TECHNICAL MEMORANDUM

# Interim Measure 11, Activity 6 – Study of Algal Conditions Management within a Reservoir Cove Using Physical Measures

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## 1.0 Introduction

The Klamath Hydroelectric Settlement Agreement (KHSA) includes Interim Measure (IM) 11 (Interim Water Quality Improvements), which is intended to address water quality improvement in the Klamath River during the interim period leading up to potential dam removal. Several Interim Measure 11 activities were conducted during 2015 and extending into 2016, which included IM 11 Activity 6 Study of Algal Conditions Management within a Reservoir Cove Using Physical Measures.

### 1.1 Issue Background

Cyanobacteria (also commonly known as blue-green algae) are seasonally-dominating components of the phytoplankton community in the Klamath Basin. Cyanobacteria are a potential nuisance because some species produce substances toxic to humans, pets, livestock, and other organisms. While there are an abundance of algae species in Iron Gate and Copco reservoirs, the primary species of concern for this study is *Microcystis aeruginosa* (*Microcystis*). *Microcystis* is the focus because of its potential to produce microcystin, which in turn can have adverse health effects at higher concentrations.

Microcystin has been detected from Upper Klamath Lake downstream into the lower Klamath River including in Copco and Iron Gate reservoirs (Raymond 2010; Watercourse 2011, 2012, 2013, 2014, 2015; Kann et al. 2015; Eldridge 2015). Nutrient-laden water flowing into Copco and Iron Gate reservoirs from the upper basin, along with long water residence times and calm lacustrine conditions in the reservoirs themselves, favor the growth and surface blooms of cyanobacteria. During the summer and early fall, *Microcystis* cell densities and microcystin concentrations in Copco and Iron Gate reservoirs have reached and exceeded guidelines established for posting advisories in recreation water (see State Water Board 2010 for guidelines). As a result, warning notices have been posted and advisories issued for the reservoirs and the Klamath River downstream of Iron Gate dam.

The distribution of *Microcystis* and microcystin in Copco and Iron Gate reservoirs is not uniform. Localized high abundance of *Microcystis* can result from the ability of the organism to control its buoyancy and predominate at the surface and from the effects of wind advection with can accumulate *Microcystis* in coves or on windward shores. These coves are often favored public access points to the reservoirs with land-based recreational facilities and boat launches. Because cyanobacteria can accumulate in these locations, specific control methods for the coves within the reservoirs are of particular interest for improving water quality conditions.

## 1.2 Purpose

This report describes the assessment approach and results of a conceptual feasibility study of cove algal conditions management using physical measures, such as vertical and lateral mixing to reduce algae growth and accumulation. It is intended that this conceptual feasibility study is an initial analysis that provides an assessment and guidance for future more-refined analysis that could be pursued.

The purpose of Activity 6 was to assess potential algae control strategies for a reservoir cove. Mirror Cove, located on the Camp Creek arm of Iron Gate reservoir, was selected as the cove to study (Figure 1). Iron Gate reservoir is located on the upper Klamath River from about River Mile (RM) 190.1 to RM 196.9.

