A CE-QUAL-W2 Model for Dissolved Oxygen in the Big Eau Pleine Reservoir, Wisconsin to Understand and Manage Winter Anoxia

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Executive Summary

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What is it?

The ***Big Eau Pleine Dissolved Oxygen Model*** uses size and shape of the reservoir, weather, river flow and water level in a computer simulation to project how oxygen concentrations vary under the ice in the Big Eau Pleine. The model was developed by researchers at the University of Wisconsin-Stevens Point and the University of Wisconsin-Extension along with a technical committee of individuals from BEPCO, DNR, WVIC, Marathon County and the River Alliance. The Model used the Army Corps of Engineers CE-QUAL-W2 modeling system. The figure below shows how the model segments the reservoir and calculates the dissolved oxygen concentration throughout the reservoir.

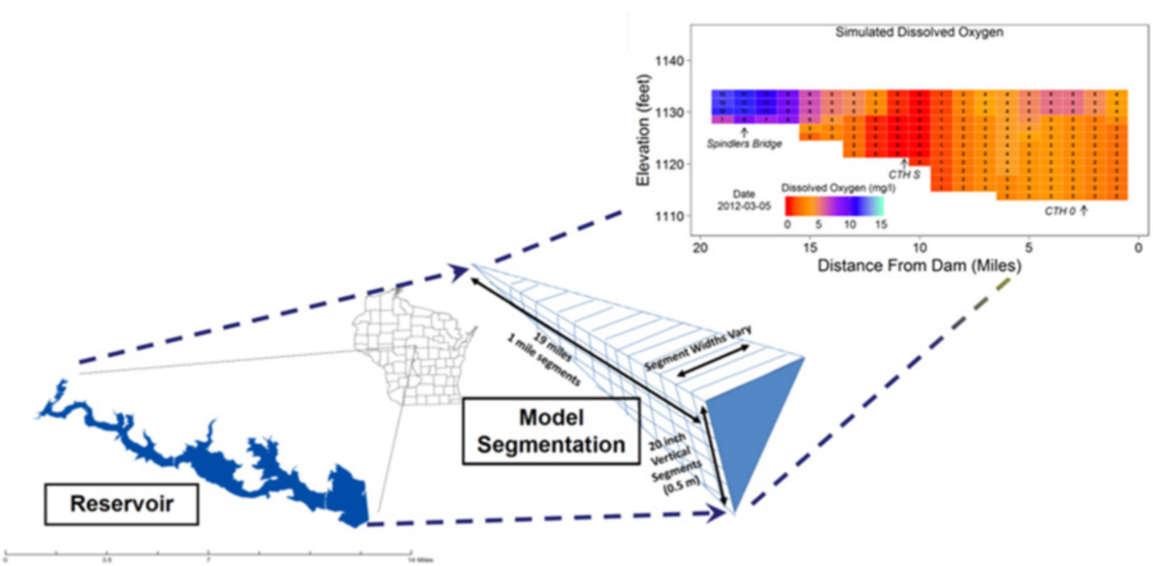


Figure 1. Schematic illustration of how the Big Eau Pleine Dissolved Oxygen Model simulates the shape of the reservoir and calculates a dissolved oxygen concentration in the reservoir profile

Why did we do this?

The ***Model*** was used to understand oxygen concentrations under the ice during the winter because the Big Eau Pleine has had problems with winter fishkills since it was created in the 1930s. The model allows us to compare the importance of individual factors on winter oxygen concentrations. It is important to note that while the model uses a state-of-the-art computer simulation tool, it simplifies the many and complex processes that occur in the reservoir.

What did we learn?

Oxygen is used under the ice by bacteria decomposing organic material that has accumulated in the sediments. This ***sediment oxygen demand*** is very high in the Big Eau Pleine. That is consistent with the large quantity of nutrients that flow in from the watershed, the resulting high concentration of phosphorus in the reservoir and the conversion of that phosphorus to algae in the reservoir.

Oxygen depletion during the winter follows warming of the water in the reservoir. During the winter, heat stored in the sediment during the summer warms the water from the bottom. This accelerates the upward propagation of low oxygen water during the winter. In reservoirs like the Big Eau Pleine, the high sediment area and the high sediment oxygen demand can rapidly deplete oxygen in the water under the ice.

Figure 2 shows a typical yearly pattern of water ice formation, water level lowering and dissolved oxygen depletion. The study showed the importance of ***winter length*** or the time between ice formation and the spring flush that replaces much of the water in the reservoir on oxygen concentration. In many years, the spring flush occurs by early March. In a few years, the spring flush occurs much later. In 2013, that flush did not occur until March 30.

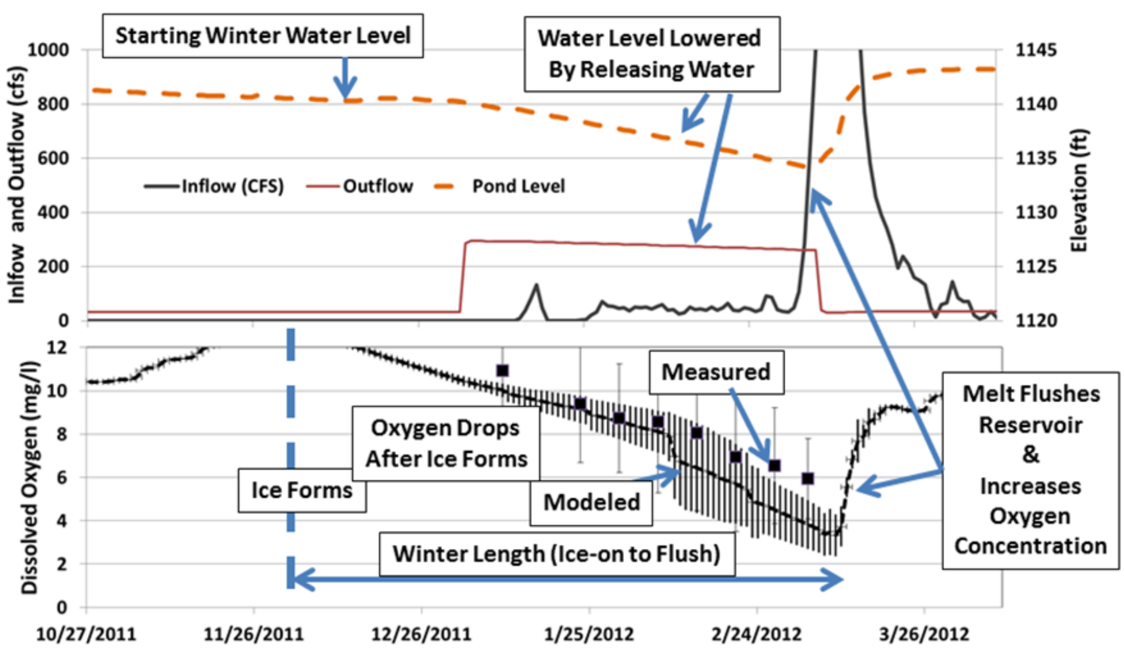
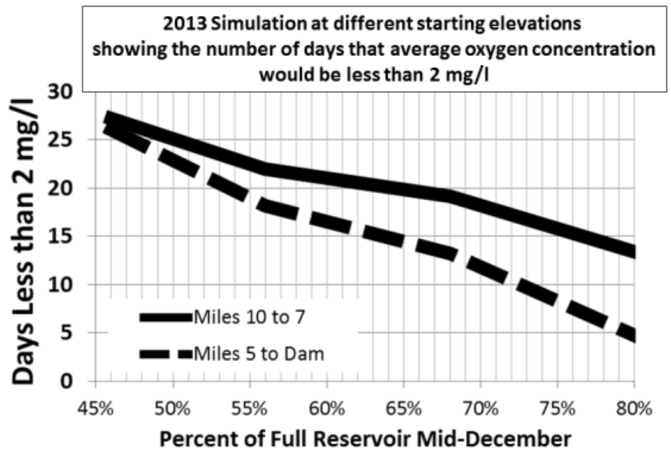


Figure 2. Comparison of water level operation (above) and dissolved oxygen concentrations (below) during a typical winter in the Big Eau Pleine Reservoir

The w***ater level in the reservoir*** is important to how the oxygen concentration drops during the winter. The model can be used estimate how different water levels would have affected the oxygen concentrations. For example, Figure 3 shows how, using characteristics of the 2013 winter, higher starting water levels at the start of winter would decrease the number of days that the average oxygen concentration is low. For example, starting the winter at 60% full, would result in almost ten more days where the dissolved oxygen would be greater than 2 mg/l than starting at 45% full.

Figure 3.



The model can be used to examine ***the combined effect of water level and winter length***. As Figure 3 shows, for the very long winter length in 2013, although the duration of lower oxygen levels is shorter as the starting elevation is increased, the model projects some days of low oxygen under all the starting water elevations shown.

The study shows how ***reductions in sediment oxygen demand*** will benefit the reservoir. Similar to higher starting elevations, a reduction in sediment oxygen demand leads to more days during the winter that the oxygen concentration is higher. The model projects that a ten percent reduction in sediment oxygen demand would add another week where the average oxygen would be above 2 mg/l near the dam.

The ***aerator*** was also examined in the model. It uses mixing to create an opening in the ice that allows oxygen to transfer from the atmosphere to the water. The result is that the aerator can provide a zone of higher oxygen concentrations. The model suggests this zone will not travel far in low-flow winters but that it should be able to overcome the oxygen demand in the vicinity of the aerator.

For ***more information***, you can view the full report at *www.uwsp.edu/cnr-ap/watersheds*

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1. Introduction

The Big Eau Pleine Reservoir (BEP) in Marathon County, Wisconsin is an important recreational fishery and storage reservoir in the Wisconsin River system with a long history of dissolved oxygen depletion during the winter. Its location is shown in Figure 1. It has an area of 6,677 acres and a maximum depth of 46 feet. The reservoir was created in 1936 by damming the Big Eau Pleine River as a storage reservoir to hold spring runoff and release it later to reduce peak flows and increase low flows in the Wisconsin River. It operates in tandem with other reservoirs managed by the Wisconsin Valley Improvement Company (WVIC). With its large area and a working water level range of 20 feet, it has the largest storage volume of any of the reservoirs in the Wisconsin River system (WVIC, 2015). As a recreational fishery, the BEP contains northern pike, muskellunge, walleye and panfish. The Big Eau Pleine Reservoir has blooms of algae in the summer and depletion of dissolved oxygen in the winter. These problems fundamentally originate in the transfer of nutrients and organic matter from the watershed to the reservoir. Nutrients lead to algae growth that ultimately settles to the bottom and depletes oxygen when it is decomposed. The oxygen depletion can lead to anoxia or dissolved oxygen concentrations that are too low to sustain the fishery.

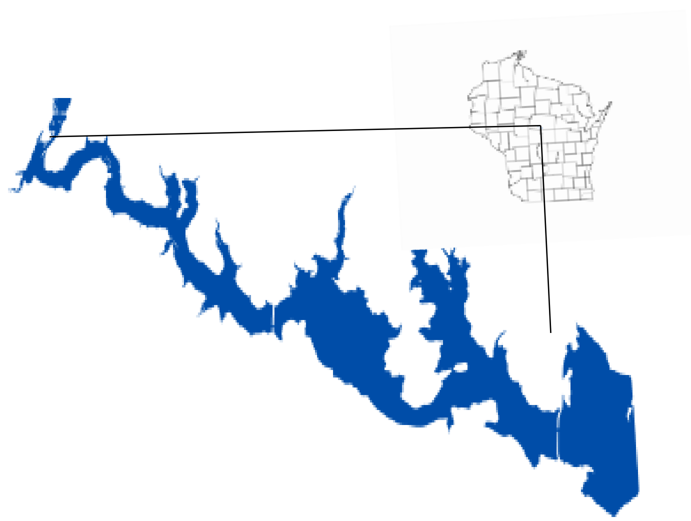


Figure 1. The Big Eau Pleine Reservoir and its location in Wisconsin.

The Big Eau Pleine Reservoir has a 363 square mile watershed with a high runoff generating potential. A high percentage of the watershed is comprised of agricultural and other developed land uses, with much of the developed land in agricultural fields and trafficked areas. These areas can result in rapid conveyance of rain and melted snow through waterways and drainage channels. This rapid transport increases the rate of nutrient transfer from land to water. In the Big Eau Pleine watershed, developed and exposed soils, low infiltration rate soils, wet soils and exposed Precambrian bedrock all act to increase runoff rates.

The oxygen concentration during the winter in the Big Eau Pleine Reservoir reflects the balance between oxygen input, oxygen output and the change in the amount of oxygen stored in the reservoir. Before the reservoir freezes, oxygen is transferred from the atmosphere and winds mix the water. After the reservoir freezes, the only sources of oxygen are inflow from the Big Eau Pleine River, algal photosynthesis under the ice and oxygen from aeration. Oxygen is lost through the decomposition of organic matter in the sediment (often termed the "sediment oxygen demand" or "SOD"), decomposition of organic matter in the incoming streamflow (termed "biochemical oxygen demand" or "BOD"), and outflow from the reservoir.

Over the last forty years, several recommendations have been made to reduce the likelihood of winter anoxia and fishkills in the Big Eau Pleine. Shaw (1979) and Sullivan (1979) suggested that higher water levels in early winter would reduce the impact of sediment oxygen demand on oxygen concentrations. Shaw also recommended a minimum pool of 25% to 30% of full volume at the end of the winter. Coon (1998) described how reservoir elevation, streamflow and drawdown timing were all important to the movement of upstream anoxic water and consequently to downstream anoxia in the Big Eau Pleine. He suggested a flexible management strategy that using those factors to control the development and movement of the oxygen depleted zone. BEPCO (2011) analyzed forty years of reservoir data and showed that there were no fish kills when the reservoir was both 60% full at the start of winter and 20% full at the end of winter. In the years where fishkills were reported, one or both of those criteria were not met. BEPCO (2011) suggested starting the winter with 60% of full volume and ending with no less than 20% of full volume. While all these studies suggested a relationship between water levels and anoxia in the Big Eau Pleine, the extent to which streamflow, weather, runoff and other factors combine with water level to contribute to the depletion of oxygen is not known.

The purpose of this study was to develop a computer simulation model to improve our understanding of winter oxygen concentrations in the Big Eau Pleine and evaluate management actions to prevent anoxia. While the sources of winter oxygen depletion are understood, the extents to which site-specific conditions and year-to-year variations in runoff, water level, air temperature, and ice cover determine oxygen concentrations are not. In this study, we incorporated eighteen years of monitoring in the Big Eau Pleine Reservoir into the development of a simulation tool using the CE-QUAL-W2 model in order to describe year-to-year variations in dissolved oxygen concentrations and explore how management actions might be developed to improve them.

2. Methods

2.1 Overview

To simultaneously evaluate the roles of factors that likely influence dissolved oxygen in the reservoir, the CE-QUAL-W2 model incorporates watershed inflow, reservoir geometry, water level management and aeration. It is a two-dimensional dynamic oxygen model that has been applied to reservoirs and lakes worldwide. It was developed by the United States Army Corps of Engineers and the Department of Civil and Environmental Engineering at Portland State University. It is particularly appropriate for reservoirs that have lateral homogeneity and longitudinal and vertical water quality gradients. The long and narrow morphology of the BEP make it a good candidate for the CE-QUAL-W2 model. Most applications of the model have been in growing season or unfrozen conditions. Few previous studies examined the dissolved oxygen concentrations in a reservoir under ice cover. While the CE-QUAL-W2 model has the ability to simulate water conditions under ice, this is a relatively novel application of the model and we used the model and results from previous studies to develop a conceptual understanding of how oxygen depletion occurs in the BEP.

2.2 Parameter Estimation

Reservoir Morphology. In the BEP CE-QUAL-W2 model developed for this study, the reservoir was divided into nineteen segments along the centerline from the dam upstream to STH HWY 153. Segment locations were approximately centered on locations where monitoring data has historically been collected by WVIC. Each segment had a length of 1 mile (1600 meters).

The shape of each segment was characterized by an average width estimated for each half meter depth. These dimensions were approximated using the bathymetric map of the reservoir created in 1969 (WDNR) and a review of historical aerial photographs. Figure 2 shows the importance of elevation change to water width in several upstream segments. The widths at each depth were then used to calculate the volume of the reservoir at different water levels. As shown in Figure 3, the width and depth relationship used in the model corresponds to the reported relationship in the reservoir. The results of the model are summarized in Figure 4 as the volume of water in each reservoir segment at different water level elevations. Most of the water volume in the Big Eau Pleine Reservoir is in the downstream half as shown in Figure 5. The largest volume segments are those nearest the dam.

Figure 2. Examples of segmentation and comparison of the influence of elevation on channel width in the Big Eau Pleine Reservoir.

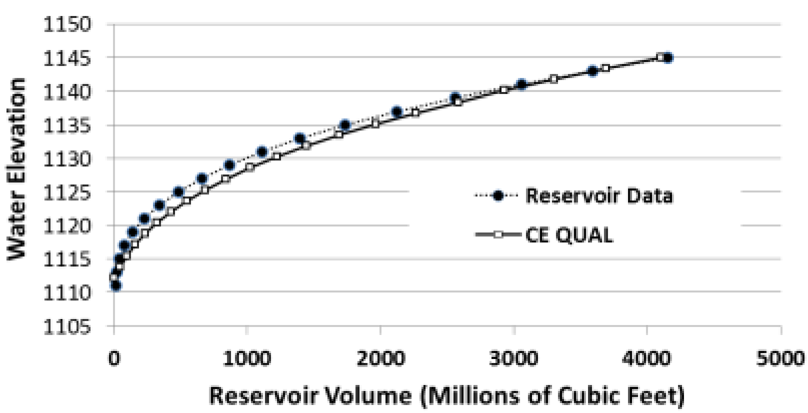


Figure 3. Volume/elevation relationship in the Big Eau Pleine Reservoir. Reservoir data provided by WVIC and the CE-QUAL data from bathymetry used in the model

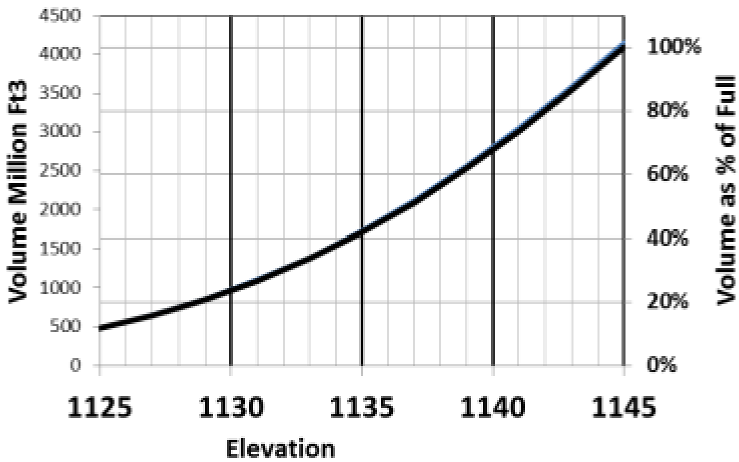


Figure 4. Relationship between reservoir water elevation and both the volume (left) and percentage of full resevoir volume (right).

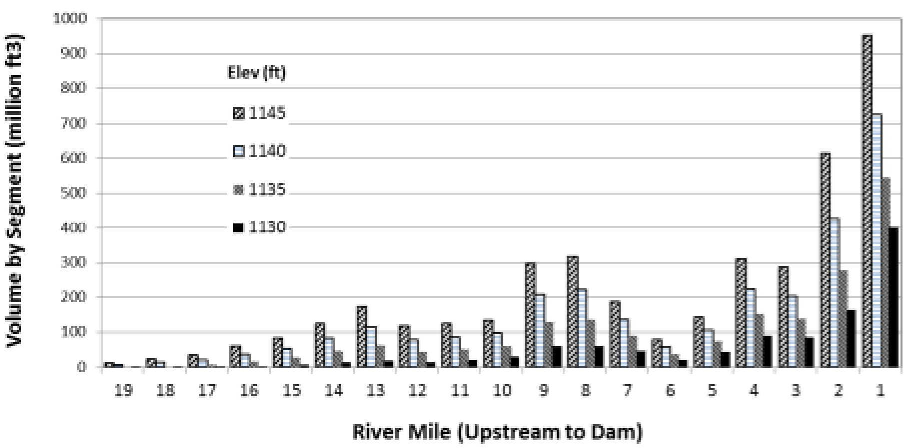


Figure 5. Reservoir volume by mile segment at different water elevations.

Model Weather and Flow Input. The model used daily weather, tributary flow and reservoir outflow data. Temperature and wind speed/direction were based on data from the nearby Marshfield, WI weather station. Daily air temperature was calculated as the average of the maximum and minimum for the day. Fifty percent cloud cover was assumed. The inflow into the reservoir on a day was based on the outflow from the next day and the change in volume from the next day to the current day. The calculation used was:

$$(\text{Flow In})_{Day1} = (\text{Reservoir Volume})_{Day2} - (\text{Reservoir Volume})_{Day1} + (\text{Flow Out})_{Day2}$$

If the calculated daily inflow was negative, the calculator assumed a minimum inflow (2 cubic feet per second) and tracked the water gained in the reservoir and subtracted it later when the inflow was greater so that the water budget was maintained. For the CE-QUAL input file, the estimated daily inflow was smoothed across four days with half assigned to that day, and twenty percent from each adjacent day and ten percent from a second day. This smoothing prevented extremely abrupt changes in inflow that could lead to problems with the model solver. This approach yields a good match between measured and modeled elevations as shown in Figure 6.

