turnover and resulted in decreased DO concentrations.

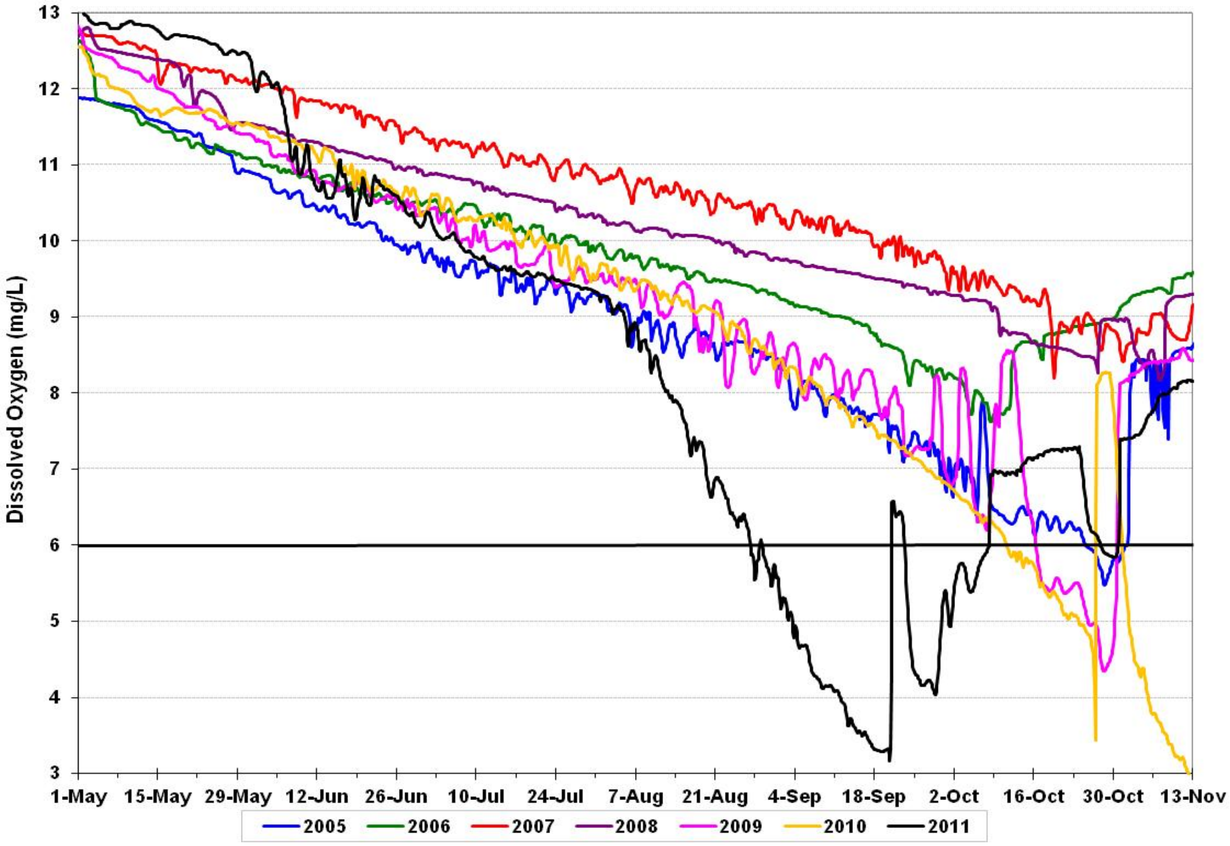

Figure 4-3. Simulated dissolved oxygen concentrations near the flood tunnel centerline elevation 438.9 m (1440.0 ft) at site O1 – Near the Dam at Lake Oahe, from May 1 to November 13.

4.3 COLDWATER HABITAT

Coldwater habitat (CWH) is defined as water in the reservoir that meets the minimum DO concentration of 6 mg/L and maximum temperature of 18.3 degrees C, and is therefore suitable habitat for certain species of coldwater fish. CWH was empirically estimated in Lake Oahe based on measured water temperature and dissolved oxygen depth profiles applied to reservoir zone volumes for each measurement location.

The calibrated CE-QUAL-W2 model was used to estimate CWH by summing the volume of water that met the total CWH temperature and DO criteria. CWH is expressed in units of million-acre feet (MAF) in this report because acre-feet are the conventional unit for reporting reservoir storage volume.

4.3.1 COLDWATER HABITAT VOLUME

CWH volumes were computed from the 2005 through 2011 simulations using the habitat output feature in the W2 model. Estimated CWH volumes were assumed to be accurate because they are based on direct measurements of temperature and DO concentrations performed during 2005 through 2011 water quality monitoring activities; however, the reservoir zone volumes are subject to error. Simulated CWH volumes are plotted against empirically estimated CWH volumes in Figures 4-4 through 4-10. Simulated reservoir volume is displayed for reference. To account for differences in the bathymetry file and estimated CWH volume the estimated values were set equal to simulated when the entire reservoir met CWH criteria. Error statistics for the computed versus estimated CWH volumes are presented in Table 4-1.

Fit of simulated CWH versus survey estimated CWH is relatively close in all years. The model accurately simulates the onset of CWH depletion in every year. In the 2008 simulation the model values are less than the estimated CWH volumes for the entire May to November time period; this is the only year where model error appears to be systematic instead of random. The 2009 year shows the best agreement between the computed and estimated volumes, 2006 is an excellent example of the dynamic aspect of the model with turnover occurring in the model at the same time as in the observed data. The model displays the potential to accurately simulate CWH during when temperature and DO measurements are not available and can be used evaluate the impact of water quality measures used to preserve CWH.

Table 4-1. Average annual absolute and root mean square errors between estimated and simulated CWH volumes.

	Coldwater Habitat Volume (MAF)	
Year	Absolute	Root-Mean Square
2005	0.23	0.29
2006	0.36	0.66
2007	0.44	0.65
2008	0.47	0.61
2009	0.19	0.25
2010	0.58	0.81
2011	0.31	0.48
Average	0.37	0.57

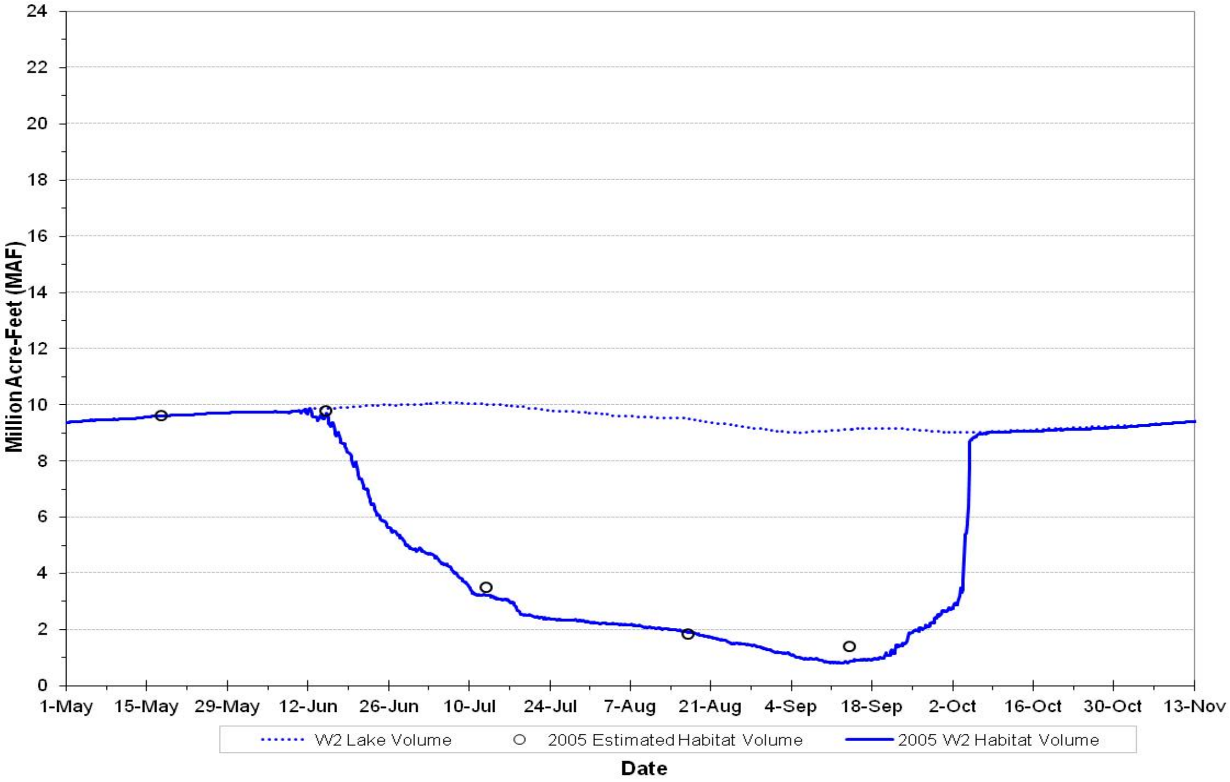

Figure 4-4. Simulated and estimated total CWH (million acre-feet) in Lake Oahe during 2005.

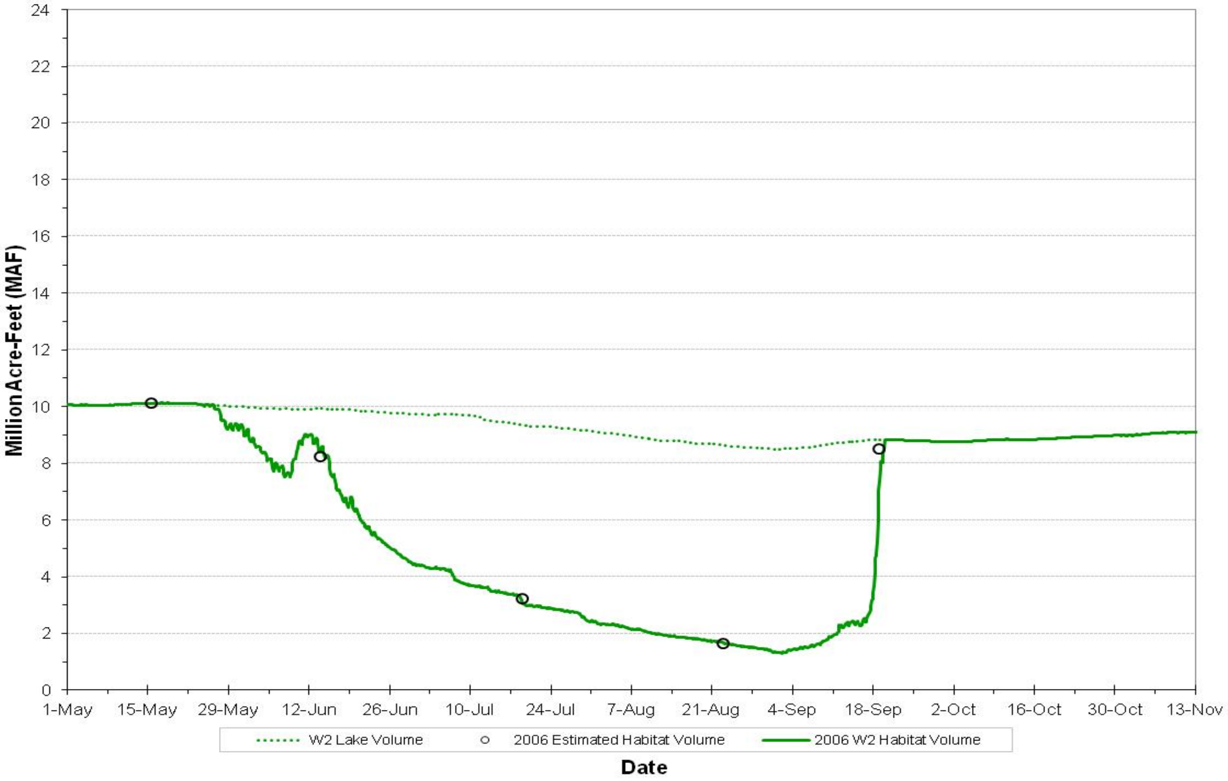

Figure 4-5. Simulated and estimated total CWH (million acre-feet) in Lake Oahe during 2006.

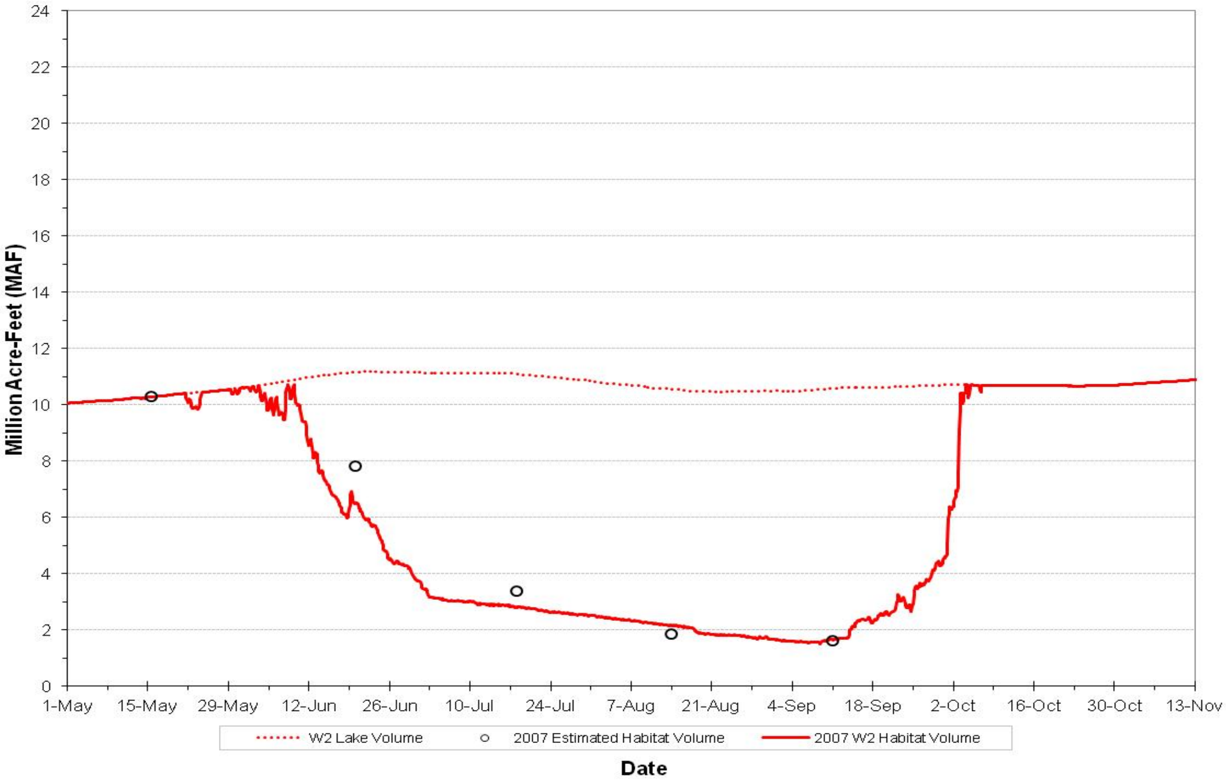

Figure 4-6. Simulated and estimated total CWH (million acre-feet) in Lake Oahe during 2007.

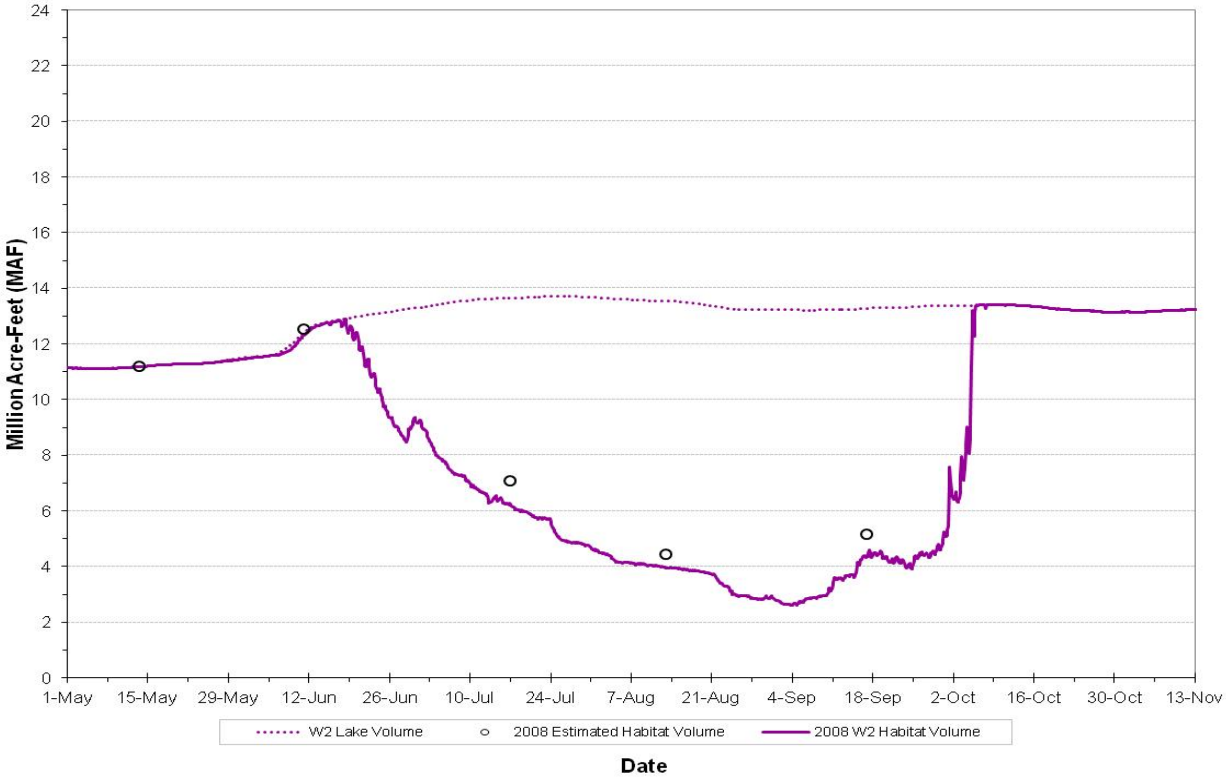

Figure 4-7. Simulated and estimated total CWH (million acre-feet) in Lake Oahe during 2008.

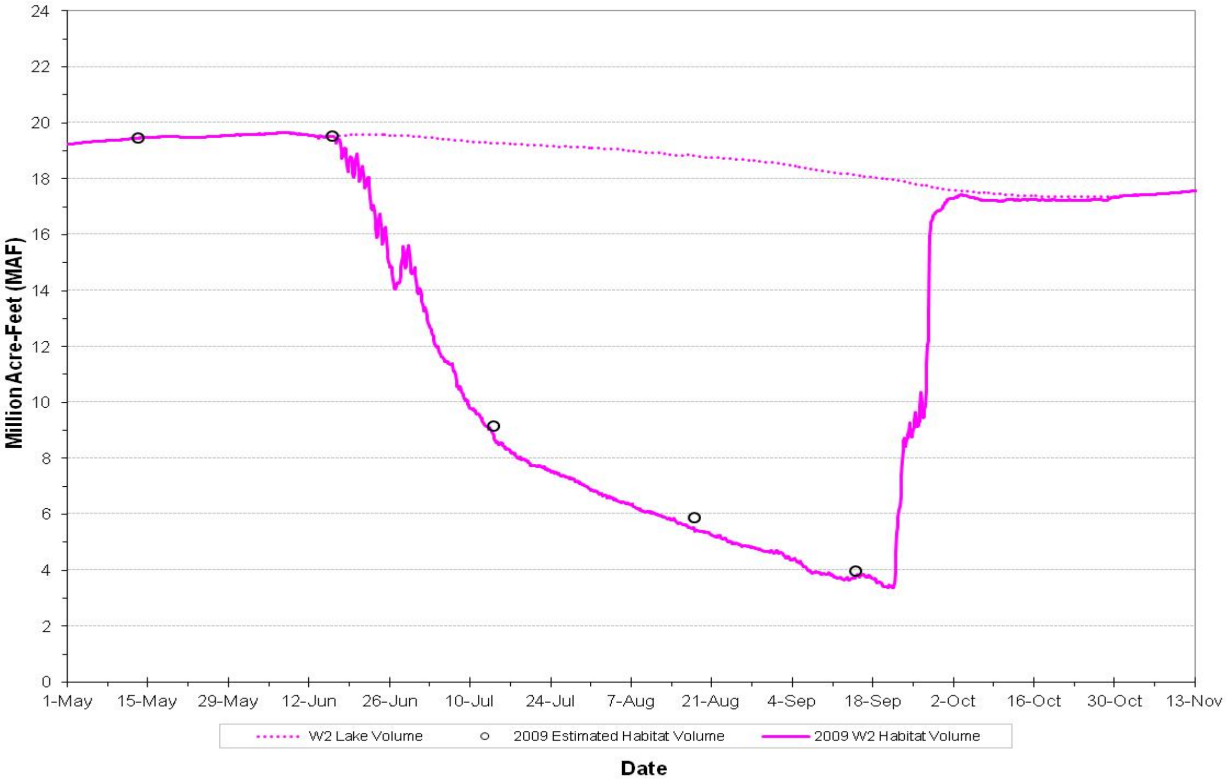

Figure 4-8. Simulated and estimated total CWH (million acre-feet) in Lake Oahe during 2009.

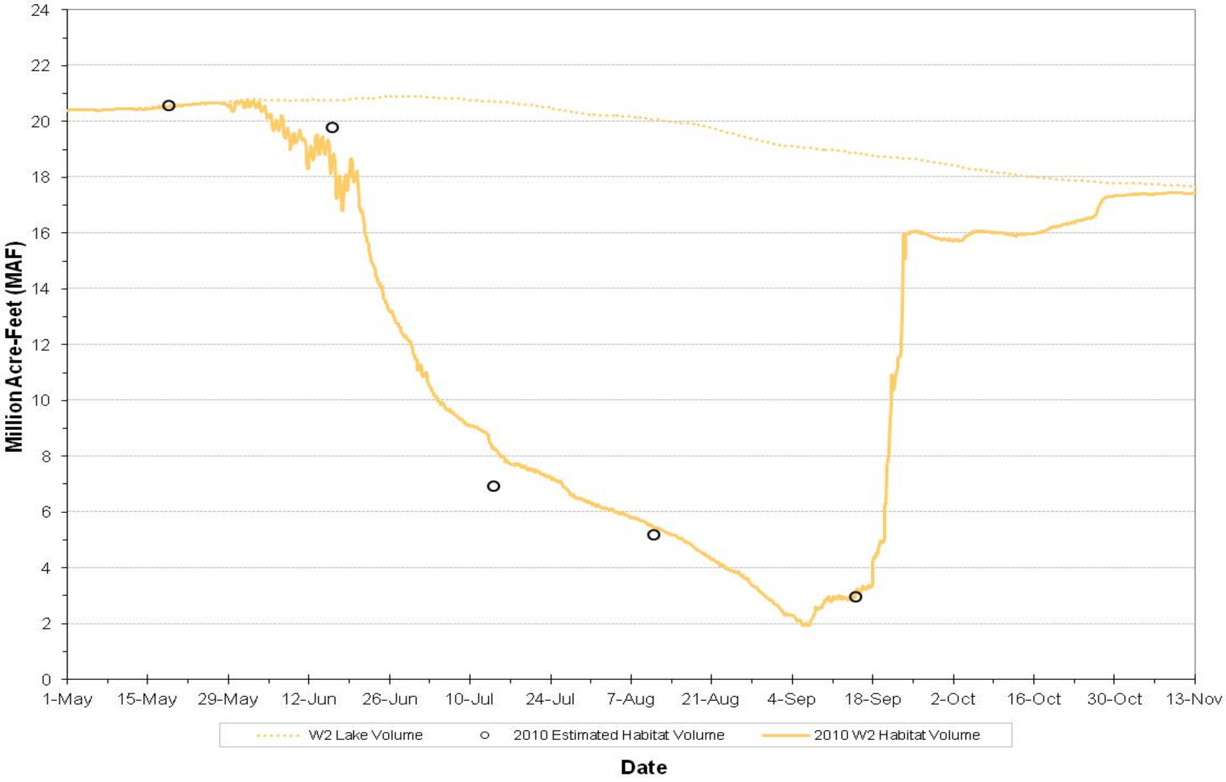

Figure 4-9. Simulated and estimated total CWH (million acre-feet) in Lake Oahe during 2010.

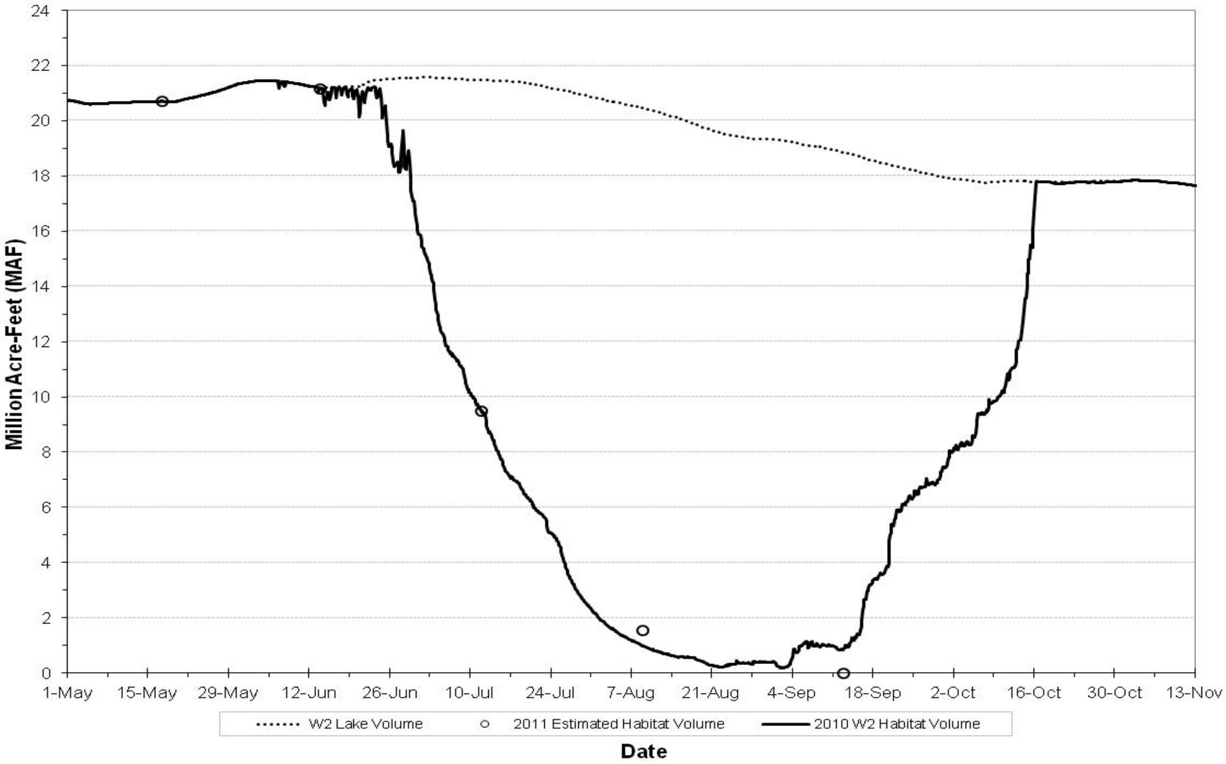

Figure 4-10. Simulated and estimated total CWH (million acre-feet) in Lake Oahe during 2011.