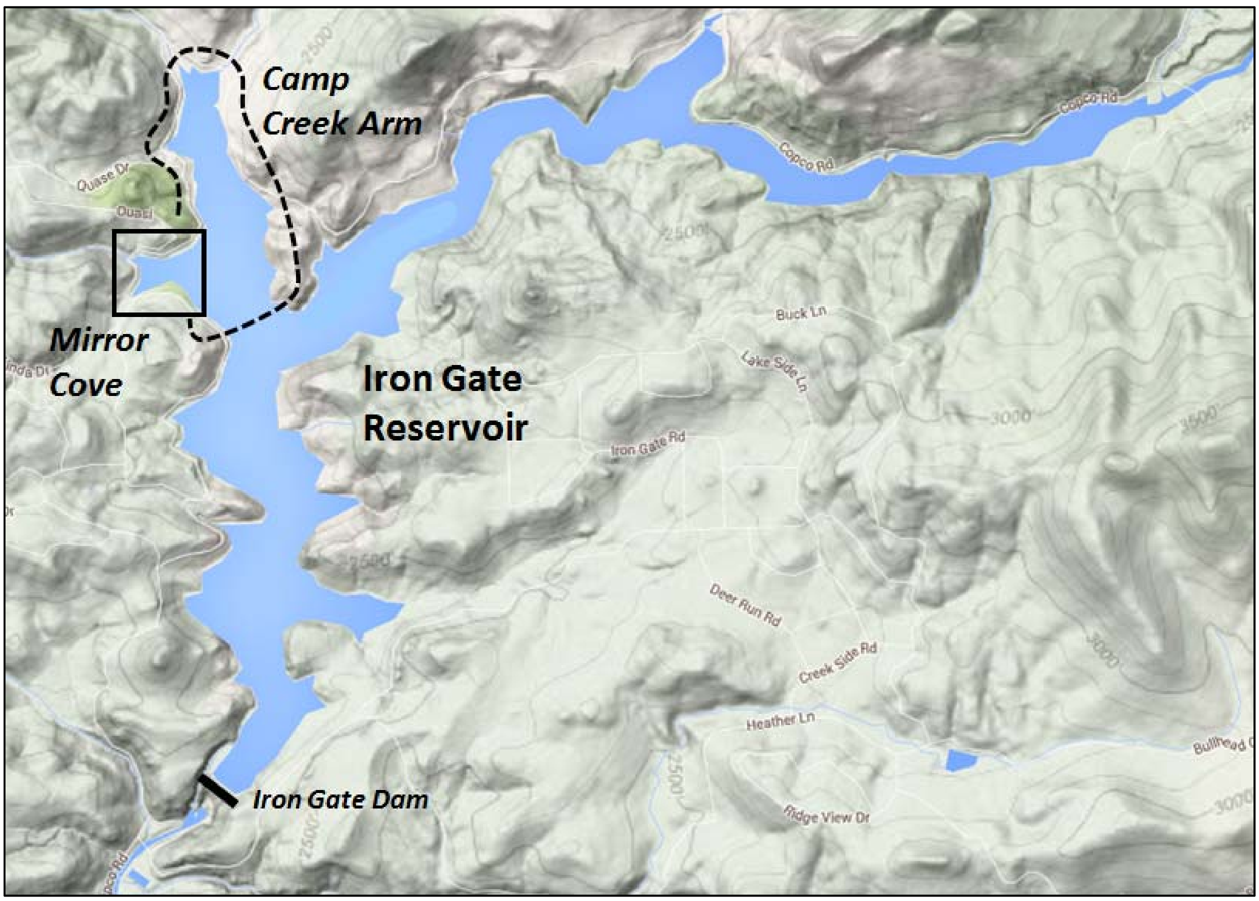


Figure 1. Location of Mirror Cove in Iron Gate Reservoir.

The study focused on algae management using physical techniques such as hydraulic manipulation, and horizontal and vertical mixing. These physical techniques are intended to: (1) mix the water column sufficiently to disrupt favorable conditions for cyanobacteria growth and formation of surface blooms, particularly *Microcystis*; and (2) accelerate flow exchange to overcome intrinsic algal growth rates and thereby reduce cyanobacteria standing crop, again particularly *Microcystis*. The aim of the study is to provide conceptual feasibility information to assess whether these techniques may potentially provide effective and economic algae control that could help reduce public health concerns in high-use areas of the reservoirs.

A draft of this report was circulated to the Interim Measures Implementation Committee (IMIC) for review on April 13, 2016. Comments subsequently received from IMIC members were reviewed by PacifiCorp and the draft report was revised as appropriate; all comments and responses are included in Appendix A.

# 2.0 Theoretical Foundations

## 2.1 Vertical Mixing and Displacement from the Surface Photic Zone

This study used the water column mixing findings of Huisman et al. (2004) as a theoretical foundation. Their work specifically and quantitatively determined how mixing works to suppress cyanobacteria blooms, particularly of *Microcystis*, at the field scale. Huisman et al. (2004) showed that turbulent diffusion (mixing intensity) as function of basin depth wholly determines dominance of cyanobacteria (Figure 2). Hence, blooms of *Microcystis* cannot develop if water-column depth exceeds a critical depth and turbulent mixing exceeds a critical turbulence. This study assessed approaches and techniques for effectively accomplishing such vertical mixing and therefore displacement of *Microcystis* based on this theoretical foundation.

