TECHNICAL MEMORANDUM

TO: Chuck Reid, Manager, CCBWQA
FROM: Kevin Bierlein, PhD, Christine Hawley, and Jean Marie Boyer, PhD, PE; Hydros Consulting Inc.
SUBJECT: Cherry Creek Reservoir Bubble-Plume Modeling Report
DATE: April 30, 2019

The Cherry Creek Basin Water Quality Authority (Authority) requested that Hydros Consulting (Hydros) apply a coupled bubble-plume and water-quality model to further assess the existing destratification system in Cherry Creek Reservoir and evaluate possible modifications to the existing system to improve reservoir water quality. While the original reservoir model included representation of the destratification system, use of the coupled bubble-plume model provides a more mechanistic simulation of the existing system and the ability to evaluate the water-quality response to specific design modifications. Specifically, the following questions were targeted with this application, focusing primarily on summertime chlorophyll *a* concentrations and dissolved oxygen (DO) at the bottom of the reservoir:

- What would be the effectiveness of the existing destratification system if compressor shutdowns could be avoided?
- What would be the benefit of increased air flow rates to the existing array of diffuser heads?
- What would be the benefit of increasing the number of diffuser heads with the same current air flow to each diffuser head?
- What would be the benefit of increasing both the number of diffuser heads and the flow rate to each of the diffuser heads?
- From these runs, can the chlorophyll *a* standard be met with an enlarged destratification system? If so, what is the minimum size of that system? If not, what is limiting the system from achieving that objective?

This technical memorandum documents the application of the coupled bubble-plume and water-quality model to Cherry Creek Reservoir. It also presents the results (simulated water-quality response) of scenario runs conducted to answer the questions listed above. The memo is organized in six sections:

1. Background;
2. Coupled Model Description;
3. Application to Cherry Creek Reservoir;
4. Scenario Results;
5. Conclusions and Recommendations; and
6. References.

1 Background

Cherry Creek Reservoir (Figure 1) is a 13,000 acre-ft flood-control reservoir located southeast of Denver, Colorado. The reservoir is a popular recreation area and a high-quality walleye fishery. The Cherry Creek Basin Water Quality Authority (Authority) exists to protect and improve water quality in the reservoir to meet applicable water-quality standards. Key water-quality concerns for the reservoir include periodic nuisance cyanobacteria (blue-green algae) blooms and high chlorophyll *a* concentrations. The reservoir has failed to consistently meet the current site-specific chlorophyll *a* standard of 18 µg/L, which is assessed as a July through September average.

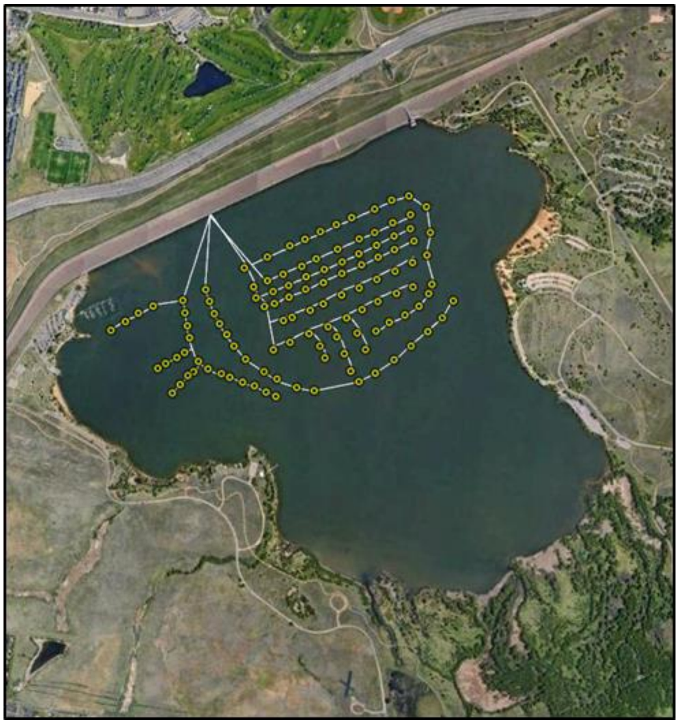

Figure 1. Cherry Creek Reservoir and Destratification System Footprint ***(Background aerial image from Google Earth; imagery date May 13, 2017)***

The Authority has implemented numerous projects over the years in the watershed and the reservoir in an effort to improve water quality in Cherry Creek Reservoir. In-reservoir efforts include installation of a compressed-air destratification system (in-reservoir footprint shown in Figure 1). Mixing from the destratification system was intended to increase DO at the bottom, thereby reducing internal loading of nutrients and resulting chlorophyll *a* concentrations (AMEC et al., 2005). The mixing from the destratification system was also intended to reduce cyanobacteria concentrations by disrupting their buoyancy advantage over other types of algae (AMEC et al., 2005). The existing destratification system consists of an air compressor that forces air through 115 circular diffuser heads (JRS Engineering, 2018) that are spread over approximately 350 acres of the 850 acre reservoir. The system had 116 diffuser heads until a damaged diffuser head was removed in 2018 (JRS Engineering, 2018). The diffuser heads release air bubbles approximately 0.75 m above the reservoir bottom (Swanson, 2018) at a flow rate of 2.4 SCFM (standard cubic feet per minute) per head (AMEC, 2006). The destratification system was operated from 2008 through 2013 (from roughly April through November each year) and in the spring of 2017 and 2018.

In 2015, based on ongoing water-quality concerns, the Authority identified a need to develop a water-quality model of the reservoir. To meet that need, a two-dimensional hydrodynamic and water-quality model of Cherry Creek Reservoir was developed by Hydros (Figure 2; Hydros, 2017) using CE-QUAL-W2 (Cole and Wells, 2017). The model and supporting data analysis identified the following as key drivers of the observed chlorophyll *a* and cyanobacteria response in the reservoir:

- Relatively shallow depth and resulting polymixis (frequent vertical mixing of the water column) due to wind;
- High levels of internal and external phosphorus loading; and
- Nitrogen limitation creating favorable conditions for nitrogen-fixing cyanobacteria.

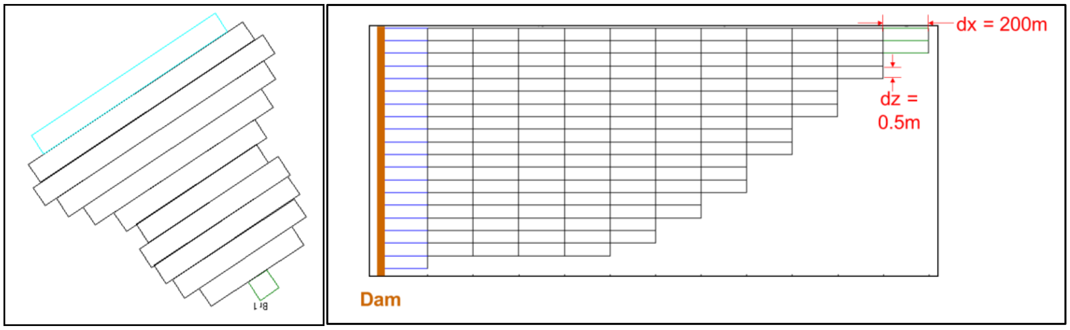

Figure 2. Plan and Profile Views of Cherry Creek Reservoir Model Segmentation

In addition to identifying key drivers of the algal and cyanobacteria response, the model and associated data analysis (including data from 2003 – 2013) indicated that the current destratification system was not able to meet its objectives. This finding was based on the fact that operation of the destratification system from 2008 – 2013 did not result in consistent achievement of the chlorophyll *a* standard, nor did it maintain oxygenated conditions at the bottom of the reservoir.

Additional model scenario simulations of the years 2003 – 2013 also identified that, with enough mixing, a destratification system could achieve oxygenated conditions at the bottom of the reservoir to reduce anaerobic internal loading and chlorophyll *a* concentrations. The mechanism used to increase vertical mixing in the model scenario run (AERATEC module in CE-

QUAL-W2) was a simple multiplier on vertical mixing, rather than a mechanistic representation of the destratification system. As such, the model could not provide the necessary information to identify potential upgrades to the destratification system that could achieve this level of mixing.

As a result, the Authority requested that a coupled bubble-plume and water-quality model be applied to Cherry Creek Reservoir to allow a mechanistic representation of the mixing induced by the destratification system. This type of model is capable of incorporating the effects of potential modifications to the destratification system (such as increased air flow or additional diffuser heads), and can be used to simulate how the reservoir would likely respond to such modifications.

2 Coupled Model Description

The coupled model incorporates the bubble-plume model of Wüest et al. (1992) into CE-QUAL-W2 (Cole and Wells, 2017). These models are briefly described below.

CE-QUAL-W2 is a widely-used reservoir water-quality modeling software package. It is an open-source, two-dimensional, laterally-averaged hydrodynamic and water-quality model that simulates water temperature, DO, nutrients, total organic carbon, chlorophyll *a*, and many other chemical and biological constituents and processes that occur in lakes, reservoirs, and rivers. The model software is well-accepted, and was used to develop the existing water-quality model of Cherry Creek Reservoir (Hydros, 2017).

The Wüest et al. (1992) model simulates a bubble plume rising through the water column. This bubble-plume model solves a system of differential equations to calculate the volume of water moved by the bubble plume, vertical plume velocity and momentum, plume temperature and DO concentration, entrainment of ambient water into the plume, mass transfer of oxygen from the bubbles to the water, and plume detrainment. The model accounts for the physical configuration of the diffuser system, including the gas flow rate, gas type (air or oxygen), diffuser diameter, initial bubble size, and diffuser depth. It also accounts for the temperature, salinity, density, and DO concentration of the ambient water. Figure 3 provides a conceptual schematic of a single diffuser head and the associated bubble-plume simulated by the model. A detailed description of the model equations and assumptions can be found in Wüest et al. (1992). This plume model has been coupled to several water-quality models and used to simulate bubble-plume oxygenation and mixing systems in many lakes and reservoirs (e.g., Wüest et al., 1992; McGinnis et al., 2004; Singleton et al., 2010; Chen et al., 2018).

When the coupled model is simulating a period with the destratification system in operation, the bubble-plume model is used to simulate each operating diffuser head. The ambient temperature, total dissolved solids (TDS), and DO profiles are passed from CE-QUAL-W2 to the bubble-plume model. The bubble-plume model then solves for the volume of water entrained from each model layer and determines the layers where the plume detrains. The entrainment and detrainment flows are then passed back to the CE-QUAL-W2 model and transported appropriately from the entrainment layers to the detrainment layers. Oxygen that is transferred from the bubbles to the water in the plume is also added to the detrained water. Thus, the coupled model mechanistically simulates the resulting mixing patterns and transfer of DO from the bubbles to the surrounding water.

The coupled model also includes a factor to account for the increased oxygen demand that is typically observed when oxygenation or destratification systems are operating, which is referred to as induced sediment oxygen demand (Gantzer et al., 2009; Beutel, 2003; Prepas and Burke, 1997; Moore et al., 1996). This phenomenon is represented in the model as a multiplier on the sediment oxygen demand that is used in each model segment when that segment contains operating diffuser heads. The multiplier was determined based on observed data during application of the coupled model to Cherry Creek Reservoir.

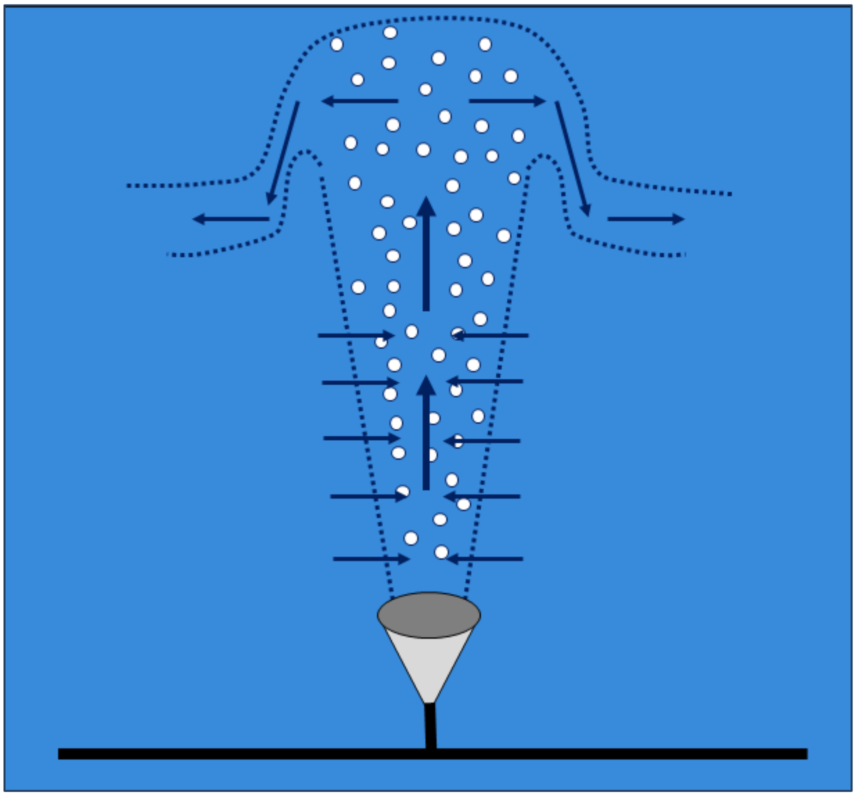

Figure 3. Schematic of a Bubble Plume

3 Application to Cherry Creek Reservoir

The following subsections describe how the coupled model was applied to Cherry Creek Reservoir.