5 ASSESSMENT OF USING THE SPILLWAY DURING THE 2011 FLOOD

5.1 SPILLWAY WITHDRAWAL

A hypothetical spillway withdrawal was evaluated using the 2011 reservoir model. Using the spillway eliminated all use of the flood tunnels and raised the elevation from which water is withdrawn from the centerline flood tunnel elevation of 438.9 m (1440.0 ft) to the spillway elevation of 486.6 m (1596.5 ft). A spillway reservoir withdrawal could potentially decrease the amount of colder, low-level reservoir water being passed downstream. This could potentially help maintain a greater volume of water in the reservoir meeting the CWH temperature criteria.

5.2 IMPACTS OF SPILLWAY WITHDRAWAL

Water temperature, nutrients, and dissolved oxygen were simulated using the hypothetical spillway outlet in simulation year 2011. The results are summarized into three figures focusing on reservoir spillway discharge temperature, temperature near the reservoir bottom (centerline flood tunnel elevation), and the volume of coldwater habitat in the reservoir as a result of the simulated conditions.

5.2.1 RESERVOIR DISCHARGE TEMPERATURE

Discharge water temperatures from the simulated spillway were compared to temperatures from the flood tunnel outlet during 2011. The discharge temperatures from May 7 to October 7 can be seen in Figure 6-1. The spillway outflow temperatures are initially similar to the flood tunnel temperatures; this is due to isothermal reservoir conditions. Thermal stratification then starts to occur in the reservoir and by June 18th there is a noticeable difference in outflow temperatures. During the period of June 18 through September 15 the temperature of the spillway releases were from 0.1 to 10.6°C higher than in the simulated flood tunnel outflows with an average increase of 2.6°C. During September 16 to October 7 convective cooling of the reservoirs surface waters dropped temperatures in the spillway releases back to or below those simulated in the flood tunnel outflows. The most important difference in outflow temperatures shown in Figure 5-1 is from mid-July to early September when spillway outflows exceed the 18.3°C CWH temperature criterion and the flood tunnel outflows are passing water which meets the temperature criterion downstream.

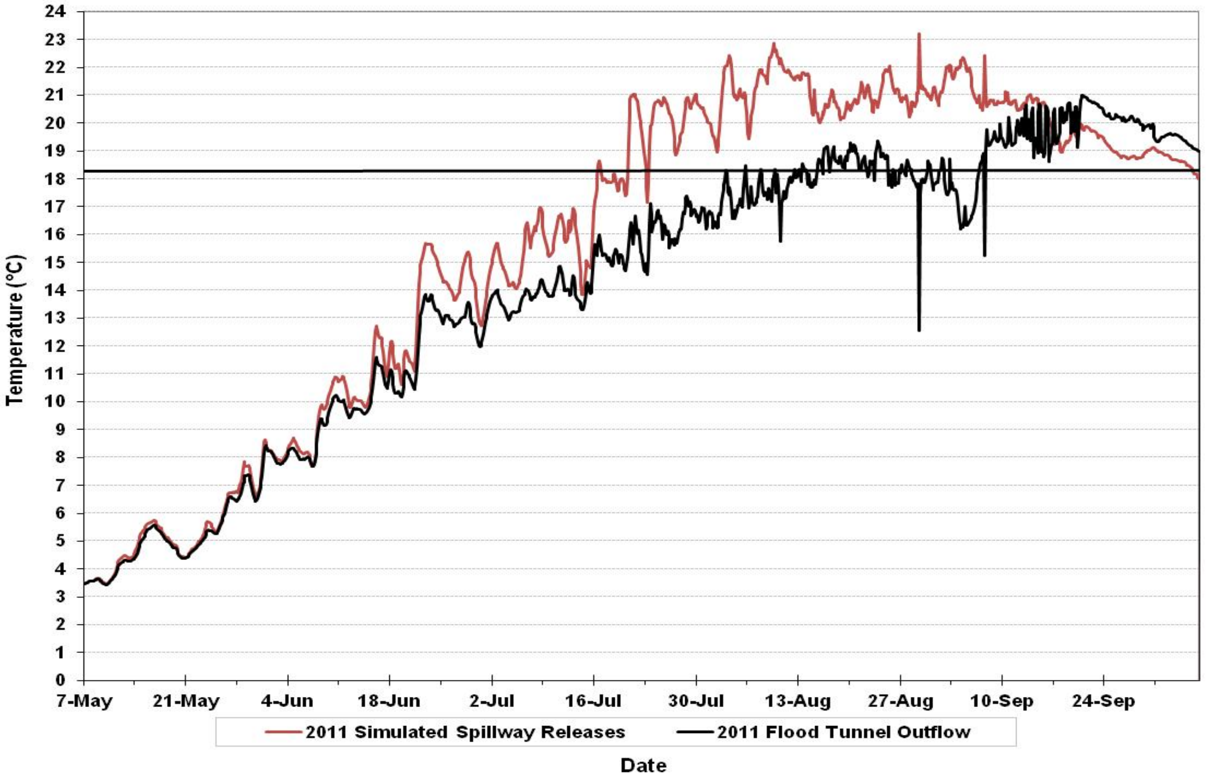

Figure 5-1. Simulated water temperature in the flood tunnel discharge during 2011 and simulated spillway scenario discharge water temperatures.

5.2.2 NEAR-BOTTOM RESERVOIR TEMPERATURE (CENTERLINE FLOOD TUNNEL ELEVATION)

The simulated near-bottom reservoir temperature time series, centerline of the six flood tunnel centerline elevations of 438.9 m (1440.0 ft), is plotted from May 7 to October 7 of 2011 in Figure 5-2. This time series compares data from the 2011 model and the 2011 spillway scenario to assess whether the 18.3°C criterion could have possibly been met under spillway scenario conditions. The 2011 time series data were shown previously in Figure 4-2 as an indication of CWH that met the 18.3°C criterion each year except for a 30 day period in 2011. Figure 5-2 shows that temperatures at the flood tunnel centerline elevation would meet the 18.3°C temperature criterion under spillway scenario conditions. The scenario temperatures shown are very similar to those which occurred in the 2007 simulation.

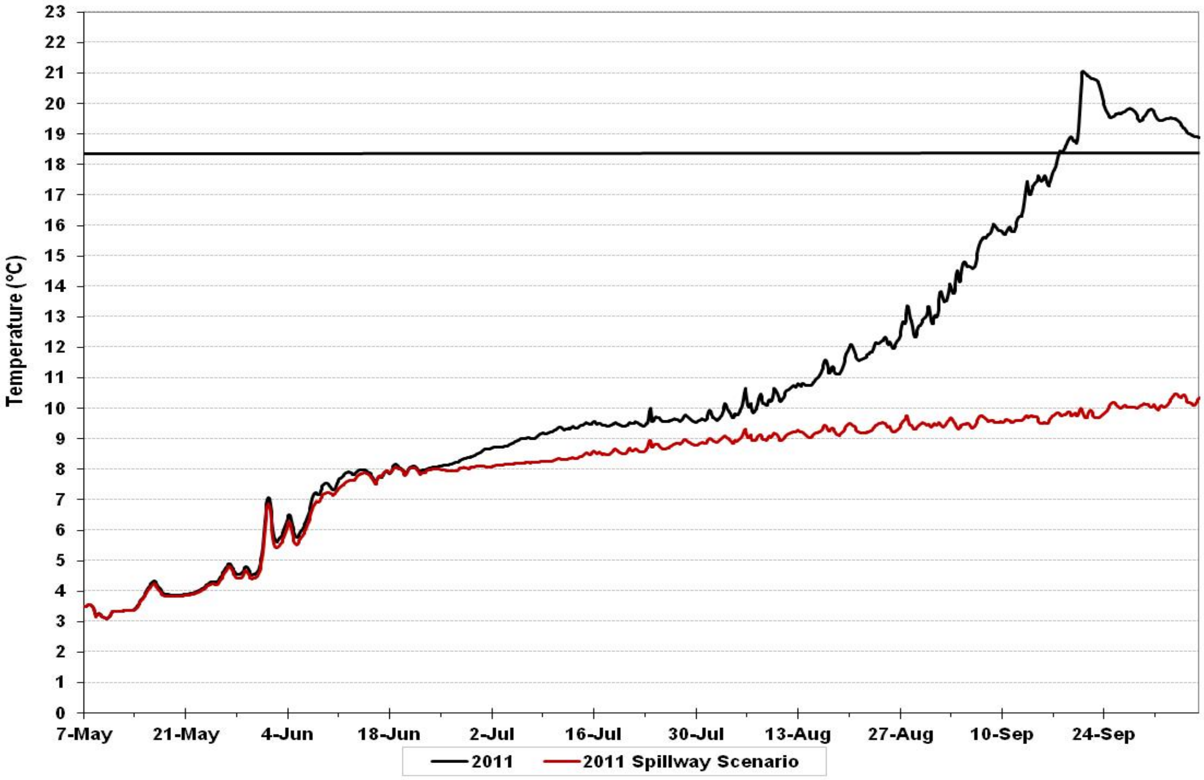

Figure 5-2. Simulated water temperatures near the reservoir bottom at the flood tunnel centerline elevation 438.9 m (1440.0 ft) during 2011 and during the spillway scenario.

5.2.3 COLDWATER HABITAT VOLUME

The impact of a hypothetical spillway withdrawal versus a flood tunnel withdrawal in 2011 is quantified in terms of coldwater habitat volume in Table 5-1. In general the simulations indicate the spillway withdrawal preserves more CWH volume than the flood tunnel withdrawal. Simulated CWH savings during the June to mid October 2011 time period ranged from 0.0 to a maximum of 7.9 million acre-feet.

Figure 5-3 is a time series plot of the simulated total CWH volume in 2011 comparing the spillway withdrawal and the flood tunnel withdrawal. From August 1 to September 15 when CWH volumes reached minimums, the total CWH volume in the spillway withdrawal scenario was an average of 1.3 MAF greater than the flood tunnel withdrawal. The model output suggests a hypothetical spillway withdrawal could have potentially provided an advantage in preserving total CWH in Lake Oahe during the 2011 flood.

Table 5-1. Comparison of biweekly simulated CWH (T < 18.3°C, DO > 6 mg/L) volume between simulations using the flood tunnels in 2011 and using a hypothetical spillway withdrawal in 2011.

Date	Simulated Optimal CWH, Million acre-feet (MAF)		
	Spillway Withdrawal	Flood Tunnel Withdrawal	Spillway / Flood Tunnel Withdrawl Difference
1 June 2011	21.39	21.39	0.00
15 June 2011	20.84	20.84	0.00
1 July 2011	16.04	15.91	0.14
15 July 2011	8.33	7.95	0.38
1 August 2011	3.67	2.08	1.59
15 August 2011	2.12	0.58	1.54
1 September 2011	1.50	0.38	1.12
15 September 2011	2.08	1.31	0.77
1 October 2011	9.67	7.58	2.09
15 October 2011	17.60	14.47	3.13
Minimum CWH	1.24	0.17	1.07

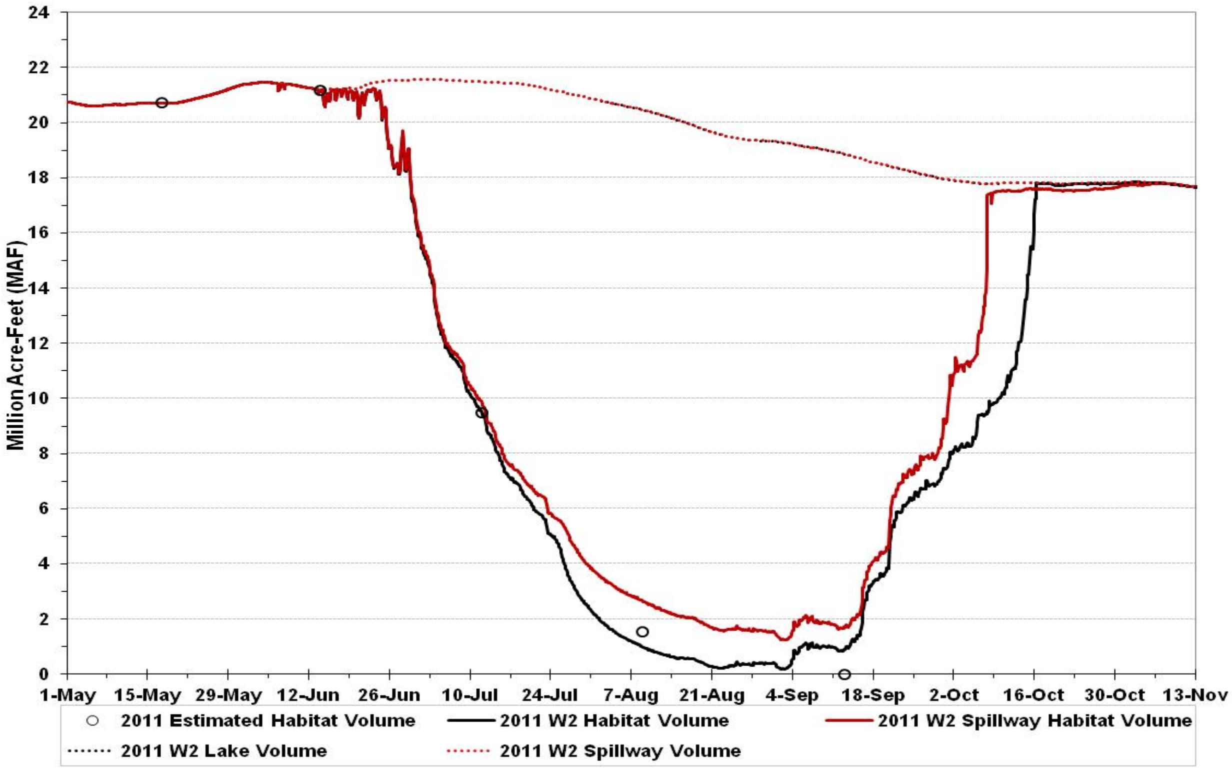

Figure 5-3. Simulated volume of CWH in Lake Oahe during 2011, using the flood tunnels (black) and using the spillway (red).

6 FUTURE MODEL APPLICATIONS

6.1 IMPACT OF WATER QUALITY IN THE CHEYENNE RIVER TO CONDITIONS IN LOWER LAKE OAHE

During low water years with data from the intensive water quality survey of Lake Oahe (2005-2007) the oxygen demand exerted from the decomposition of organic matter from the Cheyenne River was evident in model calibration. In low water years this oxygen demand could potentially impact CWH volume in the lower reservoir. Water quality monitoring of the Cheyenne River was discontinued after completion of the intensive survey in 2007. In order to better assess the effects of nutrient loading from the Cheyenne River this data should be collected when future years are to be modeled.

6.2 RESERVOIR REGULATION IMPACTS TO WATER QUALITY

A long range goal of reservoir water quality modeling is to evaluate water quality impacts in the Mainstem reservoirs as a result of system-wide operating decisions. For example a system of reservoir and river models linked in series could demonstrate the water quality impacts of storage unbalancing that regularly is performed in the upper three reservoirs, or the impact of water quality measures on the entire system. Considering the growing demand for recreational, wildlife habitat, and water supply uses a linked system of models could serve as a decision support system for future water allocations and regulation of the Mainstem System reservoirs.

7 REFERENCES

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8 SUPPLEMENT FIGURES

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Figure 7-1. 2005 temperature calibration at stations O1 and O2

