

Mile-High Decisions: **Denver**

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Considerations in the Selection, Design, and Installation of a Drinking Water Reservoir Oxygenation System

Background on Marston Reservoir

Denver Water supplies water to over one million people in the Denver metropolitan area. It has a complex water supply consisting of water diverted from multiple basins on both sides of the continental divide, as shown in Figure 1. Marston Reservoir is one of three terminal water supply reservoirs for Denver Water and functions as storage for the 250 million gallon per day Marston Water Treatment Plant (WTP). Marston Reservoir was constructed in 1899 on the site of two existing small ponds. The majority of the water supply for Marston Reservoir is diverted from the South Platte River upstream of the Denver metro area and conveyed approximately 12 miles to the reservoir via pipeline. There is a second water source, a diversion from Bear Creek that is also conveyed via pipeline. The Bear Creek water source is normally only diverted to the reservoir when necessary, as the water in the watershed is generally of a lesser quality than the water diverted from the South Platte River. The small local Marston Reservoir watershed, primarily urbanized, is diverted around the reservoir and not a source of inflow to the reservoir.

The moderate reservoir depth of 66 feet results in only a thin hypolimnion of 20 to 30 feet. The hypolimnion becomes anoxic soon after the onset of stratification in June, continuing until turnover in late September. Figures 2 and 3 illustrate the seasonal stratification and hypolimnetic

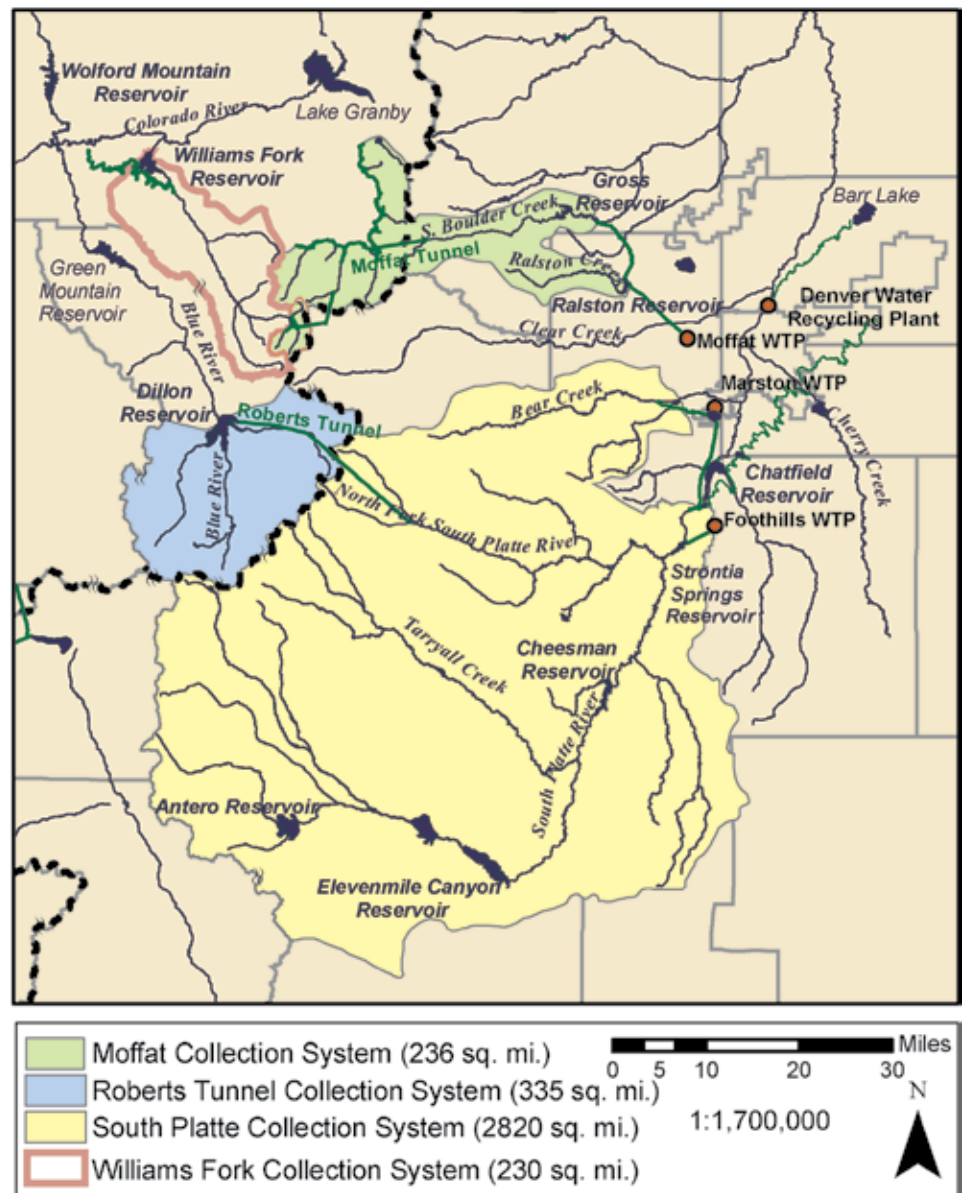


Figure 1. Schematic of Denver water collection system.