3.1 Model Setup

To simulate the actual system operations from 2008-2013, the destratification system was represented in the coupled model to reflect the physical configuration of the system in Cherry Creek Reservoir, including the number, location, elevation, structure, and air-flow characteristics of the existing diffuser heads. Each of the 116 diffuser heads (JRS Engineering, 2018) is represented as a separate bubble plume. Bubble-plume model input parameters, values, and data sources are listed in Table 1 and summarized as follows:

- GPS coordinates for each diffuser head (Wacha, 2018) were used to determine the model segment in which the diffuser head is located.
- The elevation of each diffuser head was determined using the bottom elevation at each diffuser head location and adding 0.75 m, which is approximately the distance from the centerline of the air supply line to the top of the plastic cone on each diffuser head (Swanson, 2018).
- The initial diameter of the bubble plume for each diffuser is 9”, based on the physical size of the diffuser heads (Xylem, 2019).
- Since the diffuser heads produce bubbles with diameters of 1-2 mm (Hatfield, 2018), the initial bubble size in the plume model was set to 1.5 mm.
- A time series of diffuser operations was developed based on annual destratification system operational reports (TC Consulting Services, 2009, 2010a, 2010b, 2012, 2013; JRS Engineering, 2013). The model input files were set up to allow the coupled model to simulate different startup dates for each of the five zones of the destratification system, and to account for the addition of 14 diffuser heads in July and August 2008 (Ruzzo, 2018) to bring the total to 116 heads. This allowed the coupled model to simulate the actual operation of each diffuser head in each zone, as documented in the annual operations reports.

Table 1. Summary of Model Inputs Used to Represent the Cherry Creek Reservoir Destratification System in the Coupled Bubble-Plume and Water-Quality Model

Model Input	Value / Information Type	Reference
Location of 116 diffuser heads	GPS coordinates for each diffuser head	Wacha, 2018
Elevation of 116 diffuser heads	Bottom elevation +0.75 m at GPS coordinate for each diffuser head	Swanson, 2018
Diffuser head flow rate	2.4 SCFM per diffuser head	AMEC, 2006
Initial bubble-plume diameter	9”	Xylem, 2019
Initial bubble size	1.5 mm	Hatfield, 2018
System operation time series	Each diffuser head turned on/off using actual system operations	TC Consulting Services, 2009, 2010a, 2010b, 2012, 2013; JRS Engineering, 2013

For application of the coupled model to Cherry Creek Reservoir, the same CE-QUAL-W2 input files, settings[1], and assumptions from the existing Cherry Creek Reservoir Water-Quality Model were used, with the exception of the AERATEC module, which was turned off in the coupled model due to the use of the bubble-plume model. The CE-QUAL-W2 input development and assumptions are documented in the original Cherry Creek Reservoir Water-Quality Model Report (Hydros, 2017). The coupled model met all numerical and non-numerical calibration criteria set forth (Hydros, 2017) for the full simulation period.

3.2 Model Scenarios

Using the calibrated coupled model, four sets of “what if” simulations were conducted over the period from 2008 – 2013 to answer the questions listed on page 1. The sets of simulations were:

- **Existing System with No Compressor Shutdowns**: Since the existing destratification system has had issues in the past with unplanned air compressor shutdowns, the potential value (in-terms of reservoir water-quality response) of improving the existing compressor set-up to prevent such shutdowns was assessed. This scenario was evaluated with two runs of the coupled model. The first run simulated the destratification system as it was actually operated in Cherry Creek Reservoir from 2008 – 2013. The second model run assumed the system was operated without the unplanned shutdowns during 2008 – 2013.

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[1] Three model settings related to nutrient release rates were adjusted for the coupled model to ensure appropriate sensitivity to changing DO concentrations at depth. These settings (O2LIM, PO4R, and NH4R) remain within recommended ranges and did not adversely affect the model calibration statistics.

- **Increased Air Flow Rates to the 116 Diffuser Heads**: To evaluate the potential effectiveness of increasing air flow rates only, a series of coupled-model runs were conducted with increased air flow rates to the array of diffuser heads.

- **Increased Number of Diffuser Heads with the Same Per-Head Air Flow:** A series of model runs with additional diffuser heads were simulated to assess the potential benefit of increasing the number of diffuser heads but keeping the per-head air flow rates the same as the current diffuser heads (2.4 SCFM/head).

- **Increased Numbers of Diffuser Heads and Increased Air Flow to Each Head**: Several model runs were conducted to evaluate the potential benefit of increasing both air flow and the number of diffuser heads.

The scenario runs were reviewed to evaluate the water-quality response in the reservoir, with a primary focus on DO at the bottom and summertime chlorophyll *a*. Results are described in the following section.

4 Scenario Results

The results of the four sets of coupled model simulations are discussed in Sections 4.1 through Section 4.4, with each section focusing on one set of model simulations. Each model run simulates the years from 2008 – 2013. The results presented here focus on the simulated July – September average chlorophyll *a* at all three sampling sites (CCR-1, CCR-2, and CCR-3) and bottom DO concentrations at CCR-2 (the deepest sampling site), corresponding to the primary objectives of the destratification system in Cherry Creek Reservoir. In Section 4.5, all results from Sections 4.1 – 4.4 are compared in terms of simulated average chlorophyll *a* reductions and the increase in the simulated destratification system size, relative to the existing system. Although not presented here, model output was also reviewed for all simulated constituents to ensure the overall model results were reasonable. It should also be noted that although model results are discussed as absolutes, there is uncertainty in the model predictions since the model is not a perfect representation of reality. However, the results provide reasonable estimates of the water-quality response in Cherry Creek Reservoir to destratification system modifications.

4.1 Effects of Compressor Shutdowns

As documented in the annual operation reports from 2008 – 2013 (TC Consulting Services, 2009, 2010a, 2010b, 2012, 2013; JRS Engineering, 2013), the destratification system suffered from relatively frequent shutdowns during the months of operation. Many of these shutdowns were caused by the air compressor overheating. The coupled model was run assuming that the system was operated continuously (without any shutdowns) from the spring to fall in each year from 2008 – 2013 to determine if solving the compressor overheating issues would allow the destratification system to meet the DO and chlorophyll *a* goals. Results of that simulation were compared to simulation of the actual operations from 2008 – 2013, referred to in graphics as "As Operated."

Simulation results indicate that even if the air compressor was able to operate continuously without shutdowns there would be little additional effect on bottom DO and chlorophyll *a* concentrations (Figure 4 and Figure 5). The simulated results are nearly identical for bottom DO at CCR-2. Thus, although the unplanned air compressor shutdowns are a concern, they are not the key factor that limits the effectiveness of the existing destratification system. These results show that the existing system is not capable of preventing bottom anoxia and meeting the chlorophyll *a* standard regardless of the compressor overheating issues. This finding is in agreement with the available data and current understanding of the system.

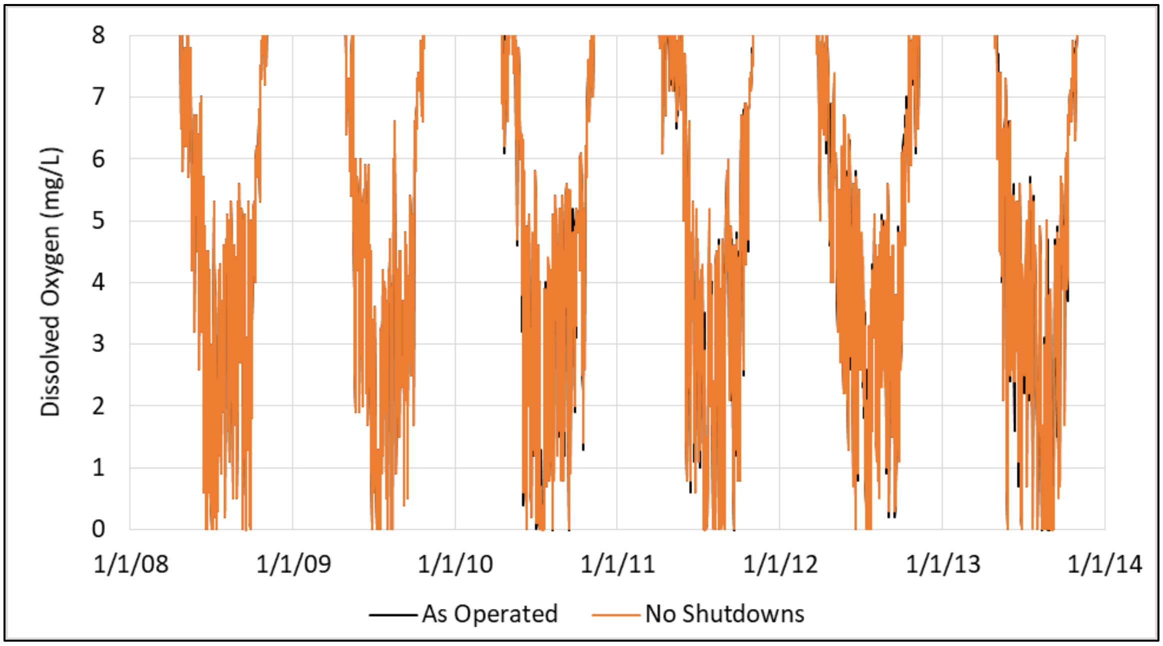

Figure 4. Simulated DO at the Bottom at CCR-2 for Model Runs with the Existing Destratification System As Operated and Without Compressor Shutdowns, 2008 – 2013. *(Notes: The Y-axis scale was limited to 0 to 8 mg/L to focus on the lower DO conditions; differences in results with and without shutdowns are difficult to discern on the graphics because they are nearly identical.)*

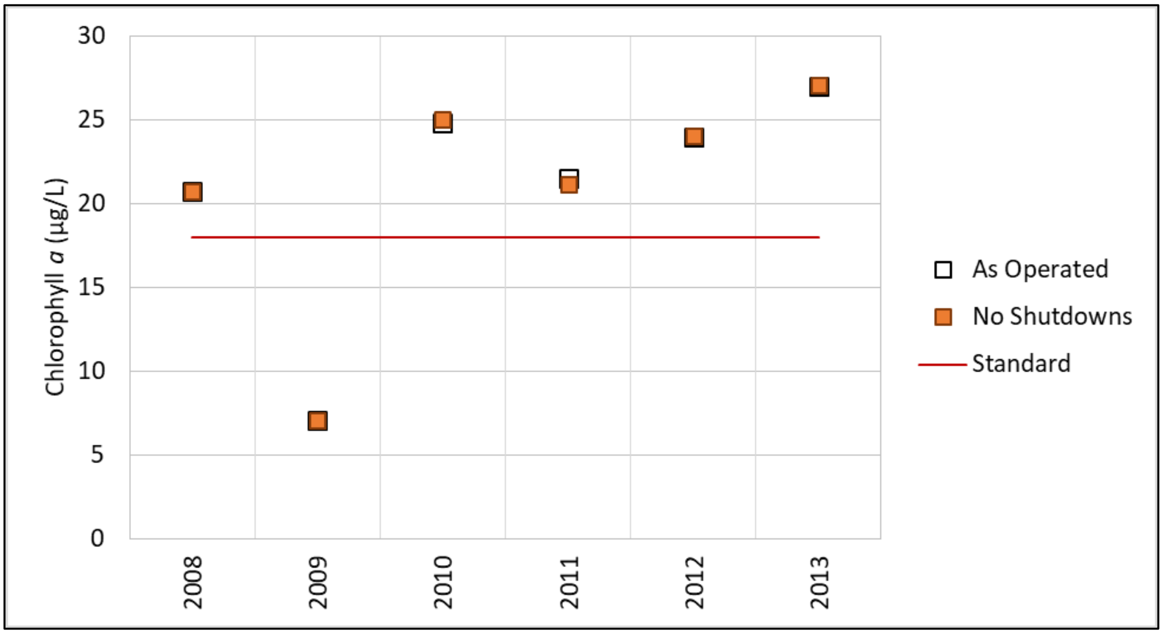

Figure 5. July - September Average Chlorophyll *a* for Model Runs with the Existing Destratification System As Operated and without Compressor Shutdowns, 2008 – 2013

4.2 Increased Air Flow to Existing Diffuser Heads

Two model scenarios were evaluated with increased air flow rates to each of the 116 diffuser heads:

1. 10 SCFM per diffuser head; and
2. 24 SCFM per diffuser head.

These two scenarios represent an increase in air flow to the current destratification system of approximately 4x and 10x, respectively, over the current flow of 2.4 SCFM per diffuser head. A flow rate of 10 SCFM per diffuser head also corresponds to the maximum operating capacity of the existing diffuser discs currently installed on each diffuser head (Xylem, 2019). Both of these options would require installation of new flow regulators, a new or additional air compressor, and may require larger distribution piping to accommodate the increased air flow. Additionally, increasing the air flow to each diffuser head to 24 SCFM would require installation of new diffuser discs capable of operating at this flow rate.

Simulated DO at the bottom at CCR-2 and July – September average chlorophyll *a* at all three sites for these two model runs are compared to a model run using the existing system flow rate (2.4 SCFM per diffuser head) in Figure 6 and Figure 7, respectively. As shown in these figures, simulation results indicate that there is limited benefit to bottom DO and average chlorophyll *a* concentrations with additional air flow to the existing diffuser heads, even with 10 times the air flow of the existing system. Bottom DO is increased by up to ~1 mg/L (Figure 6), but hypoxia continues to occur at CCR-2 in all years (Figure 8). The simulated July – September average chlorophyll *a* decreases by an average of 2.1 µg/L (range 0.2 – 4.5 µg/L) in the 10 SCFM/diffuser head scenario, and an average of 2.7 µg/L (year-by-year decreases range from 0.3 to 5.4 µg/L) in the 24 SCFM/diffuser head scenario (Figure 7 and Table 2). These decreases, while notable, are not enough to achieve compliance with the chlorophyll *a* standard, since the simulated July – September average chlorophyll *a* continues to remain above 18 µg/L in 4 of the 6 simulated years.