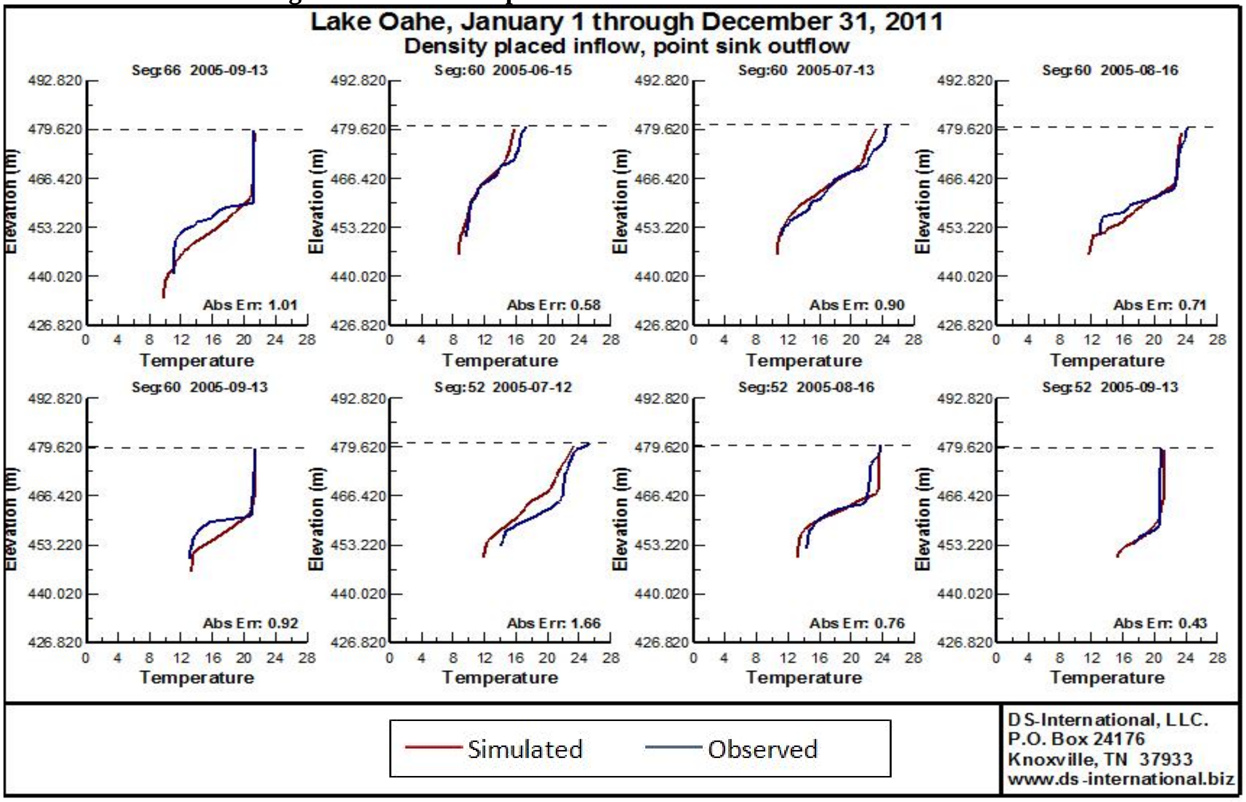

Figure 7-2. 2005 temperature calibration at stations O2, O3, and O4

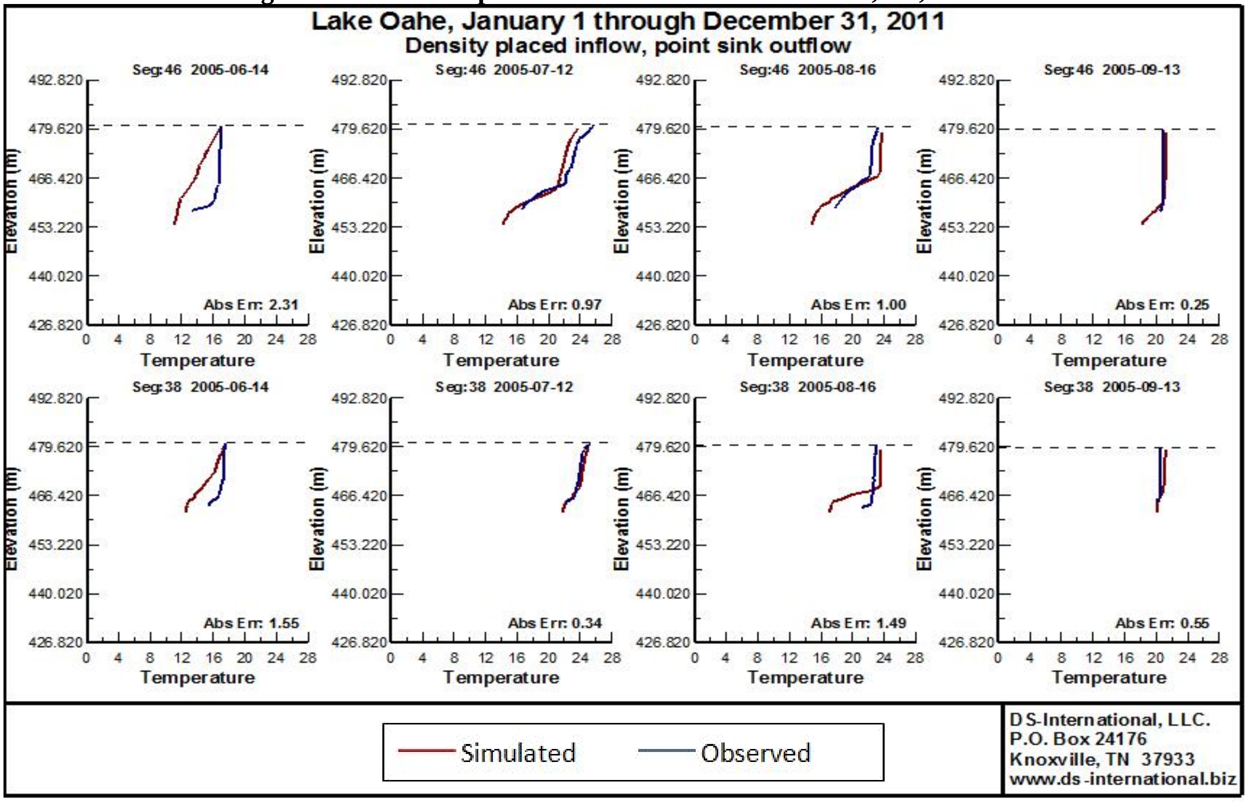

Figure 7-3. 2005 temperature calibration at stations O5 and O6

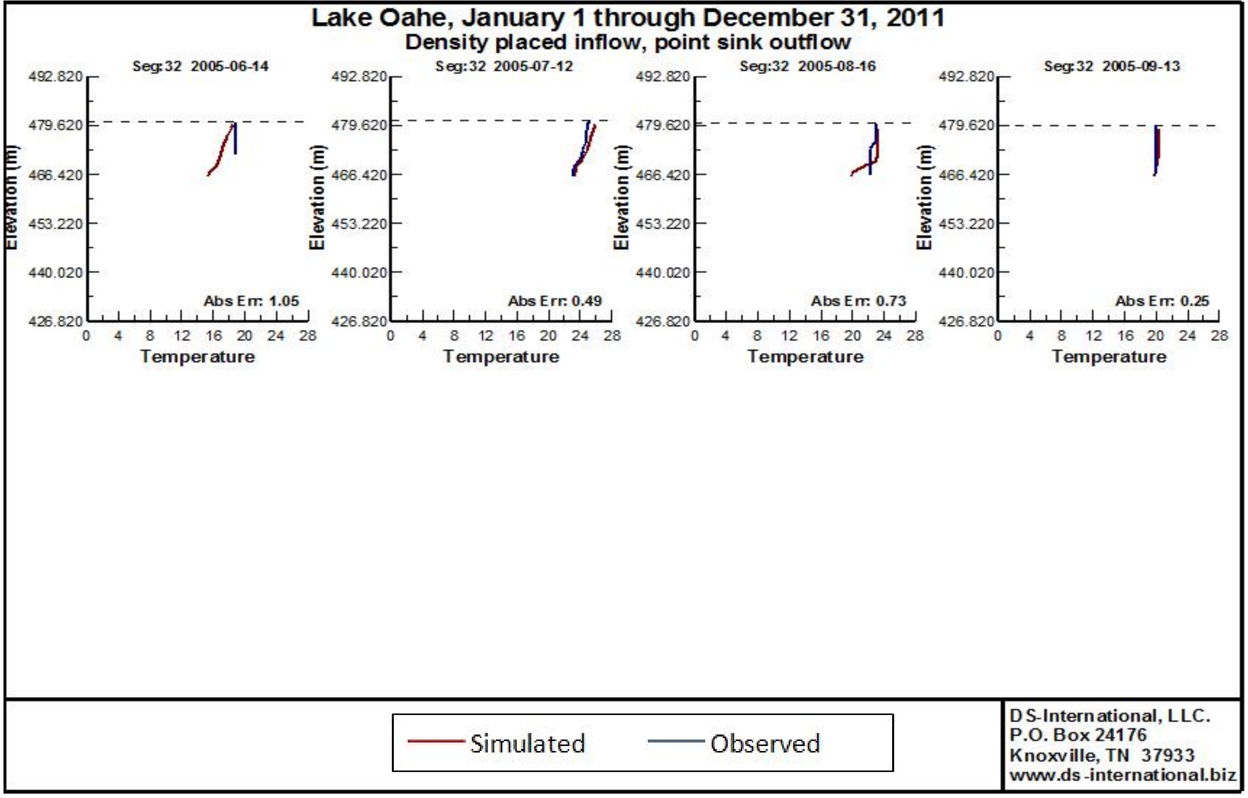

Figure 7-4. 2005 temperature calibration at station O7

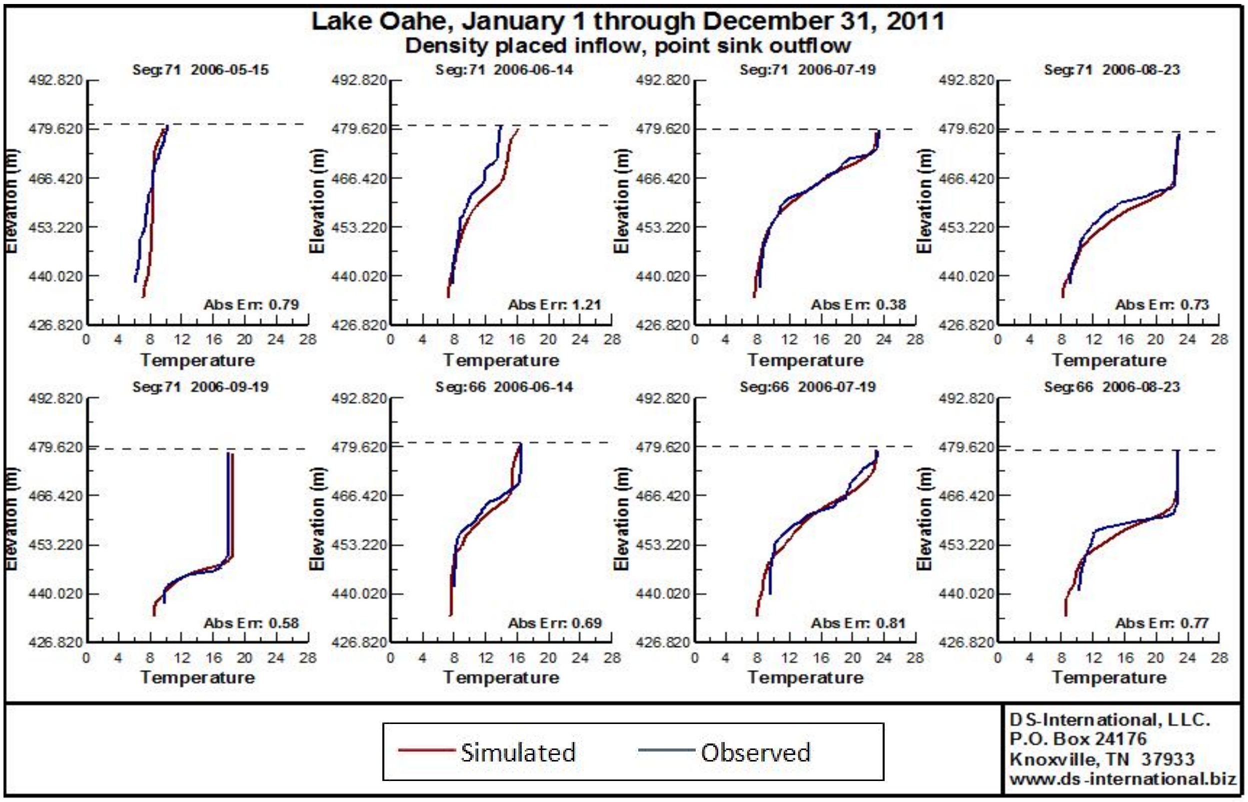

Figure 7-5. 2006 temperature calibration at stations O1 and O2

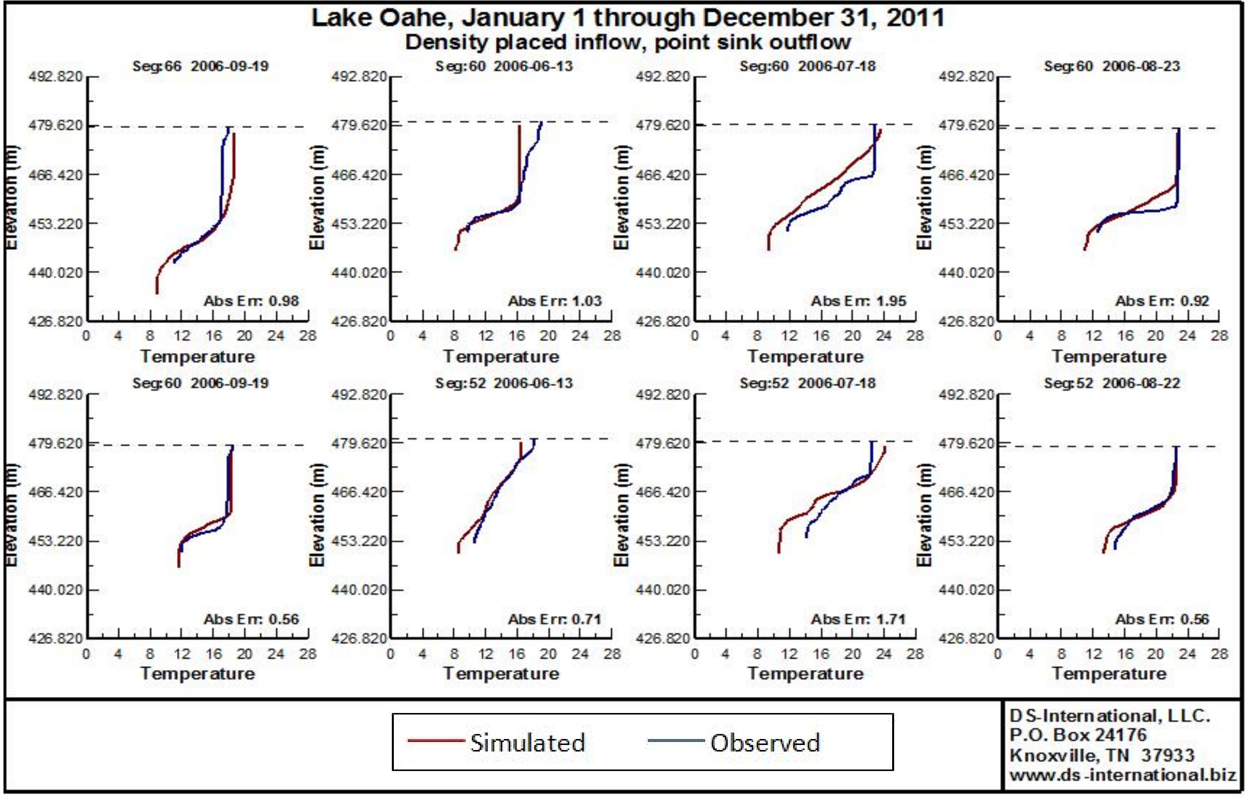

Figure 7-6. 2006 temperature calibration at stations O2, O3, and O4

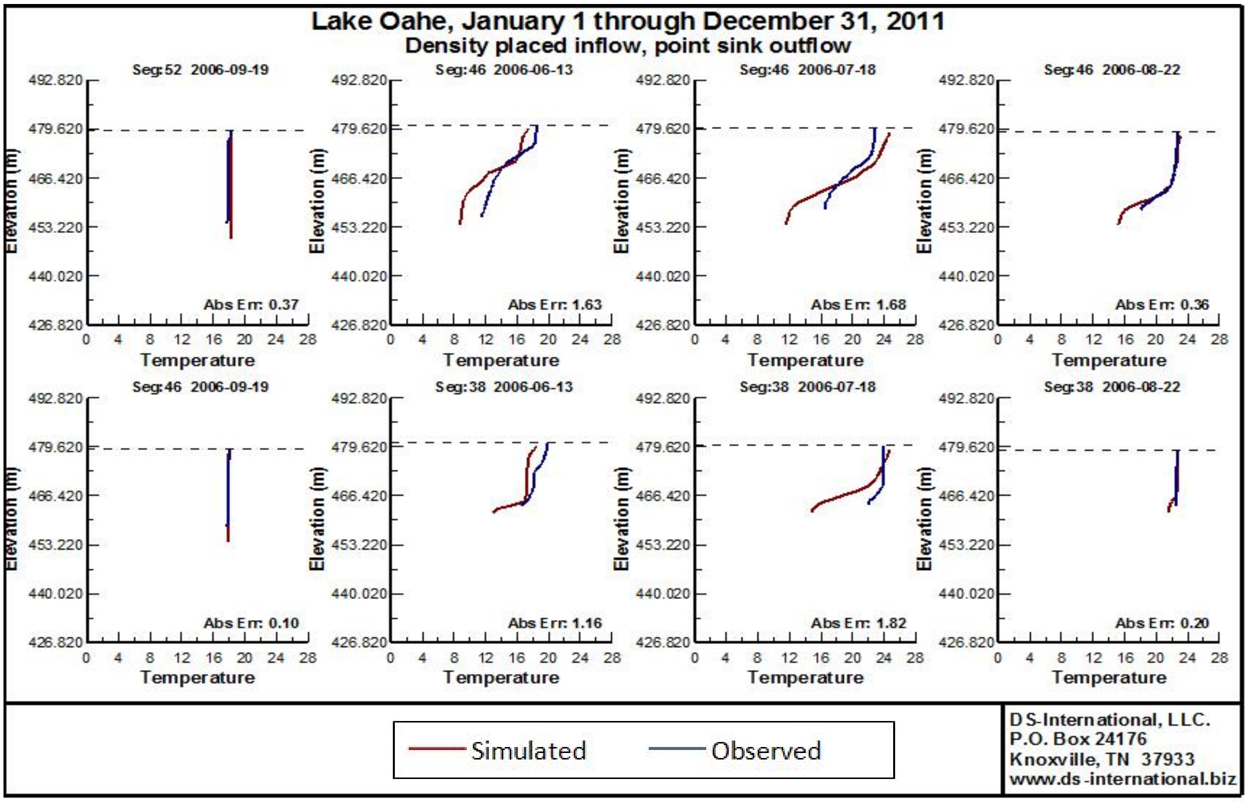

Figure 7-7. 2006 temperature calibration at stations O4, O5, and O6

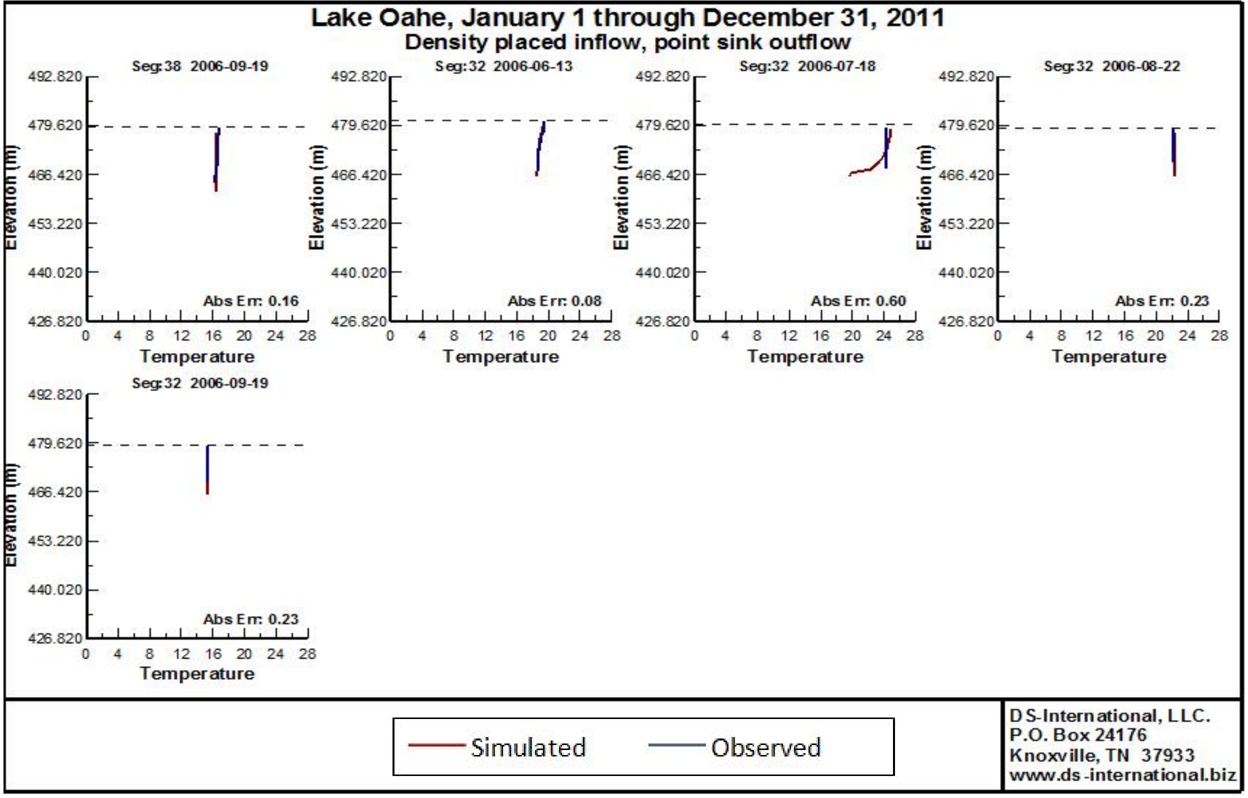

Figure 7-8. 2006 temperature calibration at stations O6 and O7

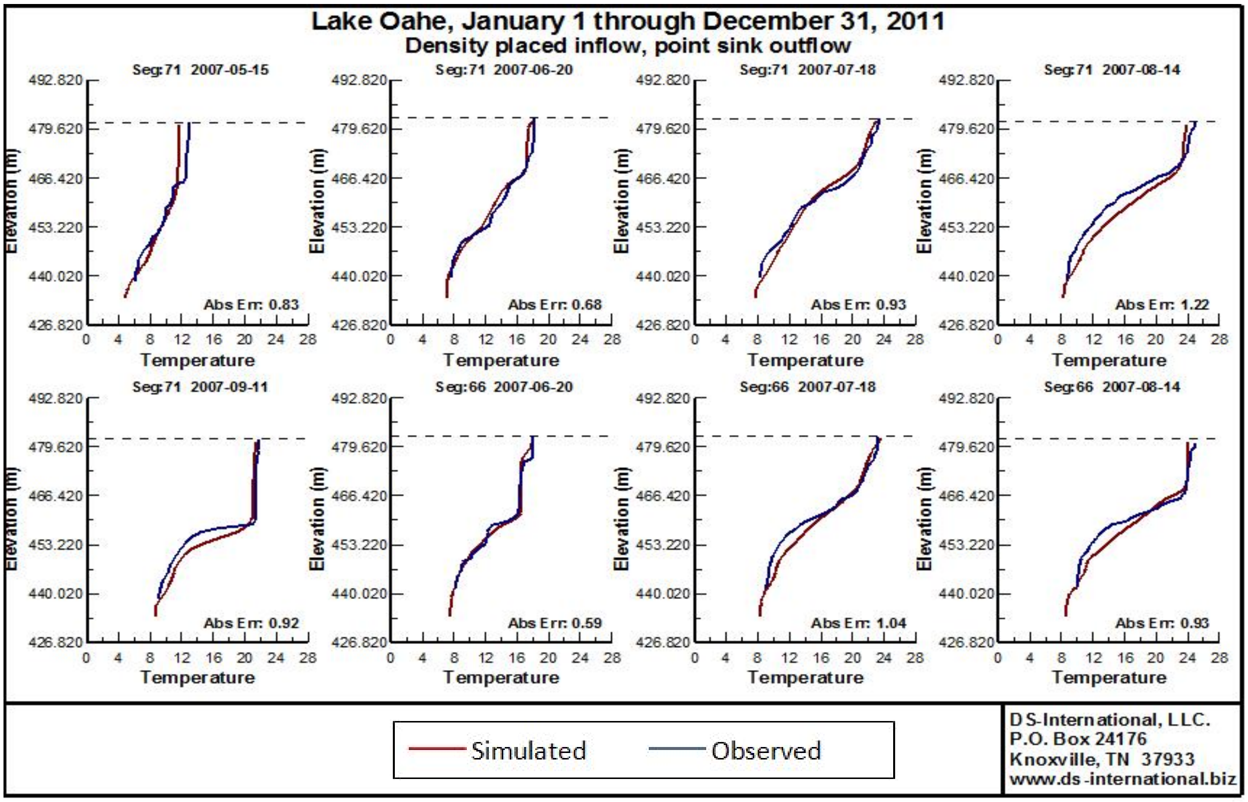

Figure 7-9. 2007 temperature calibration at stations O1 and O2

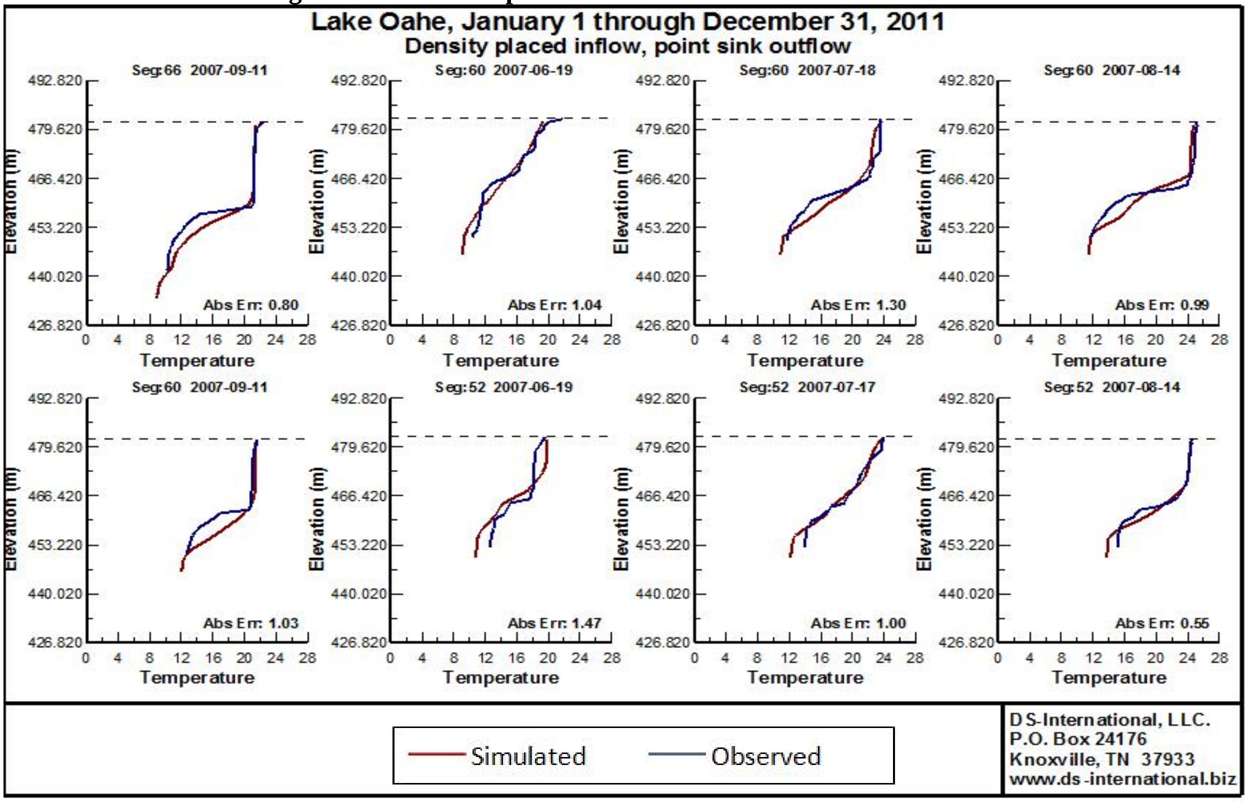

Figure 7-10. 2007 temperature calibration at stations O2, O3, and O4