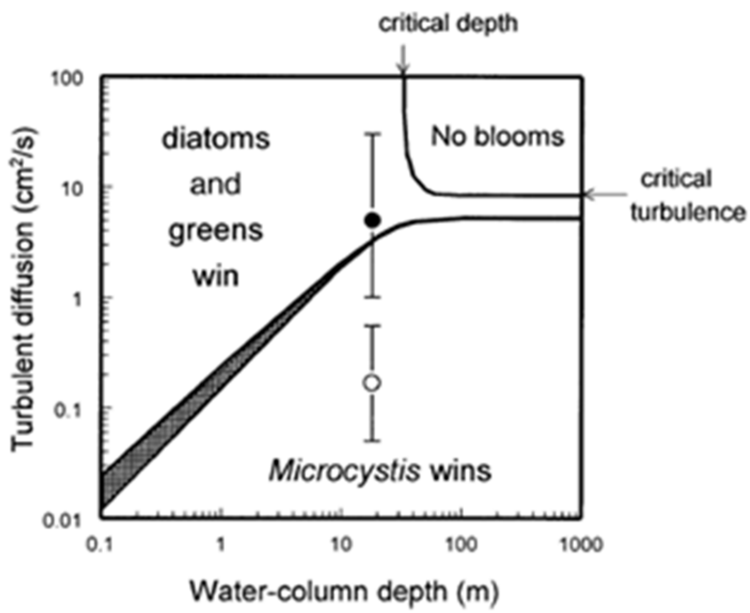


Figure 2. Predicted response of *Microcystis*, diatoms, and green algae as a function of water-column depth and turbulent diffusion (taken from Huisman et al. 2004).

## 2.2 Horizontal Advective Mixing and Displacement

This study used the concept of hydraulic manipulation that seeks to exchange or replace a volume of water through hydraulic manipulation at a rate that approaches or exceeds intrinsic algae growth rates. This creates conditions that reduce algal standing crop by dilution or washing algae out of the study area. Hydraulic manipulations of lake or reservoir retention time as a means to control algae have been investigated by several researchers (e.g., Cooke et al. 2005; Takeya et al. 2004; Welch 1978). This work has included inducing dominance shifts from nuisance to benign algal groups through hydraulic manipulations (Hayden et al. 2012; Lundgren et al. 2013; Roelke and Pierce 2011; Roelke et al. 2013). Researchers have determined threshold flows that lead to washout in various ways, such as identifying threshold Péclet number[1] (Grover et al. 2011) or through modeling efforts that calculate flow forcing of algae population dynamics by using known relationships of algae growth rates to temperature and nutrient concentrations (Cooke et al. 2005; Elliott and Defew 2012; Elliott et al. 2009; Lundgren et al. 2013; Roelke et al. 2013).

The investigations of the effects of hydraulic manipulations in reservoirs have focused primarily on the main bodies of riverine reservoirs and impoundments. However, fringing coves and shoreline features can comprise hydraulic storage zones where algae can persist (Grover et al. 2011). Daniel Roelke and colleagues at Texas A&M University have been conducting extensive research into harmful algae bloom (HAB) mitigation approaches employing hydraulic flushing of coves with deeper, HAB-free waters in Lake Granbury, Texas (Hayden et al. 2012; Lundgren et al. 2013; Roelke and Pierce 2011; Roelke et al. 2013). Roelke and colleagues have demonstrated that utilizing source water from deeper depths to displace surface waters effectively mimics aspects of natural inflow events (such as indicated in Figure 3), and can disrupt bloom initiation and bloom development (Roelke et al. 2013). In this work, water originating deep in the lake is pumped to the head of a cove (dotted blue line in Figure 3). Placement of this water in the head of the cove stimulates mixing and increases outflow into the main body of the lake. Further, Roelke and Pierce (2011) indicated that creating fluctuating environments during the periods of bloom initiation may promote more diverse phytoplankton assemblages resistant to HAB species or may support higher zooplankton populations thereby limiting HAB populations and bloom development.