The reduction in average summertime chlorophyll *a* due to increasing the system air flow is simulated to vary from year to year. The range of effectiveness reflects variability in algal growth drivers external to the destratification system. For example, in 2009 the simulated decrease in chlorophyll *a* from the expanded destratification systems is small, since the algal growth was limited by temperature during this relatively cool summer (Hydros, 2017). Over the remaining years with warmer summers, variation in the magnitude of the effects of the destratification system on average chlorophyll *a* concentrations is due to differences in water temperature and the timing and magnitude of external loading, which affects nutrient concentrations, nutrient ratios, and competition among algae groups with different biovolume-to-chlorophyll *a* ratios. This pattern of varying effects on chlorophyll *a* concentrations from year to year is also observed in the model scenarios discussed in Sections 4.3 and 4.4.

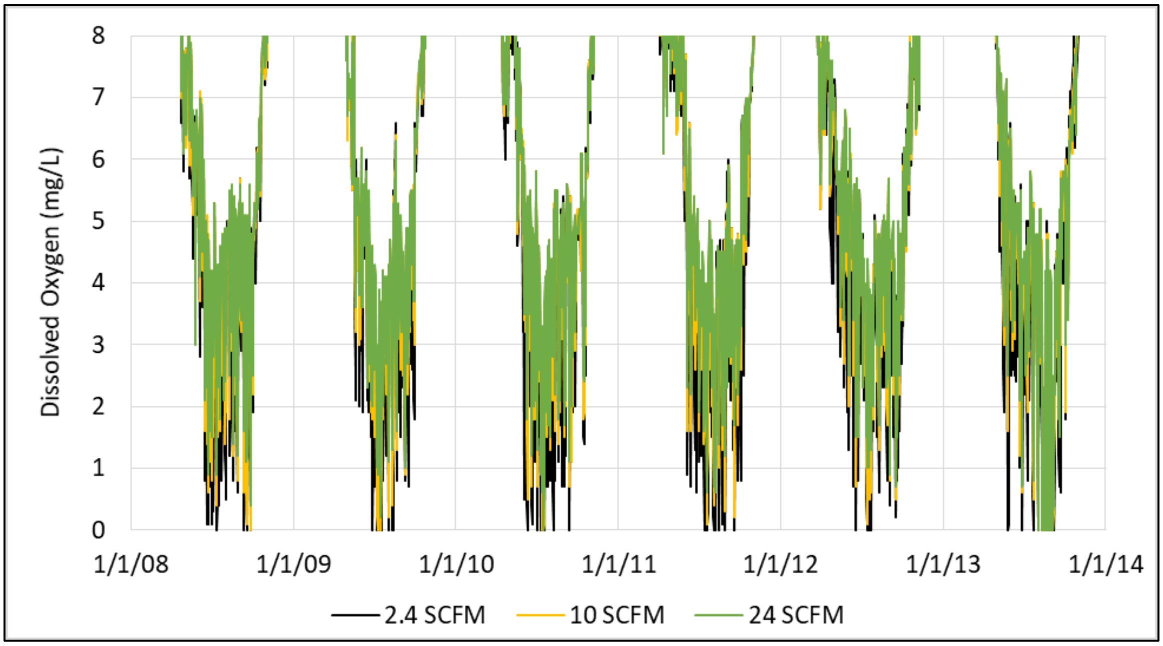

Figure 6. Simulated DO at the Bottom at CCR-2 for Scenarios with Increased Air Flow to Each Diffuser Head Compared to the Existing Destratification System (2.4 SCFM per Diffuser Head), 2008 – 2013. *(Note: The Y-axis scale was limited to 0 to 8 mg/L to focus on the lower DO conditions.)*

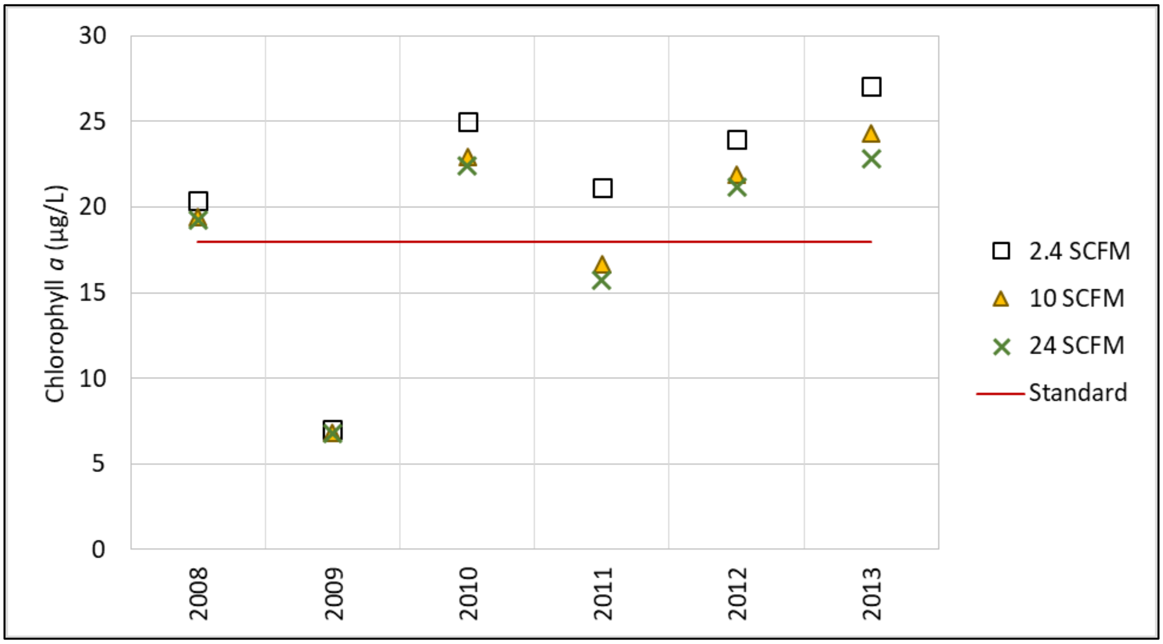

Figure 7. Simulated July-September Average Chlorophyll *a* for Scenarios with Increased Air Flow to Each Diffuser Head Compared to the Existing Destratification System (2.4 SCFM per Diffuser Head), 2008 – 2013

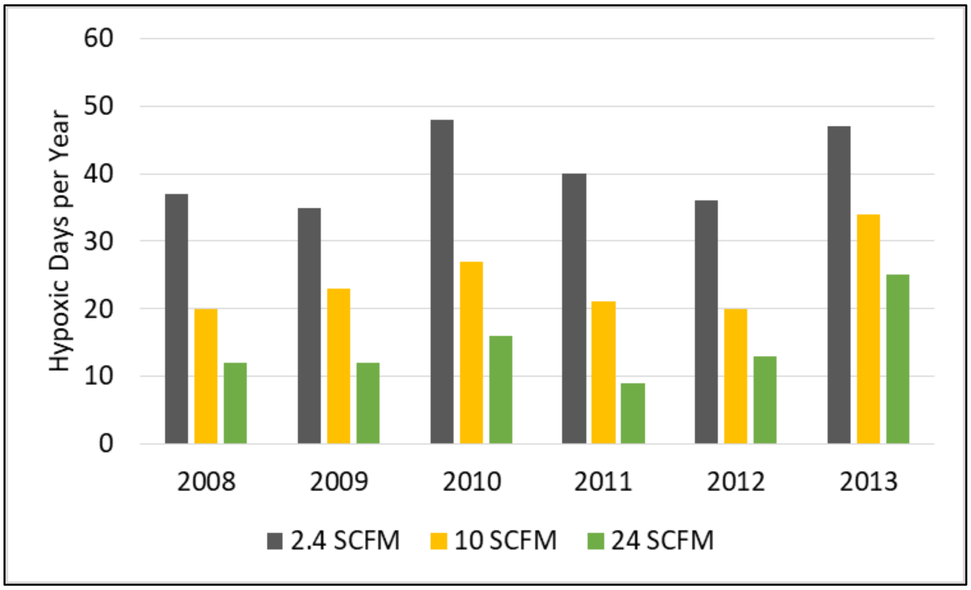

Figure 8. Count of Simulated Days of Hypoxia (DO < 2 mg/L) at the Bottom at CCR-2 for Scenarios with Increased Air Flow to Each Diffuser Head Compared to the Existing Destratification System (2.4 SCFM per Diffuser Head), 2008 – 2013

Table 2. Simulated Reduction in July – September Average Chlorophyll *a* for Scenarios with Increased Air Flow to Each Existing Diffuser Head, 2008 – 2013

Scenario	Minimum Difference among Six Years (µg/L)	Average of Six Years (µg/L)	Maximum Difference among Six Years (µg/L)
10 SCFM/Head	-0.2	-2.1	-4.5
24 SCFM/Head	-0.3	-2.7	-5.4

The limited effectiveness of even the large increases in flow rate to the existing diffuser heads is due to the fact that increasing the air flow to a single diffuser head by ten times does not also increase the volume of water moved by that diffuser head by a factor of ten. Rather, the bubble-plume model results show that the volume of water moved by the destratification system is only increased by approximately 2.4 times (from ~64 m^3/s to ~155 m^3/s) with a ten-fold increase in air flow (from 2.4 SCFM to 24 SCFM per diffuser head). Thus, simply increasing the air flow to the existing diffuser heads does not appear to be an effective option for modifying the existing destratification system to increase DO concentrations at the bottom or reduce chlorophyll *a* below the standard.

4.3 Increased Number of Diffuser Heads

Four model runs were conducted to simulate the installation of additional diffuser heads that are identical to those currently installed, each with a flow rate of 2.4 SCFM/diffuser head. The scenarios considered were:

1. **2X Heads**: Addition of 116 diffuser heads within the current system footprint (232 total diffuser heads);
2. **3X Heads**: Addition of 232 diffuser heads between the reservoir dam and CCR-3 (348 total diffuser heads);
3. **4X Heads**: Addition of 348 diffuser heads between the reservoir dam and CCR-3 (464 total diffuser heads); and
4. **5X Heads**: Addition of 464 diffuser heads between the reservoir dam and CCR-3 (580 total diffuser heads).

The additional simulated diffuser heads were added in the six model segments closest to the reservoir dam (Figure 9). The additional heads represent destratification systems with a capacity of two, three, four, and five times the air flow of the existing system. All of these options would require installation of additional diffuser heads, additional distribution piping, and a new or additional air compressor.

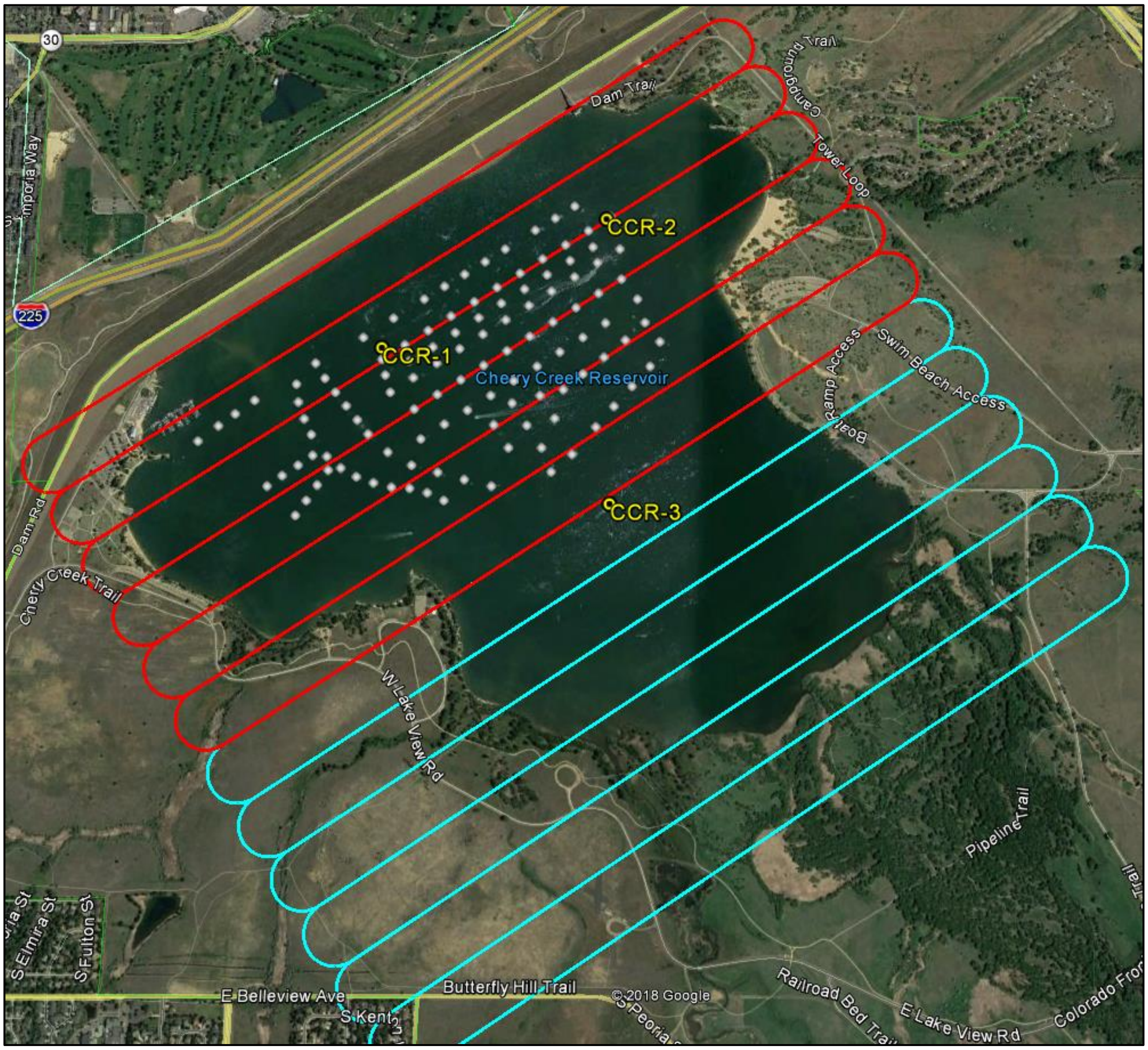

Figure 9. Overview Map of Cherry Creek Reservoir, Model Segmentation (Longitudinal Detail Only), Existing Diffuser Locations (White Points), and Sampling Locations (Yellow Points). Red Segments Correspond to Segments where Additional Diffuser Heads were Simulated with the Coupled Model.