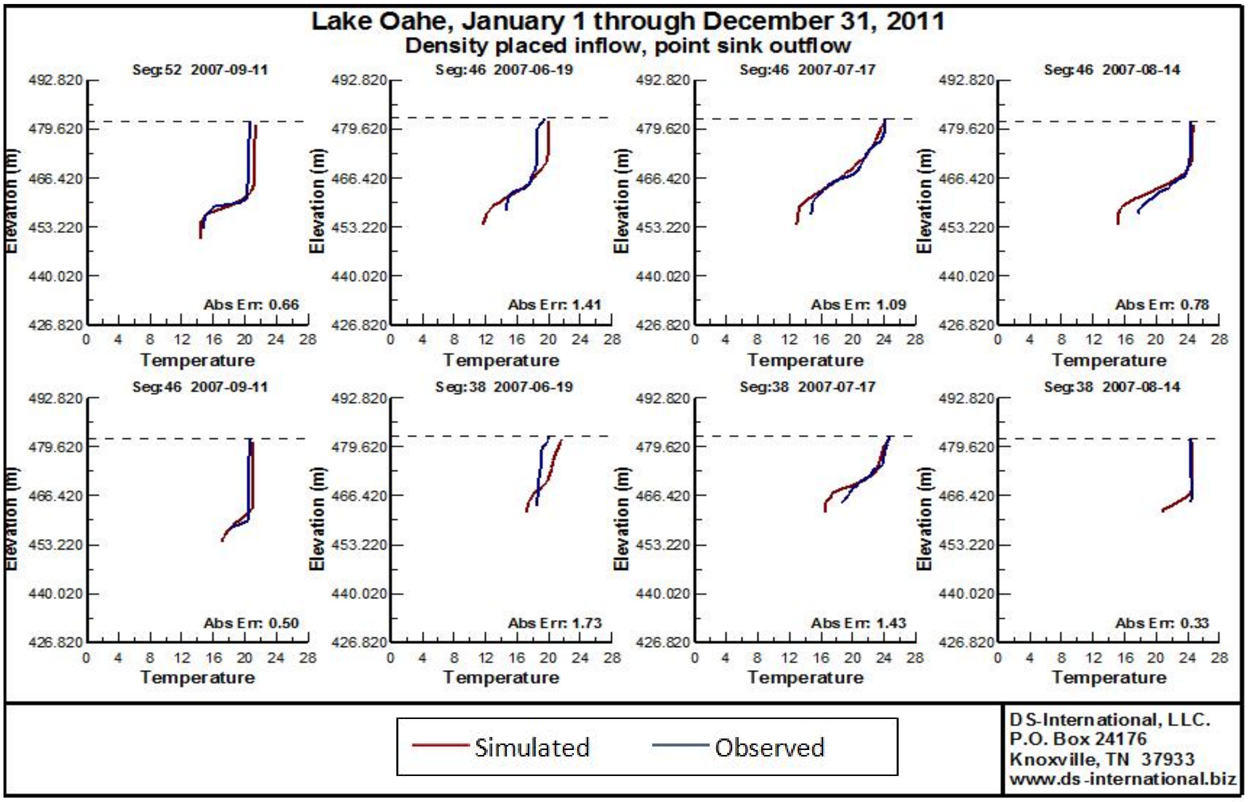

Figure 7-11. 2007 temperature calibration at stations O4, O5, and O6

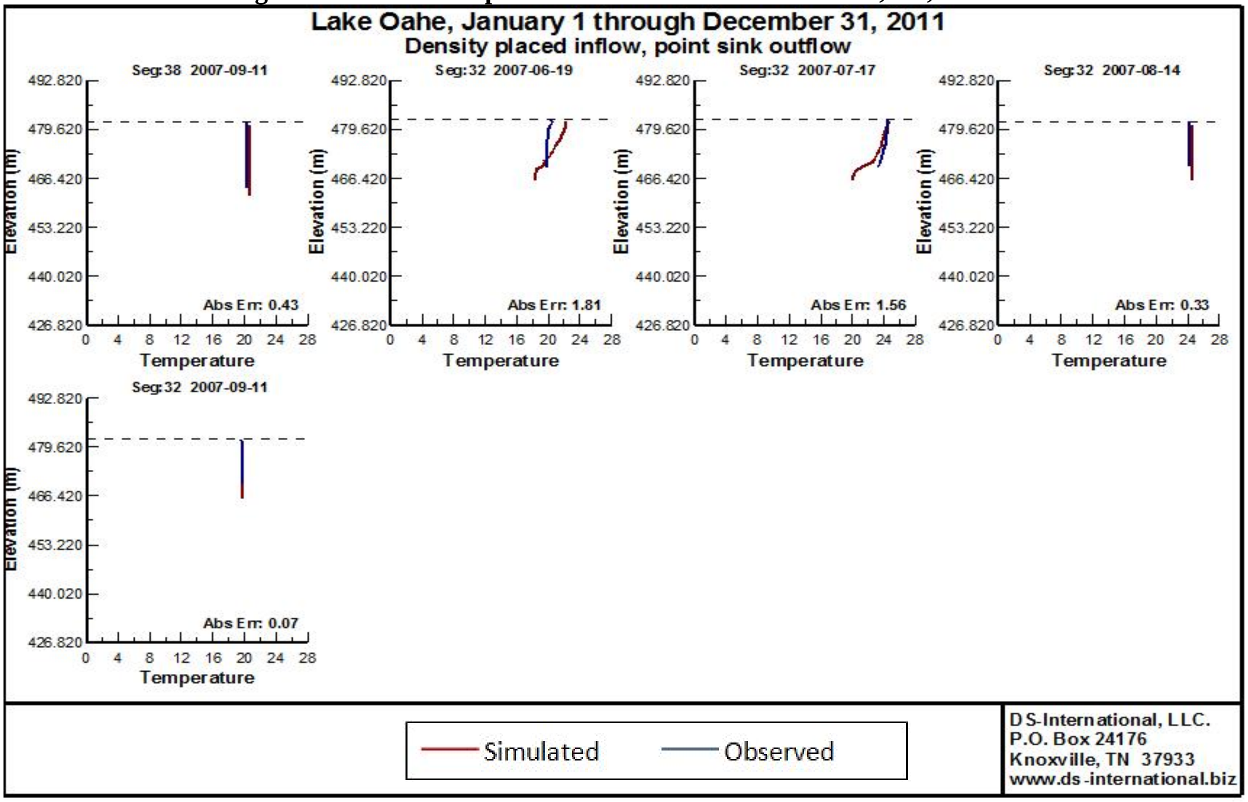

Figure 7-12. 2007 temperature calibration at stations O6 and O7

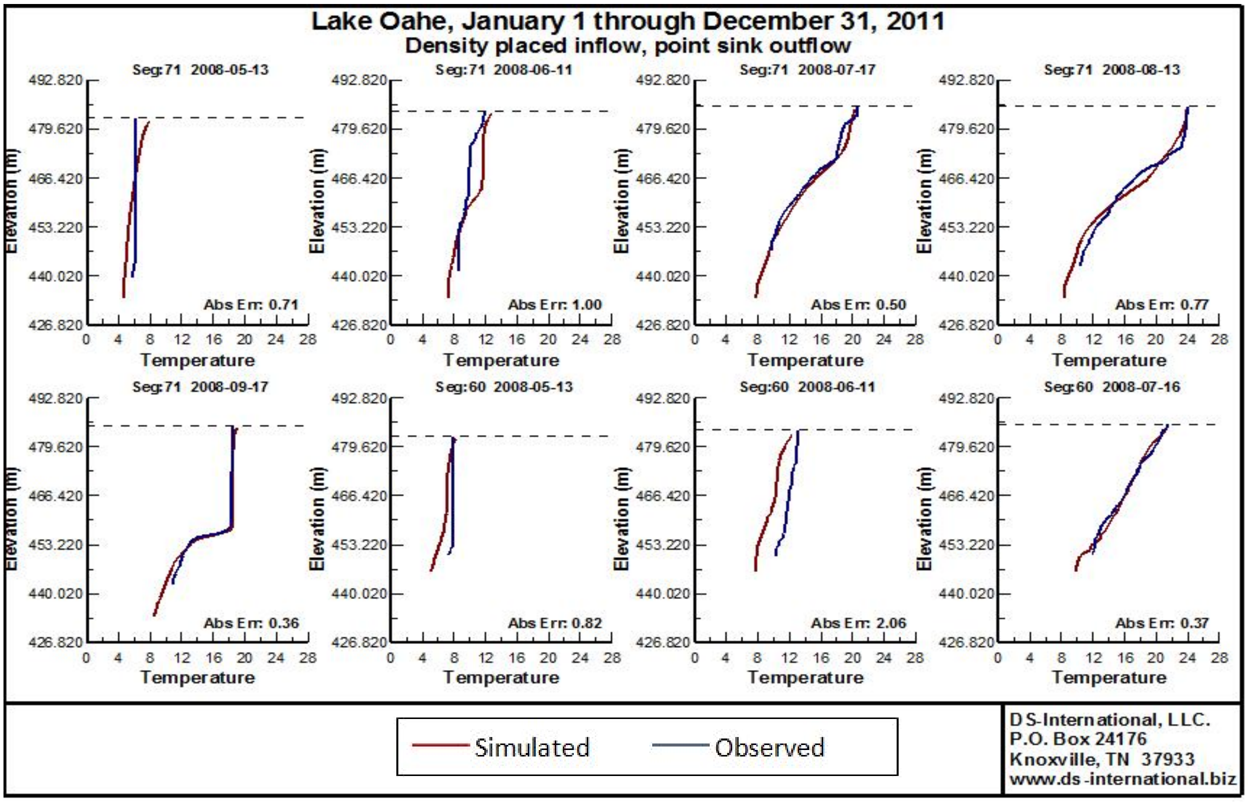

Figure 7-13. 2008 temperature calibration at stations O1 and O3

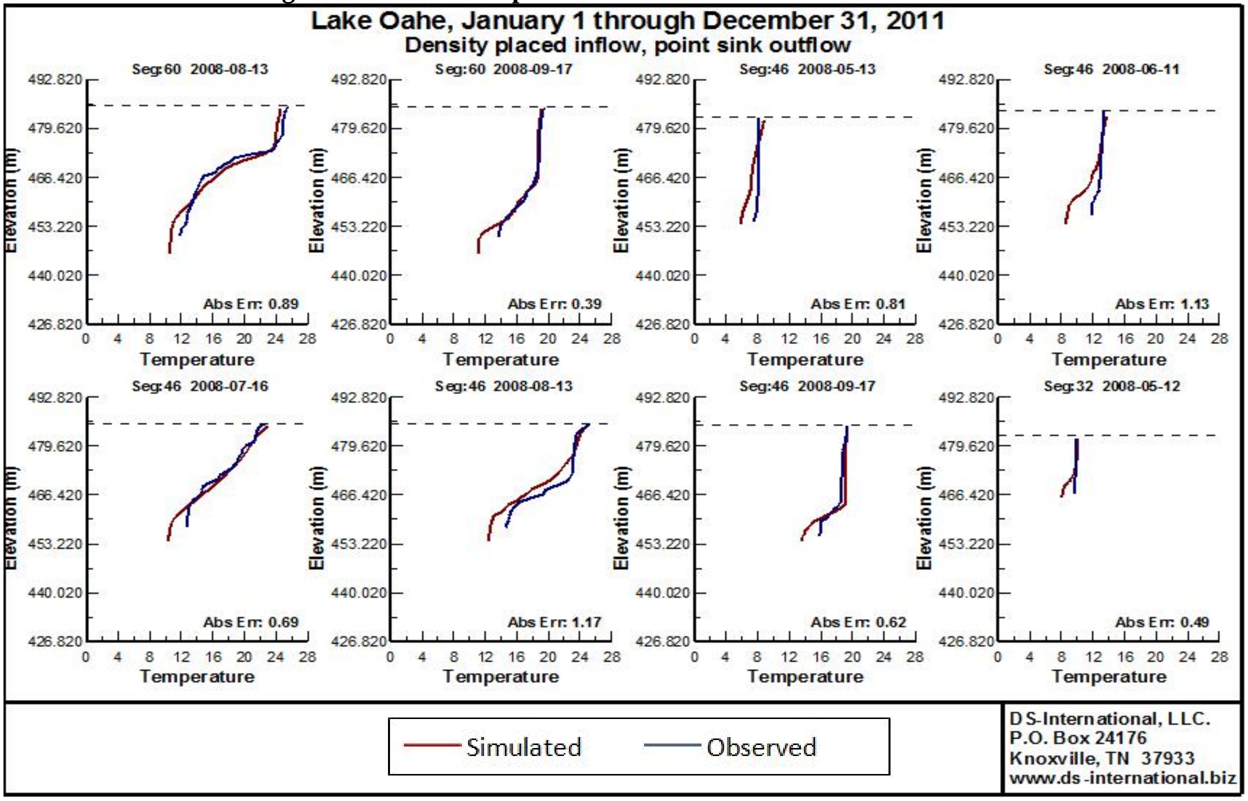

Figure 7-14. 2008 temperature calibration at stations O3, O5, and O7

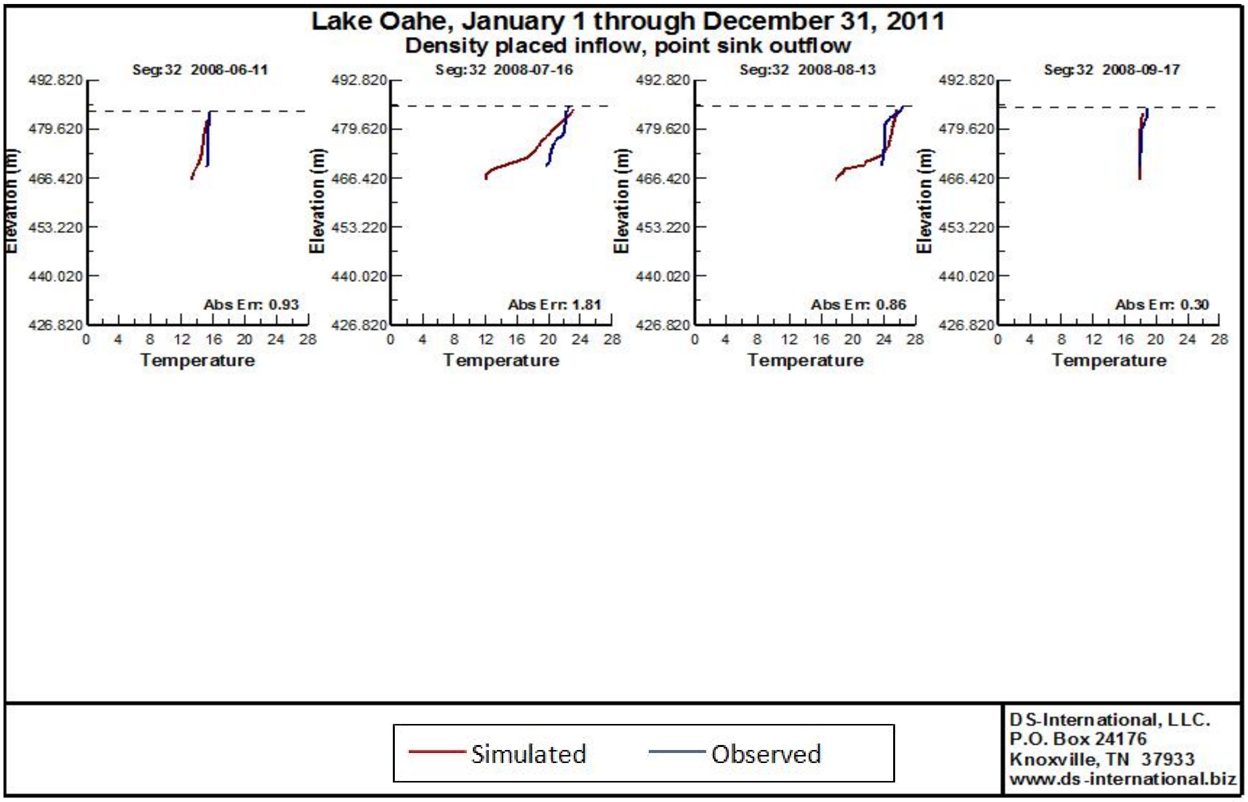

Figure 7-15. 2008 temperature calibration at station O7

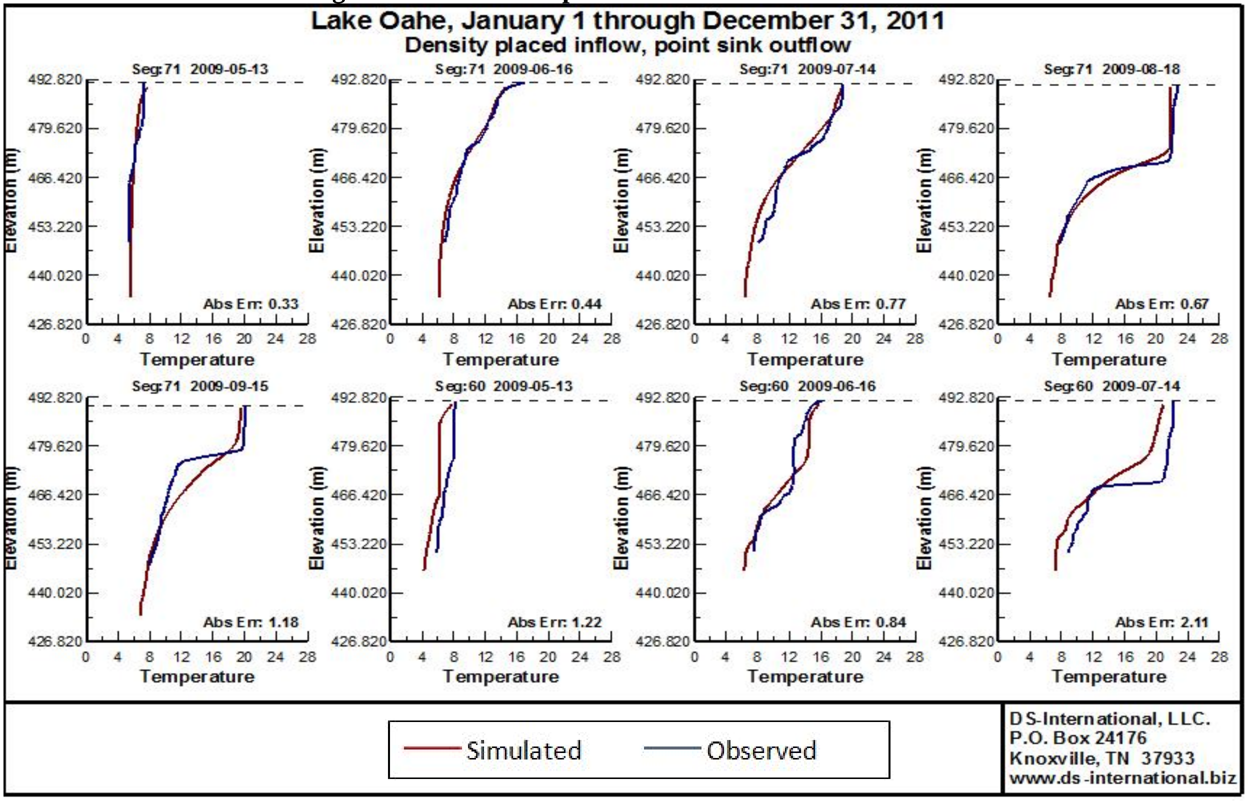

Figure 7-16. 2009 temperature calibration at stations O1 and O3

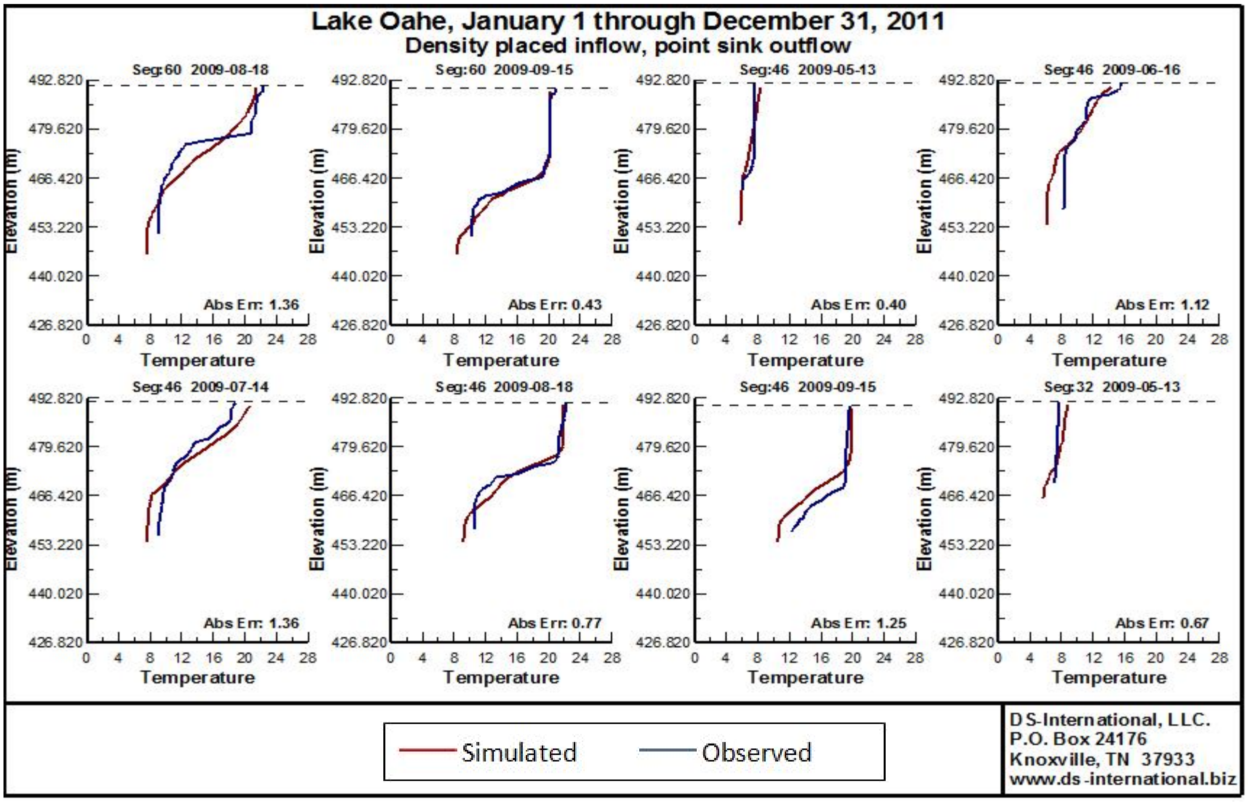

Figure 7-17. 2009 temperature calibration at stations O3, O5, and O7

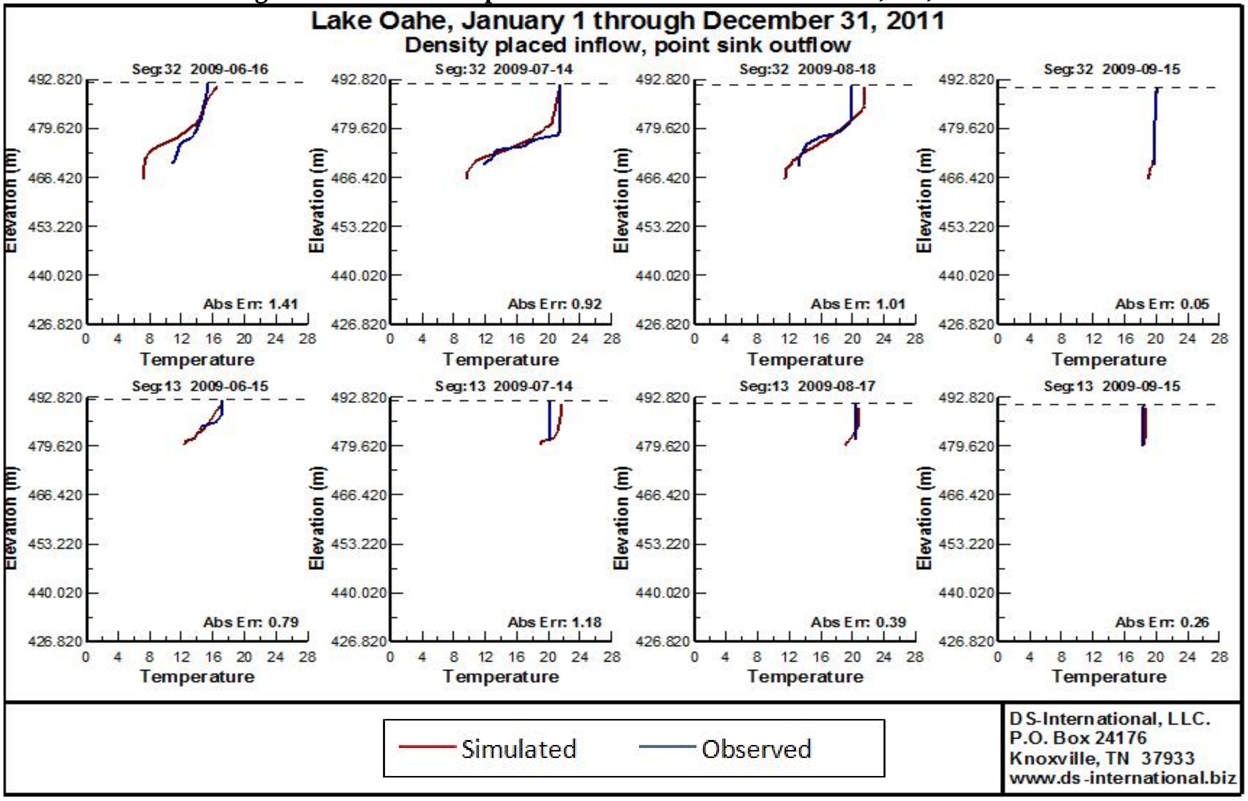

Figure 7-18. 2009 temperature calibration at stations O7 and O8

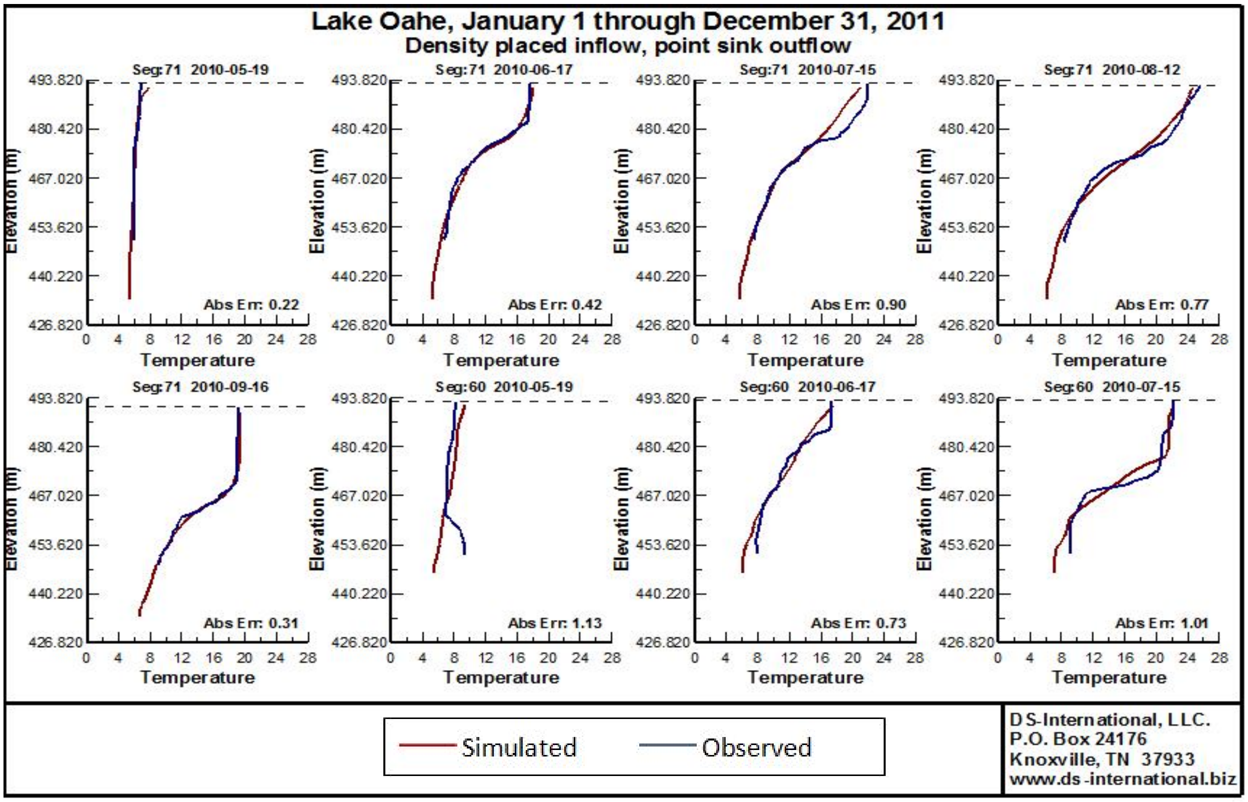