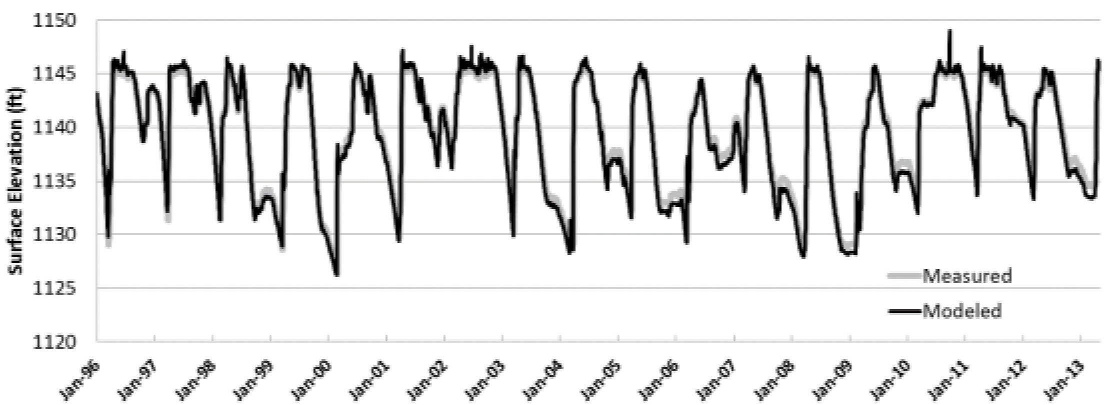


Figure 6. Comparison of measured and modeled surface elevation, 1996-2013.

The temperature of the inflow to the reservoir was generalized based on the air temperature and measurements during the winter. A triangular distribution was used during the spring, fall and summer and a minimum temperature of 0.1 degrees during the winter. The winter temperature was adjusted to the average daily temperature up to a maximum of 4 degrees C. Figure 7 shows how the assumed inflow temperatures vary during several years. Temperature monitoring from the upstream end of the reservoir suggested these were reasonable winter temperature ranges.

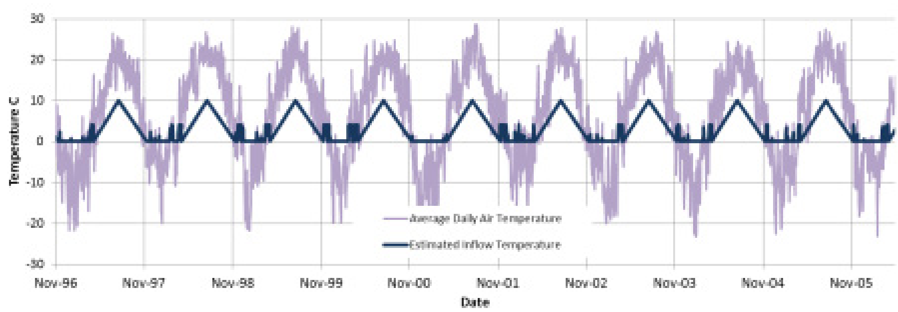


Figure 7. Comparison of the estimated inflow temperature for water entering the Big Eau Pleine Reservoir compared to the average daily air temperature. Inflow temperatures were linearly interpolated during the summer and matched to the maximum of air temperature or 0.1 degree C during the early winter.

Oxygen Depletion and Addition Rates. Oxygen is depleted in the reservoir through biological decomposition of incoming organic matter in the water and respiration that occurs at the sediment interface. This is simulated through a zero order sediment oxygen demand (SOD) proportional to the bottom area, and a first-order decomposition of the inflow biochemical oxygen demand (BOD) in the water column. Initial values for these variables were based on current literature, measured values, and recommendations from project technical staff. Adjustments were made as part of the model calibration process explained below.

The sediment oxygen demand reduces the oxygen concentration in the water under the ice at a rate that depends on the amount of sediment area relative to the water volume and the amount of time for the depletion to occur. In the Big Eau Pleine Reservoir, the ratio of sediment area to water volume is highest upstream and lowest near the dam. As the water level drops, the amount of water volume is reduced and the sediment area to water volume ratio increases. Figure 8 shows how the ratio changes with distance and water level in the reservoir. The variation in sediment area to volume can be five times larger upstream compared to near the dam. This could lead to oxygen depletion as the water moves through the first part of the reservoir. It is difficult to generalize the effect of this high area to volume ratio upstream because the residence time varies with flow rate and water level. At high flows, the water can move through the first half of the reservoir rapidly, while at low flow it takes much longer. The CE-QUAL-W2 model incorporates these daily changes in water level, sediment area to volume, and water level.

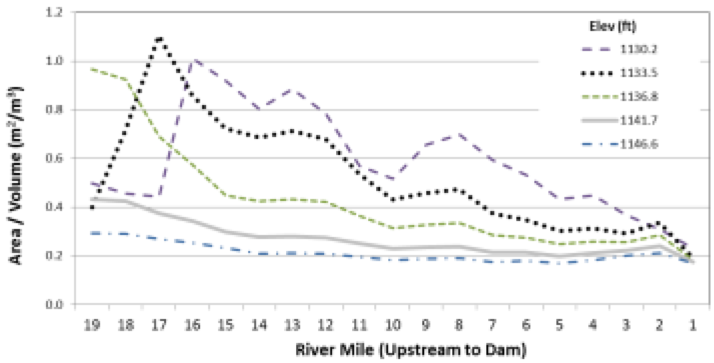


Figure 8. Changing ratio of sediment area to water volume at different locations in the reservoir at different water elevations.

The inflow biochemical oxygen demand was simulated in the model as a rainfall or runoff event-driven BOD assigned to the water entering the reservoir. Monitoring by the WVIC and WDNR at the upstream end of the reservoir was used to examine the relationship between flow and BOD both to determine how to determine which days should be assigned event flow and what BOD to assign to those flows. Higher BOD was associated with small increases in flow and/or warmer air temperatures. The measurements also generally support lower event BOD with increasing flow consistent with a dilution of incoming oxygen demand during high flows. Figure 9 shows how the measurements can be modeled as a function of flow. This approach describes a general trend and as the graph shows, it may under- or over-estimate an individual event.

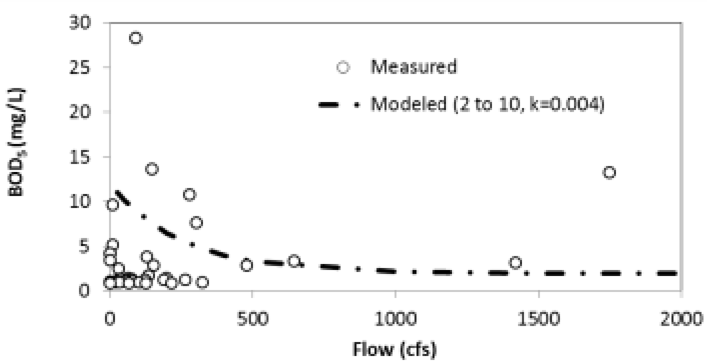


Figure 9. Measured biochemical oxygen demand (BOD5) in the reservoir and predictive relationships between flow and BOD5 used in the model. Modeled inflow BOD ranges from 10 mg/l to 2 mg/l with a first order reduction as flow increases.

Aeration. An aeration system located across from Big Eau Pleine County Park at river mile 5.6 adds oxygen to the reservoir. The system uses coarse bubbles to bring warm water in contact with the ice to open a hole that allows oxygen to be transferred from the atmosphere. The dates for adding oxygen from aeration were based on the historical record. Sullivan (1982) monitored oxygen upstream and downstream of the aeration system in 1981 and 1982 to estimate an oxygen transfer of 1000 to 1600 kg/day (2400 to 3600 lbs/day) using monitoring above and below the system and estimates of water flow through the aeration zone. Because time is required to fully open the ice and oxygen demand below the ice must be overcome, this study evaluated different oxygen addition rates and used the same daily rate for all aeration days.

2.3 Model Calibration Approach

The Big Eau Pleine oxygen model calibration was the process of determining the appropriate model inputs to match the observed measurements. The calibration approach used known values of the many of the model inputs followed by a trial and error approach to adjust the other parameters to best match the observed temperature and dissolved oxygen concentrations in the reservoir. Dissolved oxygen and temperature profile measurements collected at one mile intervals on multiple dates each year by the Wisconsin Valley Improvement Company (WVIC) were compared to model output. This was a complex process that used visual matching of the year-by-year variations in measurements and calculation of several model evaluation metrics. These efforts were aided by a graphical profiles created from model output at 236 locations to create temperature and oxygen profiles that could be compared with the measured results. Figure 10 shows example output profile.

We compared the measured and modeled dissolved oxygen across several smaller areas that were identified as critical to determining the severity of the oxygen depletion late in the winter. These areas or "metrics" were the areas shown in Figure 10 defined by the horizontal distance and vertical depth on the profile. Two metrics will be used in this report 1: Metric 2 is the upper 1.5 meter of the reservoir from Mile 6 (just upstream of the aerator) to Mile 10; Metric 3 is the upper 3.0 meter of the reservoir from Mile 4 (downstream of the aerator) through Mile 1 (near the dam). It was important to include the top of the reservoir in these metrics because that is where the highest oxygen concentrations are found during the winter. Because these metrics are based on the top of the reservoir, their actual vertical location will vary depending on the water level in the reservoir.

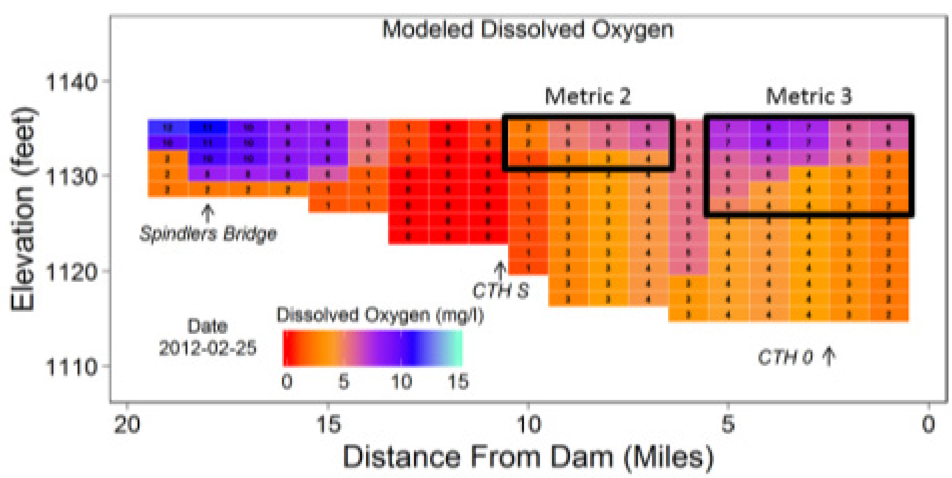


Figure 10. Reservoir cross section showing model results as dissolved oxygen concentration in each layer in each segment. Concentrations within the area for Metric 2 and Metric 3 were averaged for each day.

2.4 Model Calibration Parameter Estimation

The goal of the calibration was to develop a simulation model robust enough to describe the year-to-year differences in the dissolved oxygen concentration in the reservoir. The calibration process showed the temperature variations in the reservoir were related to the dissolved oxygen variations. As a result, both temperature and dissolved oxygen were calibrated in the model.

Temperature Calibration. Under the ice, temperature profiles in the BEP show the development of "winter stratification." Winter stratification occurs because water has its maximum density at 4 degrees C. During the winter, the cooler (less than 1degree C) water is less dense and is near the surface, while the warmer (4 degree C) water is denser and deeper in the reservoir. This impacts how incoming water is distributed in the reservoir because cooler water can flow over the warmer, denser water. It also affects oxygen depletion because if there is less mixing due to temperature stratification, the warmer water near the bottom becomes depleted in oxygen while the upper cooler water may remain oxygenated. The temperature calibration made adjustments in several parameters related to heat transfer at the ice surface and at the sediment interface. The temperature calibration adjusted the ice cover albedo (increased from 0.30 to 0.40) to reflect more radiation, increased the coefficient of water-ice heat exchange (from 10 to 13 W/m^2-degree C) to cool and heat the surface of the water, set the sediment temperature at 9 degrees C to provide warming of the water from the bottom under the ice, and increased the coefficient of bottom heating (to 1.6) to account for the complex bottom topography that could not be mimicked in the bathymetry. These were important adjustments to the model. As will be described later, the role of winter stratification is important to understanding the dynamics of dissolved oxygen depletion in the reservoir.

The onset of ice on the reservoir and the degree of mixing that occurs prior to ice formation are also important to determining the available oxygen in the reservoir. Prior to ice formation, nearly uniform density of the water in the reservoir can allow it to be easily mixed by the wind. This allows water to be oxygenated and cooled from top to bottom. Once the ice forms, oxygen addition directly from the atmosphere stops. A test of the model's ability to simulate temperature is the timing of ice development on the reservoir. Although ice-on or ice-off information was only available for a few years of the simulation period and depends on the location in the reservoir where it is determined, Table 1 shows that the model seems to provide a reasonable approximation in some years and can vary in other years.

Table 1. Measured and modeled ice-on and ice-off dates.

Model Year	Measured Ice-On	Modeled Ice-On	Measured Ice-Off	Modeled Ice-Off
2006	11/23/2005	11/25/2005		
2008			3/29/2008	3/26/2008
2009			3/18/2009	4/2/2009
2010			3/31/2010	3/8/2010
2013	12/20/2012	11/27/2012		

The CE-QUAL-W2 model does simplify the temperature and density movements under the ice and assumes some important factors, such as sediment temperature and albedo (the fraction of sunlight reflected off the surface of the snow or ice), as constant during the winter. Lake sediment temperature is at its maximum in late summer and coolest in early spring (Birge et al., 1927) and albedo varies from early winter to when the lake is snow-covered and finally in the winter when melt water on the ice increases sunlight absorption (Petrov et al., 2005). Density-driven currents are also simulated in the model at a larger scale than they likely occur. For example, mixing from the movement of warming water from shallower areas to deeper areas could occur across the width of the reservoir. This is simulated in the model as heat transfer in proportion to the sediment surface area exposed to water for each layer but not by water movement laterally. Similarly, vertical mixing when water near the sediments warms above 4 degrees C or below the ice when radiant heat is warming the top layer of the lake in late winter likely occurs as convection cells (Woodcock and Riley, 1947) that are much smaller than the one mile model segments used in the model. The model simulates all of this mixing as an exchange between layers. When there are density (temperature) differences between layers, the mixing is reduced, and when the temperature is closer between layers, the mixing between layers increases. One result is that the model tends to simulate a sharper break between cooler and warmer waters than we see in the measured profiles.

Dissolved Oxygen Calibration. The dissolved oxygen calibration was developed by comparing the measured oxygen concentrations year-by-year and exploring how that could be improved by adjusting parameters that control oxygen demand in the inflow and the sediment, and by mixing in the reservoir. This process used: 1) comparison of the measured and modeled cross section profile; 2) a linear regression between measured and modeled summaries for the cross section regions ("metrics") in the model; and, 3) time-series of the average measured and modeled oxygen concentrations for the metric regions in the model.

The calibrated sediment oxygen demand ranged from 0.35 to 0.60 g/m^2/day with the higher values closer to the dam. This is higher than the SOD for eutrophic lakes of 0.23 g/m^2/day reported by Mathias and Barica (1980) and within the range reported for some of the more nutrient-enriched lakes examined by Babin and Prepas (1985). This high SOD in the BEP is consistent with the high phosphorus loading to the reservoir from the watershed, which leads to algal production, which then leads to organic matter deposition in the sediment (Swalby, 1979; Hammermeister, 1982). James et al. (1992) reported a higher organic content of sediments closer to the dam consistent with our higher values in the downstream half of the reservoir. We simulated the SOD without temperature dependence. While we would expect that the rate of consumption is temperature-dependent, the sediment likely buffers the rate of temperature change and this allows us to compare our SOD with previous research.

The event BOD assignments were also based on a year-by-year evaluation of conditions that seem to lead to depressed oxygen in the upper portions of the reservoir at residence times that correspond to likely events in the inflow, temperature and precipitation. We developed a spreadsheet to create an inflow BOD file for the model that calculates an inflow BOD concentration for each day based on whether flow is increasing, temperature is above a threshold and/or precipitation occurs on that day. The BOD concentration is then based on the flow using the relationship shown in Figure 9. In the final calibration, the event BOD was assigned to winter days when the maximum air temperature was greater than 1 degree C and there was more than 0.25 inches of precipitation or when the maximum air temperature was greater than 3 degrees C and there was increasing flow (more than three times the lowest flow in the previous 15 days).

Table 2 summarizes the calibration parameters used.

Table 2. Calibration parameters used in temperature and oxygen simulations.

Parameter	Default	Calibrated
Albedo (fraction sunlight reflected)	0.25	0.40
HWICE (water/Ice Heat Exchange W/m2-C)	10	13
BICE (solar radiation adsorbed in ice surface)	0.6	0.7
GICE (solar radiation extinction coeff)	0.07	0.08
CBHE (coefficient of bottom head exchange)	1.0	1.65
WSV (wind sheltering coefficient)	1.0 (calibration parameter)	1.0
TSED (sediment temperature degree C)	Site specific	9
SOD (sediment oxygen demand g/m^2-d)	Site specific	0.35 (Miles 19-7) 0.40 (Mile 6) 0.50 (Mile 5) 0.60 (Miles 3-4) 0.50 (Miles 1-2)

3. EVALUATING HISTORICAL WINTER HYPOXIA IN THE BIG EAU PLEINE

3.1 Conceptual Model for Winter Oxygen

One of the objectives in this study was to examine how the model could be used to develop a better understanding of the winter dissolved oxygen concentrations in the Big Eau Pleine Reservoir. In this section, we use the simulations of the temperature, oxygen and residence time in the reservoir from three winters (2012, 2006 and 2013) as examples of the range of conditions that can be observed and as a framework to explore a conceptual model for winter dissolved oxygen in the reservoir.

In the late fall when air temperatures approach freezing, the water at the surface will cool to four degrees C and become denser than the underlying water. This leads to fall overturn. The wind can continue to mix the reservoir from top to bottom, further cool the water and oxygenate the water because there is little variation in density from top to bottom. Figure 11 shows how the measured concentrations are warm near November 1 and then cool off until early December (30 days after Nov 1). The water is coldest just before ice formation (early December). After the ice forms, the water starts to warm from the bottom. This reflects sediment warming the water. This warming reduces the density near the sediment and leads to upward convection currents. Recent research suggests this warming could also lead to flow near the bottom of lakes and reservoirs from areas of shallower water (higher sediment elevation) to deeper water. In the Big Eau Pleine Reservoir, that would move water laterally from the edge to the channel and establish a lateral current. Although not measured in the BEP, Coon (1998) reported that during some additional monitoring, they found oxygen concentrations could be higher perpendicular to the main channel. These processes all could contribute to an upward propagation of heat. Later in the winter, radiant energy from the sun and higher air temperatures also lead to warming of the water under the ice. This warming increases the density of the water near the surface and induces a circulation from close to the ice deeper into the water (Kirillin et al., 2015; Solonen et al., 2014).

The CE-QUAL-W2 model does describe fall cooling, ice formation and sediment warming in the Big Eau Pleine Reservoir. Figure 11 shows how the model simulates a cold phase near the coldest measured temperatures in the reservoir in early December (approximately 40 days after November 1). As the water warms from the sediment, the model simulates an increasing water temperature from the bottom. Later in the winter, the model simulates a relatively uniform temperature from top to bottom in the reservoir (120 days after November 1) similar to what might be encountered during convective mixing from the surface. Although the model is not describing the small-scale convective variations and lateral water movement that are likely driving these temperature variations, it is adding heat from the sediment and eventually the surface, and when the density difference between layers becomes small, mixing water between layers.

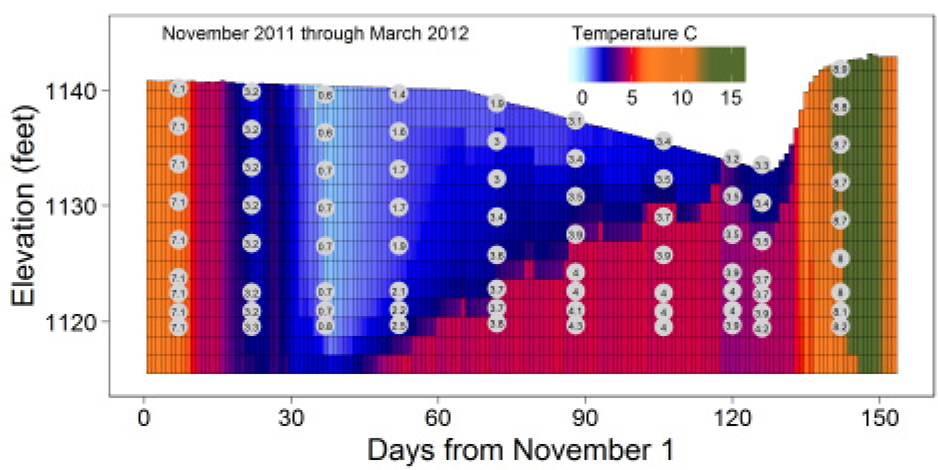


Figure 11. Measured (in circles) and modeled (color) temperature near the dam from November 2011 through March 2012.

We use an examination of three different winters to explore in more detail how the model is simulating the disappearance of dissolved oxygen and explore a conceptual understanding of the year-to-year variations in winter anoxia in the Big Eau Pleine Reservoir.

Winter 2012 (November 2011-April 2012)

The 2012 winter is an example of a relatively low inflow year that starts with an intermediate initial water level. As Figure 12 shows, flow during the winter was very low until early March when the spring melt occurred. During the winter, the reservoir elevation was lowered from approximately 1140 feet (close to 70% of full reservoir volume) to 1135 feet (40% of full volume).