Simulation results show that increasing the number of diffuser heads (with the same flow per head as current operations) results in increased bottom DO concentrations and decreased July – September average chlorophyll *a* concentrations (Figure 10 and Figure 11), though water quality objectives are not met. A system with five times the number of diffuser heads of the existing system would be required to maintain bottom DO above 2 mg/L in most years, although the model suggests there would be a few days each year where bottom DO concentrations would fall below 2 mg/L (Figure 12 and Figure 13). Additionally, in years where the reservoir water levels are drawn down, such as in summer of 2013, the largest system simulated (580 heads) would not be able to maintain aerobic conditions at the bottom of the reservoir. In the summer of 2013, the water depth in the reservoir was the lowest of the simulation period, up to 3.1 feet (0.94 m) below the six-year average of 26.3 feet (8.1 m) at the deepest point (Figure 14). The shallower water column results in less-efficient mixing from the destratification system, which is why the simulated bottom DO concentrations are not as high as other years. This drop in effectiveness when water depth decreases illustrates the limitations of a bubble-plume destratification system in shallow systems such as Cherry Creek Reservoir.

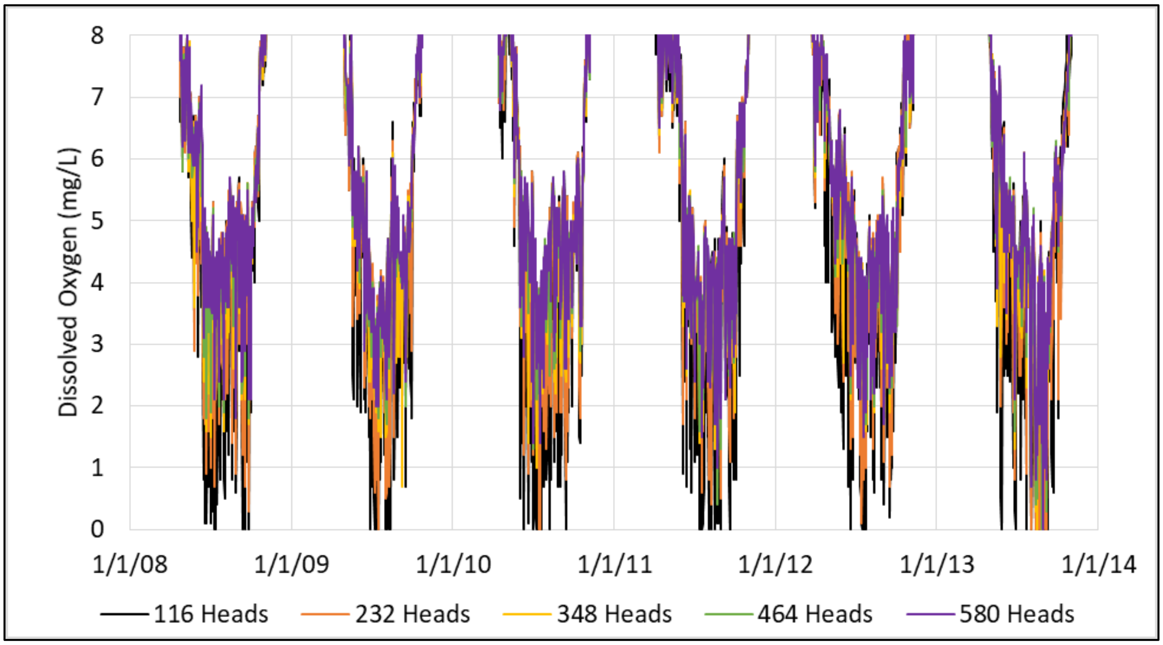

Figure 10. Simulated Bottom Dissolved Oxygen at CCR-2 for Scenarios with Additional Diffuser Heads (All at 2.4 SCFM). *(Note: The Y-axis scale was limited to 0 to 8 mg/L to focus on the lower DO conditions.)*

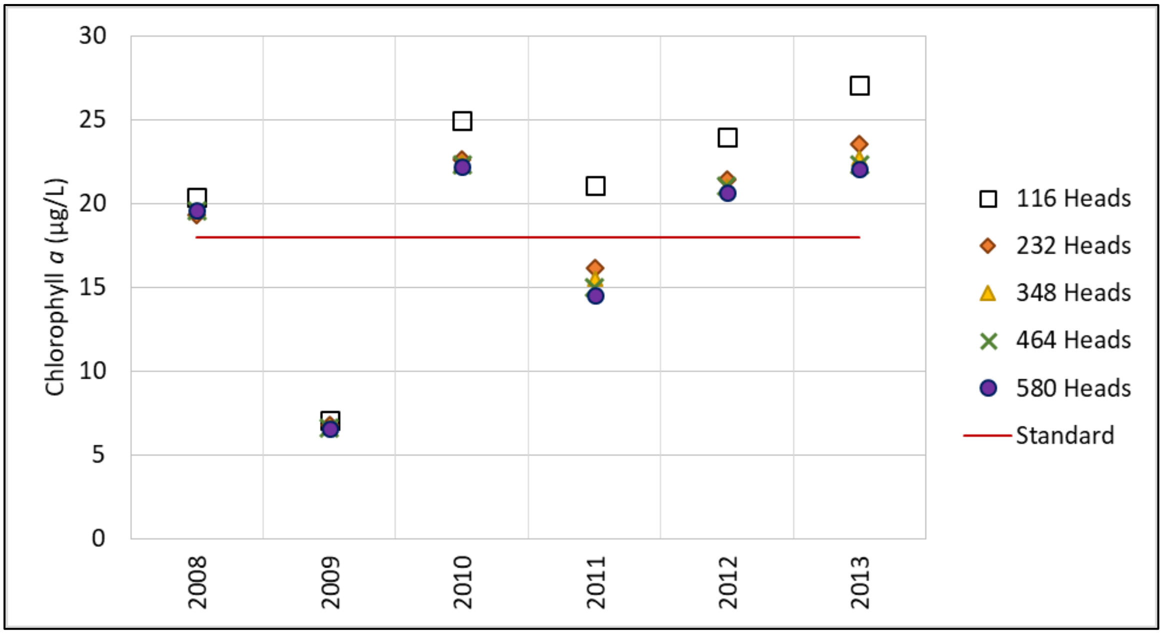

Figure 11. Simulated July-September Average Chlorophyll *a* for Scenarios with Additional Diffuser Heads at 2.4 SCFM Each

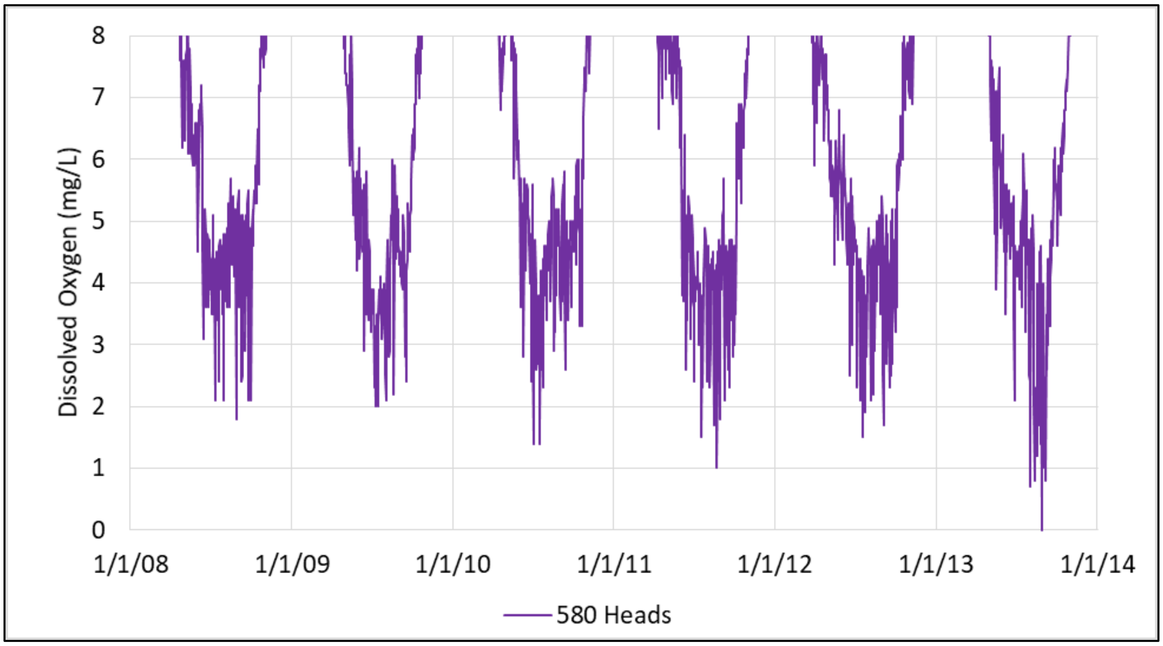

Figure 12. Simulated Bottom Dissolved Oxygen at CCR-2 for the Scenario with 580 Diffuser Heads at 2.4 SCFM Each. *(Note: The Y-axis scale was limited to 0 to 8 mg/L to focus on the lower DO conditions.)*

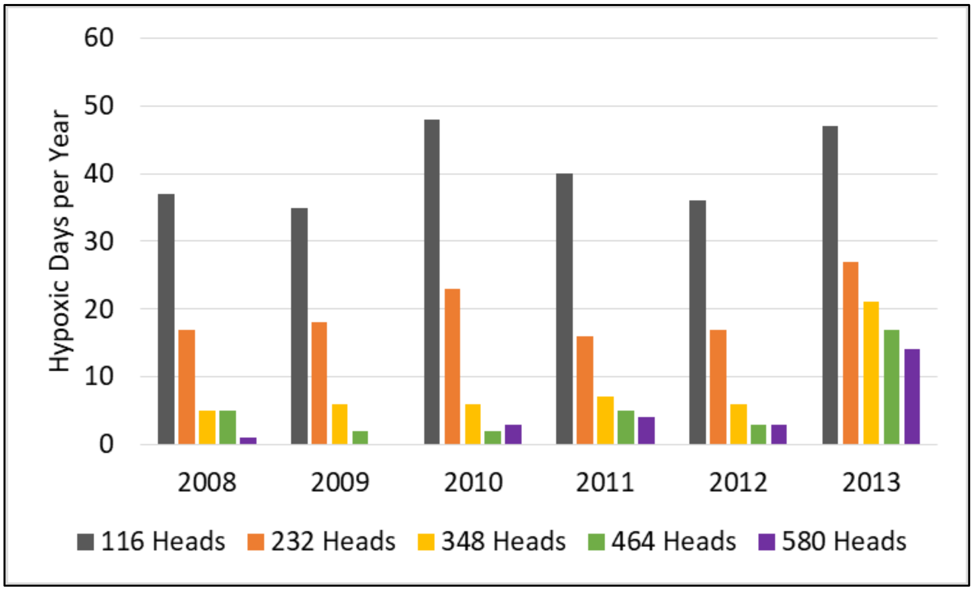

Figure 13. Count of Simulated Days of Hypoxia (DO < 2 mg/L) at the Bottom at CCR-2 for Scenarios with Additional Diffuser Heads (All at 2.4 SCFM) Compared to the Destratification System with 116 Heads, 2008 – 2013

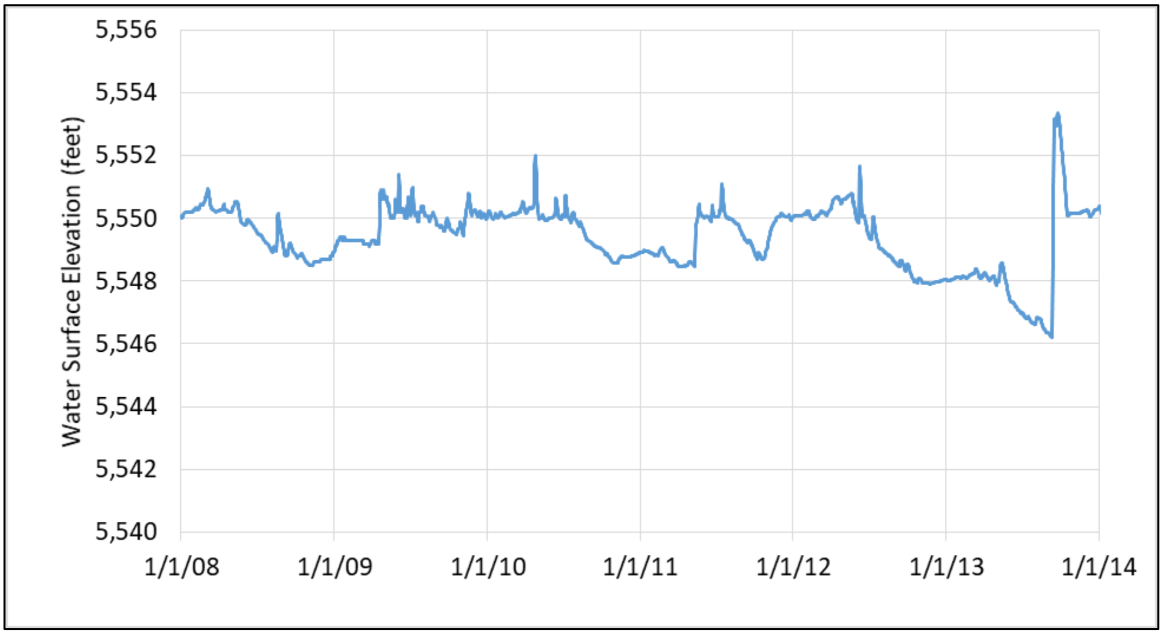

Figure 14. Observed Water Surface Elevations in Cherry Creek Reservoir, 2008 – 2013

As previously noted, even with the additional mixing from a system with as many as five times the number of diffuser heads, simulation results indicate that chlorophyll *a* concentrations would not be reduced enough to achieve compliance with the current chlorophyll *a* standard. The model suggests such a system could reduce concentrations by an average of 3.1 µg/L (range 0.5 – 6.6 µg/L), but simulated concentrations remain above the standard in 4 of 6 simulated years. The effects of each of the five scenarios on simulated chlorophyll *a* are summarized in Table 3.