anoxia. Marston Reservoir can be considered morphometrically eutrophic, with only a tiny hypolimnion relative to many other stratified lakes.

Water Quality Concerns

The reservoir has only one intake located at a low level that results in the withdrawal of anoxic water from the

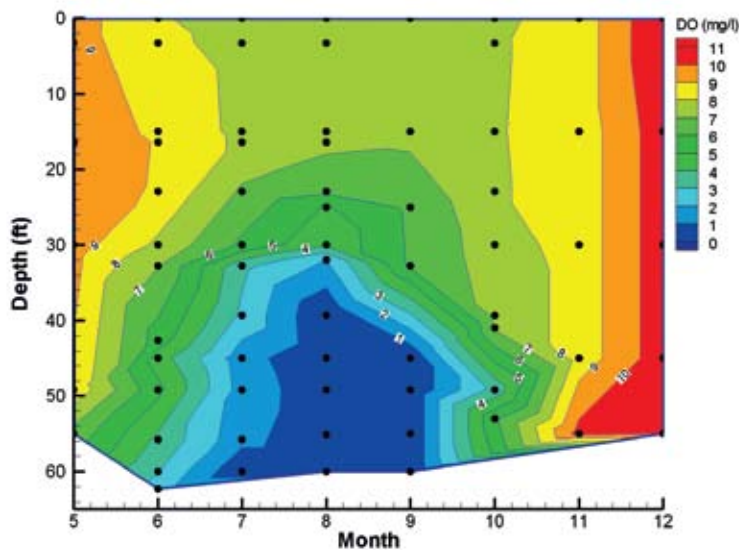
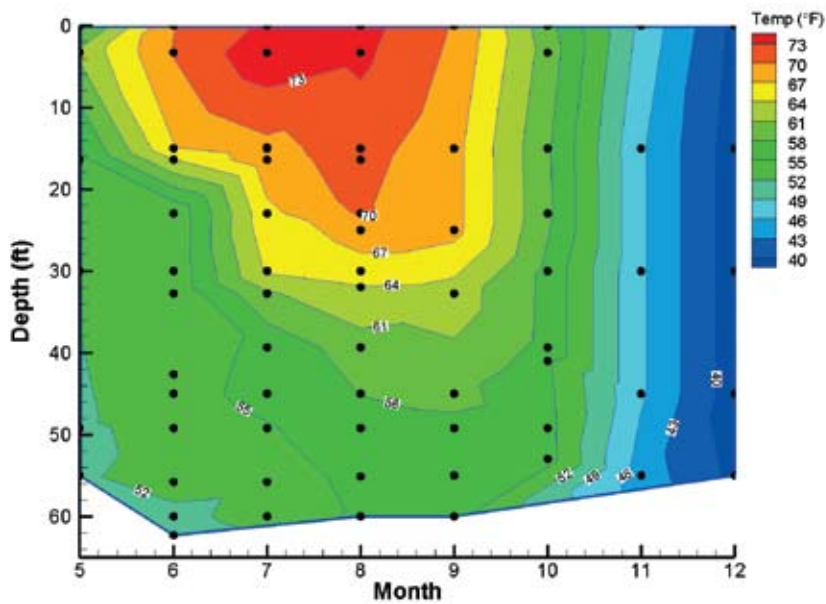
Table 1. Marston Reservoir Physical Data.

	<i>English Units</i>	<i>Metric Units</i>
Surface area	621 acres	251 hectares
Reservoir volume	19,800 acre-feet	24.4 x 10 ⁶ meters ²
Elevation of high water line above mean sea level	5,538 feet	1,686 meters
Maximum reservoir depth	66 feet	19 meters
Mean reservoir depth	26 feet	8 meters
Depth of lowest intake	43 feet	13 meters
Dead pool (storage below the lowest intake)	7,000 acre-feet	6.2 x 10 ⁶ meters ²