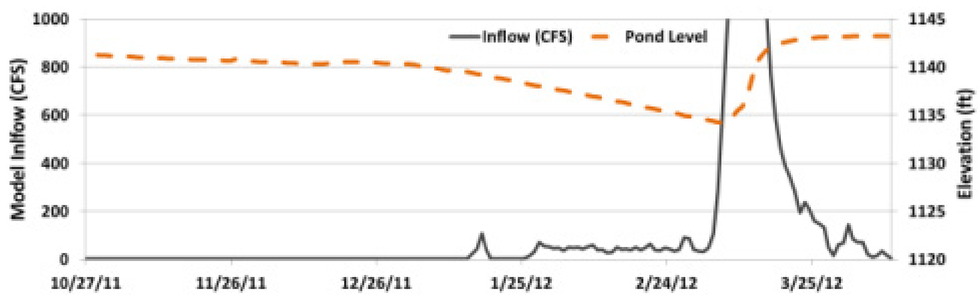


Figure 12. Variation in inflow (solid line) and reservoir elevation (dashed line) during the 2012 winter.

The 2012 winter began in early December. Both the temperature monitoring shown in Figure 12 and the modeling suggest ice formation in the first week of December. We expect the concentration of oxygen would have been close to saturation (approximately 13 mg/l) from top to bottom at that time. Simulation and monitoring results from sampling one month later are shown in Figure 13. The model simulates heating near the sediment and some upward movement. The measured results are similar although they show a more rapid upward propagation of heat than is simulated. The model shows a cool buoyant zone near the top and the measurements show a warmer surface. This difference is consistent with more convective movement and mixing in the reservoir, perhaps supplemented by lateral downslope movement, rather than the simple heating followed by density-driven mixing in the model. The model and measurements show a similar zone of greatest warming near the sediment.

Figure 13 shows that the 2012 oxygen model and measured oxygen profile maps for early January are similar with the lowest oxygen in the lower, warmest water. That is consistent with a convective upward movement of warm water from the sediment with biological decomposition near the sediment depleting the oxygen. The monitoring shows partially deoxygenated water above the bottom anoxic water. That is consistent with our interpretation of a convective mixing zone developing in the water column.

Figure 13 also shows the calculated residence time in much of the reservoir is more than 200 days in early January. That is consistent with the very low inflow during this winter and preceding fall.

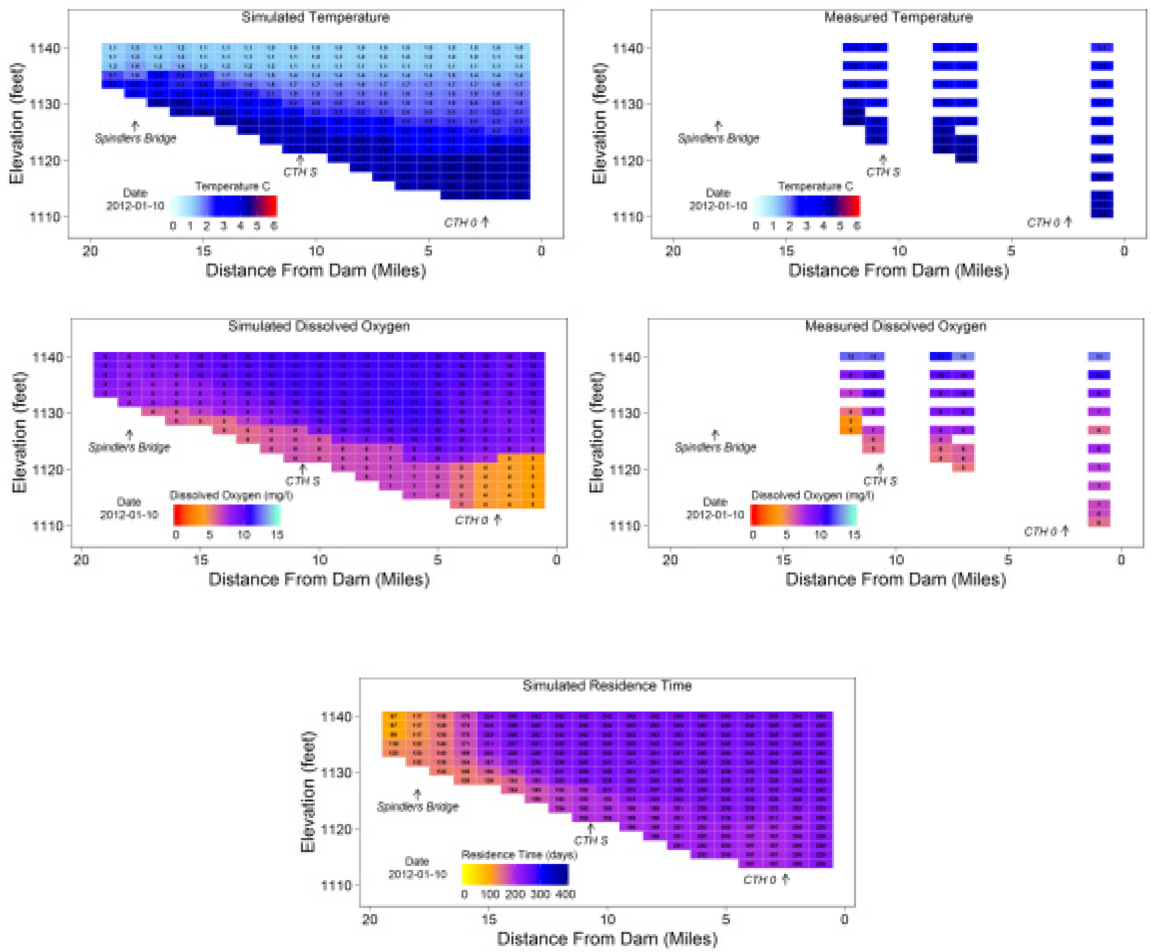


Figure 13. Results of model simulation and measured results for dissolved oxygen, temperature and residence time from early January 2012 approximately thirty days after ice formation.

The temperature and dissolved oxygen profiles approximately one month later in early February 2012 are shown in Figure 14. These show a continued upward progression of warming in both model and measurements along with an oxygen depletion that is greatest in the warmest water. The model and measurements show a similar depth of maximum warming and oxygen depletion. The difference between model and measurements is in the intermediate zone that show a mixing between the warmer deoxygenated waters and the overlying oxygenated water. The measurements also show several oxygen concentrations at the water surface that were near 14 mg/l and suggest photosynthesis was occurring under the ice. Water in the much of the reservoir is relatively old and Figure 14 also shows the residence time in the downstream half of the reservoir is still more than 200 days.

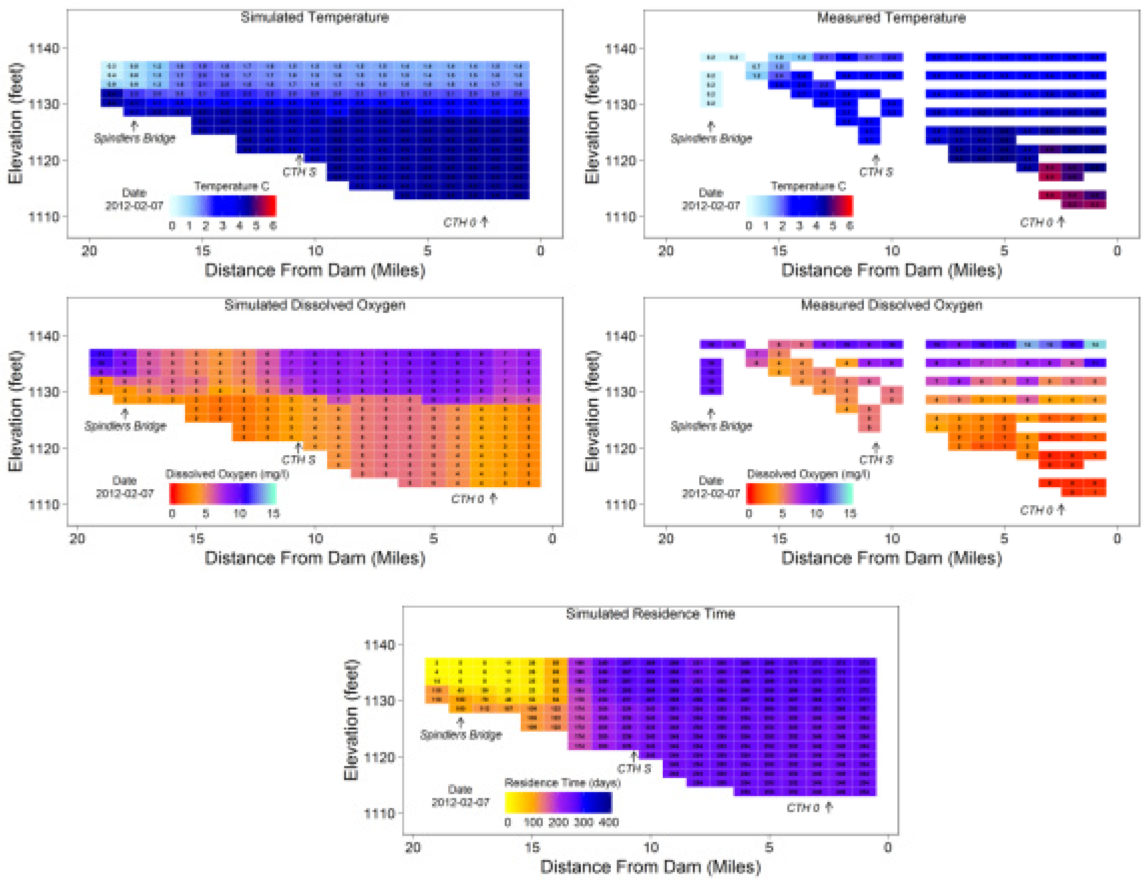


Figure 14. Results of model simulation and measured results for dissolved oxygen, temperature and residence time from early February 2012 approximately sixty days after ice formation.

Figure 15 shows the temperature and oxygen during the 2012 winter several days before the spring flush. The aerator was on and the model shows that as slightly cooler water at Mile 6. Measurements are not available at Mile 6 during aeration, but immediately downstream of the aerator the water was slightly cooler. That is consistent with the aerator contacting water with the atmosphere. Much cooler temperatures are also shown at the upstream end of the reservoir where melt water was starting to enter. Much of the oxygen has been depleted and both model and measurements show concentrations between zero and 3 mg/l. Higher concentrations are shown in the model at the aerator and just downstream of the aerator. Higher concentrations are shown in the measurements just downstream of the aerator and at the surface near the dam. The high concentrations near the surface are consistent with the photosynthesis that was present earlier. The residence time distribution figure shows very young water at the upstream end of the reservoir, but downstream near the dam the water was still more than 200 days old.

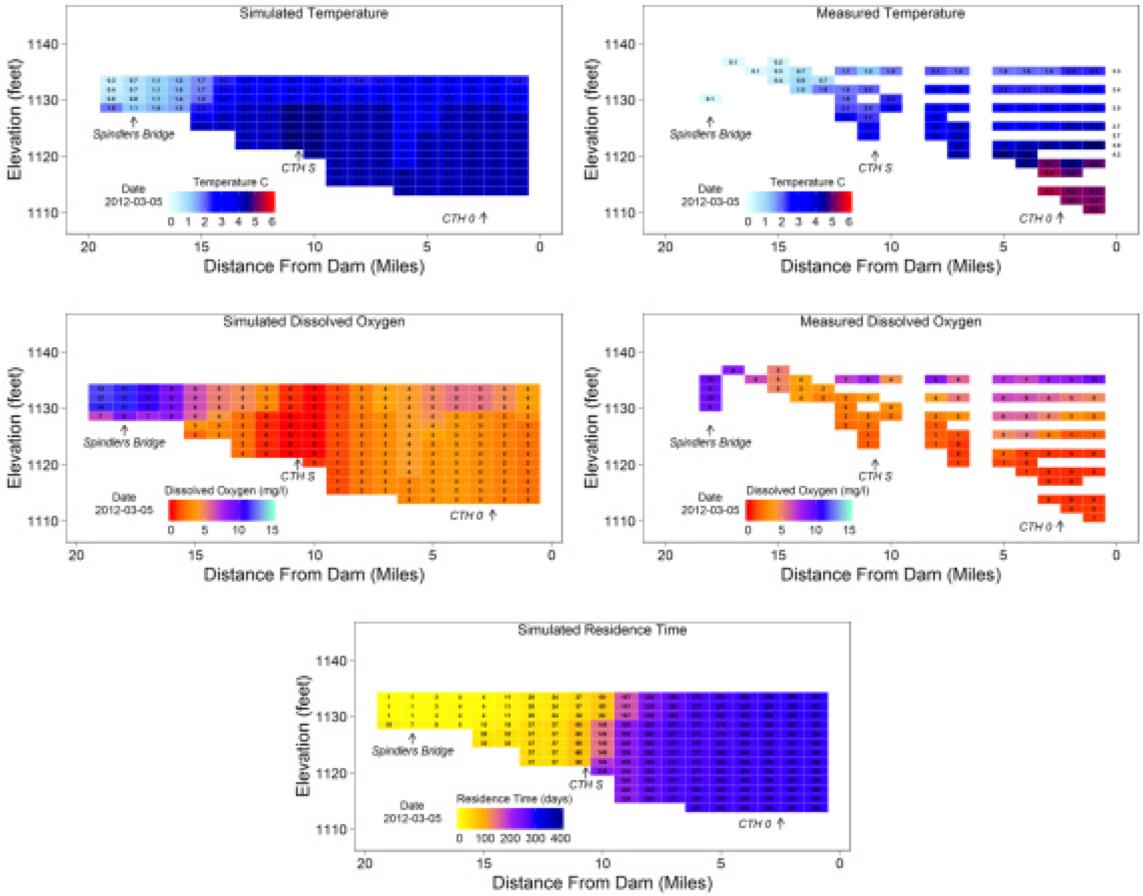


Figure 15. Results of model simulation and measured results for dissolved oxygen, temperature and residence time from early March 2012 approximately ninety days after ice formation.

Winter 2007 (November 2006 through April 2007)

The 2007 winter had intermittent and higher inflow than 2012. Figure 16 shows the water elevation began at approximately 1137.5feet (55% of full volume), increased during the middle of the winter, and then ended at 1135 feet (40% of full volume. Figure 16 shows the temperature in November started cooler, then warmed and then cooled again before freezing in early December. After freezing, sediment warming of the water led to an upward propagation of heat as the winter progressed.

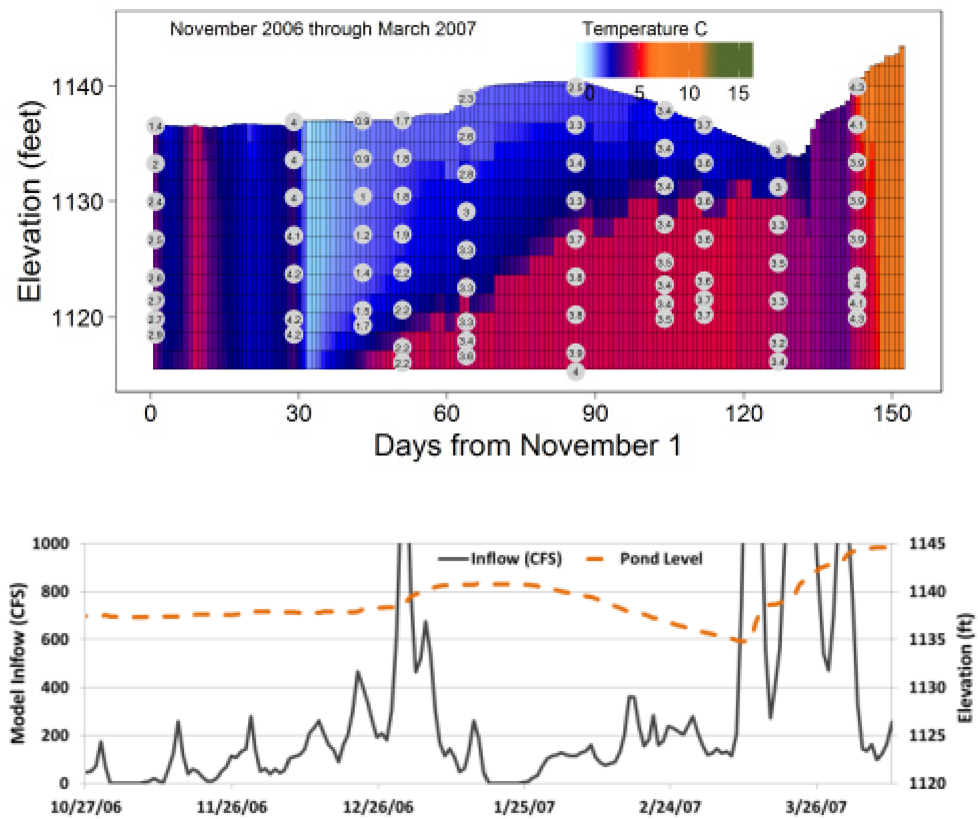


Figure 16. Upper figure shows the measured temperature profiles (circles) and simulated temperature pattern (colors). Lower figure shows the variation in inflow (solid line) and reservoir elevation (dashed line) in the 2007 winter.

Figure 17 shows that by early January, the water near the bottom was warm and there was a cooler, buoyant layer near the top in both the model and the measurements. The residence time distribution shows that very young water extended more than halfway into the reservoir from the inflow event in late December. High oxygen concentrations remained across much of the reservoir except for a depleted area near the front end of the inflow pulse. That is consistent with inflow BOD either from runoff or erosion of the upstream sediment (James et al., 1992) or displacement of deoxygenated water that was near the bottom upstream before the inflow event.

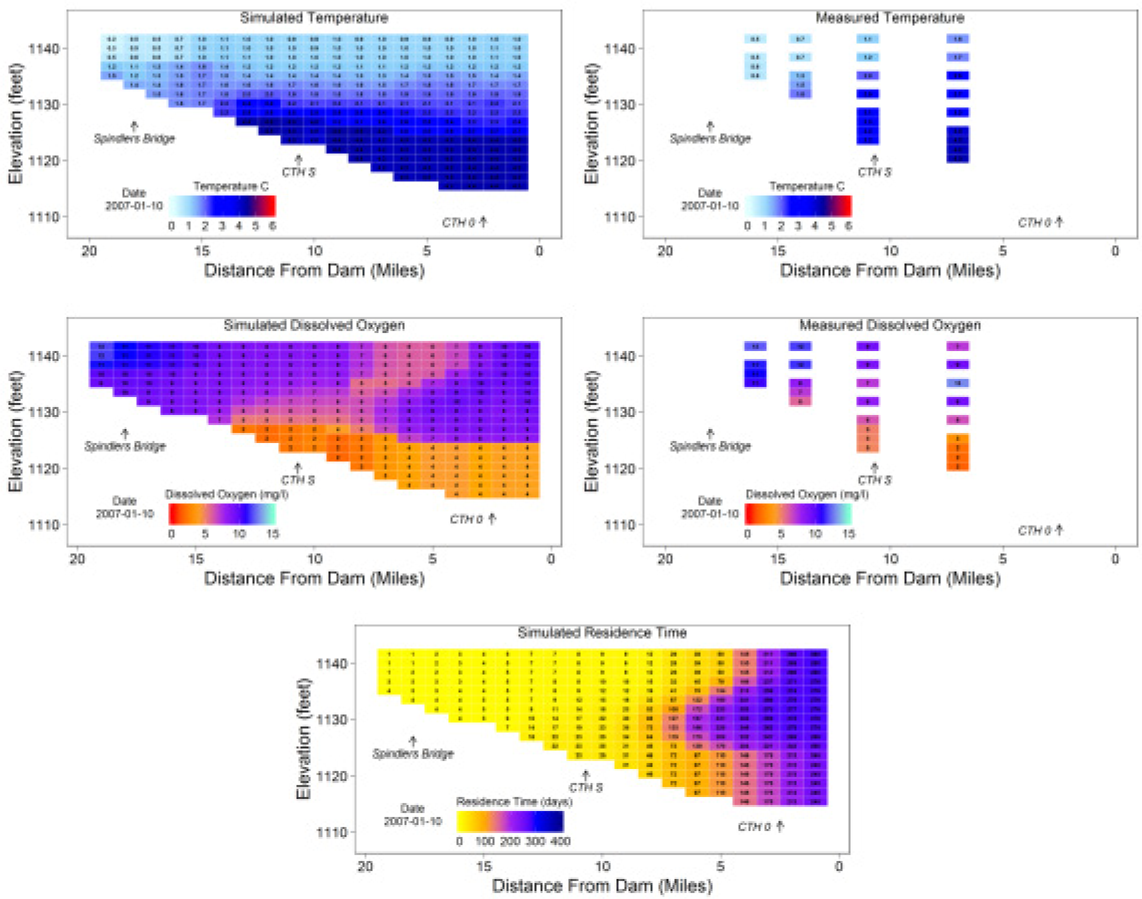


Figure 17. Simulated and measured temperature (upper), dissolved oxygen (middle) and residence time (lower) in the Big Eau Pleine Reservoir on January 10, 2007, approximately five weeks after ice formation.

Figure 18 shows model results and measurements from the end of February 2007. The residence time distribution shows that water near the dam was more than 200 days old, but most of the length of the reservoir had relatively young water. Sediment warming extended up to the base of the ice. Extensive oxygen depletion is shown in both measured and modeled for the warmest water near the sediment. Very high measured oxygen concentrations at the surface suggest oxygen addition through photosynthesis. In the older water near the dam, these higher oxygen concentrations extended more than two meters below the surface and would be consistent with a radiant convection pattern that warms water which then moves downward. That is not simulated in the model where oxygen concentrations are only 4 mg/l near the dam. The aerator had been on for five days at this time and the model shows increased oxygen in the aerated segment. The elevated oxygen just downstream of the aerator could reflect some mixing from the aerator or photosynthesis.