Table 3. Simulated Reduction in July – September Average Chlorophyll *a* for Scenarios with Additional Diffuser Heads at 2.4 SCFM Each, 2008 – 2013. Reductions are relative to the model run of the system with 116 diffuser heads.

Scenario	Minimum Difference among Six Years (µg/L)	Average of Six Years (µg/L)	Maximum Difference among Six Years (µg/L)
232 Heads	-0.3	-2.5	-5.0
348 Heads	-0.4	-2.8	-5.6
464 Heads	-0.4	-3.0	-6.1
580 Heads	-0.5	-3.1	-6.6

The coupled model suggests that for a given increase in air flow capacity to the system, the simulated chlorophyll *a* concentrations would decrease by a larger amount with the additional diffuser heads than with only increasing air flow to the existing heads (Figure 15). The scenario with a total of 464 diffuser heads represents a system four times larger than the existing system, and reduces the simulated July – September average chlorophyll *a* by 3.0 µg/L on average (range 0.4 – 6.1 µg/L). The scenario with 10 SCFM to each of the existing 116 diffuser heads (Section 4.2) represents a system 4.2 times larger than the existing system, and only reduces the simulated July – September average chlorophyll *a* by 2.1 µg/L on average (range 0.2 – 4.5 µg/L). Increasing the diffuser head count is a more-efficient method for increasing the amount of mixing than increasing the flow to each of the existing diffuser heads. Doubling the count of diffuser heads will approximately double the volume of water moved by the system, assuming the additional diffuser heads are located at similar depths and the plumes do not overlap. This is compared to only a 2.5x increase in water moved when the air flow to each of the existing 116 diffuser heads is increased by 10x (Section 4.2).

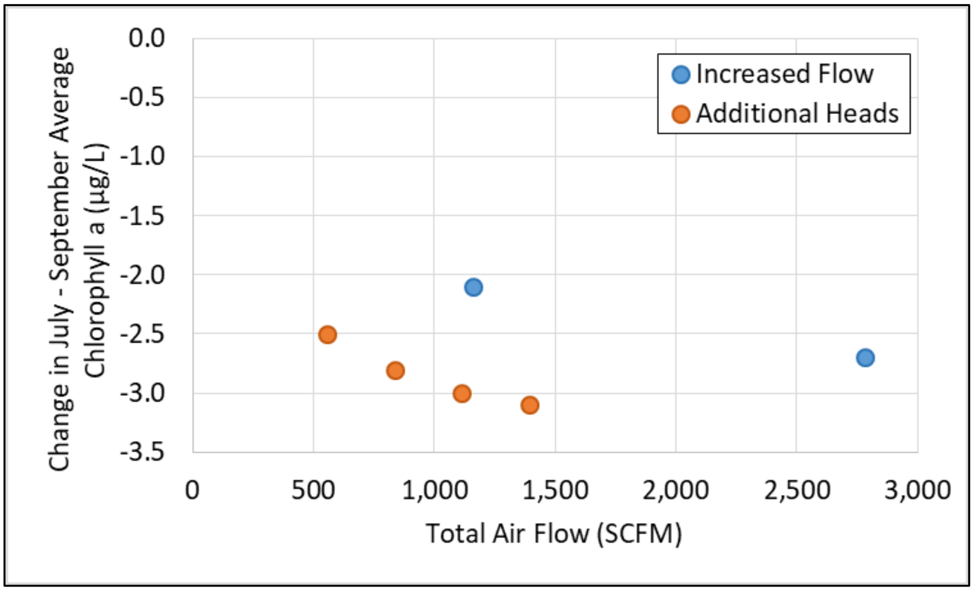

Figure 15. Comparison Between Simulated Changes in July – September Average Chlorophyll *a* for Scenarios with Increased Air Flow to the Existing 116 Diffuser Heads and Additional Diffuser Heads at 2.4 SCFM Each

It should also be noted that adding diffuser heads to increase the amount of mixing has additional physical constraints. The diffuser heads must be sufficiently spread out to prevent the overlap of bubble plumes from adjacent heads, otherwise the mixing efficiency for the diffusers will be reduced. Mixing efficiency is also lost as this spacing constraint requires additional diffuser heads to be located in shallower parts of the reservoir, and shallow depth of the water column above the diffusers is already noted as a limitation of the system for application to Cherry Creek Reservoir.

4.4 Increased Number of Diffuser Heads and Increasing Air Flow to Each

Sixteen model runs were conducted to simulate the installation of additional diffuser heads with increased air flow rates to each diffuser head (Table 4). The additional heads and flow rates represent destratification systems with total air flow capacities ranging from 4.2 to 50 times the capacity of the existing system. All of these options would require installation of new diffuser heads, additional distribution piping, and a new or additional air compressor. It is recognized that some or all of these hypothetical system expansions may be beyond acceptable cost/size limitations; however, this wide range of simulated system expansions was conducted to provide the understanding required to support subsequent design, costing, and management decisions.

Table 4. Model Scenarios with Additional Diffuser Heads and Increased Air Flow to Each Head

Scenario	Total Diffuser Heads	Air Flow per Diffuser Head (SCFM)	Air Flow Capacity Relative to Existing System
2X Heads, 5 SCFM	232	5	4.2x
2X Heads, 7.5 SCFM	232	7.5	6.3x
2X Heads, 10 SCFM	232	10	8x
2X Heads, 24 SCFM	232	24	20x
3X Heads, 5 SCFM	348	5	6.3x
3X Heads, 7.5 SCFM	348	7.5	9.4x
3X Heads, 10 SCFM	348	10	12.5x
3X Heads, 24 SCFM	348	24	30x
4X Heads, 5 SCFM	464	5	8.3x
4X Heads, 7.5 SCFM	464	7.5	12.5x
4X Heads, 10 SCFM	464	10	16.7x
4X Heads, 24 SCFM	464	24	40x
5X Heads, 5 SCFM	580	5	10.5x
5X Heads, 7.5 SCFM	580	7.5	15.6x
5X Heads, 10 SCFM	580	10	20.8x
5X Heads, 24 SCFM	580	24	50x

Simulated DO concentrations at the bottom at CCR-2 for these sixteen scenarios are shown in Figure 16 through Figure 19. Simulation results show that increased DO at the bottom would occur in response to combinations of additional diffuser heads and increased air flow to each head, though there are apparent diminishing returns for larger and larger systems. The scenarios show that the lowest simulated increase in total air flow rate needed to maintain 2 mg/L DO (an approximate threshold below which conditions are considered hypoxic) at the bottom for most days in most years corresponds to a system with 348 diffuser heads with 5 SCFM to each head (Figure 20 through Figure 23). This equates to a system with approximately 6.3 times the air flow capacity of the existing destratification system; however, bottom DO concentrations under this scenario would be well below 2 mg/L in years with lower storage (such as 2013). As previously noted, this is due to the reduction in mixing efficiency for a shallower water column that occurs when the reservoir is less full. To more closely approach a minimum of 2 mg/L DO in all years including 2013 would require a system with 580 diffuser heads and 10 SCFM of air flow to each head (Figure 19). This represents a system with more than 20 times the air flow capacity of the existing destratification system. Although 2 mg/L is less than the original 5 mg/L design goal used for the existing destratification system (AMEC et al., 2005), it is the threshold between hypoxic (<2 mg/L) and aerobic conditions and is typically high enough to reduce anoxic internal loading from the sediment (e.g., Testa and Kemp, 2012; Beutel, 2006), which is the intended purpose of increasing the DO concentrations.

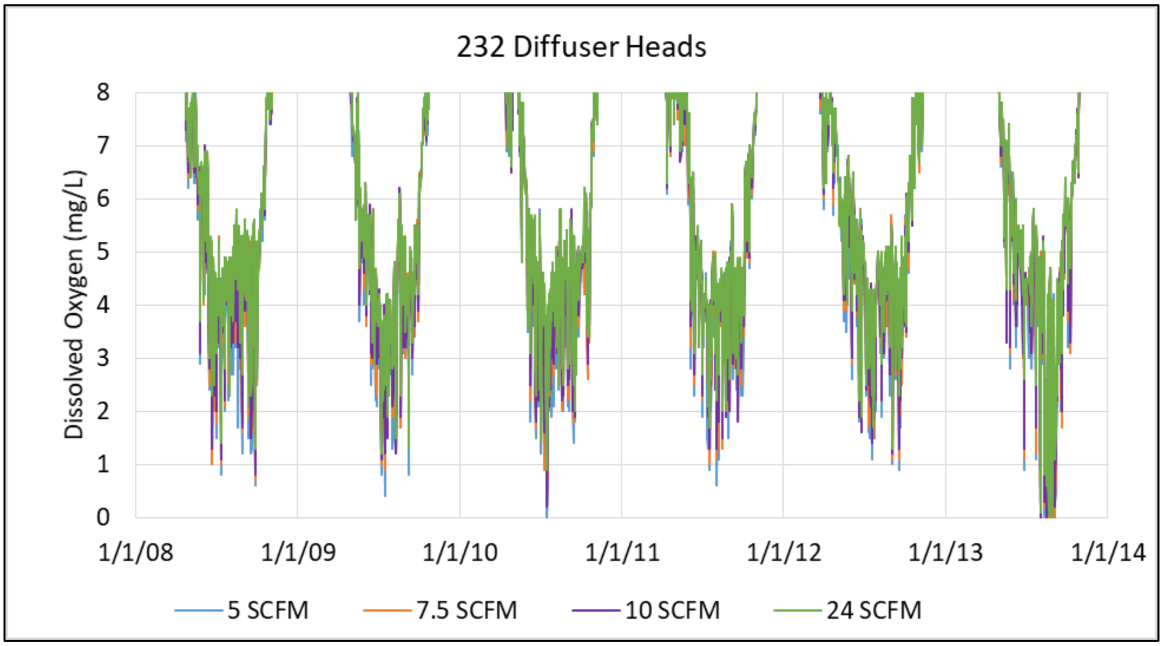

Figure 16. Simulated Bottom Dissolved Oxygen at CCR-2 for Scenarios with 2X (232) Total Diffuser Heads and Increased Air Flow to Each Diffuser Head, 2008 – 2013. *(Note: The Y-axis scale was limited to 0 to 8 mg/L to focus on the lower DO conditions.)*

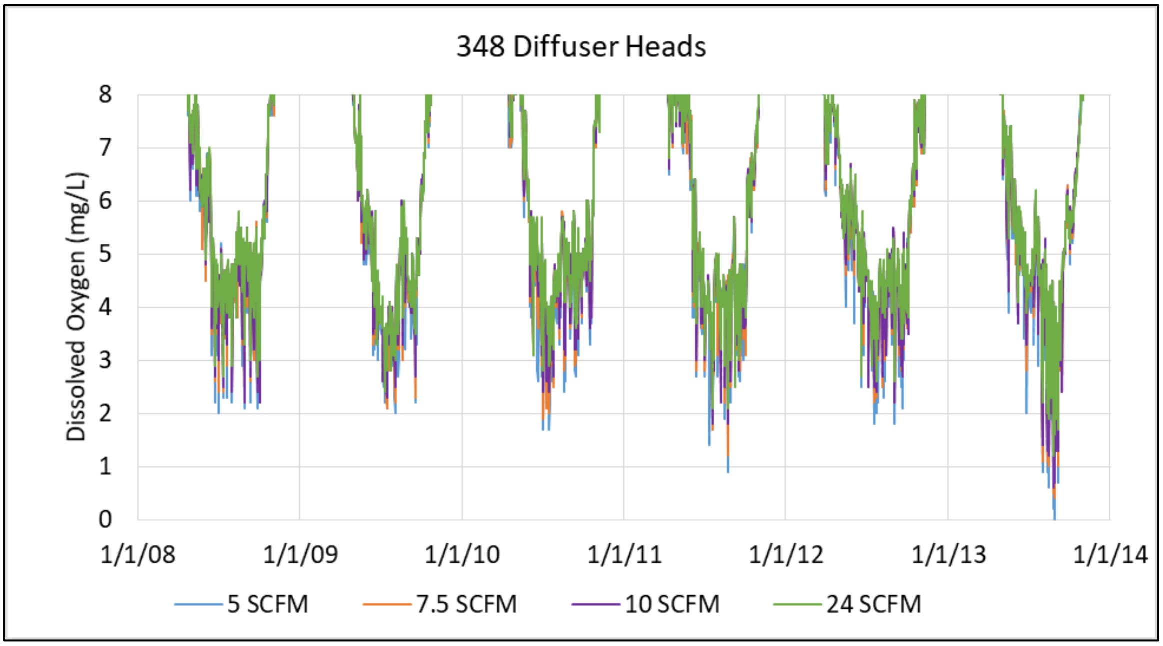

Figure 17. Simulated Bottom Dissolved Oxygen at CCR-2 for Scenarios with 3X (348) Total Diffuser Heads and Increased Air Flow to Each Diffuser Head, 2008 – 2013. *(Note: The Y-axis scale was limited to 0 to 8 mg/L to focus on the lower DO conditions.)*