Figure 7-19. 2010 temperature calibration at stations O1 and O3

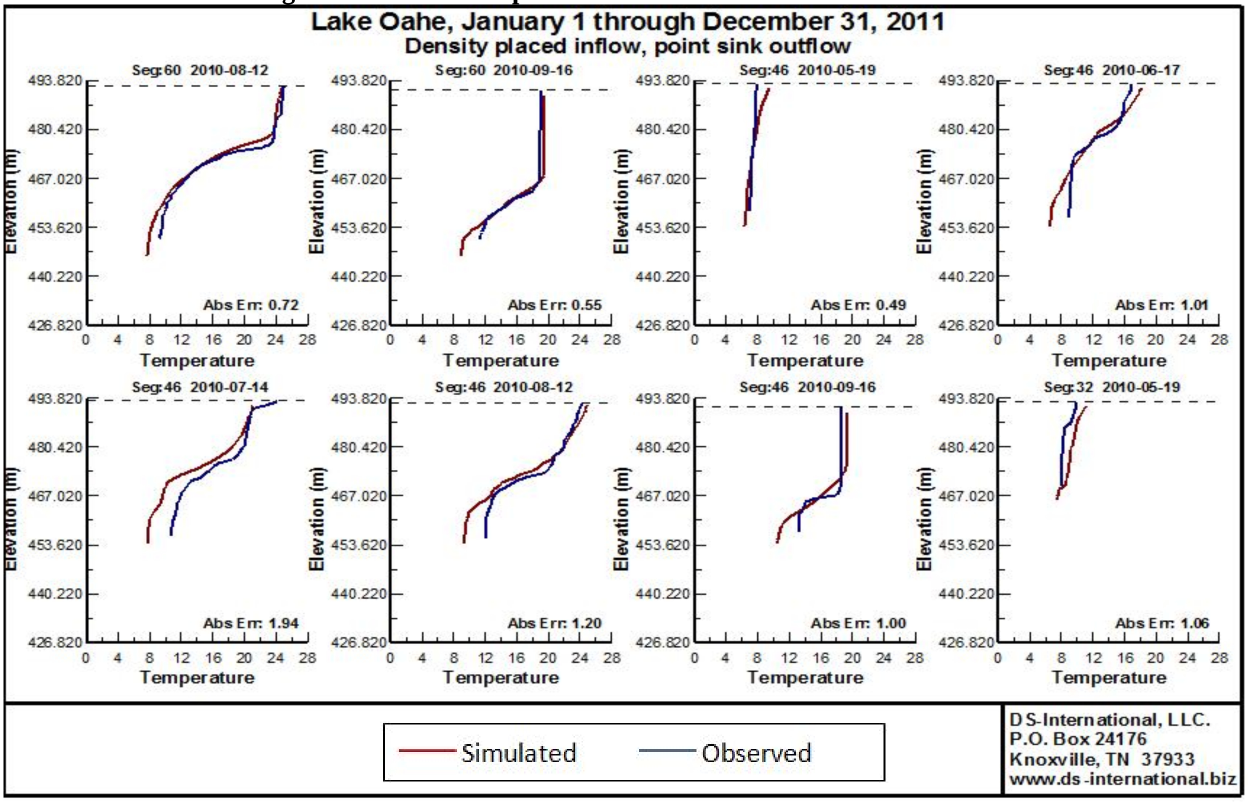

Figure 7-20. 2010 temperature calibration at stations O3, O5, and O7

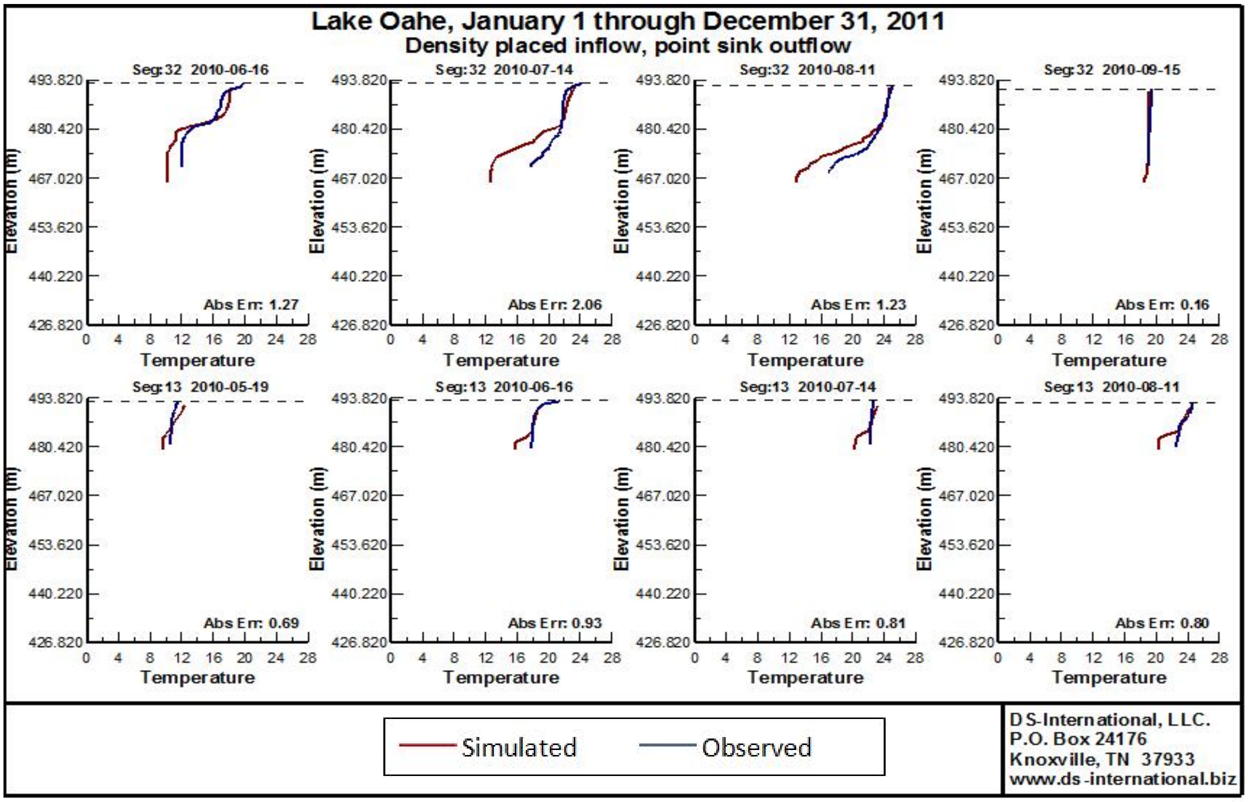

Figure 7-21. 2010 temperature calibration at stations O7 and O8

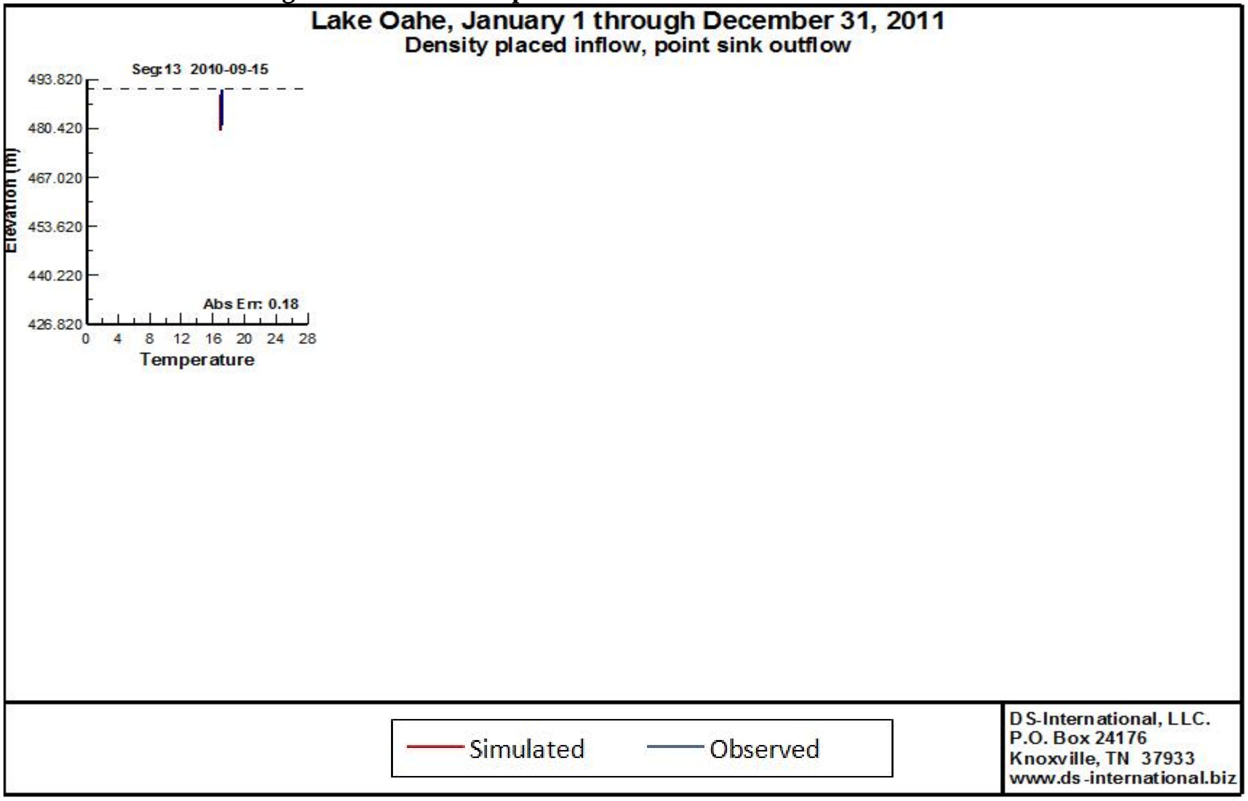

Figure 7-22. 2010 temperature calibration at station O8

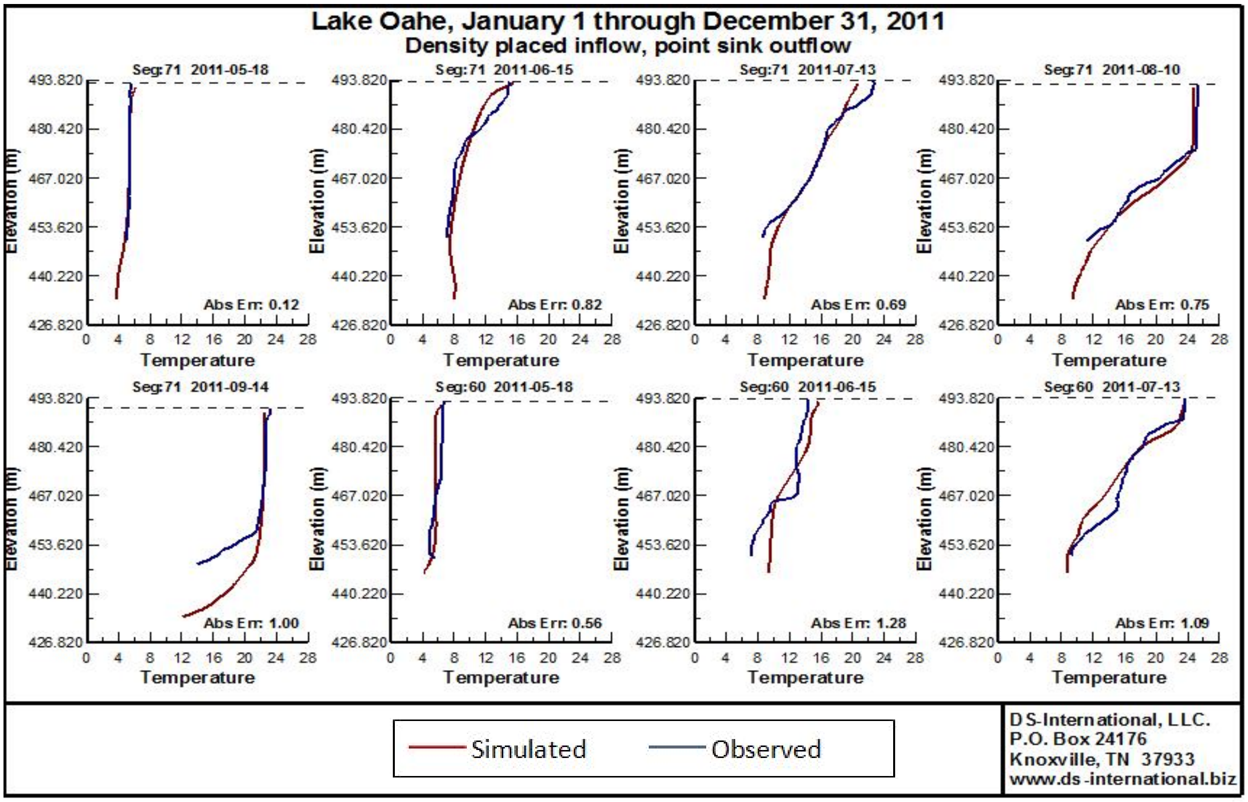

Figure 7-23. 2011 temperature calibration at stations O1 and O3

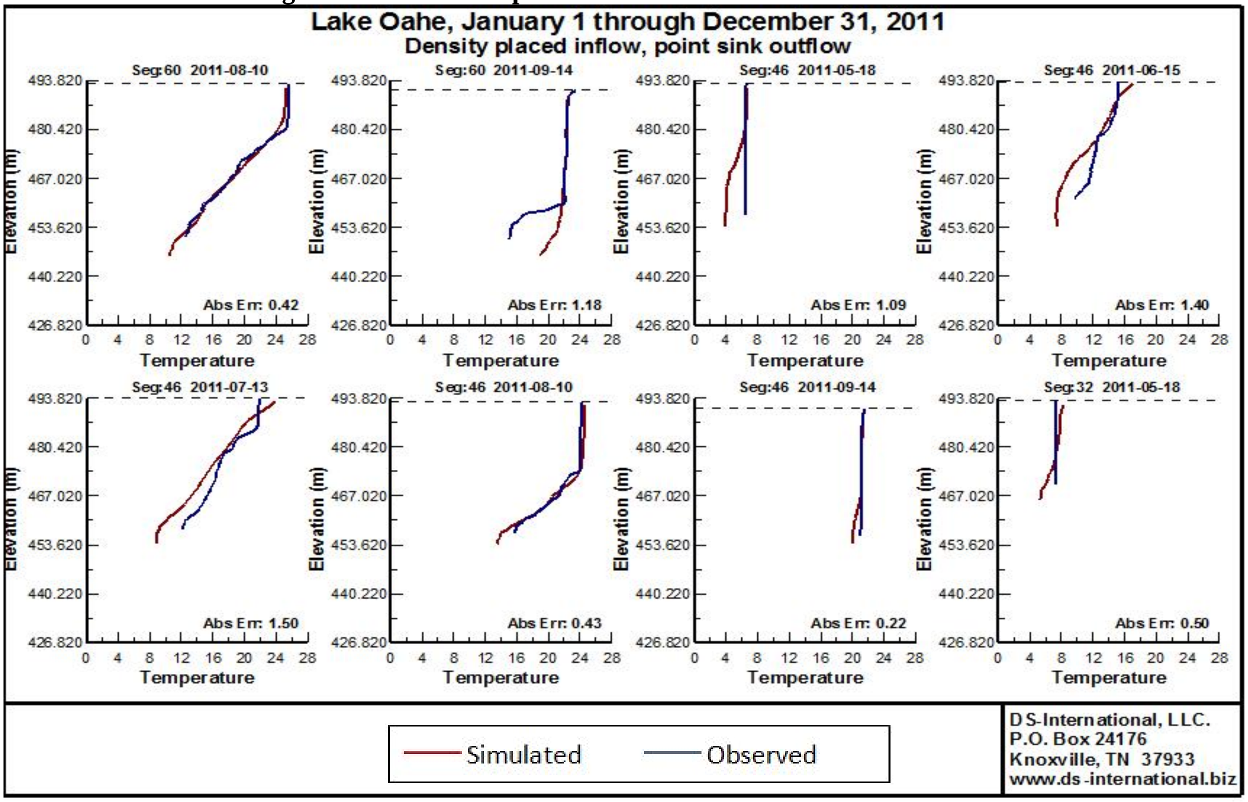

Figure 7-24. 2011 temperature calibration at stations O3, O5, and O7

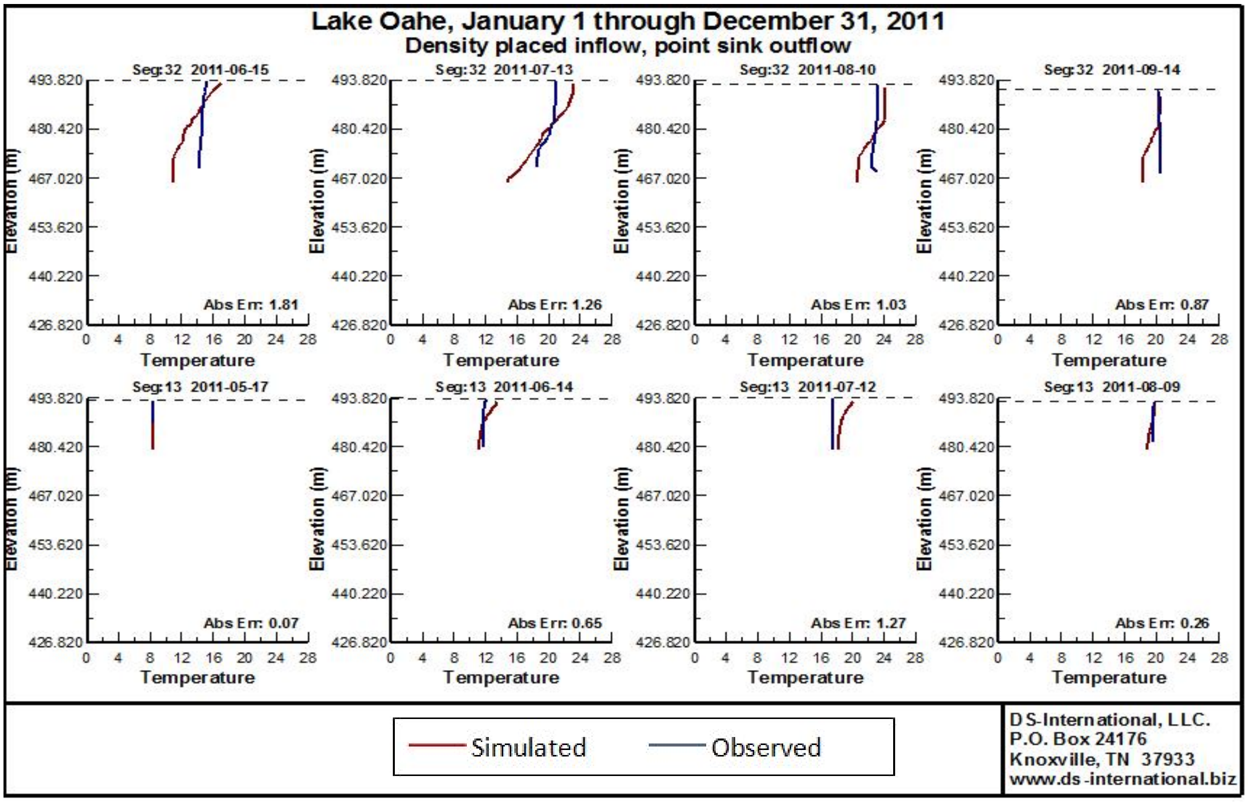

Figure 7-25. 2011 temperature calibration at stations O7 and O8

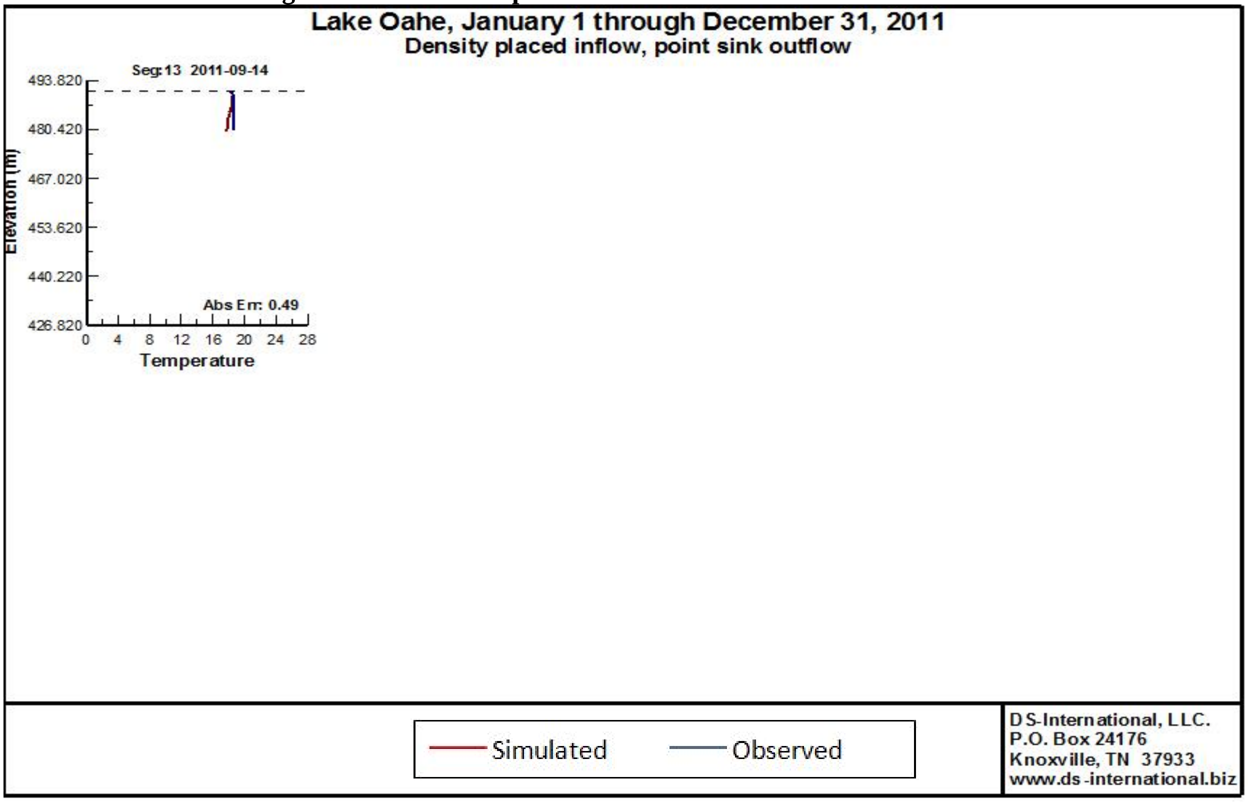

Figure 7-26. 2011 temperature calibration at station O8

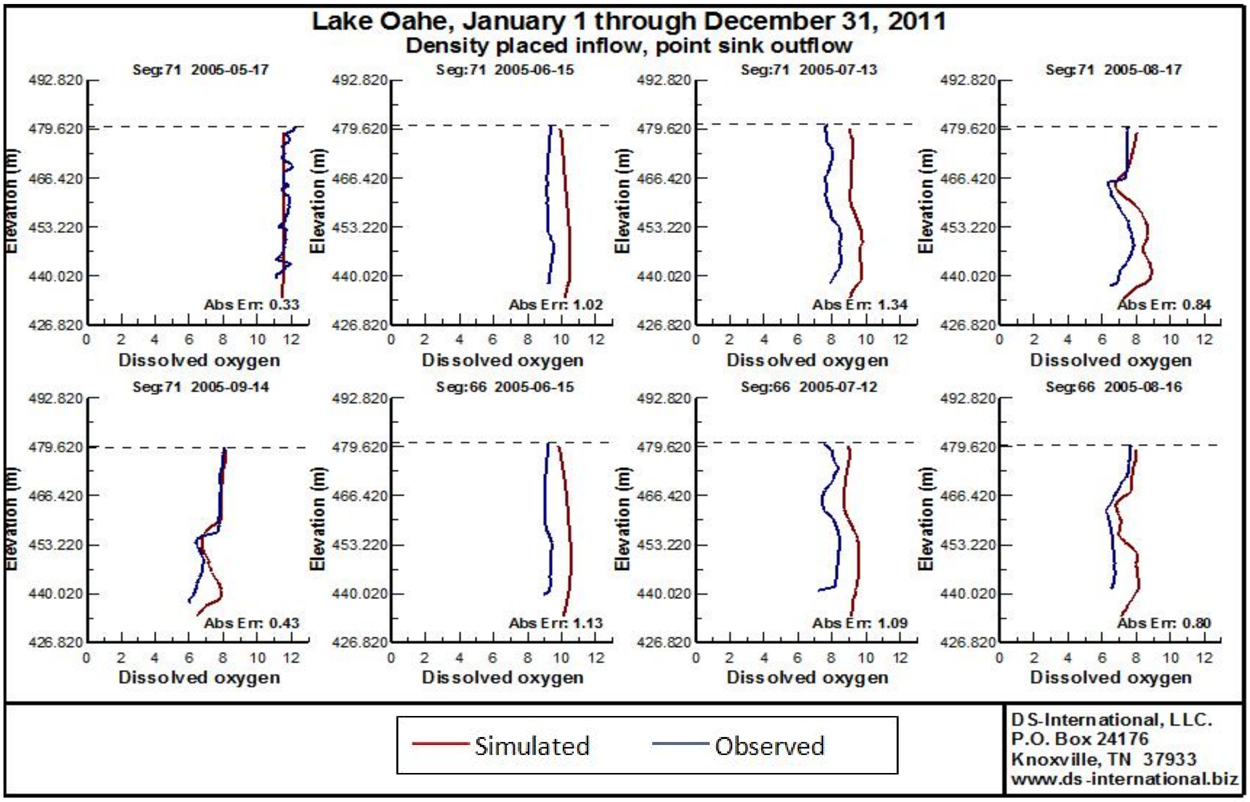

Figure 7-27. 2005 Dissolved Oxygen calibration at stations O1 and O2