hypolimnion to the water plant during the peak summer water demand season. In many years, objectionable taste and odors (which may be caused by elevated levels of manganese) occur in mid-summer after anoxia and during /after the autumn turnover in both the raw and treated water. Additional water quality concerns include organic taste and odor, Eurasian watermilfoil, and wastewater impacts in the Bear Creek watershed supply. These water quality issues limit the desirability of use of the reservoir for water supply. Paradoxically, by most standard measures, the reservoir water quality is very good with low chlorophyll *a* (annual mean < 4 μg/l) and high Secchi depth (annual mean >4.5 m). As a result of periodic taste and odor complaints from customers receiving water from the Marston WTP, Denver Water constructed a pipeline that allows the water plant operators to convey water from the South Platte directly to the Marston WTP and bypass the reservoir. The bypass is the preferred water source when water quality in the reservoir is of a lesser quality than the water in the South Platte River. The use of the bypass presents some concerns, as it results in more complicated operation of the water system, a reduction in the volume of water that can be treated, and increased vulnerability to unpredictable impacts to the South Platte River, including several major forest fires in the South Platte River watershed upstream of Denver’s diversion, the possibility of major storms, and the effects of drought.

Denver Water takes pride in delivering high-quality water to its customers. Dissolved metals withdrawn to the water plant during stratification and post-turnover algal blooms and related taste and odor are likely the result of summer anoxia and related internal loading of metals and nutrients. Improvements to the treatment processes at the Marston WTP have helped, but not eliminated customer complaints. The use of powdered activated carbon at the WTP to address taste and odor has proven to be expensive and of limited effectiveness.

Over the past 15 years, Denver Water has studied the Marston Reservoir water quality concerns and evaluated various strategies to ensure the ability to consistently deliver high quality water to its customers. These previous studies



Figures 2 and 3. Average monthly Marston Reservoir temperature and dissolved oxygen, May-October, 2000-2007.

suggested that aeration or oxygenation of Marston Reservoir could address the dissolved metals and internal loading. A multi-level intake was also considered to provide maximum flexibility in selecting the best quality water in the reservoir. The multi-level intake remains under consideration, but has been delayed due to its high cost.

Selection of Oxygenation

Hypolimnetic aeration or oxygenation was determined to be a cost-effective measure that addressed many of the water quality concerns. Denver Water, working with Alex Horne Associates and CDM, conducted a comprehensive analysis of hypolimnetic treatment options. Considerations included the effects of the thin hypolimnion and Denver’s high elevation and the desire to suppress internal loading of nutrients and maintain stratification to keep cool water delivered to the WTP. A matrix of options was prepared and hypolimnetic oxygenation using a submerged downflow contact oxygenation (SDCO), commonly referred to as a “Speece Cone,” was selected for final design and installation for the following reasons:

- Low turbulent method that would produce a high DO level above the sediments
- Suppression of nutrient releases in the microzone at the sediment surface
- High dissolved oxygen over the sediments
- Silent operation (reservoir is closely bordered by residences)
- Possibility of horizontal water flow over the sediments
- Small footprint and few pipelines on the reservoir bed
- Efficient oxygen transfer at 5,500 feet elevation
- Maintains temperature gradient in the hypolimnion
- Success in reversing internal-loading generated eutrophication in other reservoirs

Design Considerations

The design of the Speece Cone was done in collaboration with CDM, Denver Water, and ECO2 Technologies – the manufacturer of the Speece Cone. The system is sized for a maximum oxygen feed rate of 2,000 lb/day (0.90 metric

<i>Water Quality Concern</i>	<i>Likely Cause(s)</i>	<i>Potential In-lake Remedies</i>
Elevated levels of dissolved metals during the fall	<ul style="list-style-type: none"> • Anoxia in hypolimnion during stratification • Anoxia related to thin hypolimnion and sediment oxygen demand 	<ul style="list-style-type: none"> • Multi-level intake for selective withdrawal • Aeration or oxygenation
Summer algae blooms	<ul style="list-style-type: none"> • Excessive nutrients in epilimnion 	<ul style="list-style-type: none"> • Reduce nutrients in inflow
Autumn post-turnover algae blooms and related taste and odor	<ul style="list-style-type: none"> • Internal loading during anoxia mixed to the surface after turnover • External loading of nutrients 	<ul style="list-style-type: none"> • Reduce nutrients in inflow • Aeration or oxygenation to eliminate anoxia and internal loading • Alum treatment of lake sediments to address internal loading • Dredging to address internal loading
Eurasian watermilfoil	<ul style="list-style-type: none"> • Water quality impacts to drinking water quality are uncertain 	<ul style="list-style-type: none"> • Chemical treatment (undesirable since it is a terminal drinking water reservoir) • Drawdown (current practice) • Weed harvesting (current practice) as part of drawdown

tons/day). The system was designed to run from the time the reservoir first stratifies in May until turnover occurs in the fall (Figure 4).