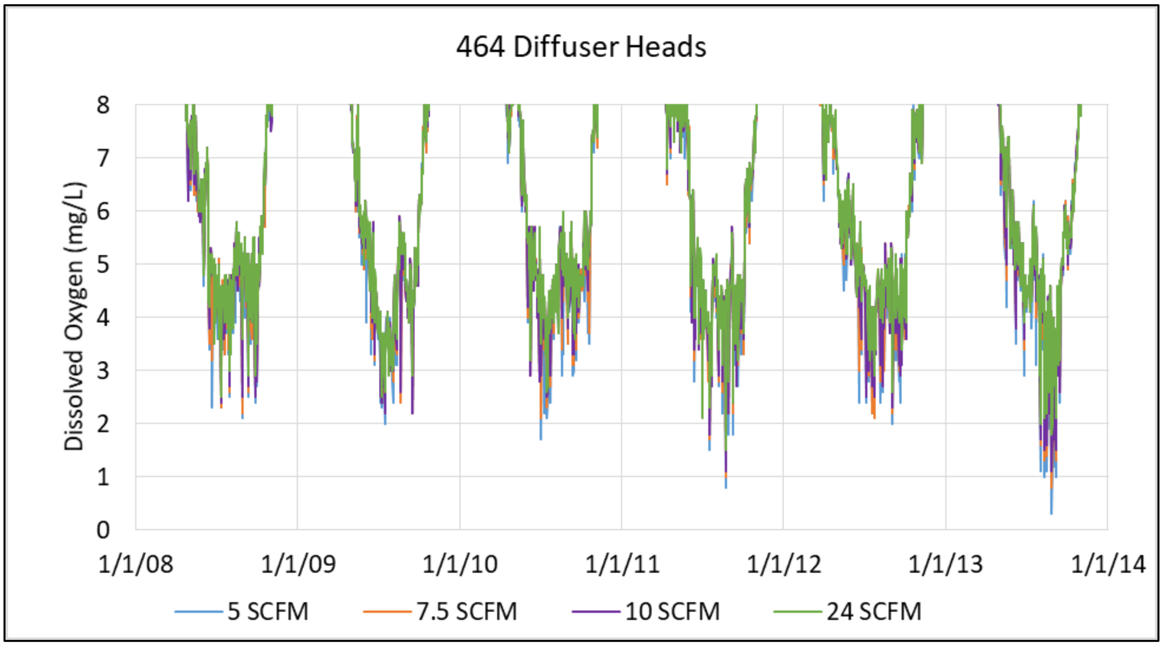

Figure 18. Simulated Bottom Dissolved Oxygen at CCR-2 for Scenarios with 4X (464) Total Diffuser Heads and Increased Air Flow to Each Diffuser Head, 2008 – 2013. *(Note: The Y-axis scale was limited to 0 to 8 mg/L to focus on the lower DO conditions.)*

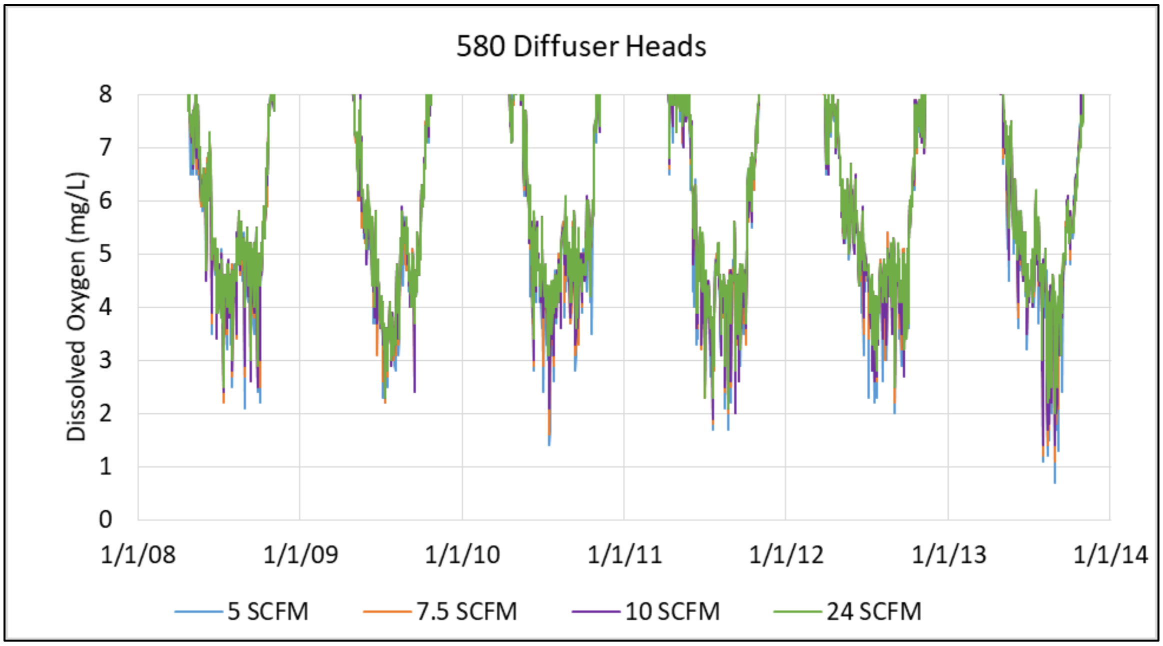

Figure 19. Simulated Bottom Dissolved Oxygen at CCR-2 for Scenarios with 5X (580) Total Diffuser Heads and Increased Air Flow to Each Diffuser Head, 2008 – 2013. *(Note: The Y-axis scale was limited to 0 to 8 mg/L to focus on the lower DO conditions.)*

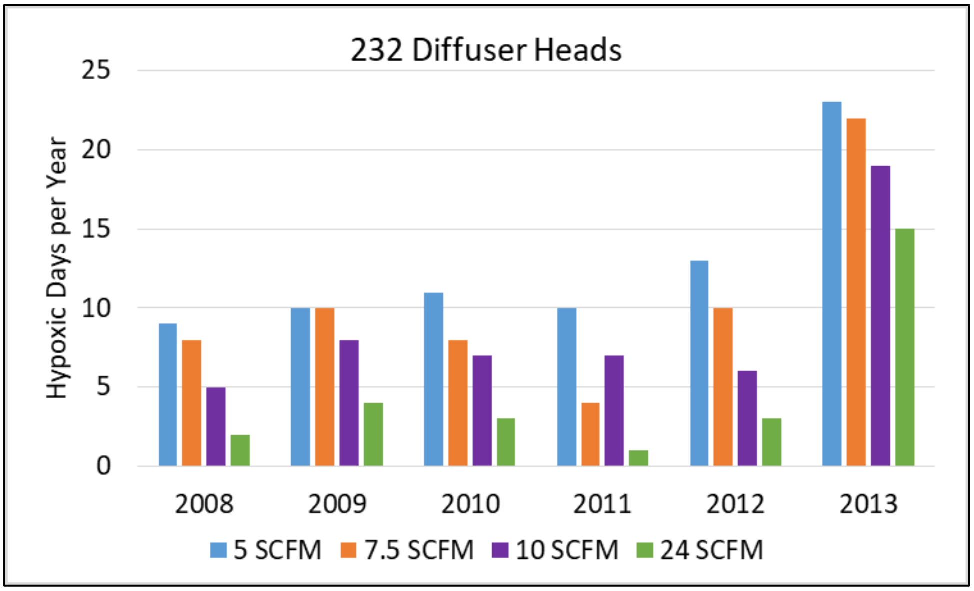

Figure 20. Count of Simulated Days of Hypoxia (DO < 2 mg/L) at the Bottom at CCR-2 for Scenarios with 2X (232) Total Diffuser Heads and Increased Air Flow to Each Diffuser Head, 2008 – 2013

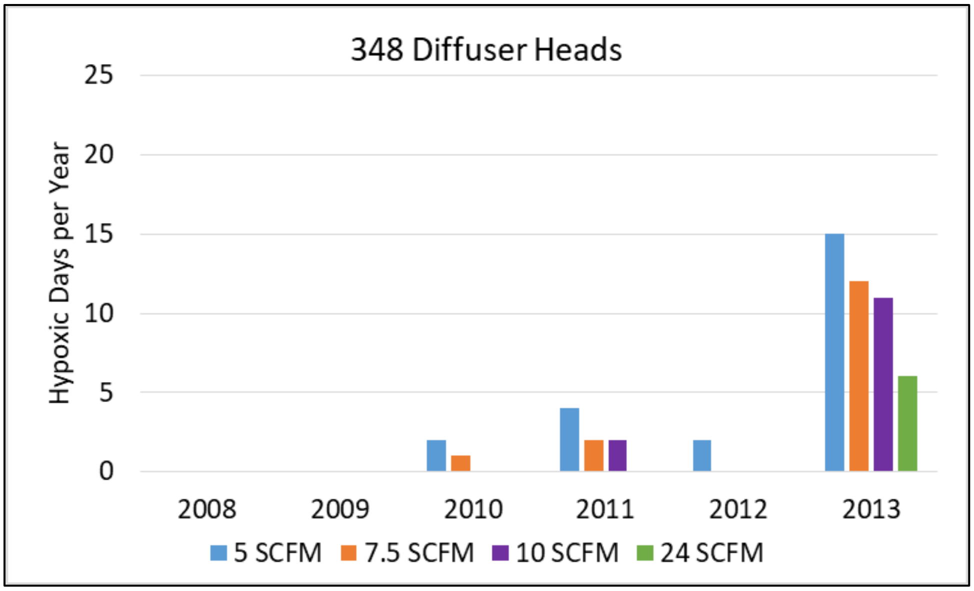

Figure 21. Count of Simulated Days of Hypoxia (DO < 2 mg/L) at the Bottom at CCR-2 for Scenarios with 3X (348) Total Diffuser Heads and Increased Air Flow to Each Diffuser Head, 2008 – 2013

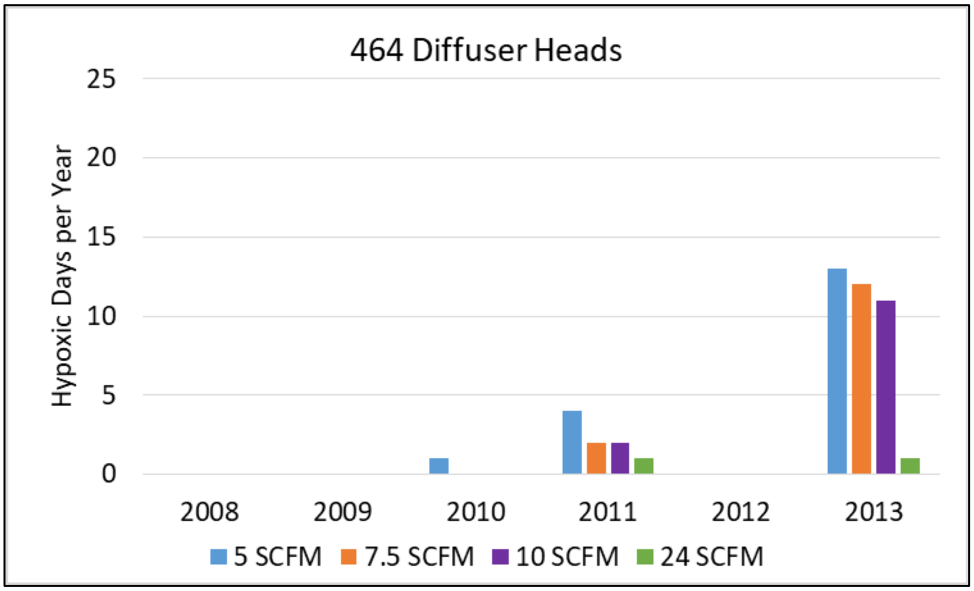

Figure 22. Count of Simulated Days of Hypoxia (DO < 2 mg/L) at the Bottom at CCR-2 for Scenarios with 4X (464) Total Diffuser Heads and Increased Air Flow to Each Diffuser Head, 2008 – 2013

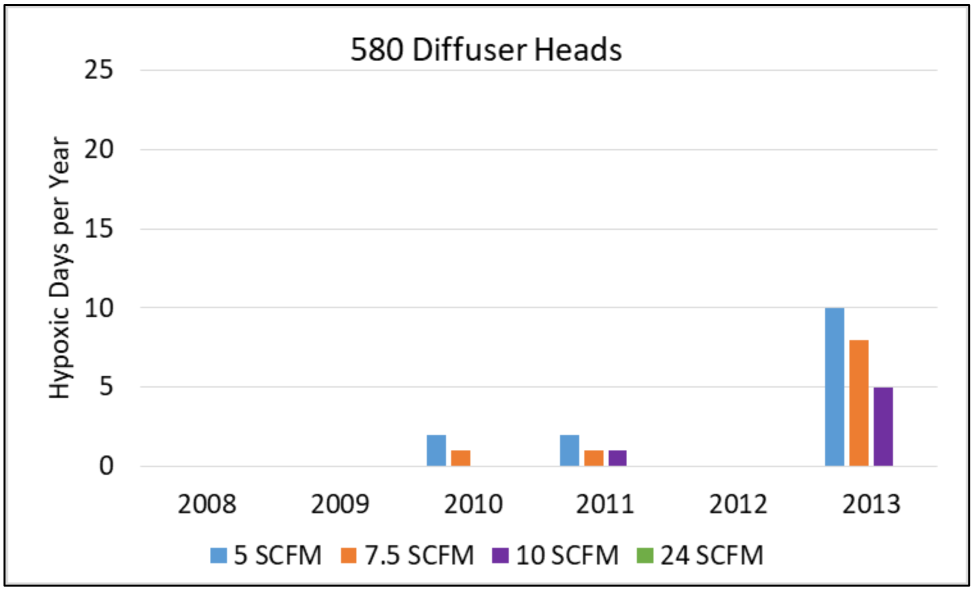

Figure 23. Count of Simulated Days of Hypoxia (DO < 2 mg/L) at the Bottom at CCR-2 for Scenarios with 5X (580) Total Diffuser Heads and Increased Air Flow to Each Diffuser Head, 2008 – 2013

As noted for DO, model results show progressive reductions in summertime chlorophyll *a* with larger destratification systems; however, there is a trend of diminishing returns and none of the designs meet the current chlorophyll *a* standard (Figure 24 through Figure 27). The coupled model indicates that the upper limit of average chlorophyll *a* reductions is on the order of 3.7 µg/L, as seen for the largest system simulated (Table 5; 5x heads at 24 SCFM/head; ~50 times the air flow of the current system). However, simulation results also suggest that much of this benefit (2.9 µg/L reduction in chlorophyll *a*) could be achieved with a smaller expansion such as the 2X heads, 5 SCFM, corresponding to ~4.2 times the air flow capacity of the existing system (2.9 µg/L reduction in chlorophyll *a*; Table 3). The following section compares simulated reductions in chlorophyll *a* concentrations for all system expansion runs described in Sections 4.1 through 4.4 to more fully evaluate the increased air flow as a function of water-quality response for the different designs.