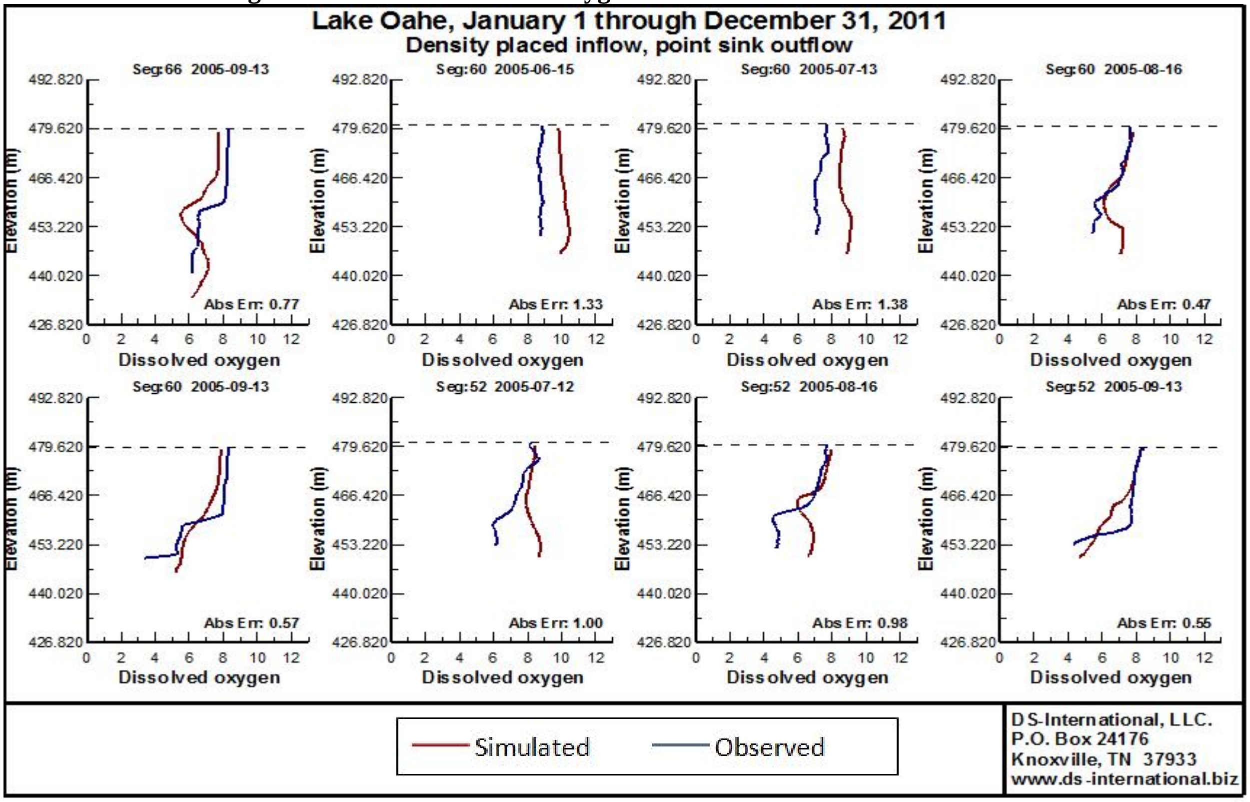

Figure 7-28. 2005 dissolved oxygen calibration at stations O2, O3, and O4

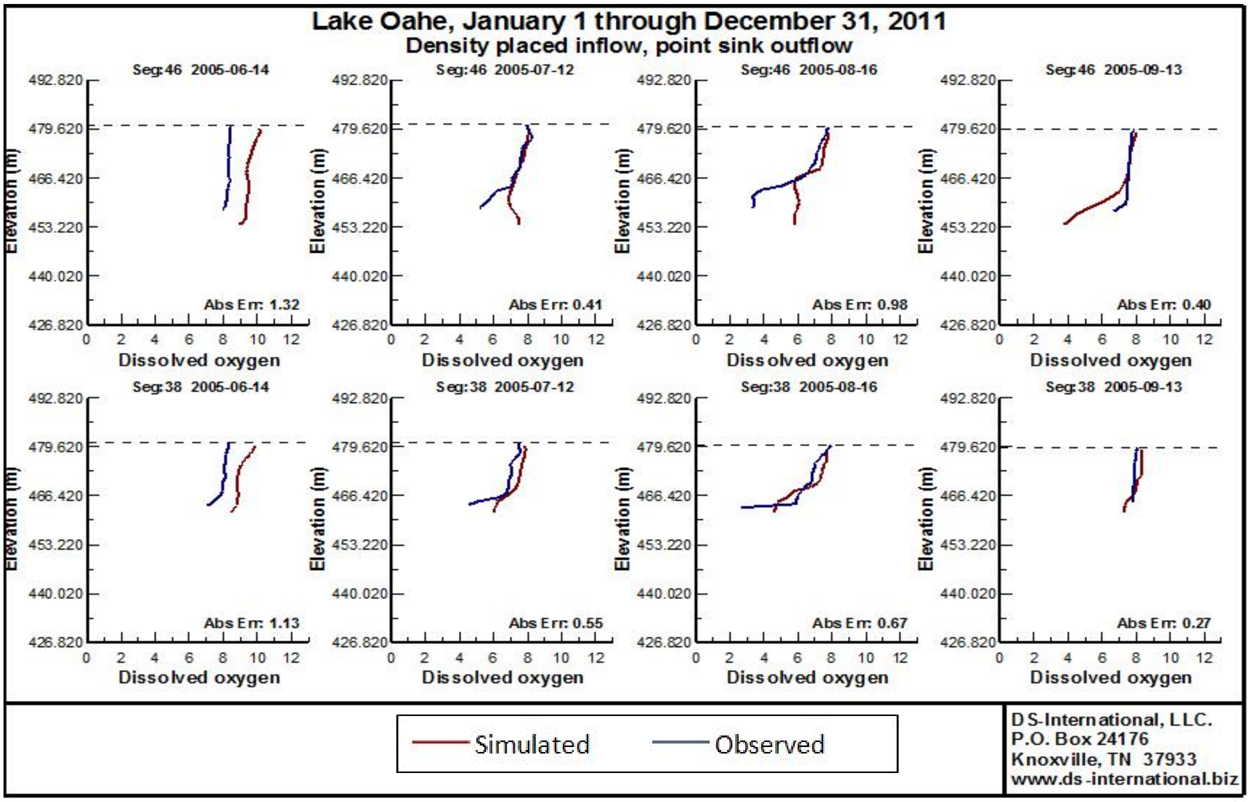

Figure 7-29. **2005 dissolved oxygen calibration at stations O5 and O6**

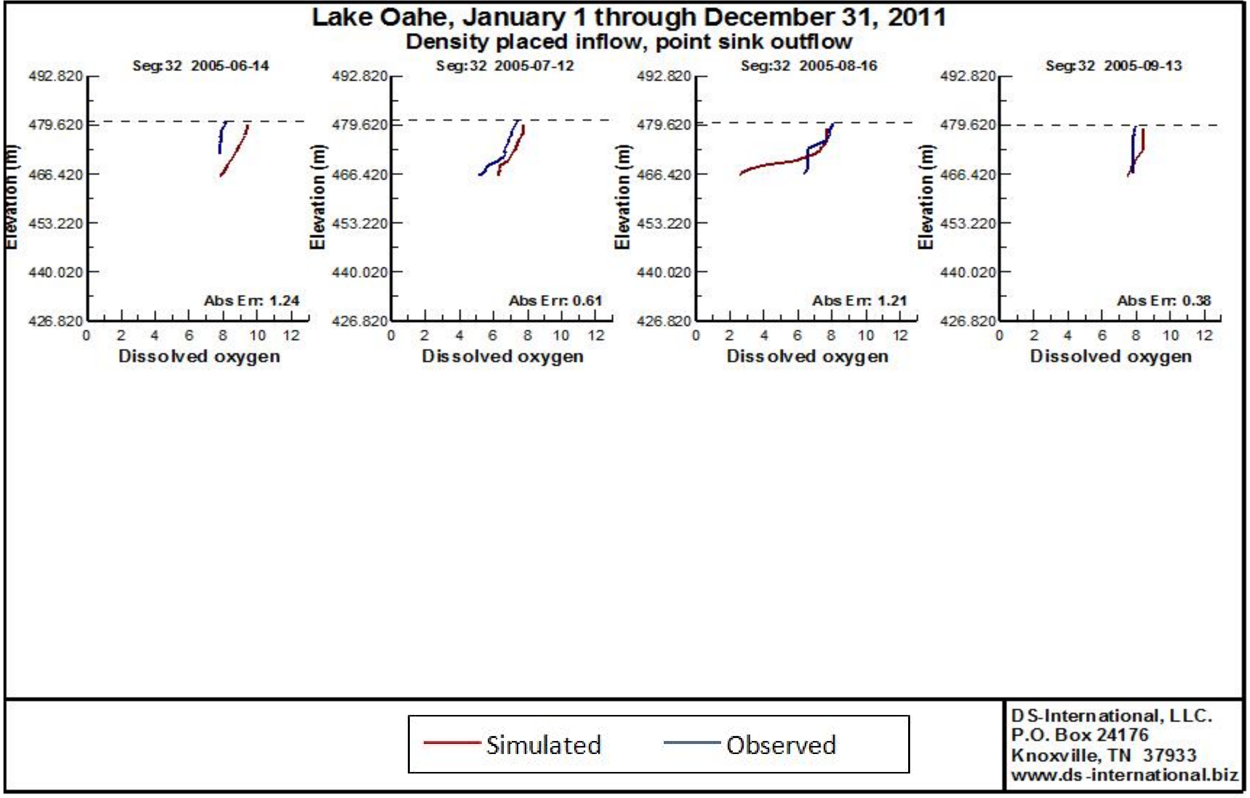

Figure 7-30. **2005 dissolved oxygen calibration at station O7**

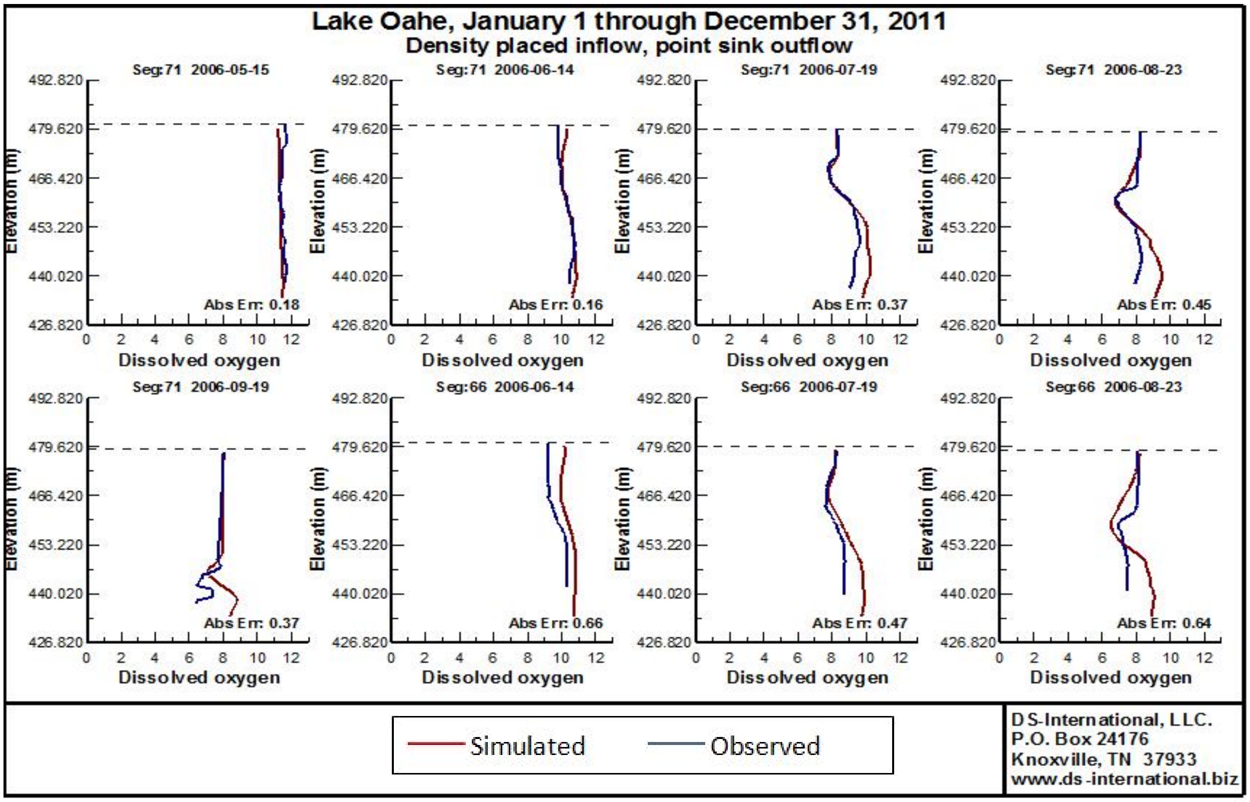

Figure 7-31. **2006 dissolved oxygen calibration at stations O1 and O2**

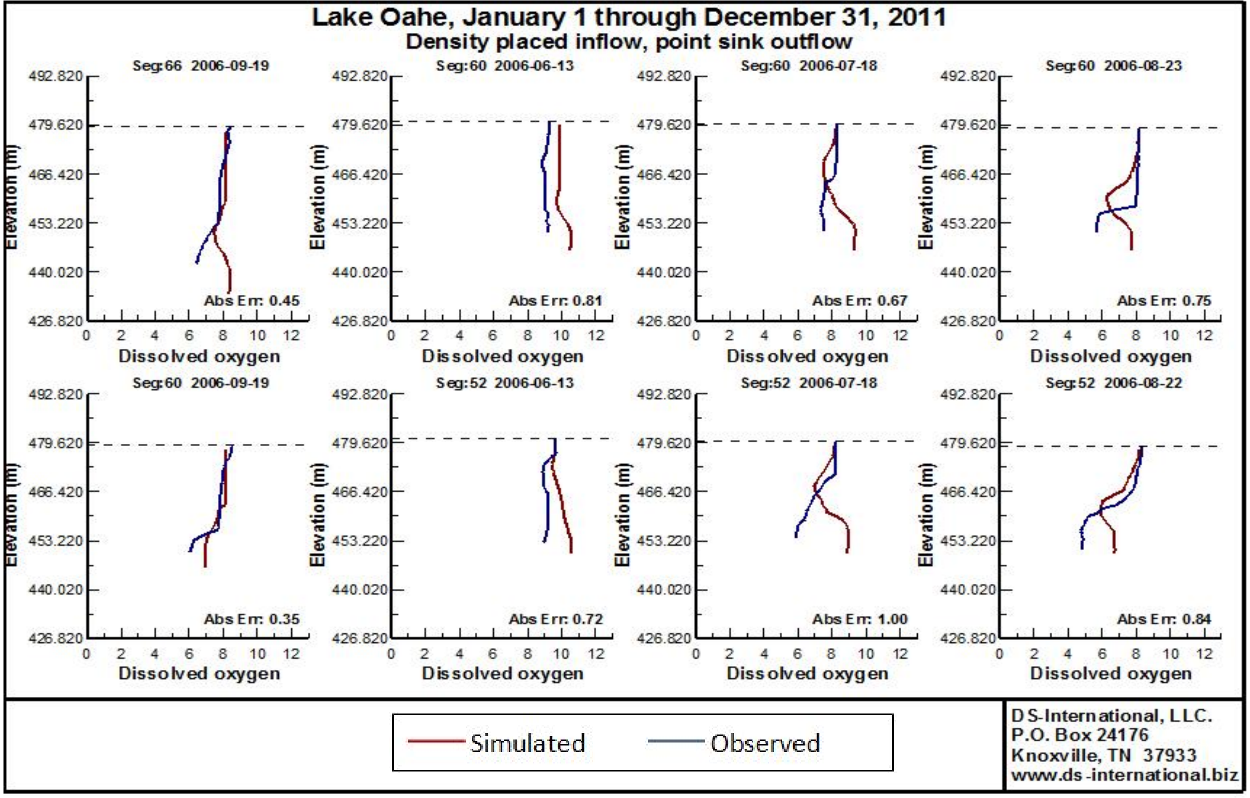

Figure 7-32. **2006 dissolved oxygen calibration at stations O2, O3, and O4**

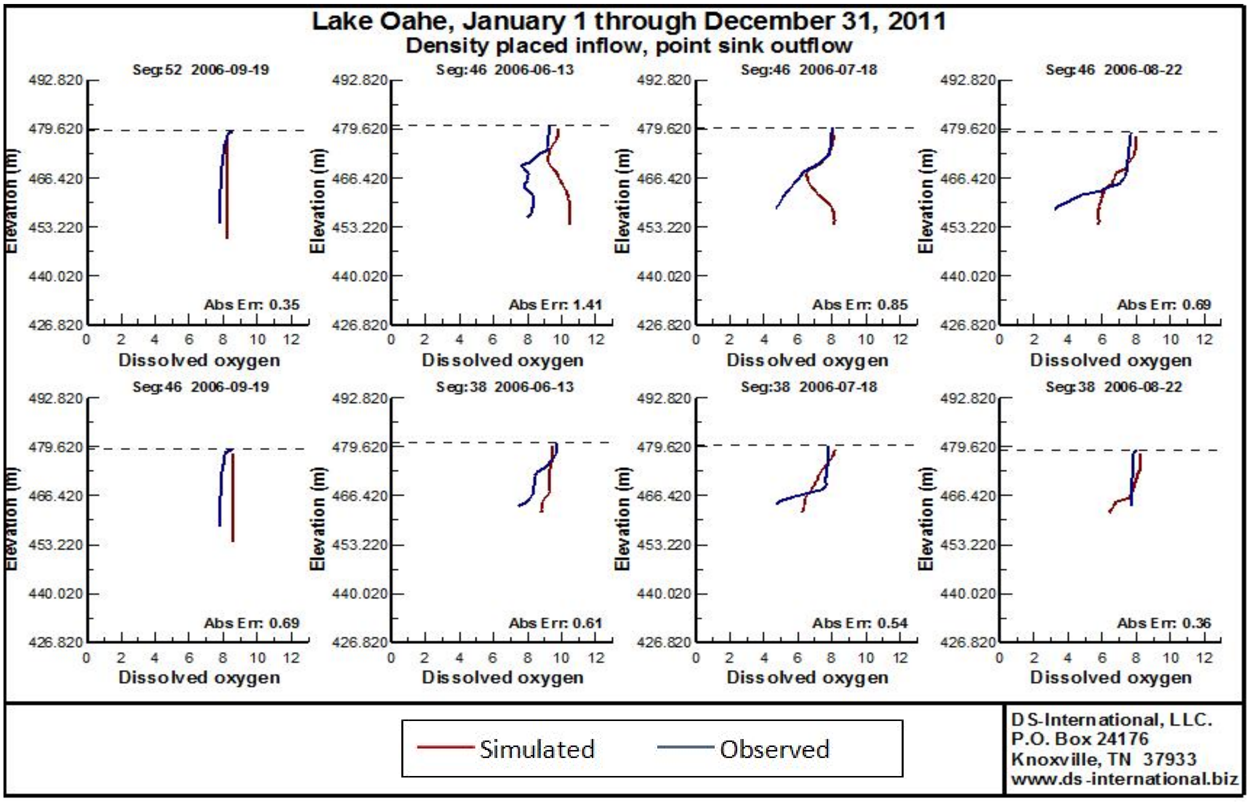

Figure 7-33. **2006 dissolved oxygen calibration at stations O4, O5, and O6**

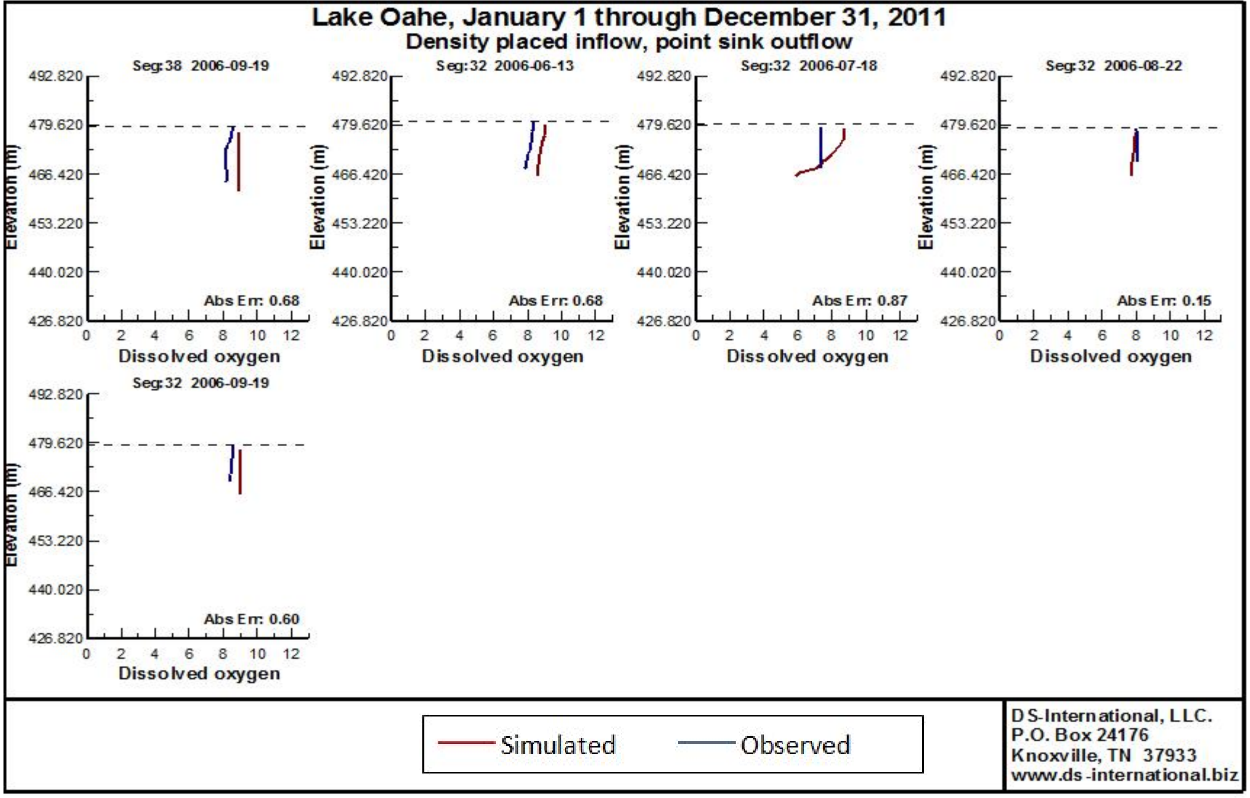

Figure 7-34. 2006 dissolved oxygen calibration at stations O6 and O7

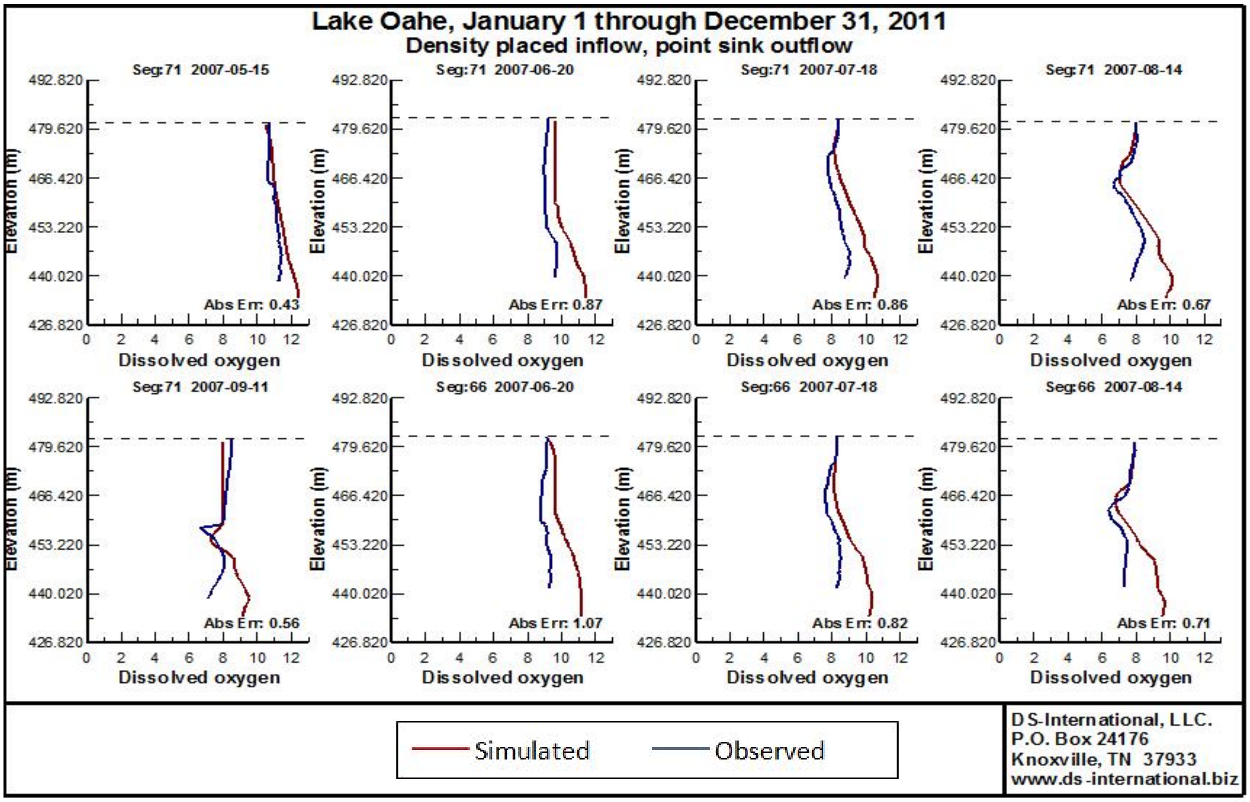

Figure 7-35. 2007 dissolved oxygen calibration at stations O1 and O2

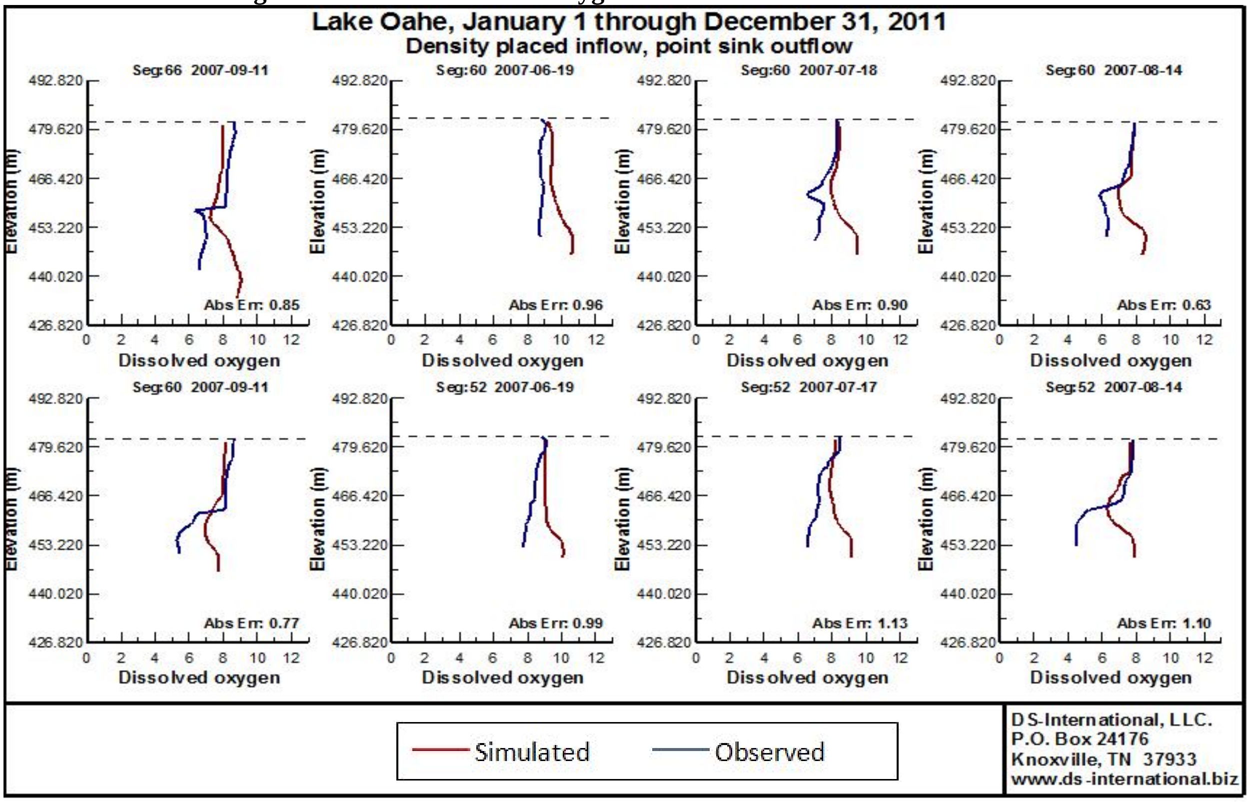