The system was sized based on both the Hypolimnion Oxygen Demand (HOD) and the Sediment Oxygen Demand (SOD). The HOD was calculated by taking the volume of the hypolimnion (approximately 13 percent of the total volume) and multiplying by the average DO demand observed in previous years. The SOD takes into account the fact that when oxygen is added to water, the sediment also uses the oxygen supplied. SOD can only be measured directly using isolated columns incubated at hypolimnion temperatures in the laboratory but it has been found to be a fairly constant function of the hypolimnion water HOD. For this project, a conservative SOD of 3.0 was used. The total amount of oxygen that needs to be supplied is expected to drop over time as the SOD is consumed. It is anticipated

that after one to three years of operation the total oxygen demand will be in the range of 500 to 750 lb/day (0.23 to 0.34 metric tons/day). Oxygenation will then be needed only to balance the losses from the Biochemical Oxygen Demand (BOD) of algal decay.

Design challenges at Marston Reservoir were magnified because of the topography of the bottom of the reservoir. Because the dam was built around two previously existing ponds, the deepest part of the reservoir is located in the center of the reservoir, versus near the dam as is normal for most reservoirs. This made the gaseous oxygen (supplied from a liquid oxygen bulk tank) and electrical lines very long (approximately 2,000 feet). The reservoir bottom was also not suitable for direct placement of the Speece Cone assembly. A geotechnical investigation found that six feet of muck had to be excavated and replaced with rock and gravel to prepare a suitable surface for placing a tremied concrete base pad for



Figure 4. Loading the Speece Cone on to the barge prior to installation.

the Speece Cone assembly and manifold piping.

Capital and construction costs for the project were approximately 2.5 million dollars. The project was installed over a five-month period and required an experienced contractor with both underwater construction and electrical subcontractors. Construction of the project required close coordination with equipment suppliers which was complicated by the fact that the Speece Cone, liquid oxygen tank, and submersible pump were all pre-purchased by Denver Water.

Operational Considerations

When the Speece Cone is in operation, water from the bottom of the reservoir is pumped through the intake screen and pump column to the top of the cone where the gaseous oxygen is also fed into the cone. As the water travels down through the cone, it dissolves the oxygen extremely efficiently. In theory, 100-percent-efficient oxygen transfer is possible, which would result in no bubbles leaving the Cone, however, 90-to 95-percent efficiency is more common. The super-oxygenated water is distributed through a 40-foot manifold into the bottom of the reservoir.

In order to monitor the effectiveness of the system, a solar operated floating

profiler system that monitors dissolved oxygen, temperature, and conductivity was installed in Marston Reservoir. The profiler system collects data twice a day and is used to monitor parameters in the reservoir.

Results

The oxygenation system began its first season of operation on May 14, 2009. The system was initially set at 100-percent output of approximately 2,000 lbs/day. This is a delivered cost of \$92/day for liquid oxygen. Figure 5 shows a comparison of the DO levels at the bottom of Marston for 2008 and 2009. At 100-percent output, the oxygenation system reversed the DO depletion and increased the levels at the bottom of the reservoir to pre-stratification levels of 10 mg/l. After nearly four weeks of operation, on June 9th, the system was turned down to a 75-percent output of 1,500 lbs/day at a cost of \$69/day. The bottom DO levels continued to remain at high levels, with DO of 10 mg/l on July 1 (Figure 5). A goal of a minimum bottom DO level of 5 mg/l had previously been established and on July 8 the oxygenation feed rate was reduced to 50 percent. The bottom DO responded with a steady decrease and the feed rate was increased to 75 percent when the DO decreased to 8 mg/l. The bottom DO

continued to decline, but at a decreased rate. On August 14, the oxygenation rate was increased to 100 percent, reversing the decline in bottom DO. These very preliminary results suggest that an oxygen feed rate between 75 percent (1,500 lbs/day) and 100 percent (2,000 lbs/day) may be needed for the first few years to maintain DO levels once the desired DO level is achieved.

With the uncertainties of the sediment oxygen demand over the next few months, continued first-year “shakedown” of the oxygenation system, and low operational costs, Denver Water is taking a conservative approach and maintaining an oxygen feed rate designed to stay well above the 5 mg/l minimum DO goal. Denver Water staff is pleased with the results to date and waiting for the late summer when anoxia is well-established and the post-fall turnover algae bloom to see if a noticeable improvement in water quality at the Marston WTP is observed. Stay tuned for a future NALMS presentation after a few years of operations.