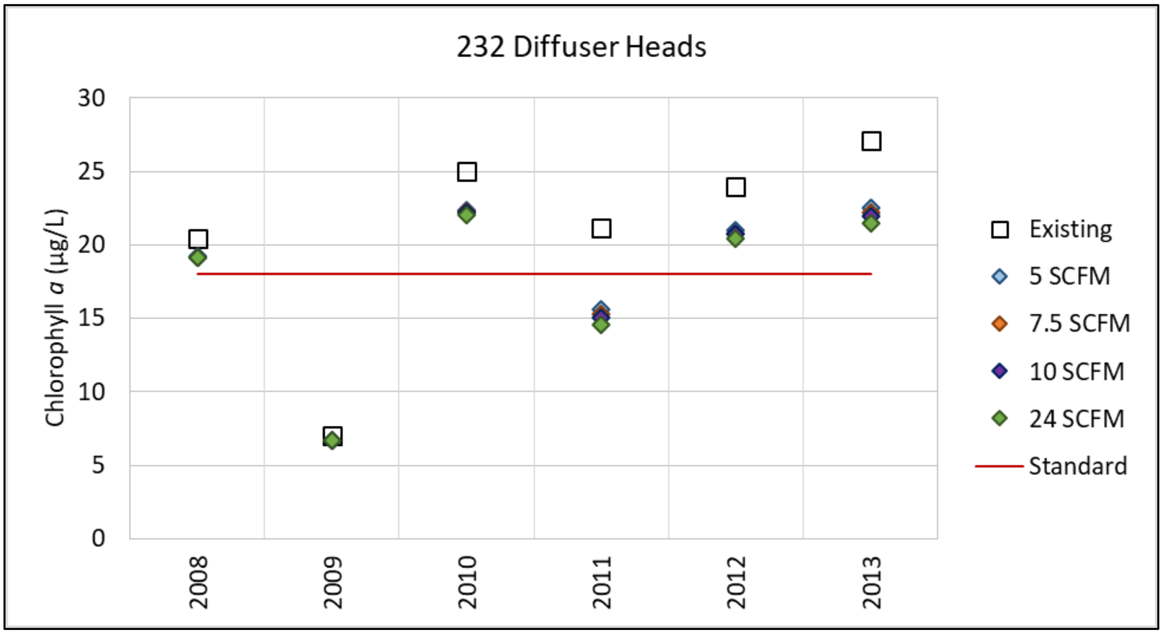

Figure 24. Simulated July-September Average Chlorophyll a for Scenarios with 2X (232) Total Diffuser Heads and Increased Flow to Each Diffuser Head, 2008 – 2013

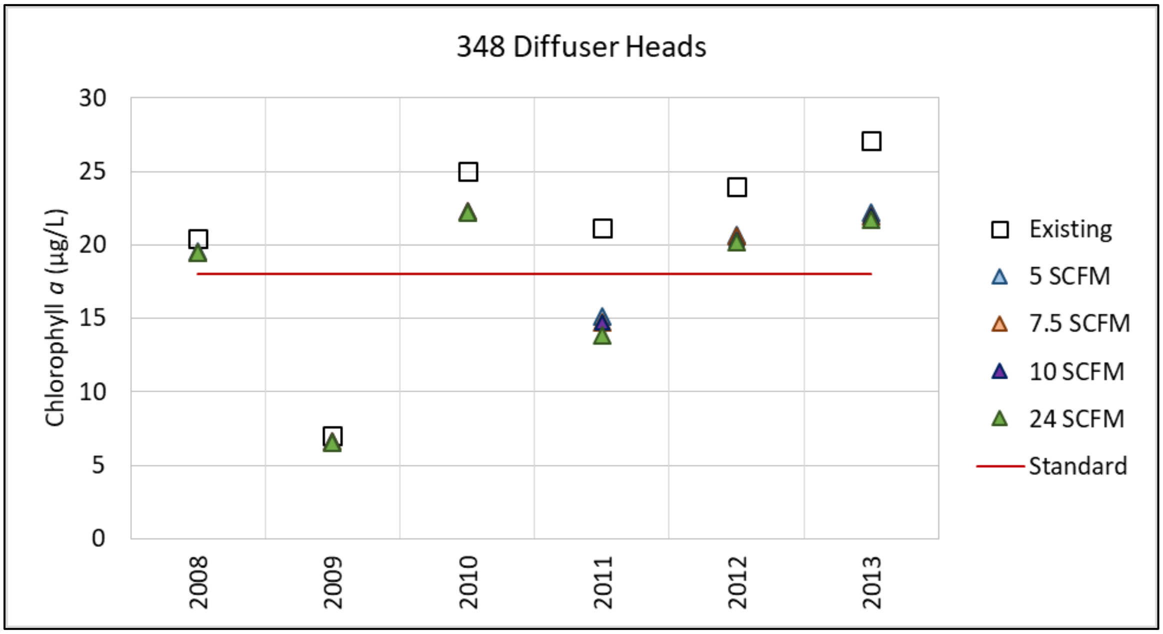

Figure 25. Simulated July-September Average Chlorophyll a for Scenarios with 3X (348) Total Diffuser Heads and Increased Flow to Each Diffuser Head, 2008 – 2013

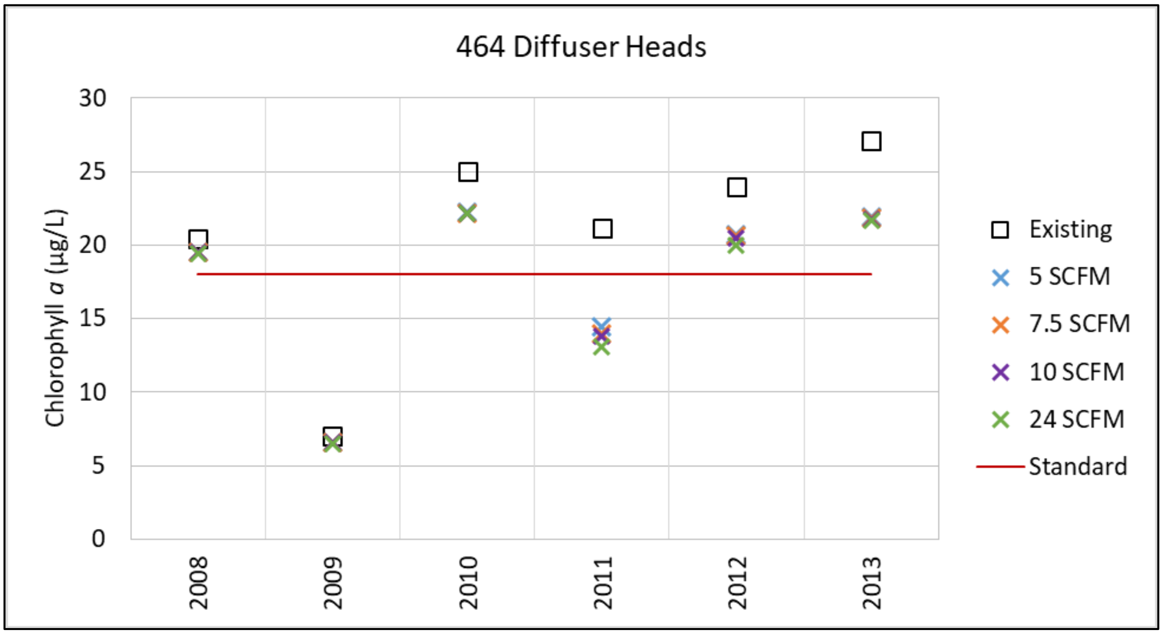

Figure 26. Simulated July-September Average Chlorophyll a for Scenarios with 4X (464) Total Diffuser Heads and Increased Flow to Each Diffuser Head, 2008 – 2013

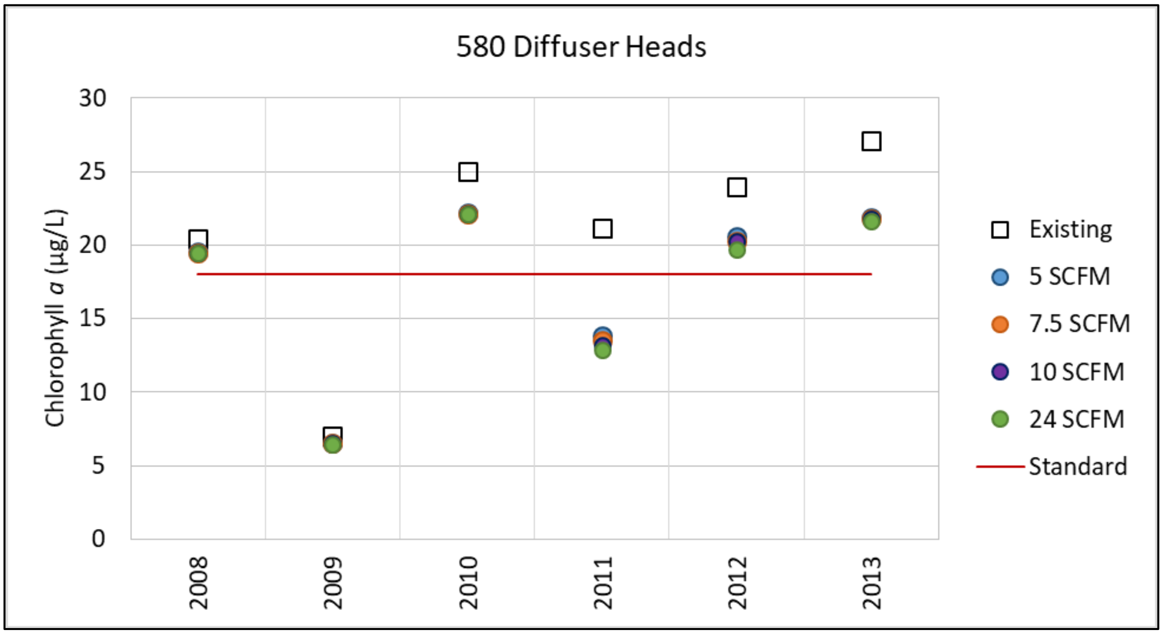

Figure 27. Simulated July-September Average Chlorophyll *a* for Scenarios with 5X (580) Total Diffuser Heads and Increased Flow to Each Diffuser Head, 2008 – 2013

Table 5. Simulated Reduction in July – September Average Chlorophyll *a* for Scenarios with Additional Diffuser Heads and Increased Air Flow to Each Head, 2008 – 2013. Reductions are relative to the model run of the system with 116 diffuser heads at 2.4 SCFM per head.

Scenario		Minimum (µg/L)	Average (µg/L)	Maximum (µg/L)	Air Flow Capacity Relative to Existing System
Total Heads	Flow per Head (SCFM)				
232	5	-0.3	-2.9	-5.5	4.2x
	7.5	-0.4	-3.0	-5.8	6.3x
	10	-0.4	-3.1	-6.1	8x
	24	-0.4	-3.4	-6.5	20x
348	5	-0.4	-3.0	-6.0	6.3x
	7.5	-0.4	-3.2	-6.4	9.4x
	10	-0.5	-3.2	-6.4	12.5x
	24	-0.5	-3.4	-7.2	30x
464	5	-0.5	-3.2	-6.6	8.3x
	7.5	-0.5	-3.3	-7.2	12.5x
	10	-0.5	-3.4	-7.3	16.7x
	24	-0.5	-3.6	-8.0	40x
580	5	-0.5	-3.3	-7.3	10.5x
	7.5	-0.5	-3.5	-7.6	15.6x
	10	-0.5	-3.5	-7.9	20.8x
	24	-0.6	-3.7	-8.3	50x

4.5 Comparison of Average Chlorophyll a Reductions for All Scenarios

This subsection compares the average annual chlorophyll *a* reduction for all model scenarios with larger destratification systems. As described in Sections 4.1 through 4.4, a total of 22 model scenarios were run to assess the effects of expanding the existing destratification system (Table 6). The magnitude of the simulated expansions ranged from 2 to 50 times the total air flow capacity of the existing system (278 SCFM). Depending on the simulation, the number of diffuser heads was increased, the air flow to each of the diffuser heads was increased, or the number of diffuser heads and air flow to each diffuser head were increased. Each of the simulated expansions resulted in a decrease in the simulated July – September average chlorophyll *a* concentrations. However, as the system expansions increased in magnitude, the additional incremental reduction in the simulated chlorophyll *a* concentrations decreased, with decreasing returns apparent particularly for any design increases over 10X the current total air flow (Figure 28).