Figure 7-36. 2007 dissolved oxygen calibration at stations O2, O3, and O4

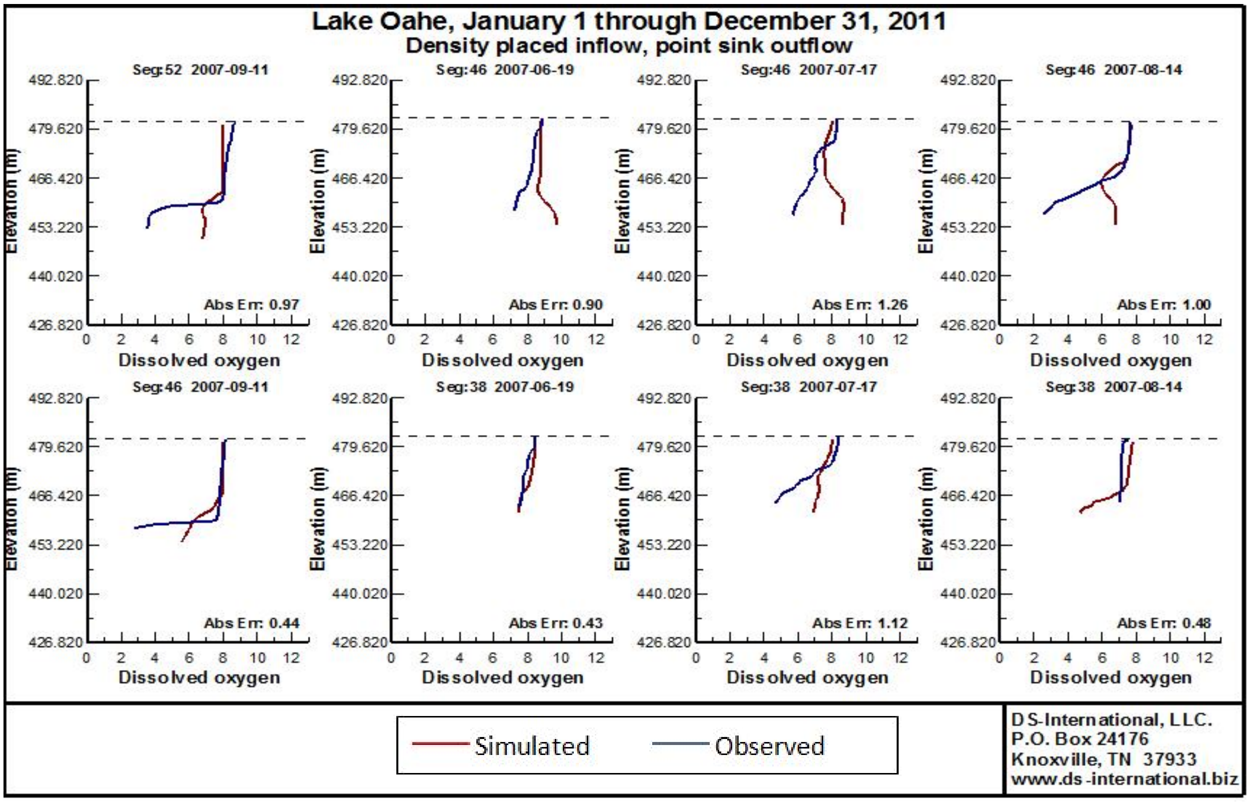

Figure 7-37. 2007 dissolved oxygen calibration at stations O4, O5, and O6

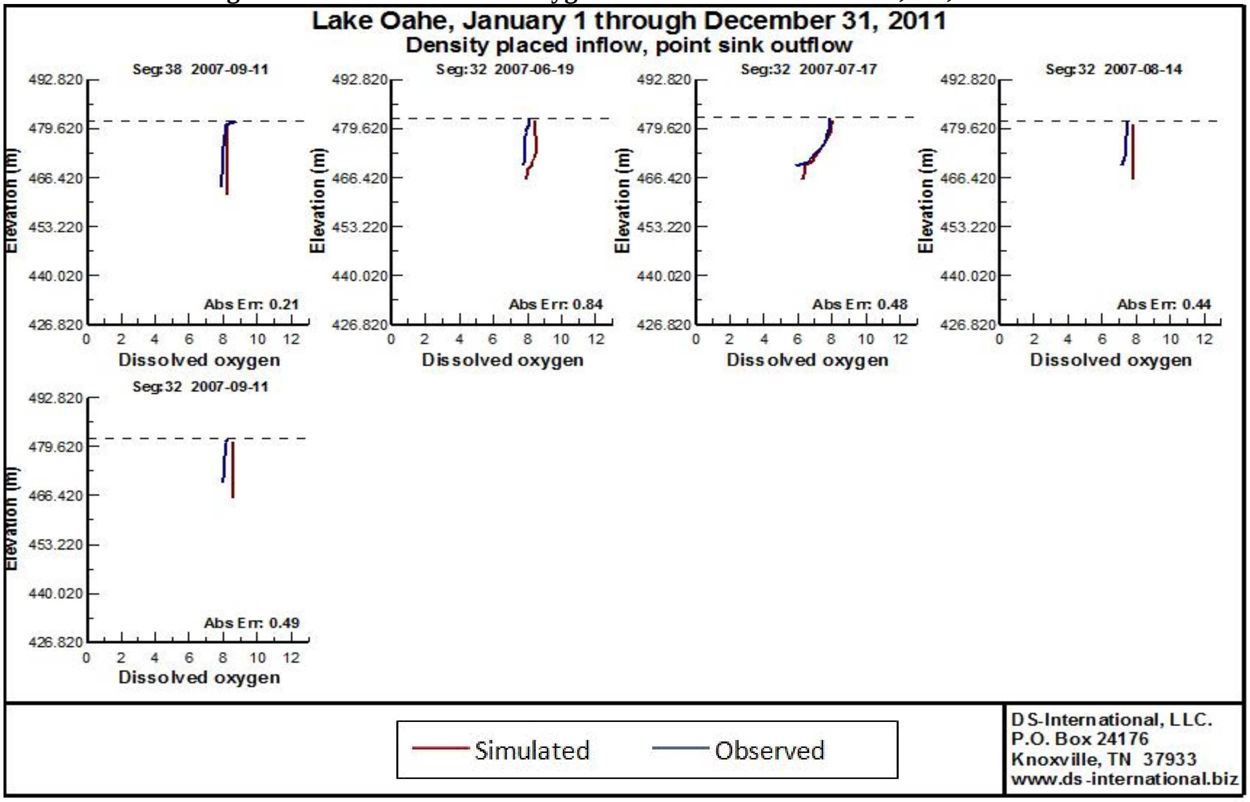

Figure 7-38. 2007 dissolved oxygen calibration at stations O6 and O7

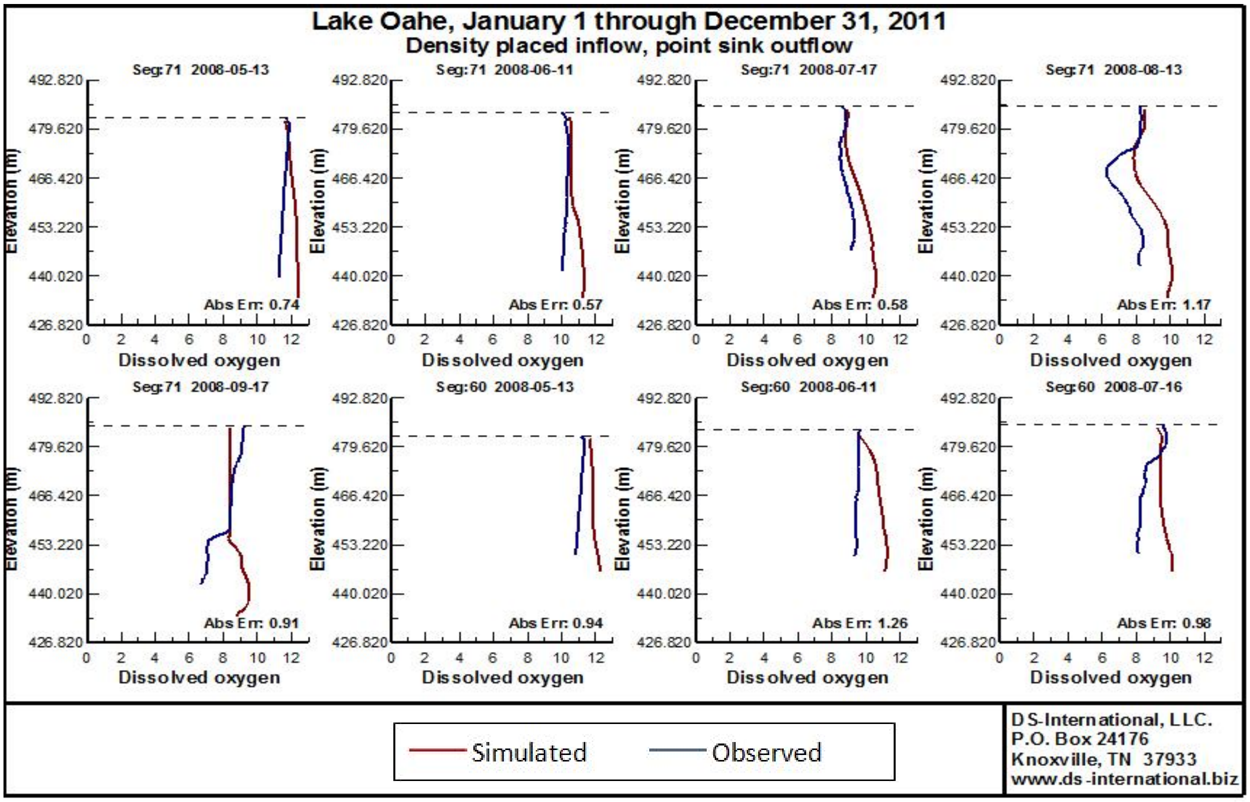

Figure 7-39. 2008 dissolved oxygen calibration at stations O1 and O3

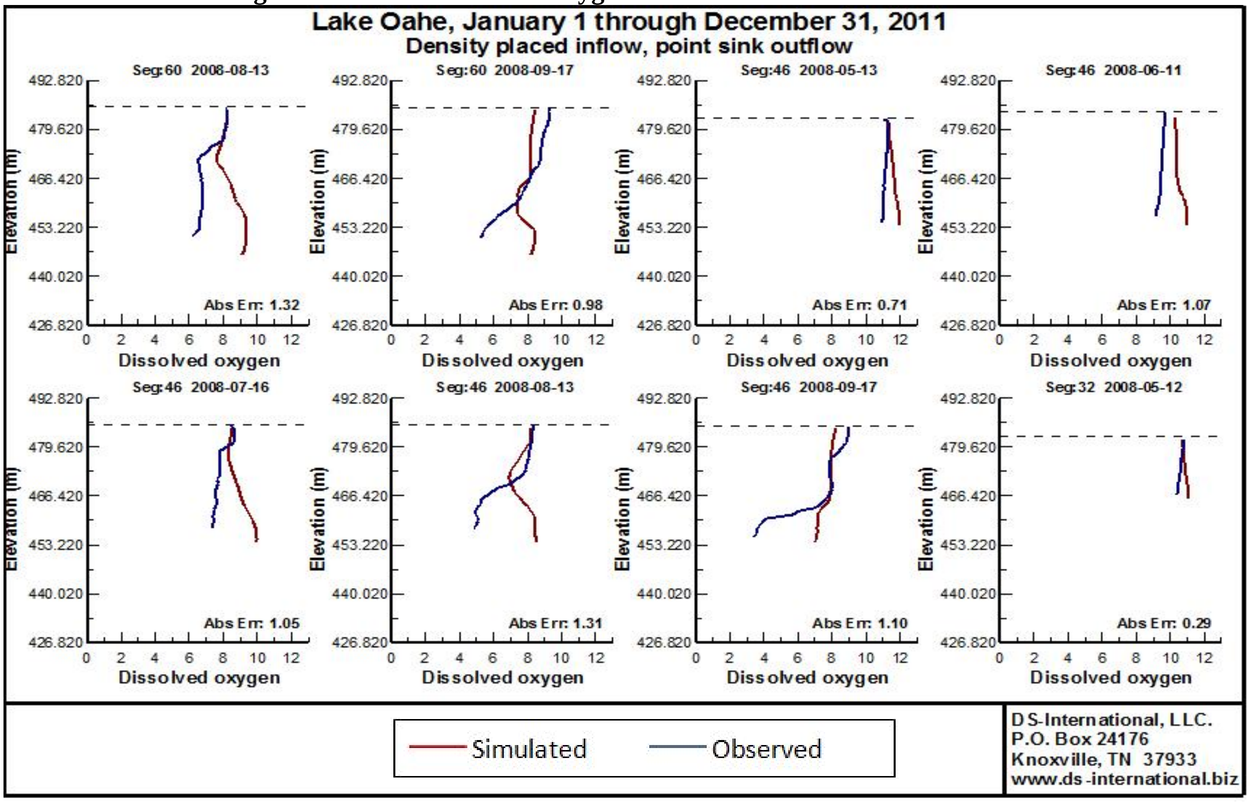

Figure 7-40. 2008 dissolved oxygen calibration at stations O3, O5, and O7

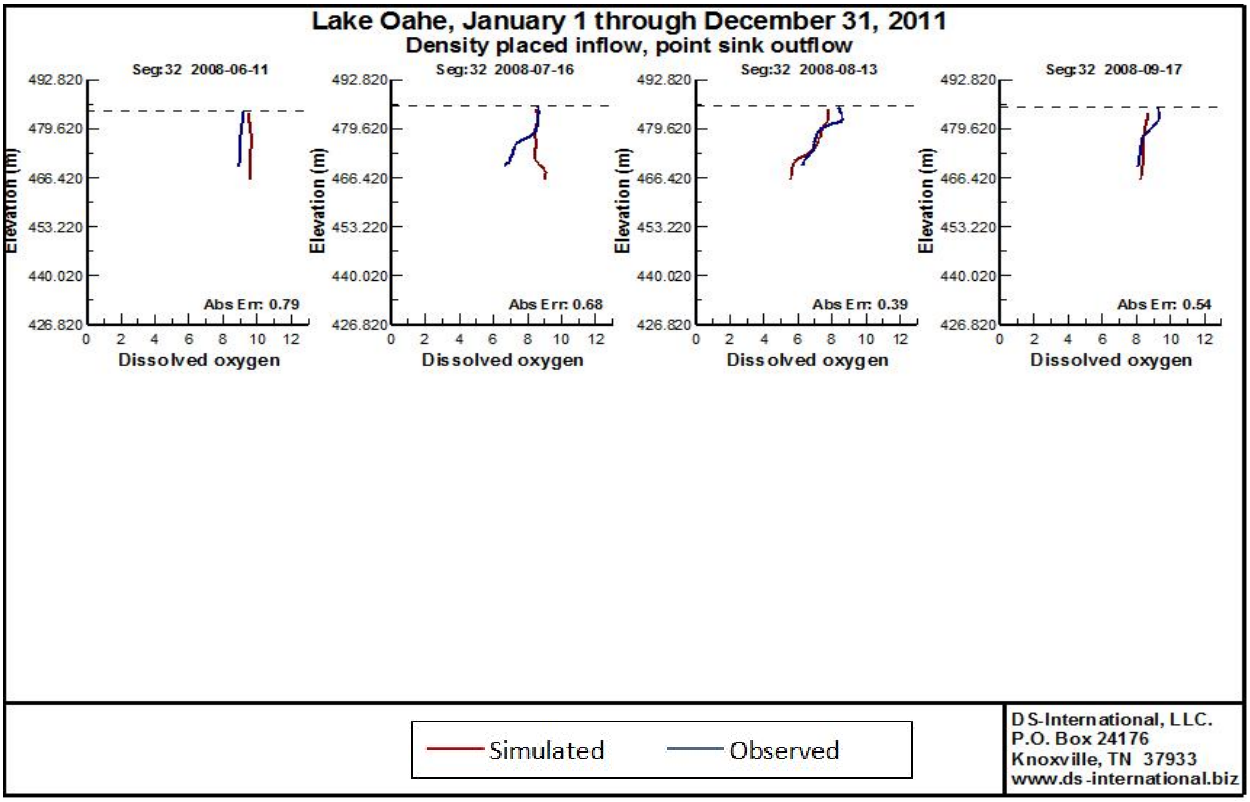

Figure 7-41. 2008 dissolved oxygen calibration at station O7

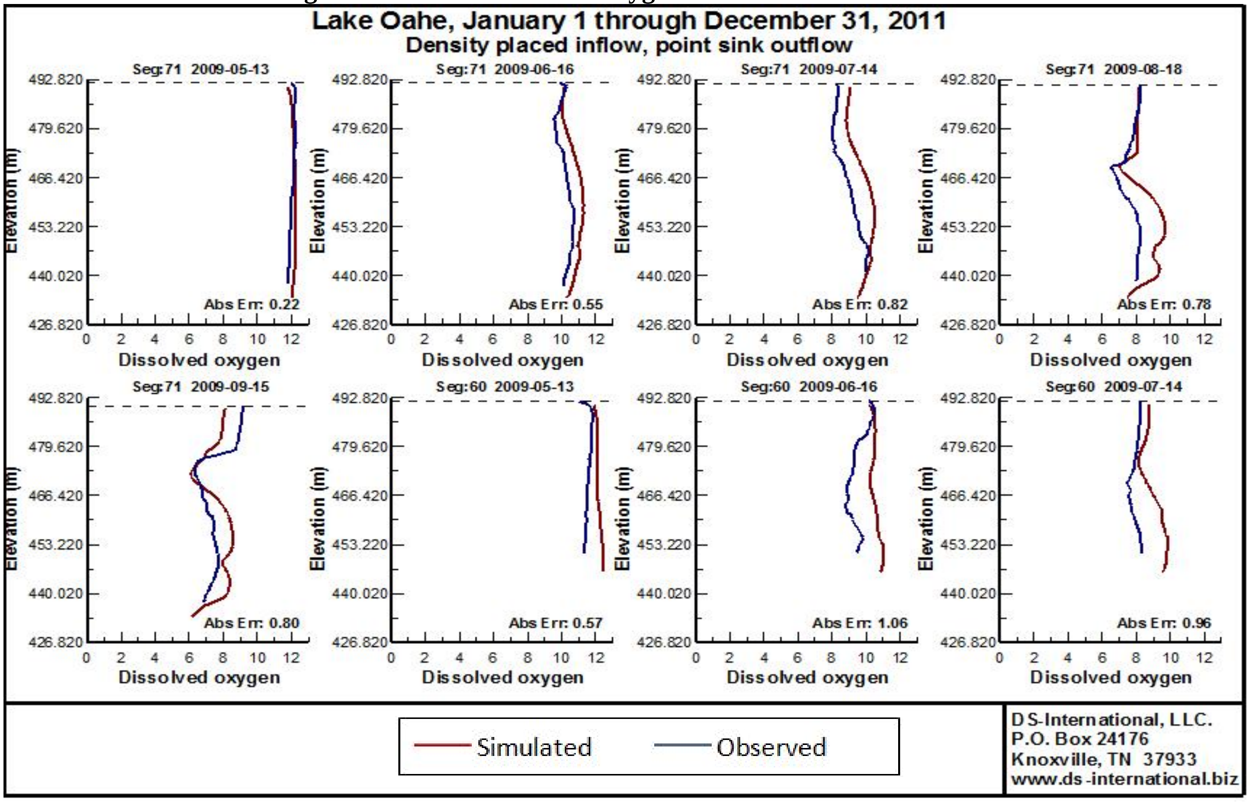

Figure 7-42. 2009 dissolved oxygen calibration at stations O1 and O3

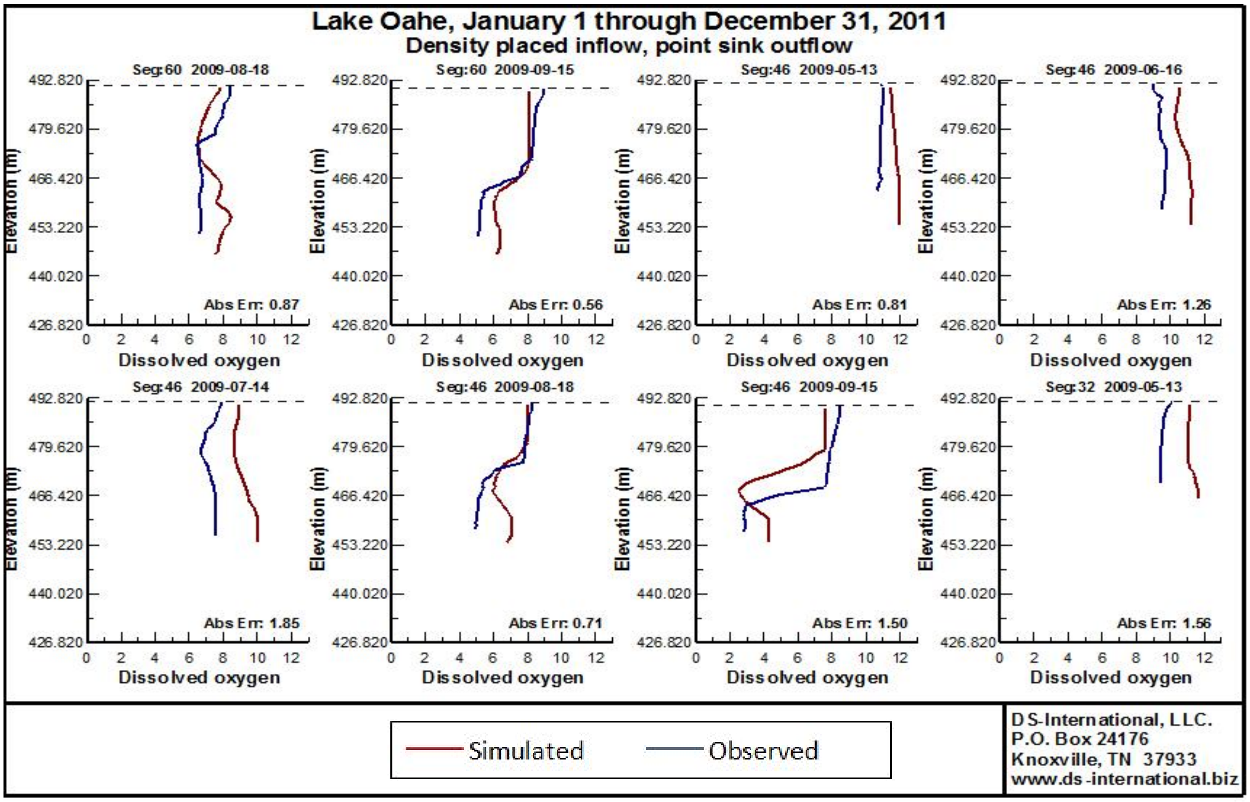

Figure 7-43. 2009 dissolved oxygen calibration at stations O3, O5, and O7

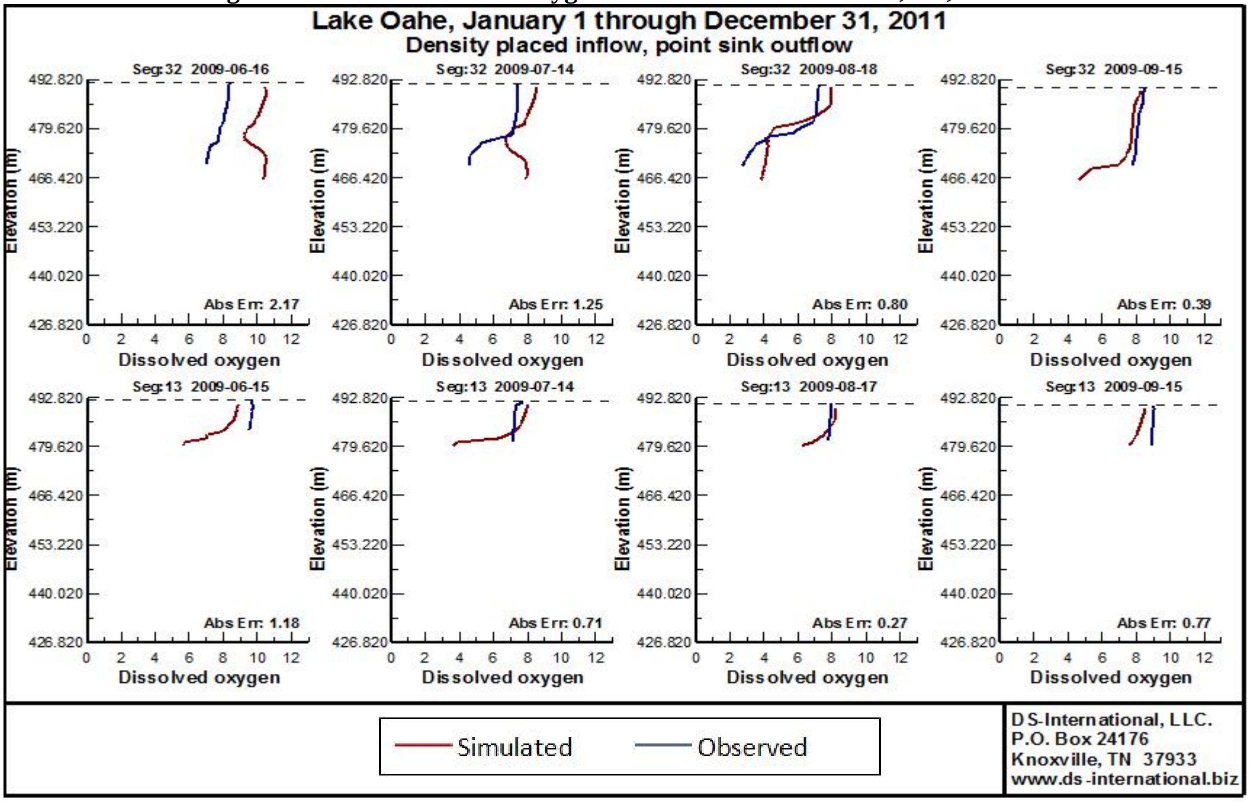