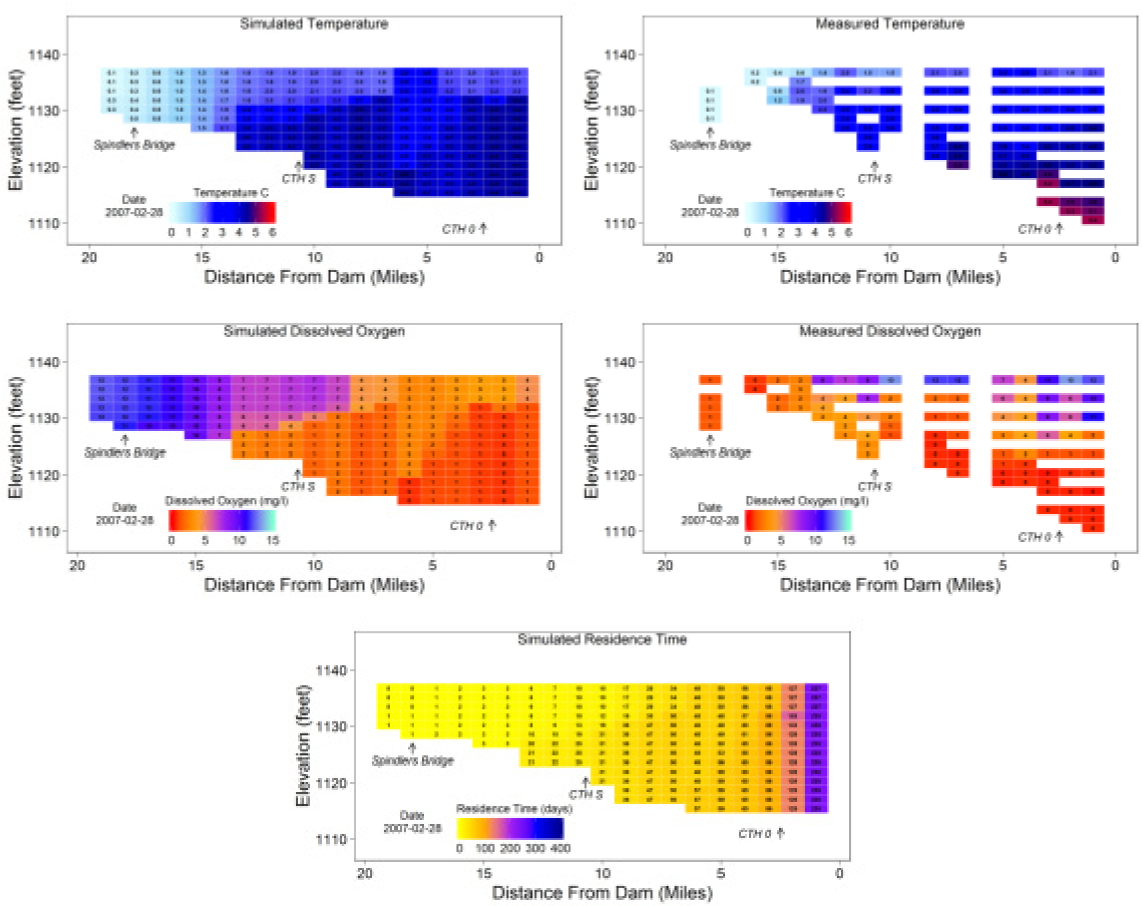


Figure 18. Simulated and measured temperature (upper), dissolved oxygen (middle) and residence time (lower) in the Big Eau Pleine Reservoir on February 28, 2007, approximately eleven weeks after ice formation.

Figure 19 shows temperature and oxygen concentrations during the spring flush at the end of the 2007 winter. High flow rates led to a pattern of temperature and oxygen that varies horizontally through the reservoir with cool, oxygenated water upstream and warmer, less oxygenated water downstream near the dam. The residence time distribution showed that water in the upstream fourteen miles was a week or less old. Water near the dam may still have been much older and there is some evidence of photosynthesis increasing the surface oxygen near the dam.

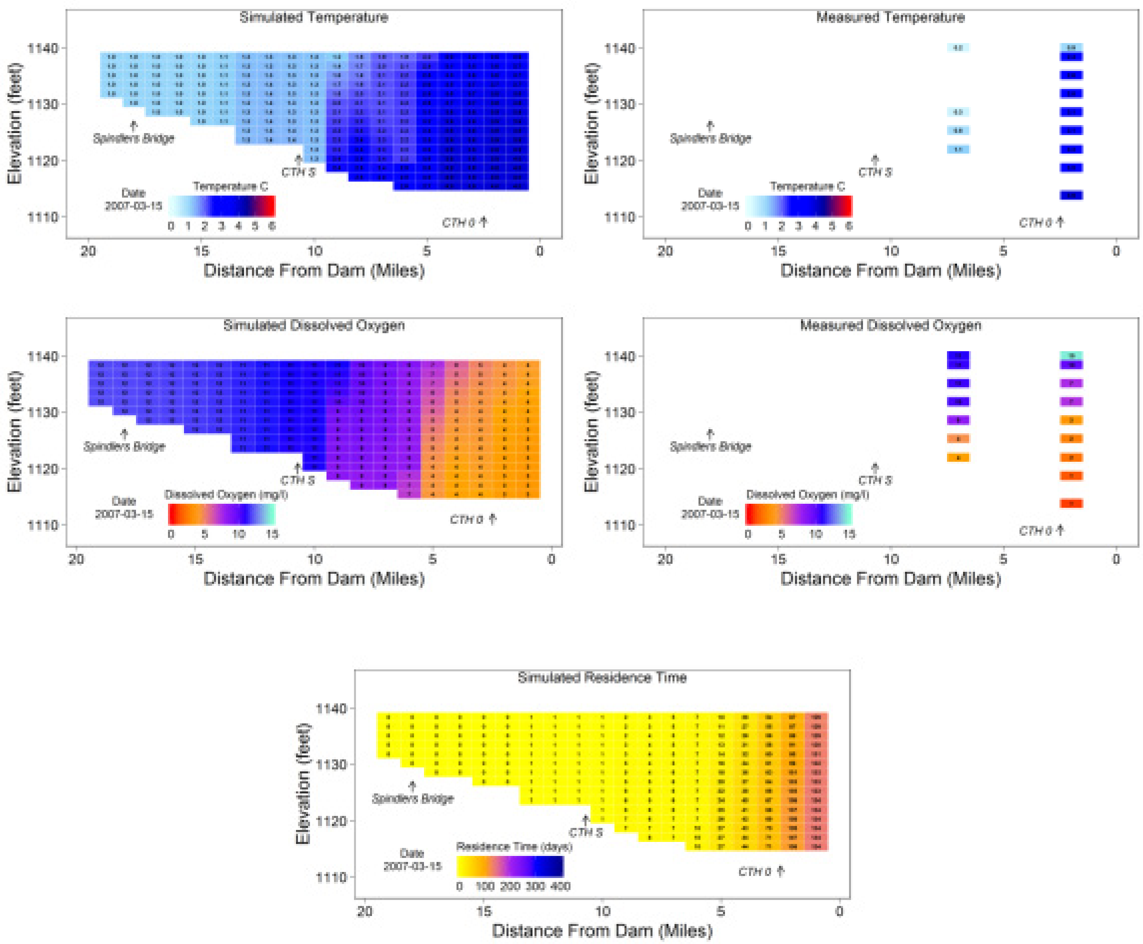


Figure 19. Simulated and measured temperature (upper), dissolved oxygen (middle) and residence time (lower) in the Big Eau Pleine Reservoir on March 15, 2007, approximately thirteen weeks after ice formation.

Winter 2013 (November 2012-April 2013)

The 2013 winter temperature, inflow and reservoir elevation are shown in Figure 20. This year had relatively low inflow and a starting elevation of 1136 feet (45% of full volume) and an ending elevation of 1135 feet (40% of full volume). The temperature profile shows the model simulates a short period of very cold water followed by warming. The simulated ice formation was in late November.

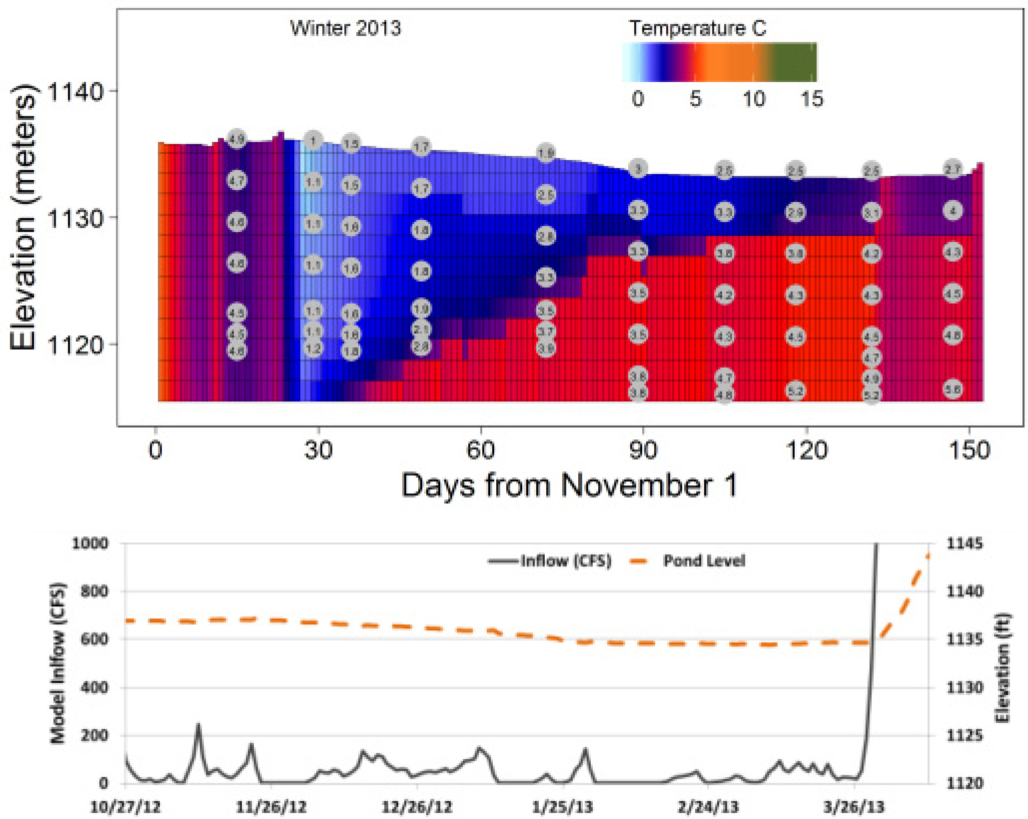


Figure 20. Upper figure shows the measured and modeled temperature during the 2013 winter. Lower figure shows the inflow (solid line) and reservoir elevation (dashed line).

Figure 21 shows the temperature and dissolved oxygen profiles for January 16, 2013. The model and measurements both showed warm sediment and deoxygenated water near the sediment. The measured values showed a mixed temperature and oxygen zone with an oxygenated zone near the surface. The model showed a transition from the warmer bottom to a cooler zone above it. Similar to the other years, the model accurately simulates the interface between the warmest bottom water and the mixed layer although it underestimates the extent of mixing between the warmest bottom water and the ice. In the January 16 profiles, the measured values showed warming to the surface while the model showed cooler water near the surface. As discussed earlier, we suspect sediment warming and convective mixing move heat upwards into the profile at a rate that is faster at the start of the winter than the model simulates.

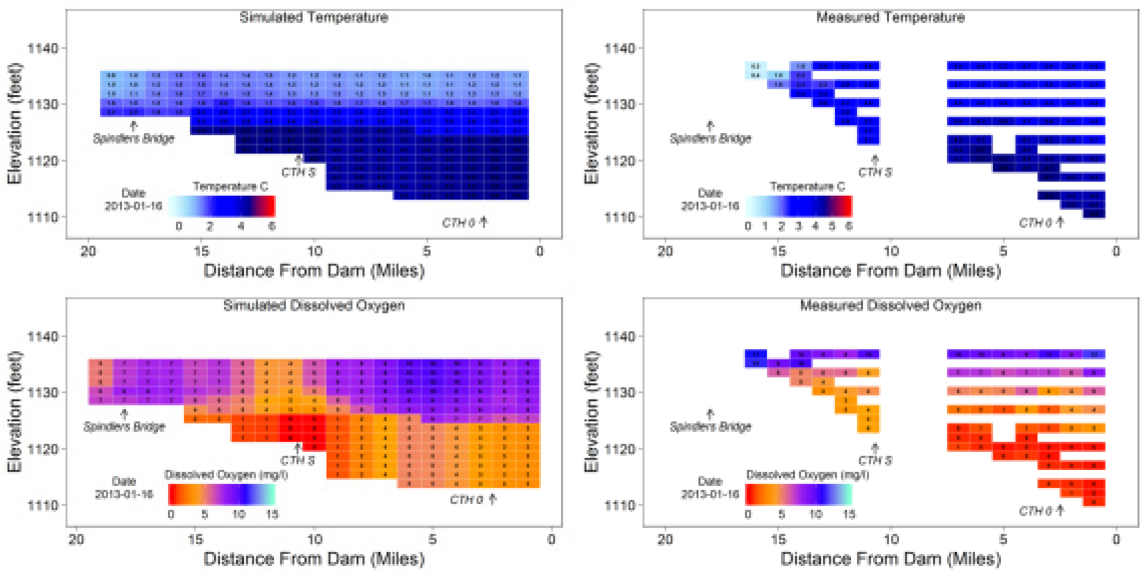


Figure 21. Simulated and measured temperature (upper), dissolved oxygen (middle) and residence time (lower) in the Big Eau Pleine Reservoir on January 16, 2013, approximately seven weeks after ice formation.

Figure 22 shows that by February 27 the heat from the sediment warmed the water, and the interface between the warmer bottom water and slightly cooler top water is close to the surface. The measured temperature profile is cooler near the surface than the model. Although the model usually starts warming the water more slowly than is observed in the measure values, by late winter the model can show warmer water than the measured overall. That may reflect that the model assumes a constant sediment temperature, while in the reservoir the sediment likely starts the winter warm and then cools over the winter as it loses heat to the water (Birge et al., 1927). There was no evidence of photosynthetic oxygen production in 2013. Similar to other years, the highest oxygen concentrations were at the surface, near the dam, but in 2013 they are only 3 to 4 mg/l in the model and that is slightly higher than in the measured profiles. The aerator had been on for two weeks at this point and there was some suggestion of more oxygenated water just downstream of the aerator in both the measured and modeled. The aerator simulation assumed an oxygen addition of 100 kg/day.

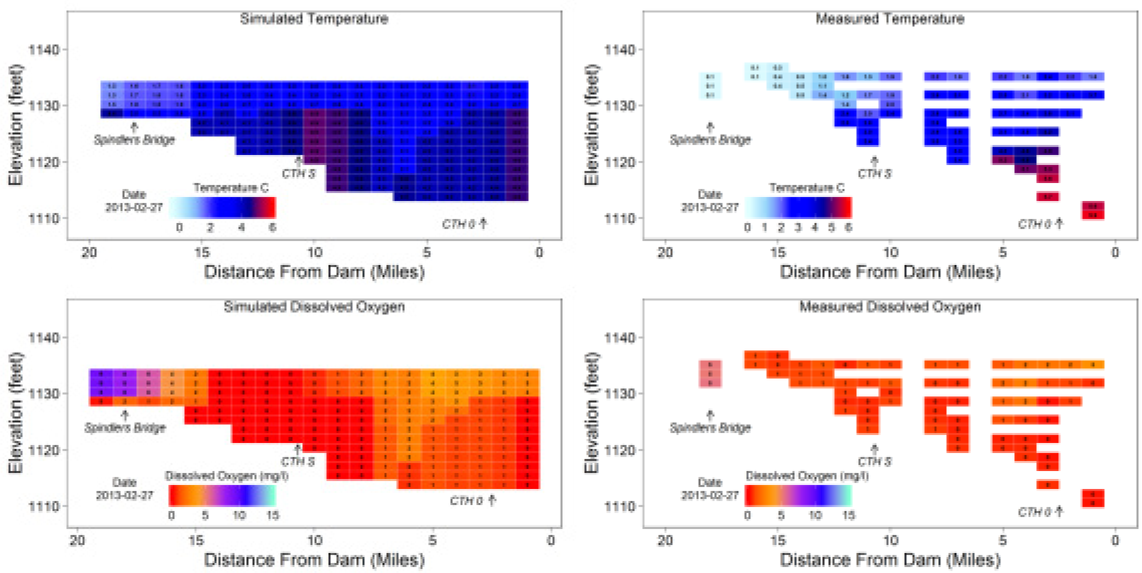


Figure 22. Simulated and measured temperature (upper), dissolved oxygen (middle) and residence time (lower) in the Big Eau Pleine Reservoir on February 27, 2013, approximately three months after ice formation.

Figure 23 shows modeled and measured profiles from March 12. The measured temperature profile near the dam showed some of the warmest winter bottom temperatures of any year. That may be evidence that sediment temperatures were very warm in 2013. We anticipate earlier in the winter, heat transfer to the water led to convective mixing and transfer of the heat through a portion of the water column. The temperatures near six degrees C in Figure 23 late in the winter could reflect higher dissolved mineral concentrations that increased the water density and stabilized higher temperature water near the bottom. Figure 23 shows oxygen concentrations continued to decrease from the bottom and concentrations near the surface were less than 3 mg/l. Similar to Figure 22, there was no evidence of photosynthetic oxygen addition.

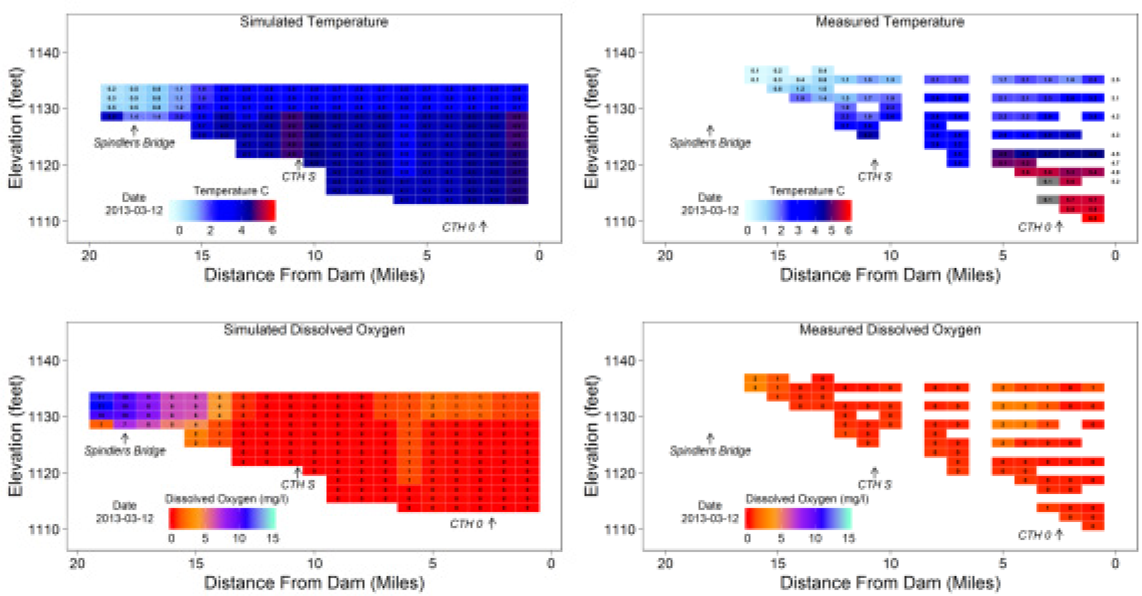


Figure 23. Simulated and measured temperature (upper), dissolved oxygen (middle) and residence time (lower) in the Big Eau Pleine Reservoir on March 12, 2013, more than 100 days after ice formation.

Figure 24 shows modeled and measured profiles from March 27, 2013. This is near the start of the spring flush. The residence time distribution shows some new water in the upstream few miles. Most of the reservoir still had very old water on this date. Very warm bottom waters were present near the dam. This condition would likely result in a bottom to top convective mixing that facilitated the depletion of oxygen. Some cooling of surface waters was shown near the dam, possibly reflecting mixing of melting or cooled water near the base of the ice. There was some oxygen in the two miles downstream of the aerated segment in the measured values but the concentrations were only approximately 3 mg/l. There was also some evidence of cooler water in those segments, perhaps reflecting movement of water cooled in the aerated segment that mixed downstream. The model assumed only 100 kg/day of oxygen addition. At the upstream end of the reservoir, recent inflow was the area of highest concentrations of oxygen in the reservoir.

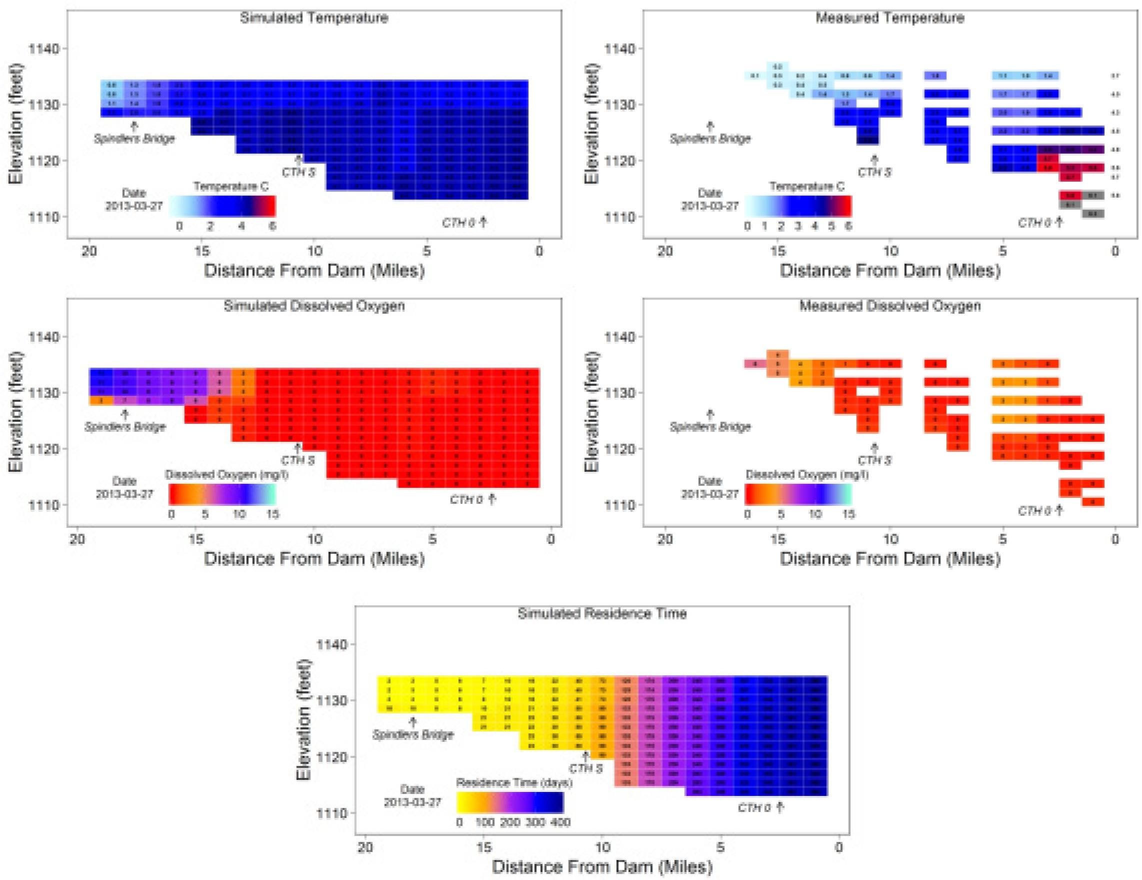


Figure 24. Simulated and measured temperature (upper), dissolved oxygen (middle) and residence time (lower) in the Big Eau Pleine Reservoir on March 27, 2013, more than 120 days after ice formation.