The model results suggest that the upper limit for the average reduction in summertime chlorophyll *a* is on the order of ~3.7 µg/L (Figure 28). The model results also suggest that much of this benefit could be achieved with a smaller expansion. For example, a system with twice the number of diffuser heads and no increase in the current flow rate to each diffuser head could reduce chlorophyll *a* by 2.5 µg/L on average. Reductions of approximately 3 µg/L could be achieved with a system with 4 times the air flow capacity of the existing system (468 heads with 2.4 SCFM per head). A cost-benefit analysis is beyond the scope of this effort, but it is a logical next step if the Authority is interested in advancing this evaluation of destratification system expansion options.

Table 6. Simulated Reduction in July – September Average Chlorophyll *a* for All 22 Model Scenarios with Larger Destratification Systems, 2008 – 2013. Reductions are relative to the model run of the system with 116 diffuser heads at 2.4 SCFM per head.

Scenario		Minimum (µg/L)	Average (µg/L)	Maximum (µg/L)	Air Flow Capacity Relative to Existing System
Total Heads	Flow per Head (SCFM)				
116	10	-0.2	-2.1	-4.5	4.2x
	24	-0.3	-2.7	-5.4	10x
232	2.4	-0.3	-2.5	-5.0	2x
	5	-0.3	-2.9	-5.5	4.2x
	7.5	-0.4	-3.0	-5.8	6.3x
	10	-0.4	-3.1	-6.1	8x
	24	-0.4	-3.4	-6.5	20x
348	2.4	-0.4	-2.8	-5.6	3x
	5	-0.4	-3.0	-6.0	6.3x
	7.5	-0.4	-3.2	-6.4	9.4x
	10	-0.5	-3.2	-6.4	12.5x
	24	-0.5	-3.4	-7.2	30x
464	2.4	-0.4	-3.0	-6.1	4x
	5	-0.5	-3.2	-6.6	8.3x
	7.5	-0.5	-3.3	-7.2	12.5x
	10	-0.5	-3.4	-7.3	16.7x
	24	-0.5	-3.6	-8.0	40x
580	2.4	-0.5	-3.1	-6.6	5x
	5	-0.5	-3.3	-7.3	10.5x
	7.5	-0.5	-3.5	-7.6	15.6x
	10	-0.5	-3.5	-7.9	20.8x
	24	-0.6	-3.7	-8.3	50x

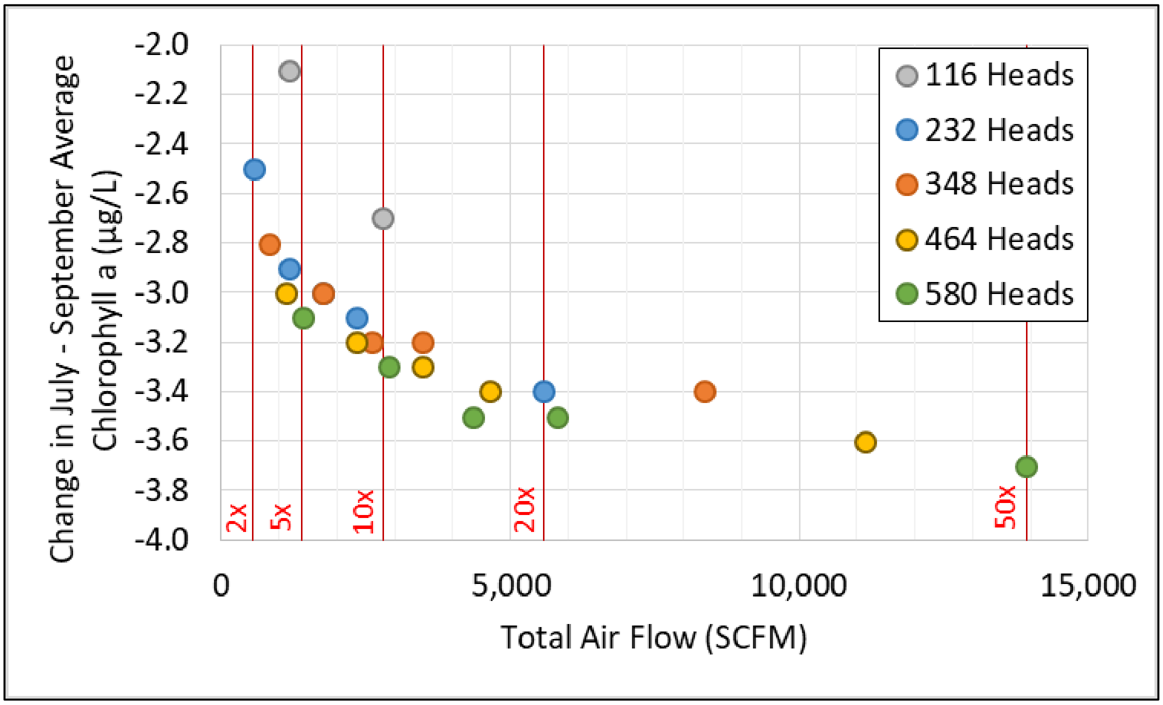

Figure 28. Comparison of the Average Simulated Decrease in July – Average Chlorophyll *a* for All 22 Model Scenarios with Larger Destratification Systems. The capacity of the existing destratification system is 278 SCFM and multipliers on that flow rate are delineated by red lines.

5 Conclusions and Recommendations

A coupled bubble-plume and water-quality model was used to simulate the destratification system in Cherry Creek Reservoir and the water-quality response to modification/expansion of the destratification system. The modeling work focused on assessing the impact of the destratification system on bottom DO concentrations and July – September average chlorophyll *a* concentrations. Overall findings from the study are summarized below, followed by a summary of the findings for each of the study-targeted questions.

5.1 Conclusions

Based on coupled model simulation results, the following findings are offered to the Authority regarding the potential benefits of modifying/expanding the existing destratification system in Cherry Creek Reservoir:

- As expected, additional air flow and/or additional diffuser heads result in lower chlorophyll *a* concentrations.
- As the total system air flow increases, the additional decrease in chlorophyll *a* concentration decreases, leading to diminishing returns.
- The magnitude of the reduction in chlorophyll *a* differs from year to year. Factors that affect this include water temperature, reservoir storage volume, nutrient ratios, and the timing and magnitude of external nutrient loading.
- The simulated decreases in chlorophyll *a* concentrations with an expanded destratification system are not large enough to meet the chlorophyll *a* standard in all years, even with 50x the air flow of the existing system.
- The use of a compressed air destratification system to successfully control algae growth is limited in Cherry Creek by the shallow reservoir depth, large surface area, and high external nutrient loading.

The findings related to each of the questions outlined at the beginning of this document are summarized below.

- **What would be the effectiveness of the existing destratification system if compressor shutdowns could be avoided?** – Although unanticipated system shutdowns due to the air compressor overheating are an issue, the coupled model suggests that even if this issue was resolved, the existing destratification system would not be able to increase bottom DO concentrations to prevent anoxic internal loading and reduce July – September average chlorophyll *a* concentrations.
- **What would be the benefit of increased air flow rates to the existing array of diffuser heads?** – The coupled model suggests that increasing the air flow rate to the existing

diffuser heads would provide some improvement to water quality; however, the improvements are modest. Even with ten times the current air flow rate, anoxia would occur at the bottom every year and chlorophyll *a* concentrations would continue to be above the standard in most simulated years.

- **What would be the benefit of increasing the number of diffuser heads with the same current air flow to each diffuser head?** – Increasing the number of diffuser heads with the same current air flow to each head (2.4 SCFM/head) induced more mixing and had a greater water-quality benefit per added total system air flow than increasing air flow to the existing number of heads. The effects on chlorophyll *a* and bottom DO, however, were limited in total effect. Even a system with five times the number of diffuser heads (580 total) at the current 2.4 SCFM would fail to keep DO concentrations above 2 mg/L during years with below-average water depth. Further, the chlorophyll *a* standard would not be met in most years. The net reduction in average summertime chlorophyll *a* for the 5X increase in diffuser heads was simulated to be 3.1 µg/L. The model suggests that much of this decrease (2.5 – 2.8 µg/L) could also be achieved with a system that has 2 – 3 times the number of diffuser heads (232 – 348 total), each at the current air-flow rate.

- **What would be the benefit of increasing both the number of diffuser heads and the flow rate to each of the diffuser heads?** – Simulated water-quality benefits generally increased with increased flow rates and numbers of diffuser heads; however, model results indicate a diminishing rate of return, particularly above total air flow increases on the order of ~10X. For all runs, including the extreme simulation of five times the number of heads with 10 times the current flow rate to each head, the maximum simulated average reduction in summertime chlorophyll *a* for the six years was 3.7 µg/L. Nearly 80% of that benefit (average chlorophyll *a* reductions of 2.9 µg/L) could be achieved with a system with 4 times the air flow capacity of the existing system (468 heads with 2.4 SCFM per head), illustrating the diminishing returns and suggesting the need for a cost-benefit analysis if an expansion of the destratification system is pursued.

- **From these runs, can the chlorophyll *a* standard be met with an enlarged destratification system? If so, what is the minimum size of that system? If not, what is limiting the system from achieving that objective?** – Based on the 22 scenarios considered, the coupled model suggests that the chlorophyll *a* standard cannot be met in all years by enlarging the destratification system. Even with a 50-fold increase in air flow capacity, the simulated July – September average chlorophyll *a* concentration decreased by an average of only 3.7 µg/L. These results highlight the difficulty in using compressed air destratification systems to alter water quality in large, shallow reservoirs such as Cherry Creek Reservoir. The efficiency of the system is limited by the shallow depth of the reservoir and the large area over which mixing is required. Additionally, even when the simulated mixing was sufficient to prevent anaerobic internal loading, the high external loading of nutrients, primarily from Cherry Creek, continued to provide nutrients for algae to grow, resulting in simulated chlorophyll *a* concentrations above the standard of 18 µg/L in most years. As a result of this study, the Authority now has insight into the potential range of benefits and limitations of an expanded destratification system, and the scale of expansion required.

5.2 Recommendations

A wide range of potential expanded destratification system designs were tested and evaluated with the coupled model. As a result of this study, the Authority now has a better understanding of the scale of the expansion required to modify the existing destratification system to increase bottom DO concentrations and reduce chlorophyll *a*. The coupled model suggests that the current chlorophyll *a* standard would not be consistently met, even with a large expansion to the destratification system. These findings highlight the difficulty of using mixing to alter water quality in large, shallow reservoirs with significant external nutrient loading such as Cherry Creek Reservoir. This information can be used by the Authority to determine a suitable path forward. Recommended next steps for the Authority to consider are outlined below.

- **Determine if Destratification is a Management Strategy the Authority Wishes to Continue Pursuing** – Although chlorophyll *a* concentrations improve with larger destratification systems, the coupled model suggests that an expanded destratification system would not be capable of ensuring the chlorophyll *a* standard is met in all years. Given the limited benefits of significant expansions to the destratification system on chlorophyll *a* concentrations, the Authority may wish to consider whether to continue pursuing an expanded destratification system as a management tool.

- **If the Authority Decides to Continue Pursuing Destratification as a Management Strategy, Then Estimate the Cost of Destratification System Modifications** – With an improved understanding of what is required to expand the system, an estimate of capital and operational costs can be developed and a cost-benefit study can be completed if the Authority wishes to continue pursuing destratification as a reservoir management strategy. The coupled model results suggest that much of the potential reduction in the July – September average chlorophyll *a* could be achieved with a number of system designs that have two to five times the air flow capacity of the existing destratification system. Such a system would be less effective at times of below average water depths (<~7.5 m). In all cases, the chlorophyll *a* standard would not be met in all years with an expanded destratification system alone.

- **Consider Other Management Options** –Other options can be considered for improving water quality in Cherry Creek Reservoir. Options include:
    - <u>Additional watershed measures to reduce nutrient loading to the reservoir</u> – Watershed measures to reduce inflowing nutrient loading are currently being implemented, but the Authority may wish to consider additional projects;

    - <u>Alum treatment to reduce internal phosphorus loading</u> – Alum has been used to reduce internal phosphorus loading in other water bodies, although there may be valid concerns regarding alum and aquatic life effects; and

  - Re-evaluating the site-specific chlorophyll *a* standard – With a better understanding of in-reservoir treatment option limitations, the Authority may or may not find it time to re-evaluate the appropriateness of the current site-specific chlorophyll *a* standard.

  Note that there are anticipated challenges and limitations associated with each of the management options listed above. The analysis of any options considered by the Authority would benefit from special studies and/or modeling to determine the potential efficacy.

  This study focused specifically on a compressed air destratification system. Other types of mixing systems and oxygenation systems could be considered but are not listed above because of similar challenges anticipated in applying such systems to Cherry Creek Reservoir. The large, shallow, polymictic nature of the reservoir would be expected to limit the effectiveness of other types of mixing and oxygenation systems, as was noted in this study of a compressed air destratification system.

- **Continue to Operate the Destratification System during Spring** – Even if the Authority chooses not to move forward with expanding the existing destratification system, the Authority may choose to continue operating the existing system in spring. Recent data indicate that operating the system during spring may help limit cyanobacteria blooms during this timeframe, though similar benefits are not observed in summer months (Hydros, 2019).

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