Figure 7-44. 2009 dissolved oxygen calibration at stations O7 and O8

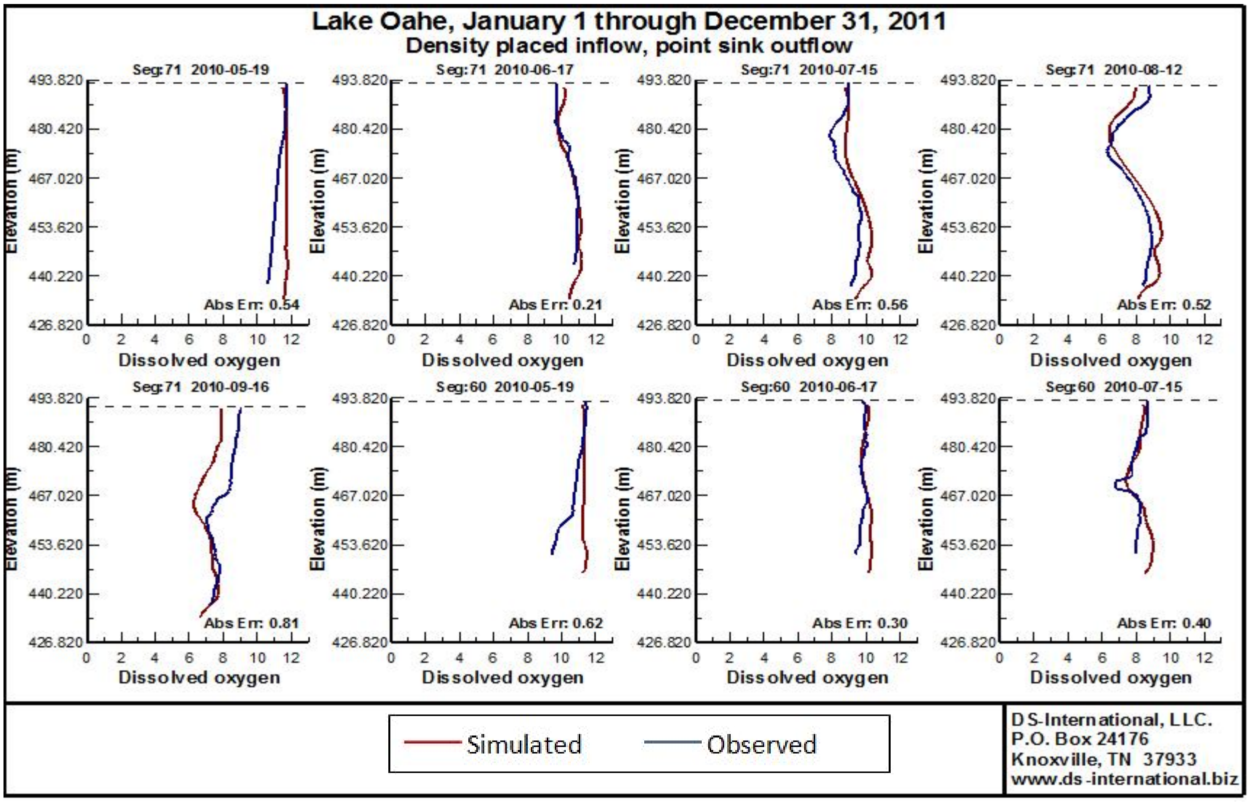

Figure 7-45. 2010 dissolved oxygen calibration at stations O1 and O3

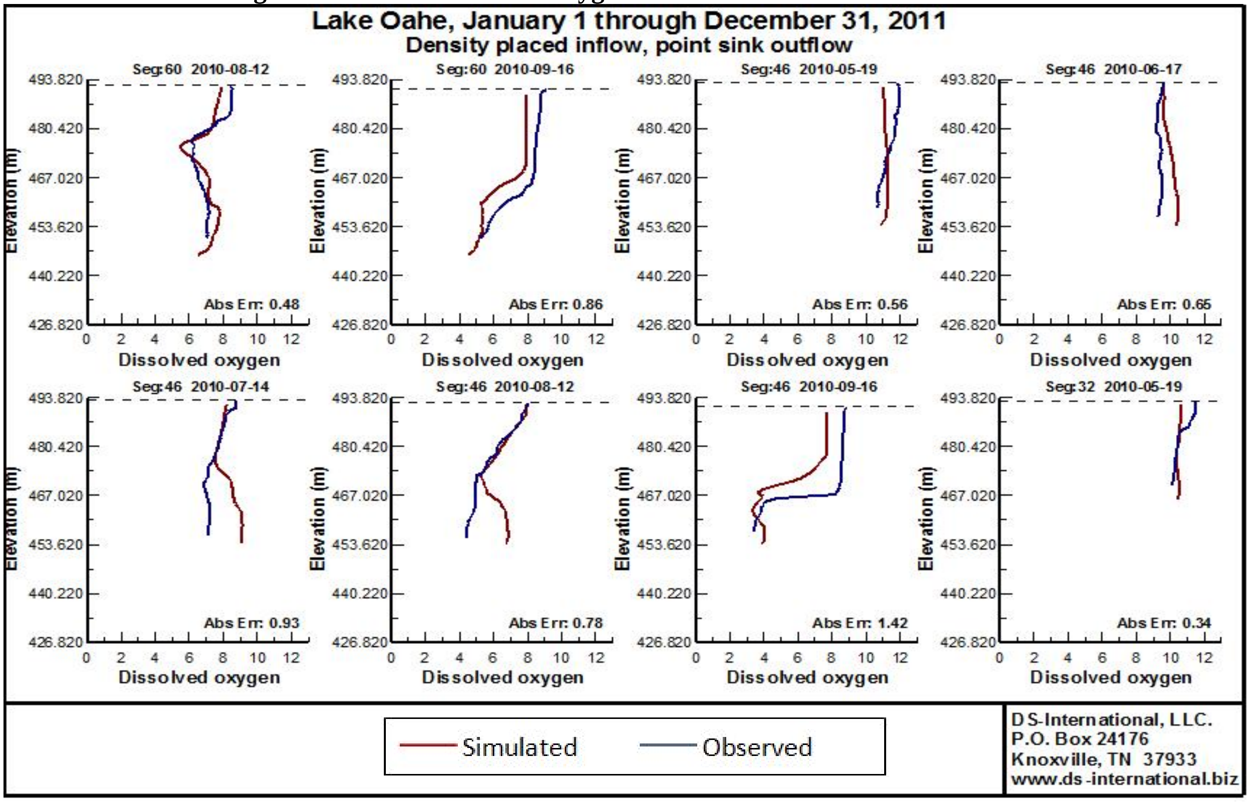

Figure 7-46. 2010 dissolved oxygen calibration at stations O3, O5, and O7

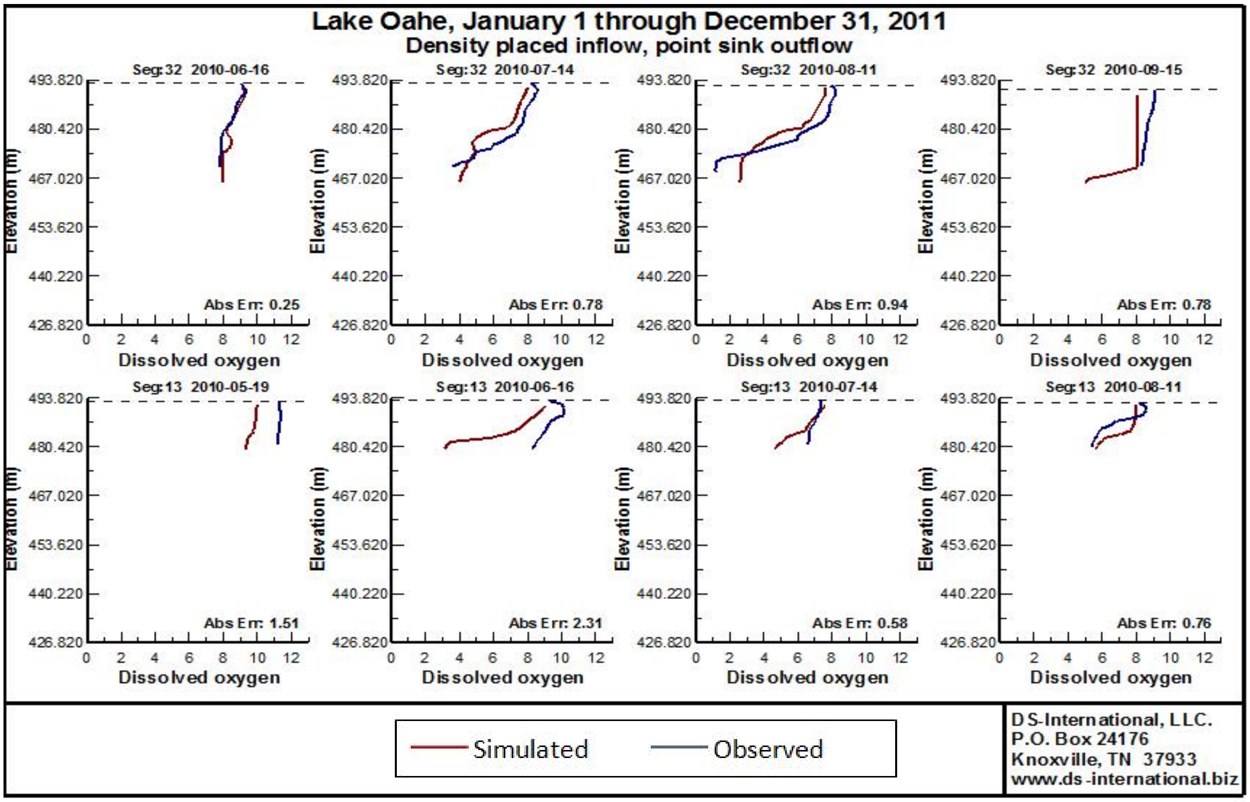

Figure 7-47. 2010 dissolved oxygen calibration at stations O7 and O8

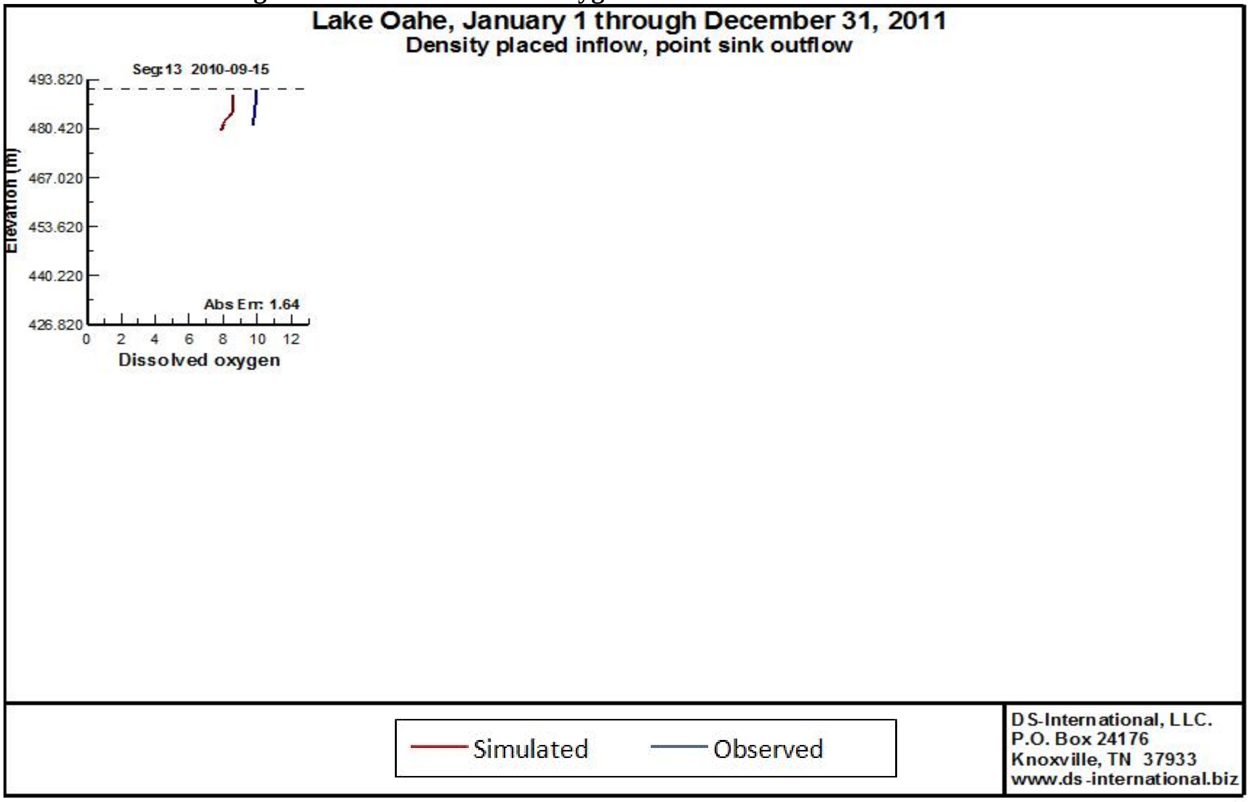

Figure 7-48. 2010 dissolved oxygen calibration at station O8

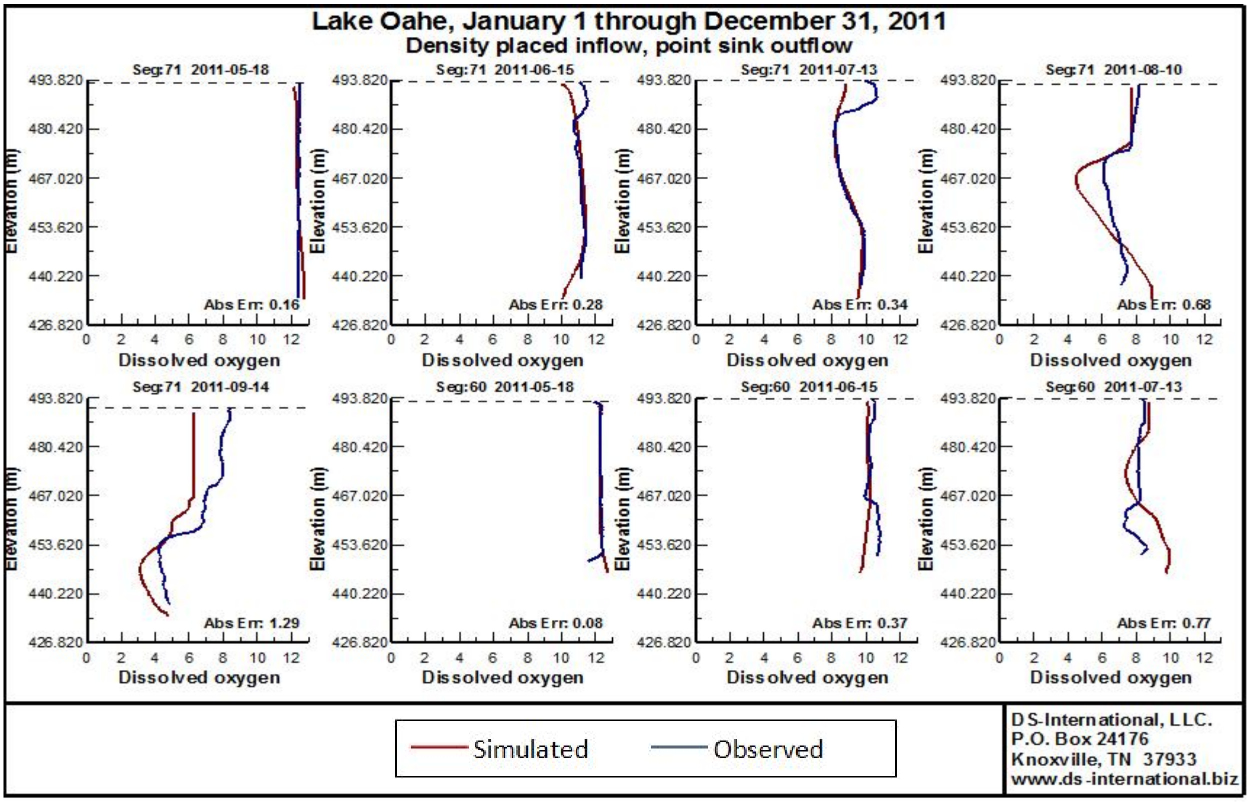

Figure 7-49. 2011 dissolved oxygen calibration at stations O1 and O3

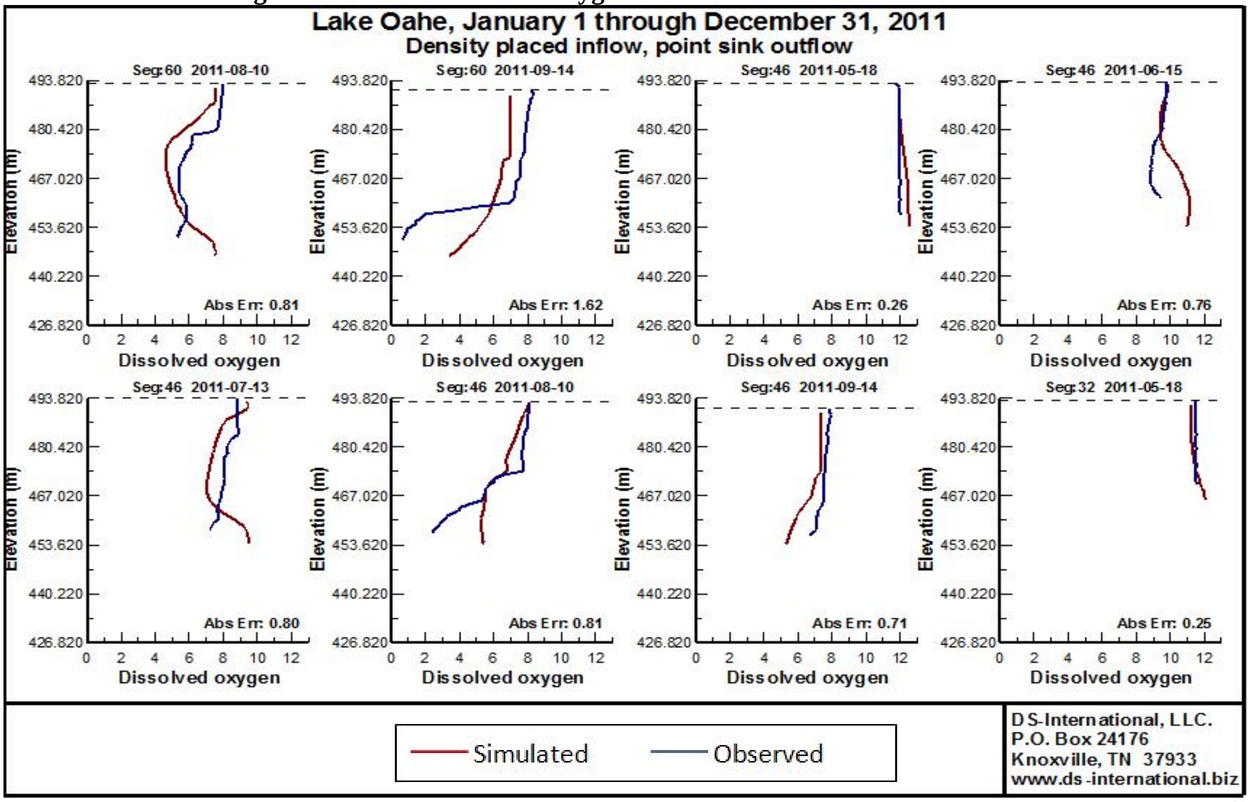

Figure 7-50. 2011 dissolved oxygen calibration at stations O3, O5, and O7

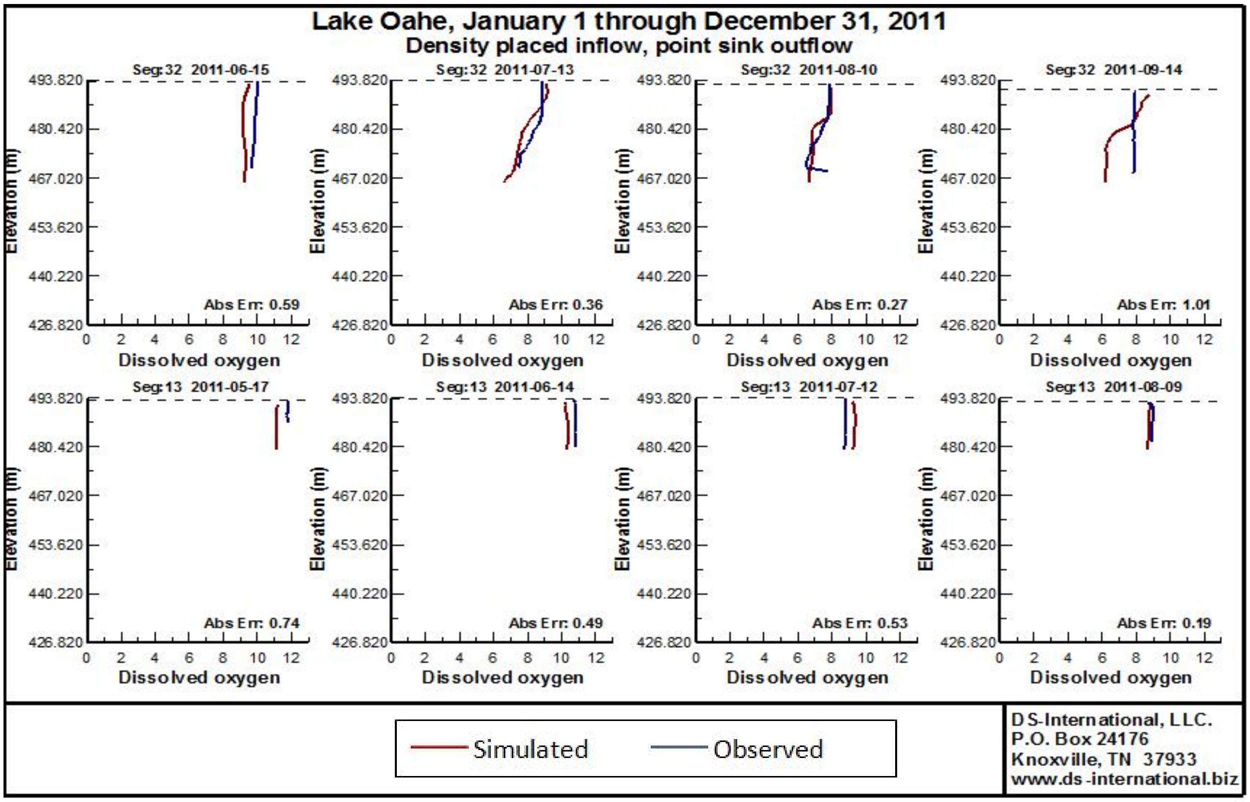

Figure 7-51. 2011 dissolved oxygen calibration at stations O7 and O8

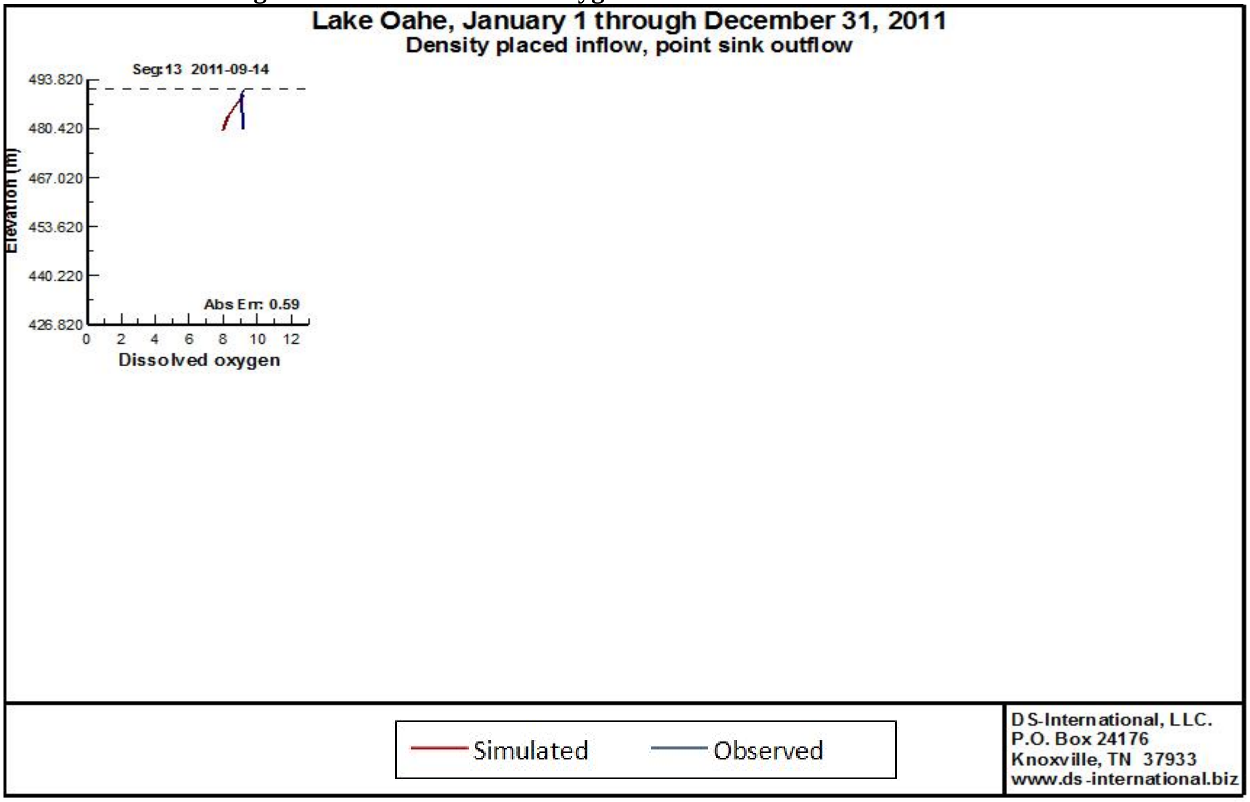

Figure 7-52. 2011 dissolved oxygen calibration at station O8