Conceptual Model Summary

The oxygen concentration patterns in 2007, 2012 and 2013 showed there are some similarities in all years, but there are also differences. Some of those differences can be inferred to reflect variations in inflow, sediment warming-induced mixing, photosynthesis under the ice and length of ice cover. Both 2007 and 2012 showed higher dissolved oxygen concentrations than predicted and the high oxygen concentrations near the dam suggested photosynthetic addition of oxygen. The 2007 winter had relatively high inflow and an exchange of water throughout most of the reservoir during the winter. Years such as 2012 and 2013 had very low inflow and the water in the reservoir was not exchanged until the spring flush. The 2013 winter was longer than either 2007 or 2012. That, combined with the lack of any photosynthetic oxygen and apparently high sediment temperatures, led to a depletion of oxygen across most the reservoir.

In summary, our conceptual model of oxygen depletion in the Big Eau Pleine Reservoir shows several causes for the year-to-year variation in oxygen concentration patterns. In some years, higher flow during the winter leads to an oxygen depletion that depends on the convergence of inflow-driven zones of low dissolved oxygen moving through the reservoir and combining with the upward expansion of sediment oxygen demand depletion zone near the dam. That is similar to the observations of Coon (1998) and James et al. (1992), although here we suggest that an additional source of low dissolved oxygen moving through the reservoir is the episodic disruption of low dissolved oxygen zones formed through weak thermal stratification. In other, and some of the more problematic years, the model simulations suggest that low inflow conditions lead to very little water movement through the reservoir during the winter and oxygen concentrations that reflect how the warmer, deoxygenated water mixes with overlying cooler, more oxygenated water. As the winter progresses, sediment warming and eventually surface warming seem to lead to top-to-bottom deoxygenation. Although this depletion can be reduced in some years through photosynthetic oxygen addition at the surface, in the absence of photosynthesis, top-to-bottom anoxia can result.

3.2 Calibrated Model

Results of the final dissolved oxygen calibration are shown in Figure 25 as the concentration of dissolved oxygen over time in the zones for Metric 2 and Metric 3. Each winter follows a similar pattern of high dissolved oxygen (near 12 mg/l) at the start of winter and then a decrease to lower dissolved oxygen during the winter. Metric 2 is the average in the upper portion of the reservoir from River Mile 7 to 10 (Figure 10) and subject to more rapid water exchange. Metric 3 is between the aerator and the dam in River Mile 1 to 5, an area with much longer water residence time in most winters. Several years show unusually high early winter dissolved oxygen (as high as 20 mg/l) which reflects algal photosynthesis under the ice. The metric calculations average the oxygen concentration over a relatively large profile and dampen some of the high and low oxygen concentrations that are shown in individual measurements. Overall, the model does represent much of the year-to-year variability in dissolved oxygen patterns.

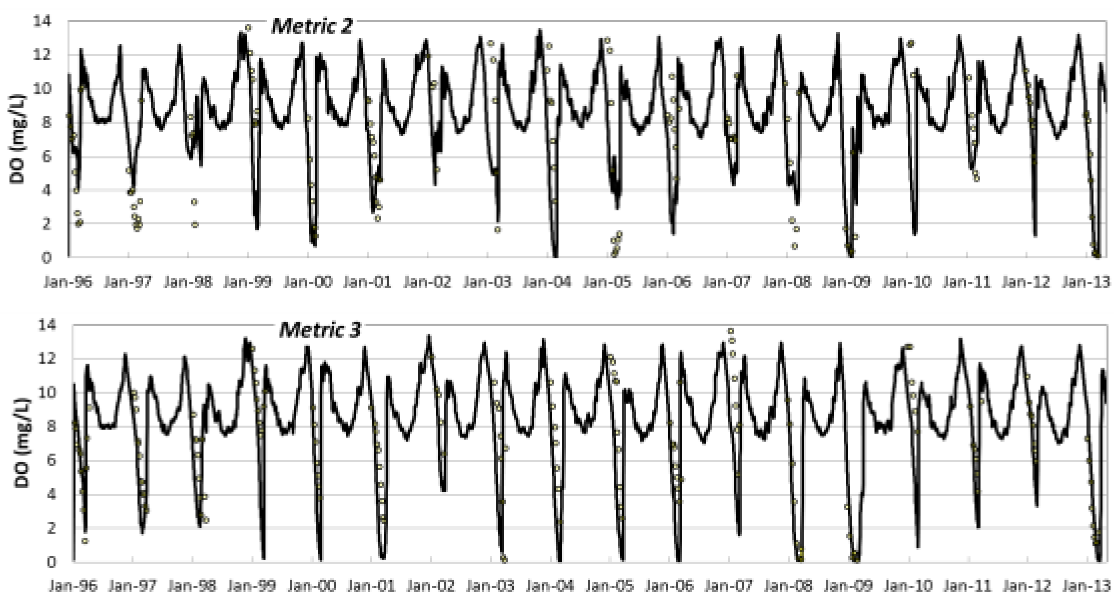


Figure 25. Daily average dissolved oxygen concentration measured within the Metric 2 (upper) and Metric 3 (lower) areas shown as symbols and the simulated for each day as lines.

The year-to-year variability in dissolved oxygen concentrations during the winter is shown in Figure 26 with the corresponding reservoir water level and inflow. The figures show how the flow, water level and oxygen concentrations all vary considerably from year to year and the extent to which the metric measurements reflect inflow and winter length.

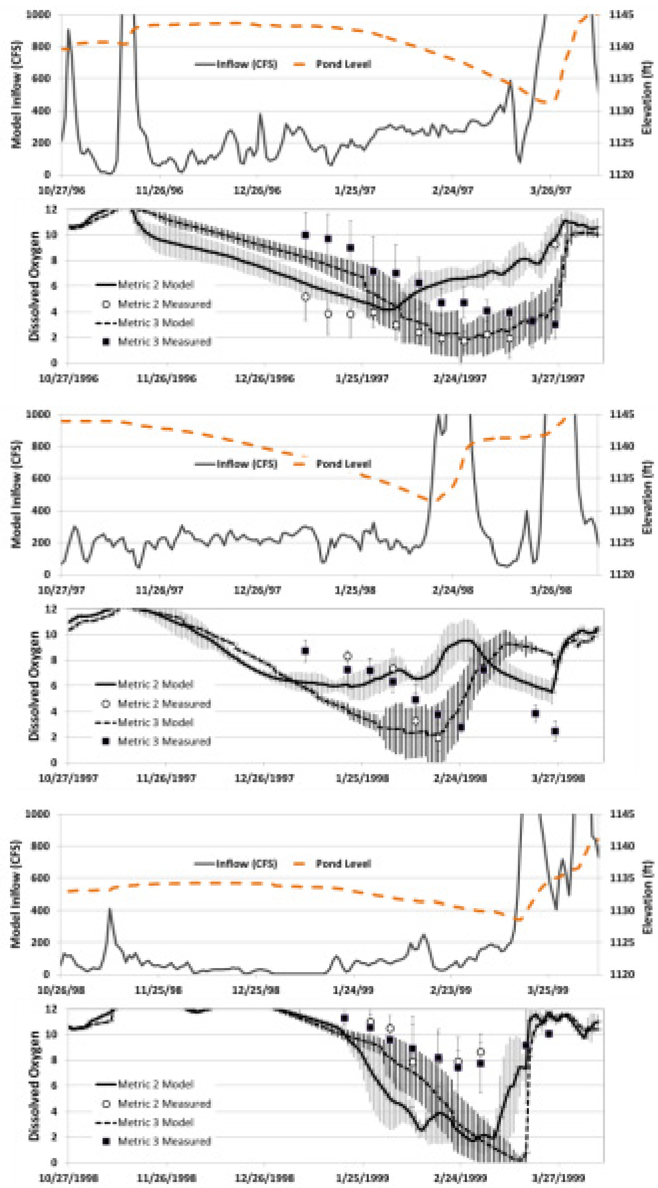


Figure 26. Comparison of the reservoir inflow and reservoir elevation (left) and the model metric dissolved oxygen concentrations tracked through each winter. Measured metric values shown as mean plus and minus one standard deviation for the measurements within the metric on that day. Range around the model metric values is the standard deviation within metric model segments on that day.

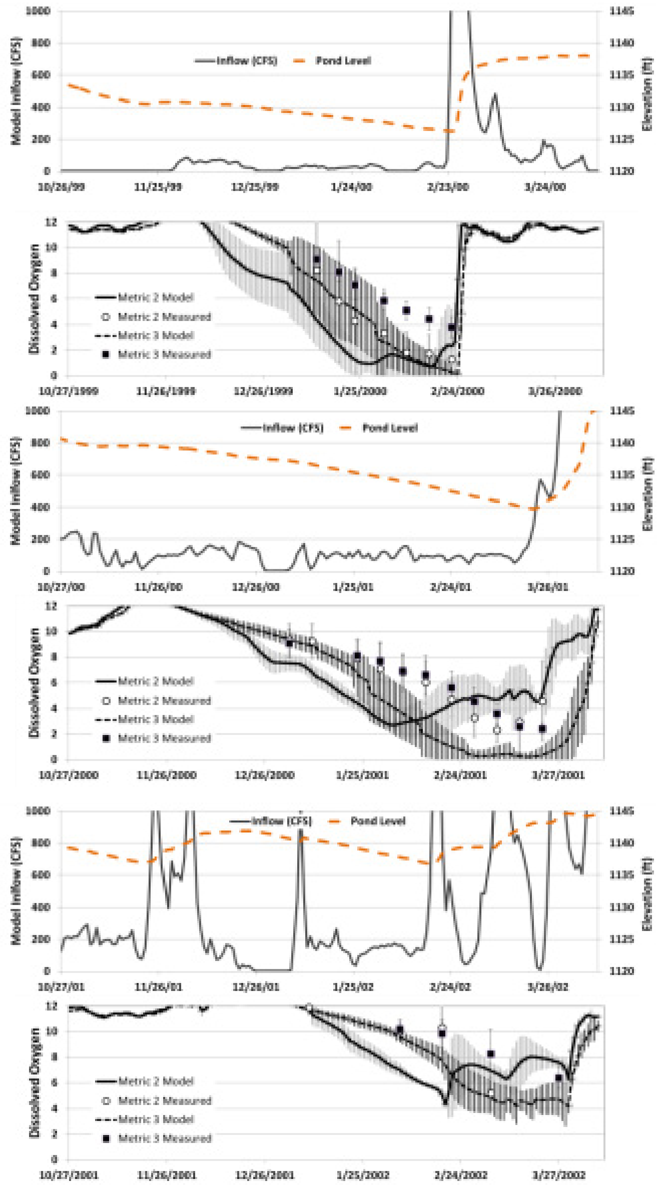


Figure 26 (continued). Comparison of the reservoir inflow and reservoir elevation (left) and the model metric dissolved oxygen concentrations tracked through each winter. Measured metric values shown as mean plus and minus one standard deviation for the measurements within the metric on that day. Range around the model metric values is the standard deviation within metric model segments on that day.

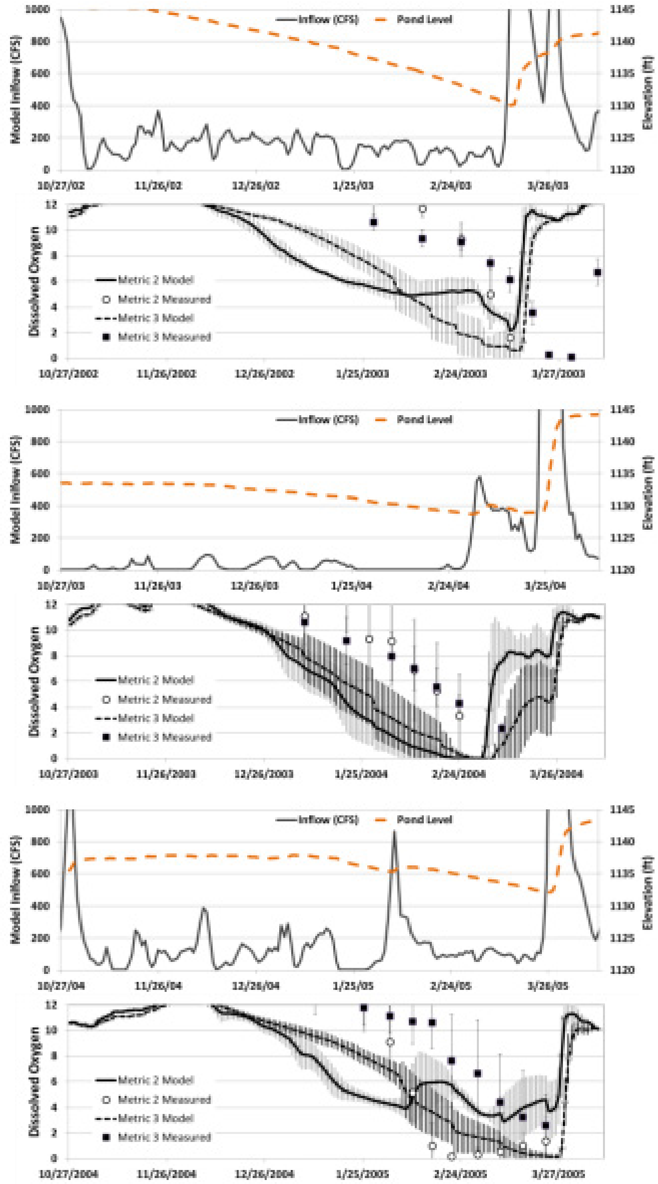
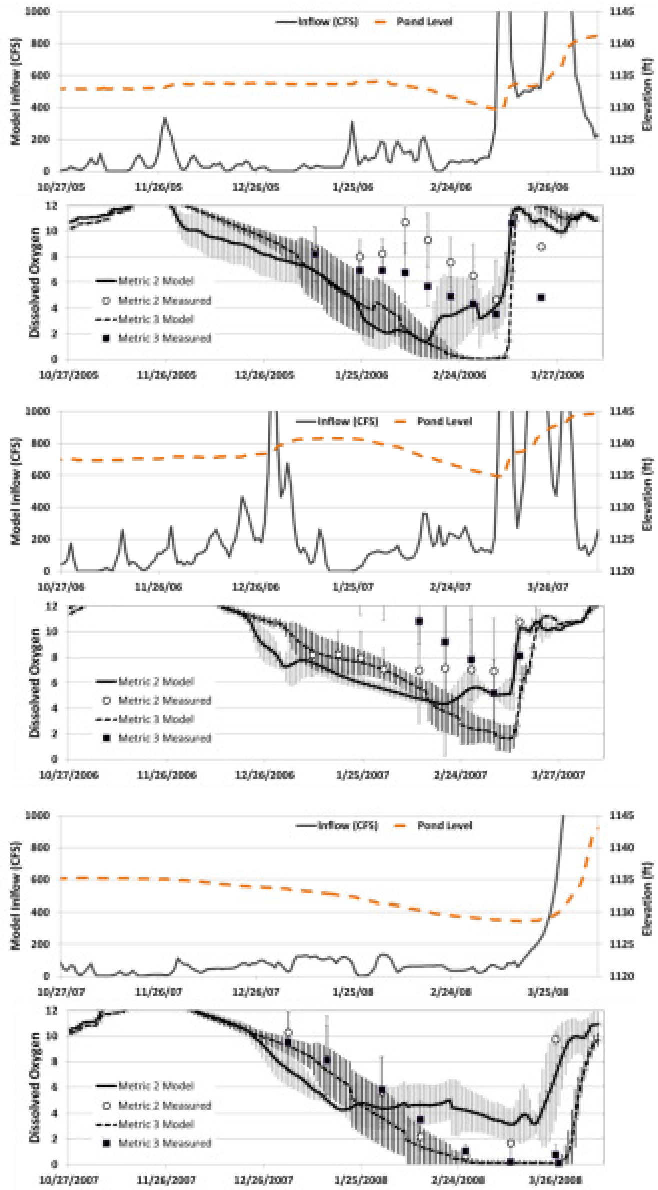


Figure 26 (continued). Comparison of the reservoir inflow and reservoir elevation (left) and the model metric dissolved oxygen concentrations tracked through each winter. Measured metric values shown as mean plus and minus one standard deviation for the measurements within the metric on that day. Range around the model metric values is the standard deviation within metric model segments on that day.



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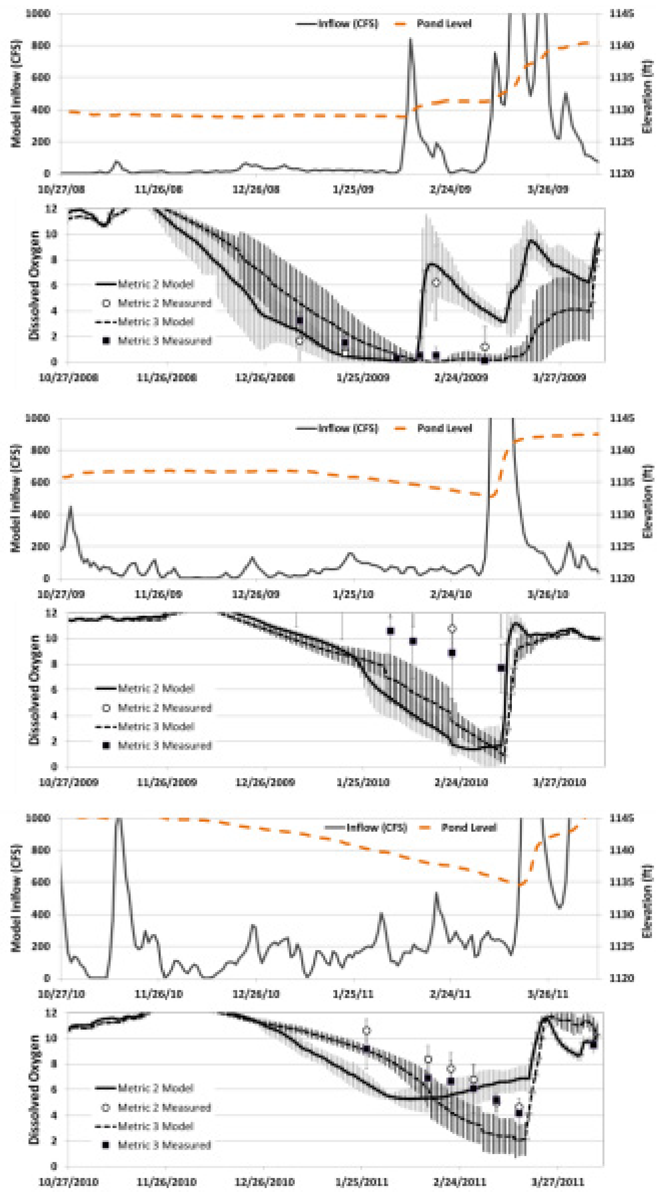

Figure 26 (continued). Comparison of the reservoir inflow and reservoir elevation (left) and the model metric dissolved oxygen concentrations tracked through each winter. Measured metric values shown as mean plus and minus one standard deviation for the measurements within the metric on that day. Range around the model metric values is the standard deviation within metric model segments on that day.

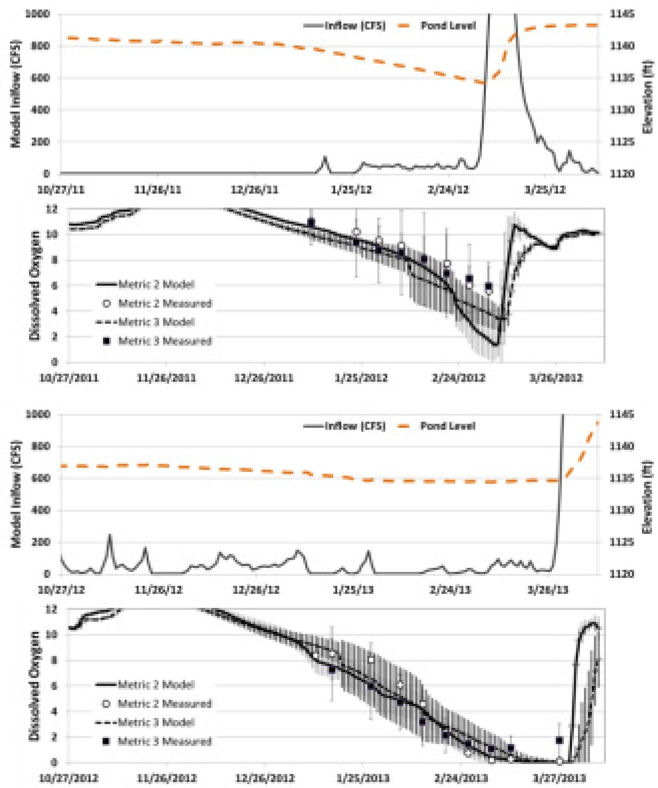

Figure 26 (continued). Comparison of the reservoir inflow and reservoir elevation (left) and the model metric dissolved oxygen concentrations tracked through each winter. Measured metric values shown as mean plus and minus one standard deviation for the measurements within the metric on that day. Range around the model metric values is the standard deviation within metric model segments on that day.