References

- Pre-design for hypolimnetic aeration/oxygenation for Marston Reservoir, Denver Colorado, Alex Horne Associates and CDM, 2006.
- Marston Multi-Level Outlet – Selective Withdrawal Performance, Tracy Vermeyen, Hydraulics Consultant, 2007.

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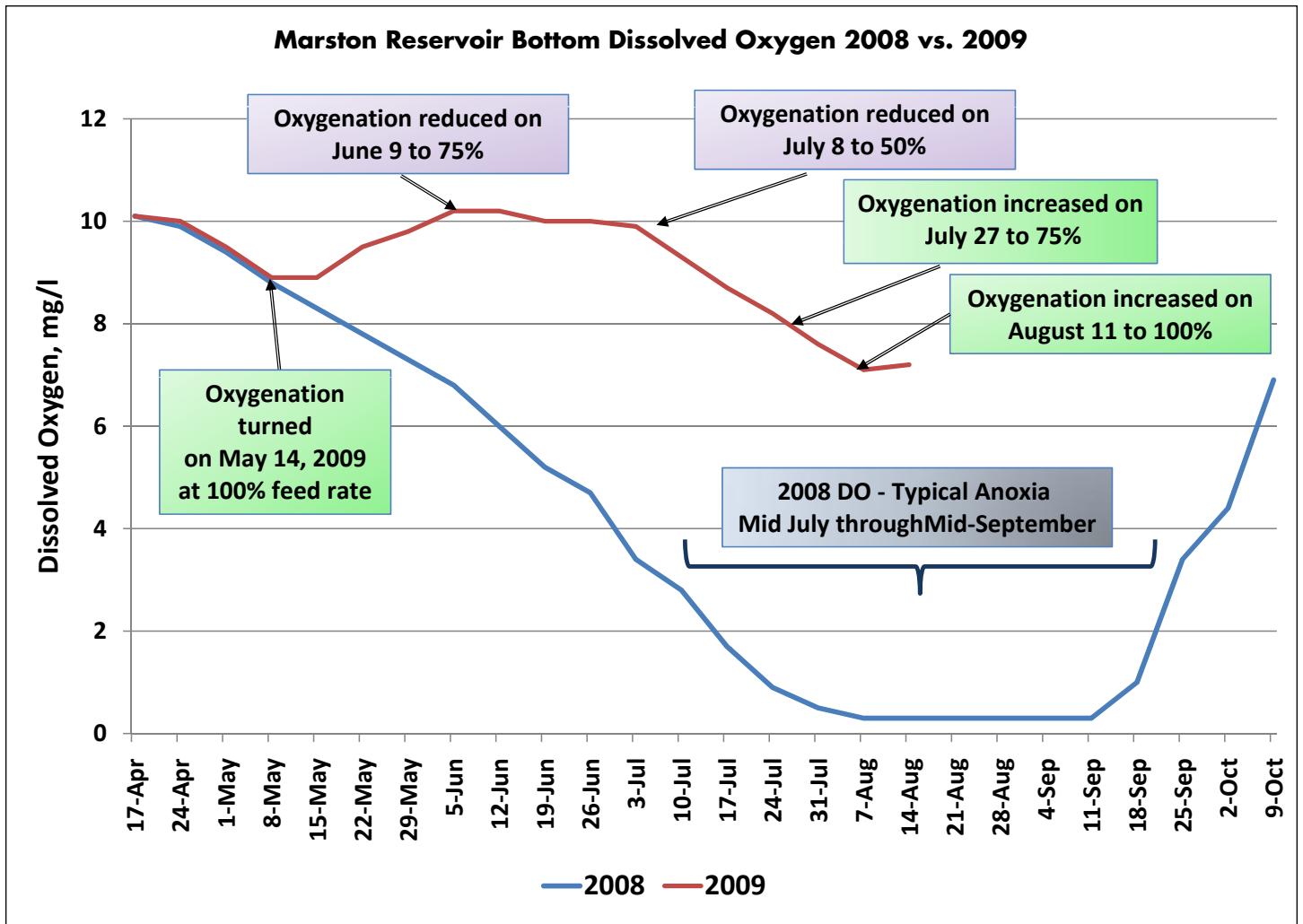


Figure 5. Comparison of bottom DO with and without oxygenation.

Kelly DiNatale is president of DiNatale Water Consultants, Inc. He is a registered professional engineer and Certified Lake Manager. He served as president of the Colorado Lake and Reservoir Management Association and as regional director and committee chair of NALMS. Kelly has 29 years of experience in the planning, design, construction, and operations and maintenance of raw water supply, water quality, watershed protection, reservoir management, water treatment, and wastewater treatment facilities, and worked on this Marston project while previously employed at CDM. 🦋