The agreement between the model and measured dissolved oxygen concentrations calculated by year for both Metric 2 and Metric 3 is summarized in Table 3 showing both a linear R^2 and a percent bias (PBias). We used the R statistical packages "lm" for linear regression and "hydroGOF" package for the percent bias calculations (R Core Team, 2013; Zambrano-Bigiarini, 2014). The R^2 is a measure of how close the model and measured data can be fit to a linear line. It ranges from 0 to 1. Values closer to one indicate a greater proportion of the variance is explained by the model. In many years, the model provides an R^2 above 0.7. This statistic is sensitive to values that are substantially different from the line and that is shown in several years with very low R^2 that reflects several points in that year that depart substantially from a linear line. The R^2 does not describe how far that line might be from a 1:1 line between measured and modeled. The percent bias (PBias) expresses how the model results are generally larger or smaller than the measurements. Exact agreement between modeled and measured would be a PBias of zero. If the PBias is negative, the model is underestimating the dissolved oxygen (predicting a lower value of dissolved oxygen than is observed). Table 3 shows that many of the years have a negative percent bias. Photosynthetic oxygen production under the ice would contribute to a negative PBias because the model does not simulate oxygen production under the ice. When measured profiles showed high oxygen concentrations (e.g., 14 mg/l), photosynthesis was likely occurring.

Table 3. Statistical evaluation of dissolved oxygen calibration by year.

Year (Winter)	Metric 2		Metric 3	
	R^2	*PBias*	R^2	*PBias*
1997	0.220	78	0.718	-28
1998	0.432	19	0.008	-11
1999	0.900	-43	0.729	-27
2000	0.611	-48	0.991	-44
2001	0.107	-20	0.790	-49
2002	0.178	-17	0.884	-18
2003	0.947	-48	0.332	11
2004	0.721	-70	0.805	-52
2005	0.256	14	0.823	-52
2006	0.026	-51	0.178	-38
2007	0.436	-25	0.923	-48
2008	0.747	-7	0.950	-24
2009	0.832	60	0.956	24
2010	0.478	-60	0.968	-42
2011	0.124	-15	0.941	-18
2012	0.973	-17	0.937	-13
2013	0.971	-15	0.933	10

4. MANAGING WINTER ANOXIA IN THE BIG EAU PLEINE RESERVOIR

A second objective of this study was to develop a better understanding of how winter anoxia could be reduced in the Big Eau Pleine Reservoir. Three factors were identified for evaluation with the CE-QUAL-W2 model: 1) Starting winter reservoir elevation; 2) Aeration; and, 3) Sediment oxygen demand.

4.1 Winter Reservoir Elevation

Previous studies, model calibration and conceptual model development described in this report show the factors that lead to anoxia in the Big Eau Pleine Reservoir include sediment oxygen demand, inflow rate, inflow events, photosynthetic oxygen production and length of ice cover. All of these variables operate on a mass of oxygen under the ice. That mass of oxygen is the product of the volume of water and concentration of oxygen. When water leaves the reservoir, the mass of oxygen is reduced at a rate that depends on the flow rate out and the concentration. As a result, the amount of water in the reservoir and the timing and rate of release are important factors in the oxygen budget. Water level management in the Big Eau Pleine Reservoir typically results in releasing more water than is entering during the summer, fall and winter and then releasing less than enters during the spring when snowmelt runoff leads to large inflow to the reservoir. This leads to an increase in reservoir elevation during the spring.

Figure 27 shows the more recent historical variation in reservoir elevations. In early November, elevations can range from less than 1135 feet to more than 1145 feet (full).

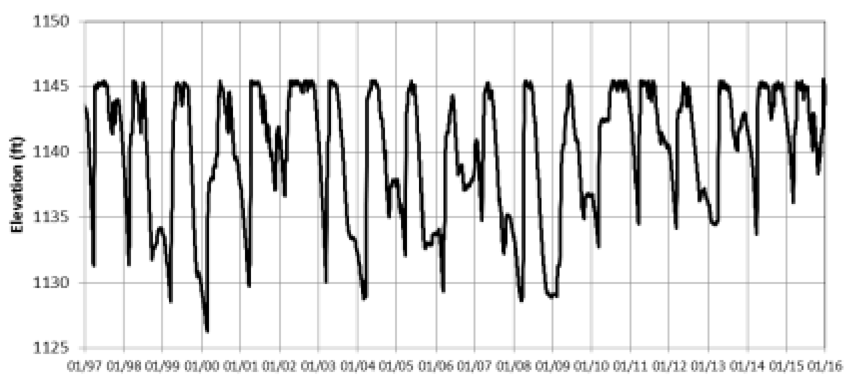

Figure 27. Reservoir elevations from January 1997 through 2015 (WVIC).

The amount of water in the reservoir can be expressed as elevation of the water surface, or volumetrically as a water volume or percentage of the maximum full water volume. Table 4 shows the relationship between reservoir elevation and the volume of water expressed as a percentage of the total water volume.

Table 4. Big Eau Pleine water elevation and volume comparison.

Reservoir Water Elevation (ft above MSL)	Volume as Percentage of Full
1142	80
1141	74
1140	68
1139	62
1138	56
1137	51
1136	46
1135	42

Because the Big Eau Pleine Reservoir is an important storage reservoir, it is important to understand the role water level has in winter anoxia. Several studies of the Big Eau Pleine Reservoir have suggested that higher winter starting elevations could reduce winter anoxia (Shaw, 1979; BEPCO, 2011). In this study, we examined how the calibrated CE-QUAL-W2 model would project the effect of the starting winter reservoir elevation. We developed an approach that uses target reservoir elevations on specific days of the year, a calculated daily release rate based on a linear change in elevation between those days, and the inflow from the calibrated model to calculate the outflow required to maintain the target elevations. That was used to create the release rate (outflow) file for the model. Figure 28 shows an example of the inflow, outflow and reservoir elevation for the 2013 winter followed by the conditions used to simulate an elevation pattern of 1136 to 1135 feet (46% of full to 42% of full) which was near the actual operating condition for that year, and 1140 to 1135 feet (68% full to 42% full) as an example of starting the winter with a higher elevation. That figure shows how these synthetic simulations use the same inflow but different outflow to generate the target elevation for each day.

The synthetic simulations were used to generate the dissolved oxygen concentration profiles for the end of March 2013 shown in Figure 29. By progressively reducing starting elevation, these profiles show that there is a higher dissolved oxygen concentration near the surface both upstream and downstream of the aerator when the starting elevation is higher, but that the increase is relatively small. Those same results are shown as metric plots in Figure 30 where they are also compared to the measured metric values. They show that by late March, the dissolved oxygen concentration is relatively low in all at all starting elevations. The metric plots in Figure 30 also show that earlier in the winter, the effect of the higher starting elevation is more marked. For example, at the end of February, the difference between metric values for the different starting elevations is close to 2 mg/l. The lower metric plot in Figure 30 shows that the synthetic simulation that starts at 1136 feet is a reasonable match to the measured metric values.

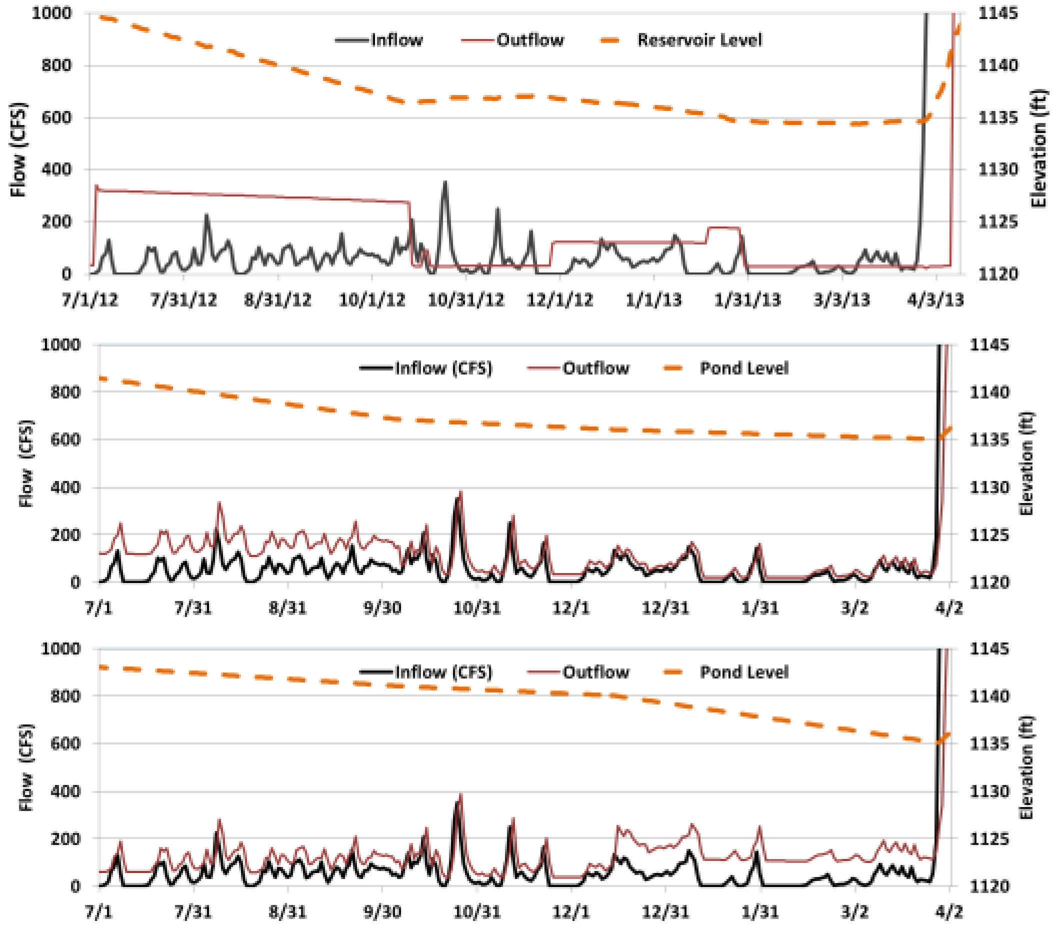

Figure 28. Example actual 2013 winter conditions (upper) followed by conditions used in the synthetic simulation of starting (12/16) and ending (3/29) elevations of 1136 to 1135 (middle) and 1140 to 1135 (lower). Pond level is the elevation of the water in the reservoir.

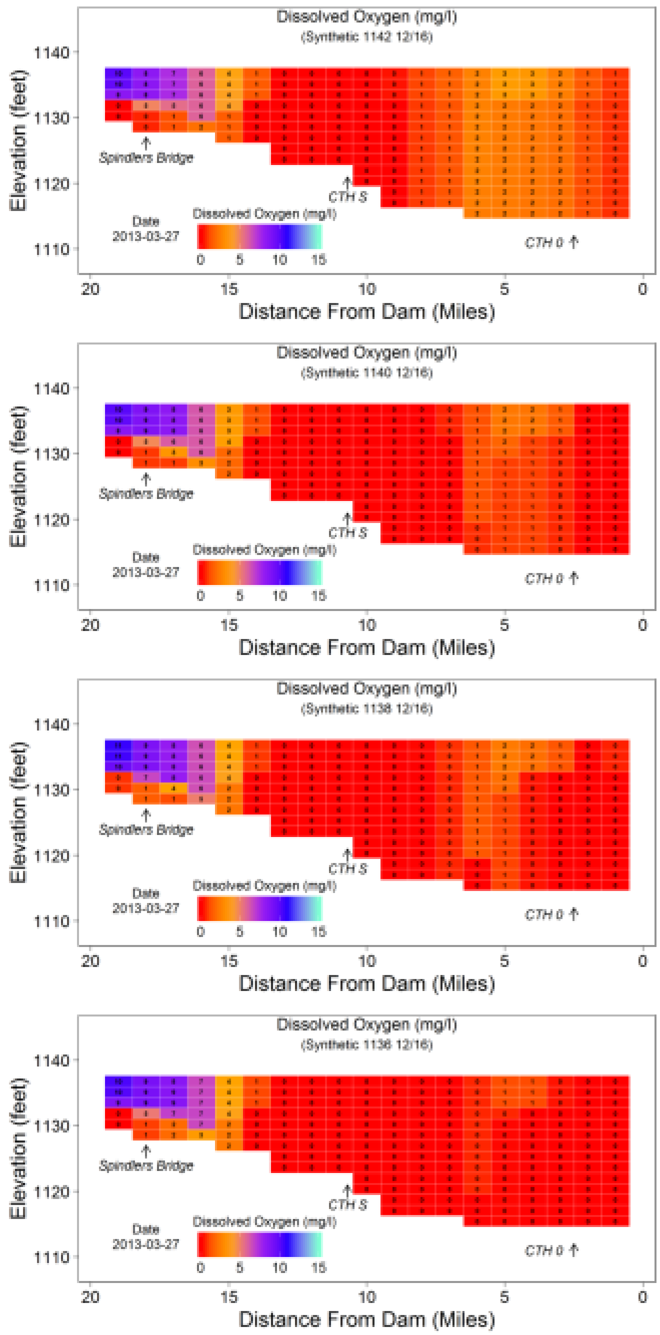

Figure 29. Comparison of simulated dissolved oxygen profiles in the Big Eau Pleine Reservoir for March 27, 2013 with progressively lower starting (December 16) elevations. Upper profile starting elevation is 1142, second is 1140, third is 1138 and bottom is 1136 feet.

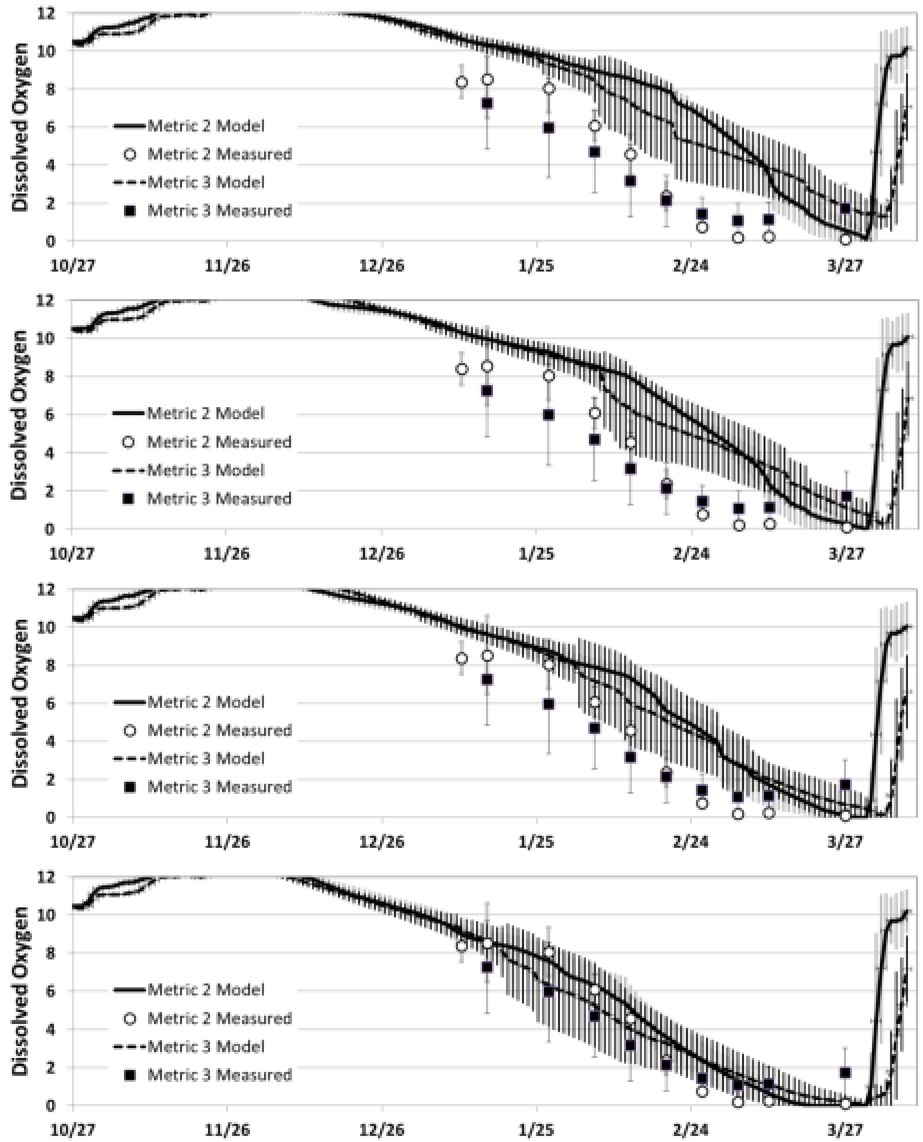

Figure 30. Comparison of Metric 2 and Metric 3 over time simulated with progressively lower starting elevation on December 16 (top:1142, 2nd: 1140; 3rd: 1138; bottom: 1136) with all simulations ending at 1135 feet on March 30. Measured results from 2013 shown for comparison with these synthetic simulations.

The importance of winter length on the dissolved oxygen concentrations can be seen in Figure 31 where the number of days the two metrics were less than 2 mg/l is summarized. That figure shows that starting the winter with the reservoir elevation higher decreases the number of days that the metric concentration will be below 2 mg/l. There are several conclusions from this comparison: 1) in all starting elevation scenarios, the dissolved oxygen is very low in the 2013 simulations by the end of March; and, 2) the benefit of the higher initial starting elevation may be larger in shorter winters (ending before early March), when the higher starting elevation is predicted to provide a 2 to 3 mg/l increase in dissolved oxygen within the metric regions.

Figure 32 shows that holding the starting elevation longer into the winter could also delay reaching lower average dissolved oxygen concentrations in the metric regions. In those simulations, the initial winter elevations was reached on December 16, held constant until January 30 and then dropped to the final elevation of 1135 feet on March 30.

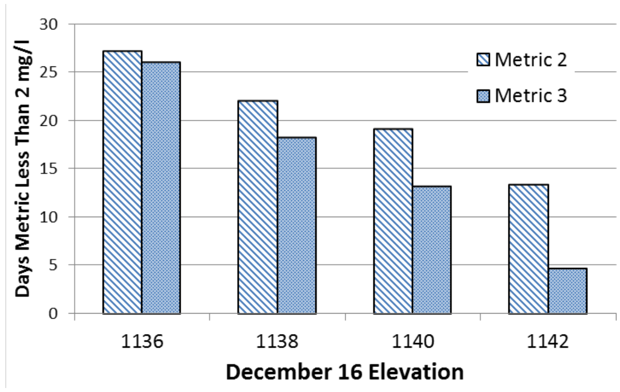

Figure 31. Comparison of days that Metric 2 and Metric 3 were under 2 mg/l in simulations that started on December 16 with the elevations shown and ended on March 30 at 1135.

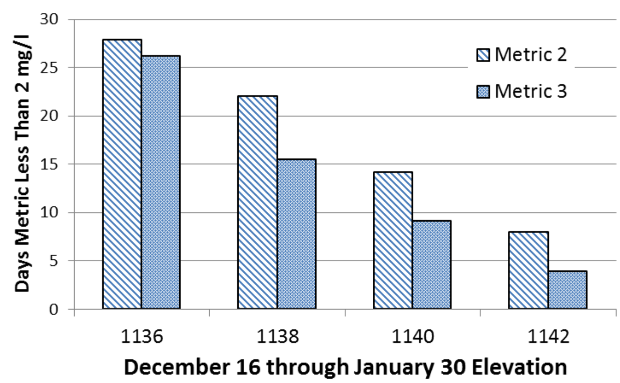

Figure 32. Comparison of days that Metric 2 and Metric 3 were under 2 mg/l in simulations that started on December 16 but remained at that elevation through January 30 before drawing down to 1135 by March 30.

4.2 The Effect of Aeration

The CE-QUAL-W2 model of the Big Eau Pleine Reservoir was used to evaluate the effect of the aeration system installed near Mile 6. This system uses blowers to add air to mix the water and create an open area in the ice that allows oxygen to be transferred from the atmosphere to the water. The amount of oxygen transferred to the water depends on the size of the open area, the dissolved oxygen concentration of the water, and the degree of mixing at the interface between the air and water. Using oxygen transfer rates from Gelda et al. (1996), an oxygen transfer of 1000 to 2000 kilograms of oxygen could be transferred per day through a 60 acre opening in the ice. Sullivan (1982), in a study of the Big Eau Pleine Reservoir, calculated an oxygen transfer of 1000 to 1600 kg/day based on upstream and downstream dissolved oxygen measurements.

The CE-QUAL-W2 model simulates aeration through mixing and oxygen addition at a specific location. While the model does not exactly mimic the process of oxygen transfer through an opening in the ice, it can be used to assess the oxygen transferred to the reservoir by comparing oxygen concentration changes predicted by the model with those measured in the reservoir. Because oxygen concentrations are not measured in the open area of the aeration system, this evaluation uses measurements downstream of the aeration system (Mile 5 and Mile 4).

Figure 33 compares measured and simulated dissolved oxygen in 2013 two weeks after the aerator was started. Because the aerator requires time to open up the ice, we would not expect the aerator to exhibit a strong impact on dissolved oxygen concentrations close to the startup. In addition, 2013 was a year with little inflow and little water movement so the effect of added oxygen would not be expected to propagate downstream rapidly. These simulations suggest an oxygen concentration difference of 1 or 2 mg/l in the upper half of the water column at Mile 5. The measured results also show only a small change. This suggests it might be reasonable to assume a transfer of 100 to 500 kg/day of oxygen transferred during the first few weeks of aerator operation.

Figure 34 shows the 2013 winter four weeks after the aerator was started. The measured results continue to show a relatively low concentration of dissolved oxygen immediately downstream of the aerator. A comparison with the simulation results are consistent with the aerator providing the equivalent of a simulated 300 to 500 kg/day of oxygen by that time.

Figure 35 shows the 2013 winter six weeks after the aerator was started. The measured values continue to show 1 or 2 mg/l dissolved oxygen in the two miles downstream of the aerator. Comparison to the model results suggests the system could be providing approximately 500 kg/day oxygen.

The same simulations were performed for 2007 and are shown in Figure 36 for a sampling period two weeks after the aerator began. This was a winter with higher flows although two weeks is not likely to be enough time for water to move fully into the downstream mile segment. The results show the oxygen concentration downstream is more consistent with an oxygen addition of 300 kg/day.

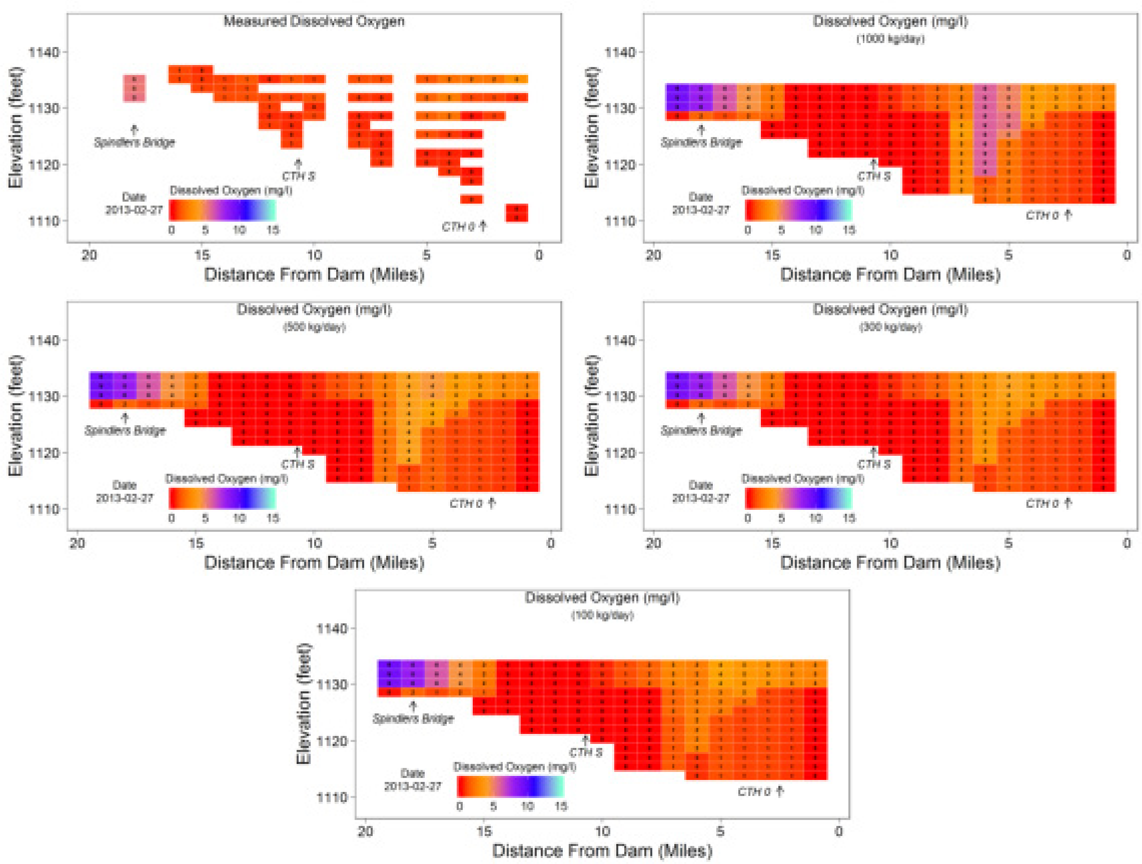

Figure 33. Comparison of dissolved oxygen profiles in the Big Eau Pleine Reservoir for February 27, 2013, two weeks after the start of aeration. Upper profile is measured followed by simulations of 1000, 500, 300 and 100 kg/day of oxygen.

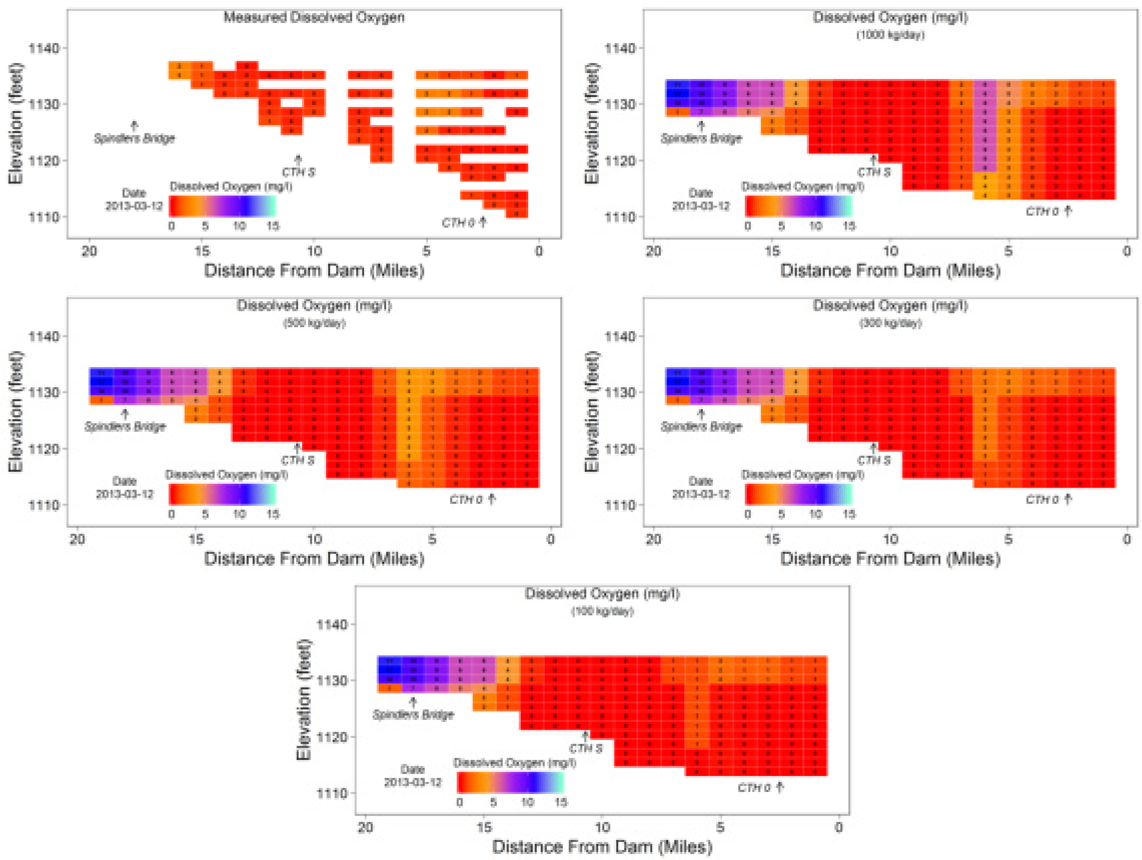

Figure 34. Comparison of dissolved oxygen profiles in the Big Eau Pleine Reservoir for March 12, 2013, four weeks after the start of aeration. Upper profile is measured followed by simulations of 1000, 500, 300 and 100 kg/day of oxygen.

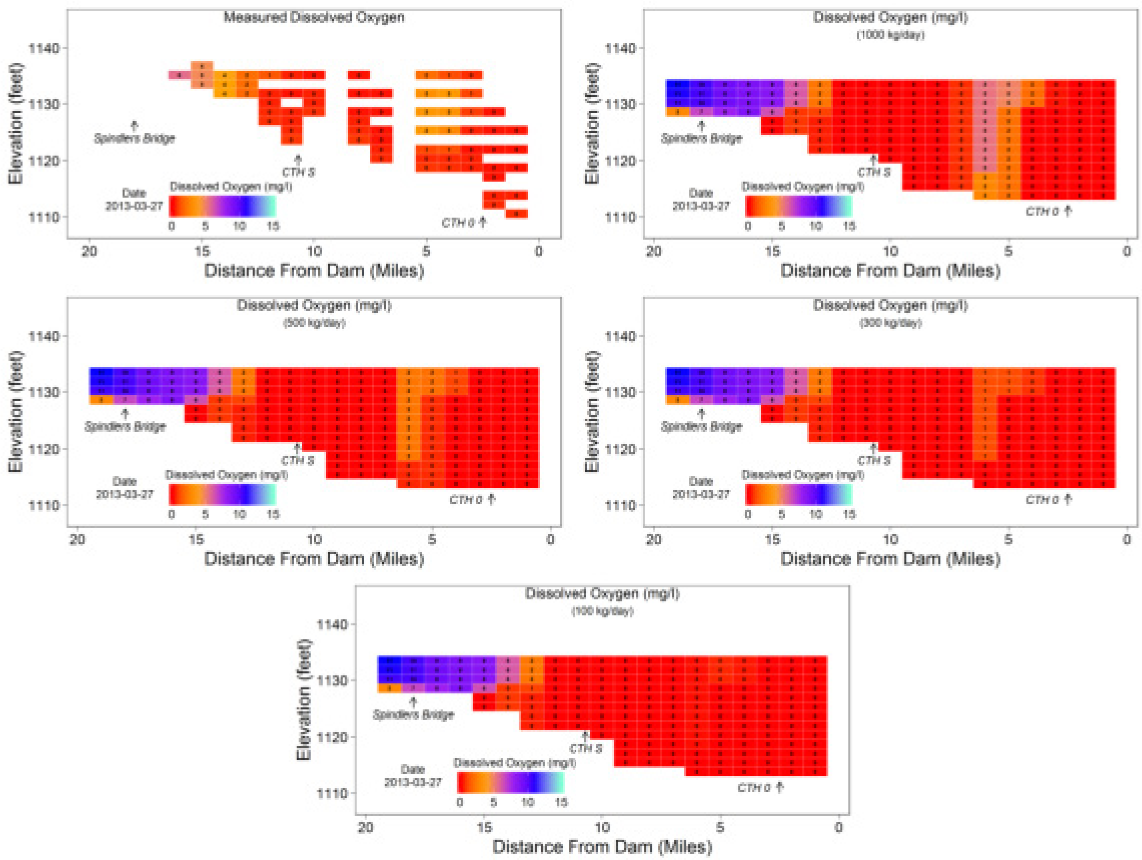

Figure 35. Comparison of dissolved oxygen profiles in the Big Eau Pleine Reservoir for March 27, 2013, six weeks after the start of aeration. Upper profile is measured followed by simulations of 1000, 500, 300 and 100 kg/day of oxygen.

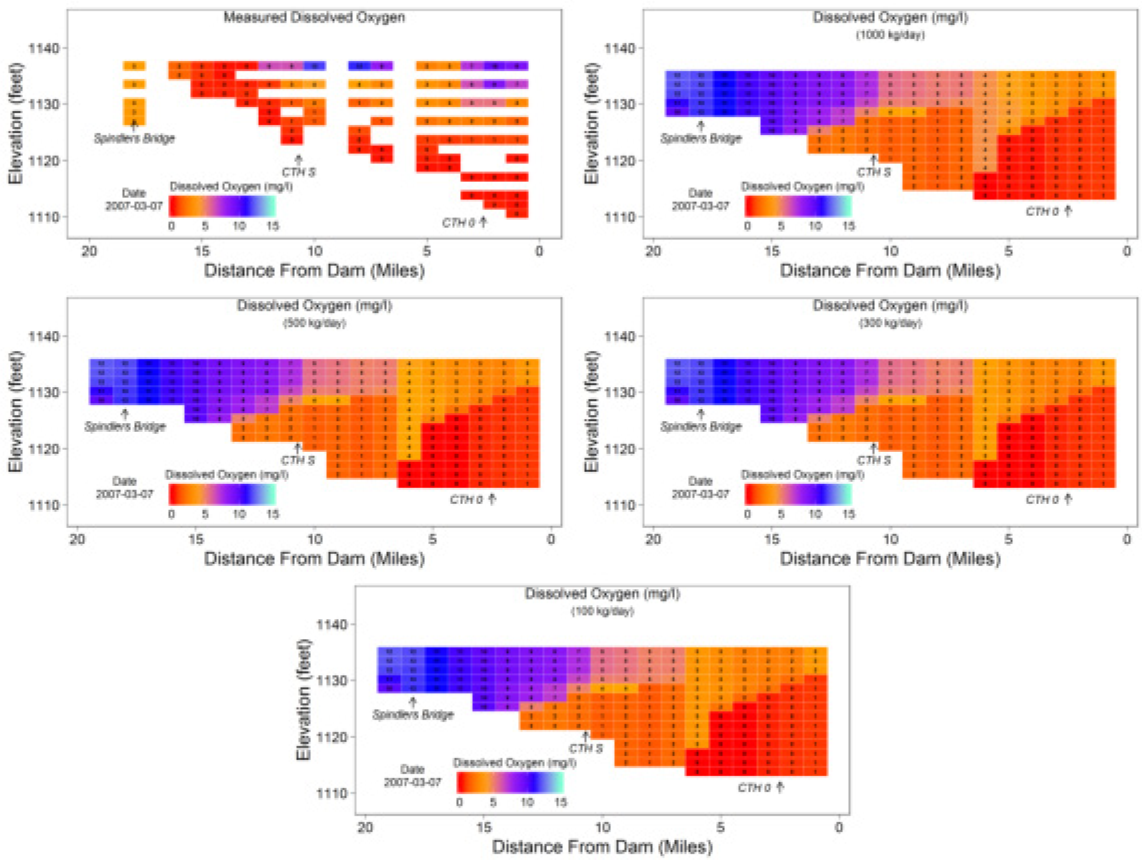

Figure 36. Comparison of dissolved oxygen profiles in the Big Eau Pleine Reservoir for March 7, 2007, two weeks after starting aeration. Upper profile is measured followed by simulations of 1000, 500, 300 and 100 kg/day of oxygen.

The aeration comparison simulations are consistent with a time lag between the beginning of aerator operation and the full impact of that aeration on dissolved oxygen concentrations in the reservoir. There are several likely explanations for this lag. First, it will take time for the aerator to create an opening in the ice to realize full transfer of oxygen from the atmosphere to the water. Second, the start of aeration will be mixing the water column and moving deoxygenated water throughout. This will reduce oxygen concentrations near the surface. Finally, if there are other oxygen-demanding substances in the water near the bottom, such as reduced iron or organic matter, some of the oxygen will be consumed oxidizing those substances.

Although the comparisons to do not provide unambiguous estimates of the oxygen mass transferred from the aeration system, they do suggest 500 kg/day is a reasonable estimate of the oxygen transfer rate for the aerator. That is less than the 1000 to 1600 kg/day calculated by Sullivan (1982), although he indicated that transfer rate suggested the aeration system in the Big Eau Pleine Reservoir was "very efficient" and he recommended further study to determine the reasons for the high transfer rate. Our modeling indicates it is difficult to assess the efficiency of the aeration system without monitoring near the opening in the ice. In the years we modeled, effects of the aerator in the segments downstream are likely to be relatively modest (e.g., 2 mg/l increase).

The CE-QUAL-W2 model was used to simulate the impact starting the aerator earlier would have on oxygen concentrations in the reservoir. In these simulations, we explored the impact of assuming 500 and 1000 kg/day, assuming the earlier starting time might lead to greater efficiency by reducing the fraction of the operating time used in the lag to create the opening and react with oxygen-consuming substances. Figure 37 shows the impact of these changes in the 2013 year assuming the aerator was providing 500 kg/day oxygen and was started 30 days earlier (mid-January) and 60 days earlier (mid-December). Figure 38 shows the simulated impact of starting the aerator 30 days earlier (mid-January) if it was providing 1000 kg/day. The simulation results show that if the aerator is only providing 500 kg/day, starting the aerator earlier would lead to a small increase in the oxygen concentration downstream of the aerator. That is consistent with a relatively high oxygen demand. We calculated a sediment oxygen demand of 0.5 to 0.6 g/m2-day in that section of the reservoir. That would correspond to more than 150 kg/day of oxygen in the 60 acre opening alone. As that oxygen moves to the much larger downstream segment, the model calculates the concentration change in the volume of the entire segment. Our simulations show that if the aerator is realizing 1000 kg/day of oxygen transfer, starting the aerator 30 days earlier should lead to an increase in oxygen concentration near the surface just downstream of the reservoir at the end of March. In the model simulations, this benefit comes from beginning the aeration at a time when there is a higher concentration of oxygen in the aeration zone and because it provides more time for the increased oxygen concentration to move downstream. In practice, additional benefits would be a likely lower concentration of oxygen-consuming substances released by the sediment and a greater average rate of oxygen transfer when the time to create the opening is a smaller percentage of the total operation period.

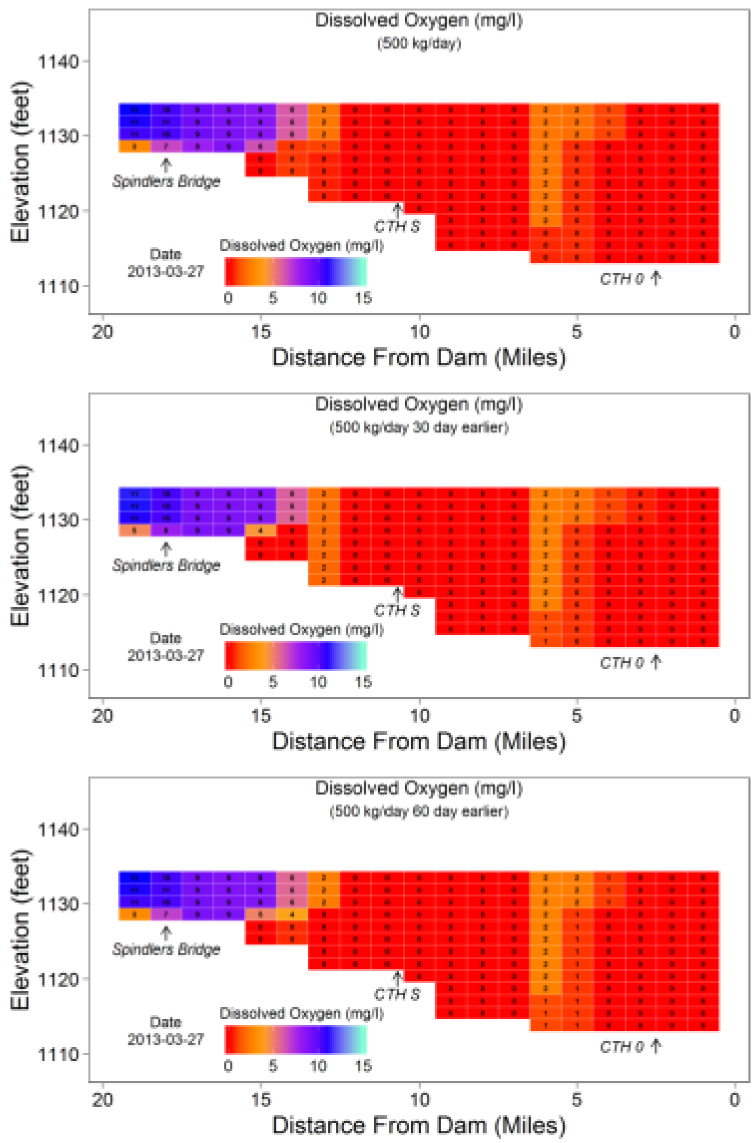

Figure 37. Comparison of dissolved oxygen profiles in the Big Eau Pleine Reservoir for March 27, 2013 comparing earlier start of the aerator. Upper profile is simulated 500 kg/day starting on February 13, second is 500 kg/day starting 30 days earlier, third is 500 kg/day starting 60 day early.

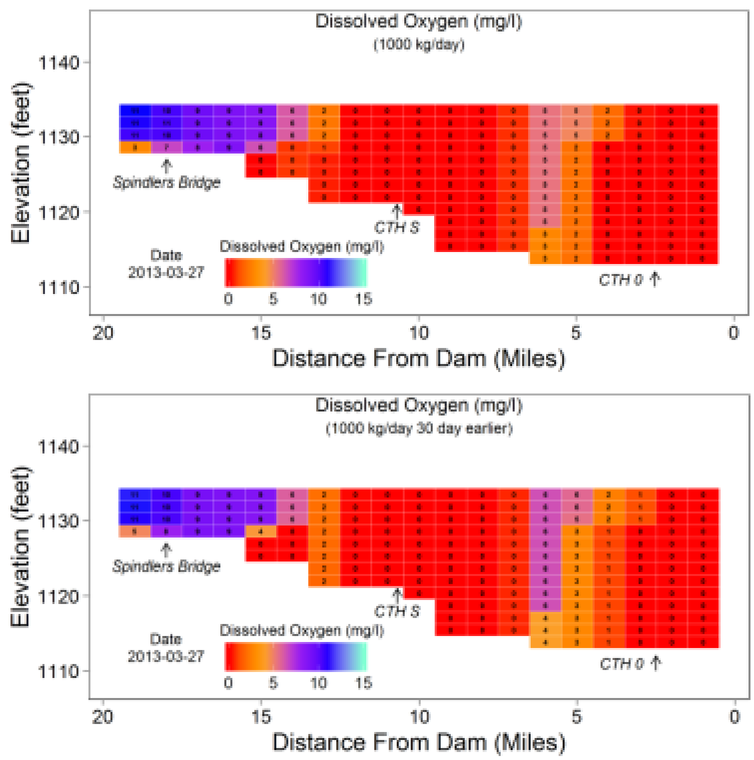

Figure 38. Comparison of dissolved oxygen profiles in the Big Eau Pleine Reservoir for March 27, 2013 comparing earlier start of the aerator and 1000 kg/day addition. Upper profile is simulated 1000 kg/day starting on February 13, second is 1000 kg/day starting 30 days earlier.

4.3 The Effect of Sediment Oxygen Demand

The dissolved oxygen in the Big Eau Pleine Reservoir measured profiles and the CE-QUAL-W2 model profiles for all years demonstrate the importance of oxygen consumption near the sediment. Oxygen depletion progresses upward from the sediment and can ultimately consume all of the oxygen under the ice. The conceptual model discussion examined how there are year-to-year variations in other sources of oxygen consumption, including inflow BOD and other sources of oxygen production such as inflow to the reservoir and photosynthetic oxygen production.

Calibrated sediment oxygen demand rates in the Big Eau Pleine Reservoir were between 0.35 and 0.60 g/m2-day. The rates were higher closer to the dam and the first seven miles were calibrated with SOD from 0.5 to 0.6 g/m2-d. Those rates are consistent with a eutrophic lake (Babin and Prepas, 1985).

A simple evaluation of the importance of sediment oxygen demand can be obtained by contrasting the quantity of oxygen that would be in the reservoir at ice-on with the quantity of oxygen that could be consumed through sediment oxygen depletion during the winter. Both of these will vary with the elevation of the reservoir. Higher initial reservoir volumes will contain more oxygen because mixing prior to freezing oxygenates most of the water. Higher reservoir volumes also increase the mass of oxygen consumed by the sediment because the sediment bottom area will be larger. Figure 39 shows how the oxygen consumed at two different sediment oxygen demand rates, 0.4 and 0.5 g/m2-day, compares with the initial oxygen in the reservoir (assuming a concentration at ice-on of 13 mg/l). Several observations can be made from this simple contrast. First, the figure shows the importance of the 1135 to 1142 reservoir elevation range. Most of the intersections between the initial oxygen mass and the consumed oxygen mass occur within those elevations. Second, the length of winter could be very important to the balance between initial oxygen and sediment oxygen demand in the reservoir. A winter length of 90 days corresponds to a late February spring flush with an early December ice-on. Many of the winters show an increase in flow by late February or early March. A winter length of 120 days corresponds to a late March spring flush. Several of the most problematic years, 2013 and 2008 for example, were late March winters after late November or early December ice-on. While instructive, this example is simplified and does not account for inflow and outflow of oxygen and photosynthetic production and BOD consumption that occurs within the reservoir, all factors that will vary from year-to-year.

The CE-QUAL-W2 model can be used to explore the importance of sediment oxygen demand on winter anoxia under conditions with varying inflow and other year-to-year conditions. A range of reductions in the SOD were used by adjusting the SOD for each segment proportionally. Figure 40 shows the measured profile for March 27, 2013 and compares that with the calibrated model after a ten and fifty percent reduction in the SOD. The figures show that the model simulates an increase in the dissolved oxygen near the dam in the SOD reduction scenarios although the extent of the reduction is relatively modest for a 10% reduction and much larger for a 50% reduction. The appearance of the profiles reflects how the model leads to a late mixing within the reservoir as warming from the surface and sediment have acted to decrease temperature variations under the ice. .

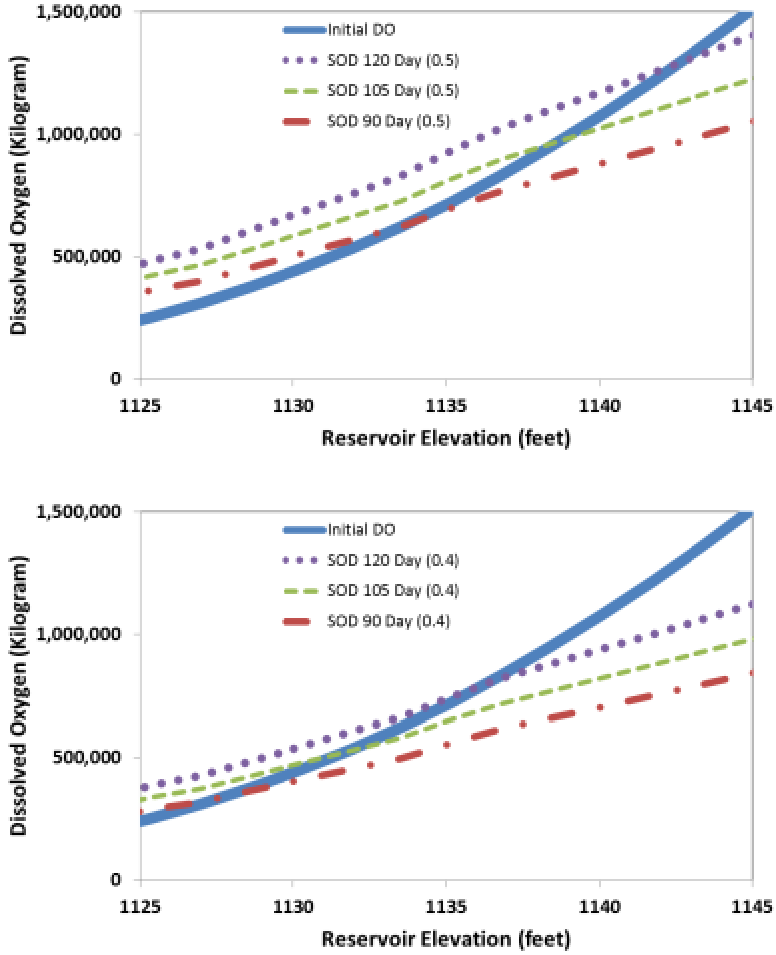

Figure 39. Comparison of the quantity of oxygen in the reservoir at the onset of freezing based on an initial concentration of 13 mg/l with the quantity of oxygen consumed at a sediment oxygen demand of 0.5 g/m2-day (upper) and 0.4 g/m2-day (lower). The sediment oxygen demand calculated for 90, 105 and 120 days after ice-on.

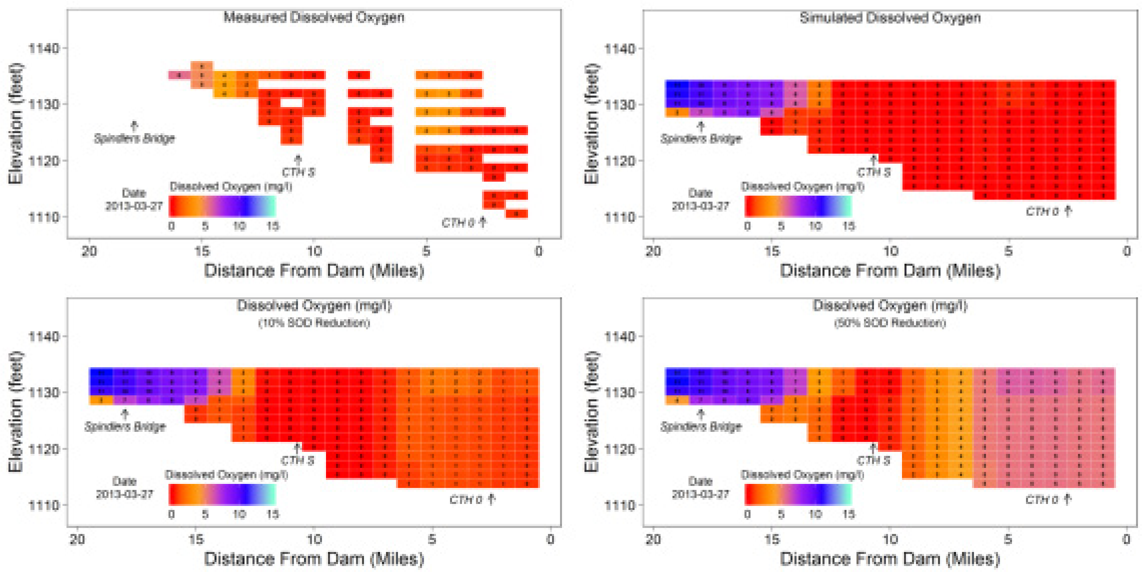

Figure 40. Simulation results for March 27, 2013 with variations in the sediment oxygen demand (SOD). Upper left figure shows the measured profiles, upper right the model results with the calibrated SOD values, the lower left figure assumes a 10% reduction in SOD across the reservoir, and the lower right figure shows simulation with a 50% reduction in the SOD across the reservoir.

The effect of multiple SOD-reduction simulations was summarized in Figure 41 as the number of days within Metric 2 and Metric 3 that the average dissolved oxygen concentration was less than 2 mg/l. Metric 2 is the area upstream of the aerator and Metric 3 is the area downstream of the aerator (Figure 10). Figure 41 shows that with the current SOD, we simulated the average dissolved oxygen concentration in both metrics would be less than 2 mg/l for almost a month. As the SOD is reduced, there is a reduction in the number of days that the average concentration in the metric region is below 2 mg/l. The rate of reduction with decreasing SOD is greater for the Metric 3 region. In that region, a 20% SOD reduction would lead to a decrease from 30 to 10 days below 2 mg/l, and a 30% reduction would keep the average dissolved oxygen above 2 mg/l in that Metric. The reduction in the number of days that the concentration is less than 2 mg/l corresponds to lengthening the winter period after ice-on before the metric values get below 2 mg/l. Similar to what was shown in the simplified SOD consumption graph earlier, decreasing SOD would not prevent very long winters from leading to very low dissolved oxygen, but would increase the length of the winter that could occur before the lower metric concentrations are reached.

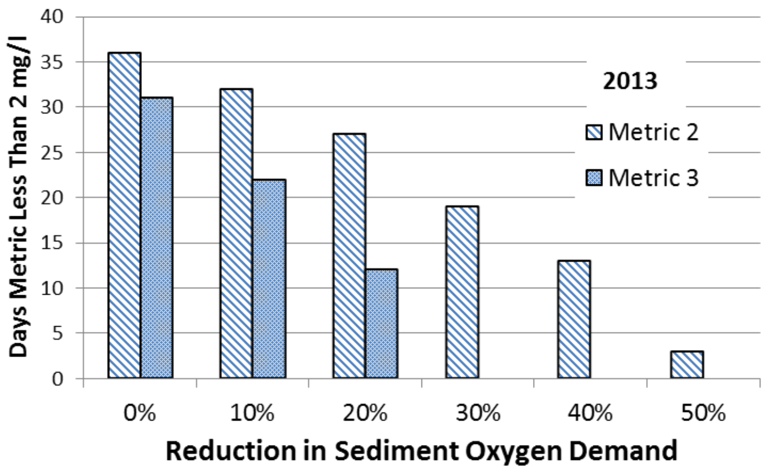

Figure 41. Comparison of the number of days that Metric 2 (upstream of the aerator) and Metric 3 (downstream of the aerator) have on average dissolved oxygen concentration less than 2 mg/l in 2013 with changes in SOD. SOD reduction shown as a percentage reduction from the calibrated values.

The sediment oxygen demand is a result of the eutrophic conditions in the Big Eau Pleine Reservoir. Biological productivity leads to greater organic matter production which ultimately settles and can be decomposed. The relationship between oxygen depletion and trophic production is complex (Muller et al., 2012), but we can begin to relate them through work of Babin and Prepas (1985). They found a correlation between spring phosphorus in a lake (TP_{sp} expressed in mg/m^2 based on the depth of the euphotic zone) and the winter oxygen depletion rate (WODR in g/m^2-d):

$$WODR = 0.124 + 0.00128 * TP_{sp}$$

Although it is a very approximate comparison, if we assume an average euphotic zone depth of 1.5 meter and an overturn phosphorus of 130 ug/l, their correlation would result in an SOD of 0.5 g/m^2-day. That is similar to that calibrated for the downstream half of the BEP. Within that concentration range, a 10 ug/l reduction in phosphorus concentration would correspond to an 8% reduction in the SOD (from 0.50 to 0.46). A 30 ug/l reduction in phosphorus concentration would correspond to a 20% reduction in the SOD (from 0.5 to 0.4).

5. Conclusions, Recommendations and Limitations

5.1 Conclusions

The results of this study show that the CE-QUAL-W2 model can be used to represent much of the year-to-year variability in the winter dissolved oxygen concentrations in the Big Eau Pleine Reservoir. The modeling suggests that this variability originates from a group of interacting factors including: 1) year-to-year differences in the water flow into the reservoir; 2) timing and duration of winter flow events; 3) timing and magnitude of spring flush events; 4) water level and the timing of level changes; 5) photosynthesis under the ice; and 6) ice formation timing and ice-cover duration.

There have been studies of the winter anoxia in the Big Eau Pleine for more than four decades. Previous studies have suggested a role for water level in the low dissolved oxygen and have also explored how inflow and water level management can coincide with the development of upstream dissolved oxygen depletion. Some of those older studies occurred when water level in the Big Eau Pleine could be lowered to less than 5% of full volume by the end of winter. Although not the subject of this study, those years would likely experience much more extensive replacement of water throughout the reservoir during the winter than the years examined in this study. The focus of this study was the more recent problematic years such as 2013 and 2009. Those are years with relatively low flow during the winter, relatively long ice cover, and approximately 20% (2009) to 40% (2013) of the reservoir volume still filled at the end of winter. Our simulations suggest that water age near and downstream of the aerator in those years was hundreds of days old by the end of winter, and the winter anoxia that develops is more likely reflecting the upward propagation of sediment oxygen demand and less likely to reflect a migration of an upstream dissolved oxygen depletion. As a result, the focus of the management evaluation was on how to retain oxygen under the ice into late March when there was little photosynthesis occurring under the ice.

Winter oxygen depletion in the Big Eau Pleine during low inflow years is largely driven by oxygen consumption near the sediment. This occurs by the decomposition of organic matter that has accumulated at the reservoir bottom. This is a biological process that uses oxygen when it is available. During the winter, the rate of upward propagation of low dissolved oxygen is accompanied by sediment warming the water which moves warmer, less dense water upwards and cooler, more oxygenated water downward. The result is an upward expansion of the anoxic zone. Because the rate of oxygen depletion is so high, the oxygen is depleted at the bottom and leads to almost no oxygen in the expanding anoxic zone.

The influx of water during the winter is often accompanied by a reduction in dissolved oxygen upstream. This appears to reflect both the addition of oxygen demanding substances in the flowing water that originates from organic matter from the watershed, erosion of bottom sediments, and/or disruption of anoxic warm water zones near the sediment. This lower dissolved oxygen water can move into the reservoir. Because inflows during the winter are often colder than the warmed bottom water, it can travel as a buoyant plume over the bottom water. When large winter inflow events occur, the upstream stratification can be disrupted and low oxygen water near the bottom can be pushed downstream. When these runoff events contain high concentrations of oxygen demanding material, they could have dramatic effects on dissolved oxygen concentrations. The episodic nature of these high BOD events meant they were not the focus of this study although the model could be used to explore their impacts. This study assigned an average BOD to winter inflow events. These flows are most likely to influence dissolved oxygen concentrations upstream of the aerator (the Metric 2 region).

The model was used to explore how the dissolved oxygen concentration in the downstream half of the reservoir late in the winter could be influenced by the reservoir water level at the start of winter. The results demonstrate the challenge of maintaining oxygen near the dam when winter extends into late March. The models shows that starting the winter at a higher water level leads to a higher average dissolved oxygen concentration at the reservoir surface, near the dam late in the winter but that it does not prevent the formation of anoxic conditions there during a very long winter. Because the length of winter and the quantity of photosynthetic dissolved oxygen that will be introduced is not known in advance of the winter, the modeling suggests that starting the winter at a higher elevation will decrease the likelihood of surface anoxia before spring runoff but not guarantee adequate dissolved oxygen near the surface during a very long winter.

The model was used to examine the influence of reaeration on oxygen concentrations in the reservoir. Although the model results are consistent with the aerator adding oxygen to the Big Eau Pleine, it is difficult to estimate the quantity of oxygen actually added. Reasons for this include the relatively long residence time of the water near the aerator, the relatively short period of time the aerator is on and the absence of dissolved oxygen measurements close to the aerator. A review of several years suggests that the aerator is realizing an overall addition of less than1000 kg oxygen/day. That is consistent with the first few weeks of aerator operation having a lower effective transfer of oxygen to the water because of the time required to create an opening in the ice and consume the oxygen demand of substances suspended by the aerator. If a large percentage of the water column is warmed and depleted of oxygen by the time the aerator is started, it will take more time to reoxygenate that water, and the mixing could deplete the remaining oxygenated water of oxygen and disperse toxic compounds such as ammonia into the overlying oxygenated water. The results of modeling the 2013 winter show that if the aerator only realizes an addition of 500 kg of oxygen/day, it will have a relatively small impact on the oxygen concentration near and downstream of the aerator because of the large oxygen demand in the system. The modeling suggests if the aerator can add 1000 kg/day or more, it can create a zone with a dissolved oxygen concentration greater than five mg/l. Starting the aerator earlier, e.g., mid-January, was simulated as beneficial to creating this refuge. The aeration modeling is a simplified representation of what actually occurs as it does not simulate the temperature reduction or turbulent mixing that is in evidence in the measured profiles and it is recommended that monitoring be performed to better evaluate the oxygen transfer rate.

The model was used to examine the influence of sediment oxygen demand on the winter anoxia in the Big Eau Pleine. The calibrated model sediment oxygen demand of approximately 0.35 g/m2-day upstream and 0.5 g/m2-day downstream in the Big Eau Pleine is relatively high compared to the amount of oxygen that would be in the reservoir at the start of winter. In the absence of additional oxygen additions through photosynthesis or aeration, these rates have the potential to consume much of the initial oxygen mass during long winters. In many years, the occurrence of a spring flush in early March and photosynthesis under the ice appear to reduce the winter anoxia. The model was used to evaluate how reductions in the sediment oxygen demand could decrease the likelihood of winter anoxia. Simulations with SOD reductions from ten to fifty percent show how the number of days that the average oxygen concentration would be low would be decreased if the SOD is reduced. This would decrease the likelihood of fish kills as it delays the onset of anoxia. The 2013 simulations suggest benefits with even a ten percent reduction in SOD leading to ten fewer days that the average oxygen concentration would be less than 2 mg/l in the downstream metric zone. Greater percentage reductions in the SOD would have increasingly greater benefits to the winter oxygen concentrations.

5.2 Recommendations for Future Work and Limitations of this Study

This modeling study applied the CE-QUAL-W2 water quality model to study the winter anoxia in the Big Eau Pleine. This was a relatively novel application of the model and required an extensive review of related research and evaluation of model inputs. It would not have been possible to calibrate this model and generate the hypotheses regarding the processes occurring under the ice without the long record of temperature and dissolved oxygen profiles collected each year on the Big Eau Pleine by the WVIC. Although the model has been useful to help us understand winter anoxia in the Big Eau Pleine and to begin to evaluate how alternative management strategies might improve winter dissolved oxygen, it generalizes the physics and biology that occurs under the ice in the Big Eau Pleine. We would propose additional monitoring and modeling efforts could include:

1) Continue the winter profiles for temperature and dissolved oxygen. These are critical to understanding the year-to-year variations.
2) Monitor oxygen closer to the aerator using a remote monitoring system during the aerator startup and after. It would be useful to understand the rate at which oxygen is transferred and that is difficult in low flow

winters with the existing monitoring. It would useful to understand the rate of oxygen transfer and if sediment conditions prevent realizing the full benefit of the aeration system.

3) Evaluate photosynthetic oxygen production under the ice. A review of the year-to-year variations in dissolved oxygen concentrations suggests substantial variations in the photosynthesis under the ice. This can apparently lead to relatively high oxygen concentrations in the cooler, buoyant water under the ice. This additional oxygen mass can dilute the impact of late winter water mixing on anoxia.
4) Monitor temperature and dissolved oxygen perpendicular to the channel. Our review of the literature and evaluation of the data suggests lateral water movement could be important to understanding the upward propagation of anoxia. A series of transect monitoring locations could be used to compare warming and anoxia early in the winter.
5) Ice on / ice off timing. Although several years had reported ice formation and ice off timing, most years did not. That is useful information for understanding the conditions near ice formation and fall mixing. It would be useful to record ice on dates at several locations along the reservoir.

It is important to recognize that any modeling has limitations. Important assumptions that relate both to the simplifications and to the representation should be understood when interpreting the results of this study. In particular, we have identified several considerations:

1) The model assumes that the oxygen concentrations and water temperatures at each mile and for each layer are uniform across the width reservoir. Because we are suggesting that winter temperature stratification may have an important influence on water movement under the ice, it is important to remember that the model does not incorporate variations in water movement that could lead to horizontal mixing or variations in residence time across the channel.
2) Comparison of the measured and modeled profiles also suggests intermediate mixing between the cooler less dense surface water and the warmer, denser bottom waters. That is generally not simulated in the model where a sharper transition between warm bottom and cooler surface waters is simulated. That may reflect some mixing that will also lead to intermediate oxygen concentrations between those zones near the dam.
3) The model assumes parameters such as albedo and sediment temperature are constant throughout the winter and from year-to-year. We know those vary over time depending on ice characteristics, snow cover and air temperature.
4) Inflow into the model was estimated based on outflow and reservoir elevation. This might lead to errors in the estimated inflow rate due to uncertainty in either reservoir elevation or outflow. The estimated inflow pattern was very similar flow to that reported at Stratford in some winters and different in others. That discrepancy could mean that the inflow used in the model was not accurately reflecting what occurred in some winters. Because inflow rates are important to the development of the dissolved oxygen profiles, this could explain some of the difficulty in describing temperature and oxygen profiles.
5) The event and background BOD used a very simple relationship between temperature, precipitation and flow. It is reasonable to assume that BOD concentrations will vary between events and this will certainly lead to differences in oxygen concentrations from those simulated. While these assumptions provide a reasonable fit to the average over many years, there could be considerable variation from event-to-event.

6. References

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