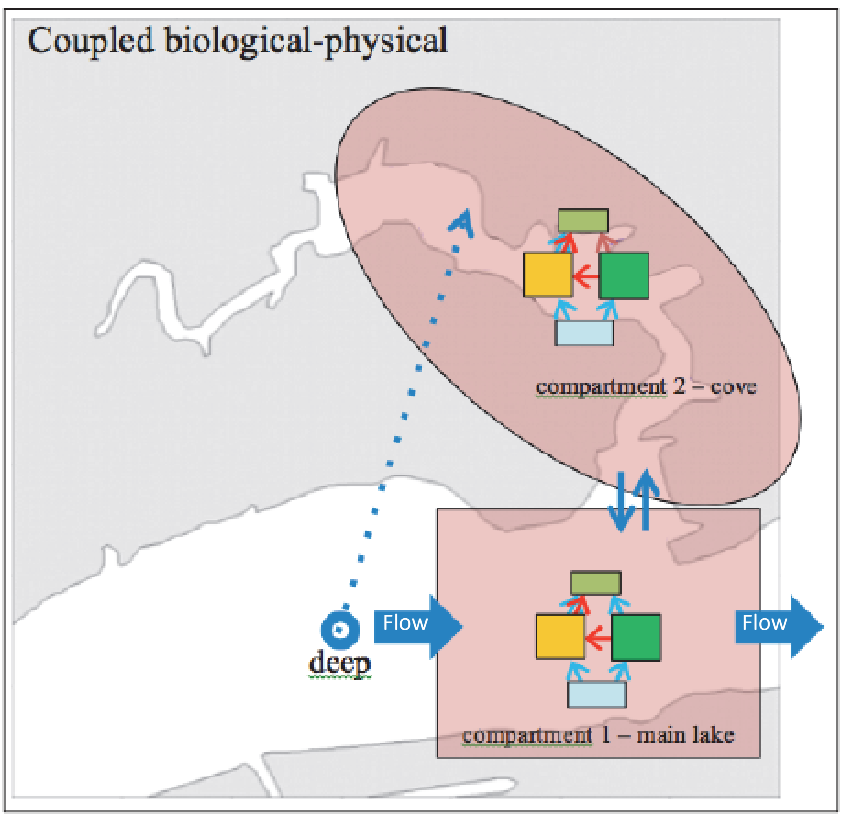


Figure 3. Conceptual illustration of utilizing source water from deeper depths to displace cove surface in lake-cove system (taken from Roelke et al. 2013; colored boxes are model components described by Roelke et al. 2013).

[1] The Péclet number is defined to be the ratio of the rate of advection of flow to the rate of diffusion driven by an appropriate gradient. A Péclet number exceeding 100, for example, is an advection-dominated system where phytoplankton are translocated and washed out (Grover et al. 2011).

# 3.0 Assessment Methods

## 3.1 Model Development and Simulations

To assist in assessment of the potential physical management techniques in Mirror Cove, the existing CE-QUAL-W2 model of Iron Gate reservoir developed by Watercourse Engineering (PacifiCorp 2005, 2014) was extended to incorporate Mirror Cove. The physical basis of the original CE-QUAL-W2 model includes bathymetry of Iron Gate reservoir as provided by Eilers and Gubala (2003).

A bathymetric survey of Mirror Cove was conducted in August 2015 to improve the detail and accuracy of the model's geometric representation of the cove (Figure 4). This bathymetry was subsequently used to develop an additional branch in CE-QUAL-W2 to specifically represent Mirror Cove. This branch included eight additional segments of approximately 50 meter (m) [164 feet (ft)] in length. Layer vertical thickness in the model was 1.0 m (3.28 ft), consistent with the remainder of the Iron Gate reservoir CE-QUAL-W2 grid (Figure 5).

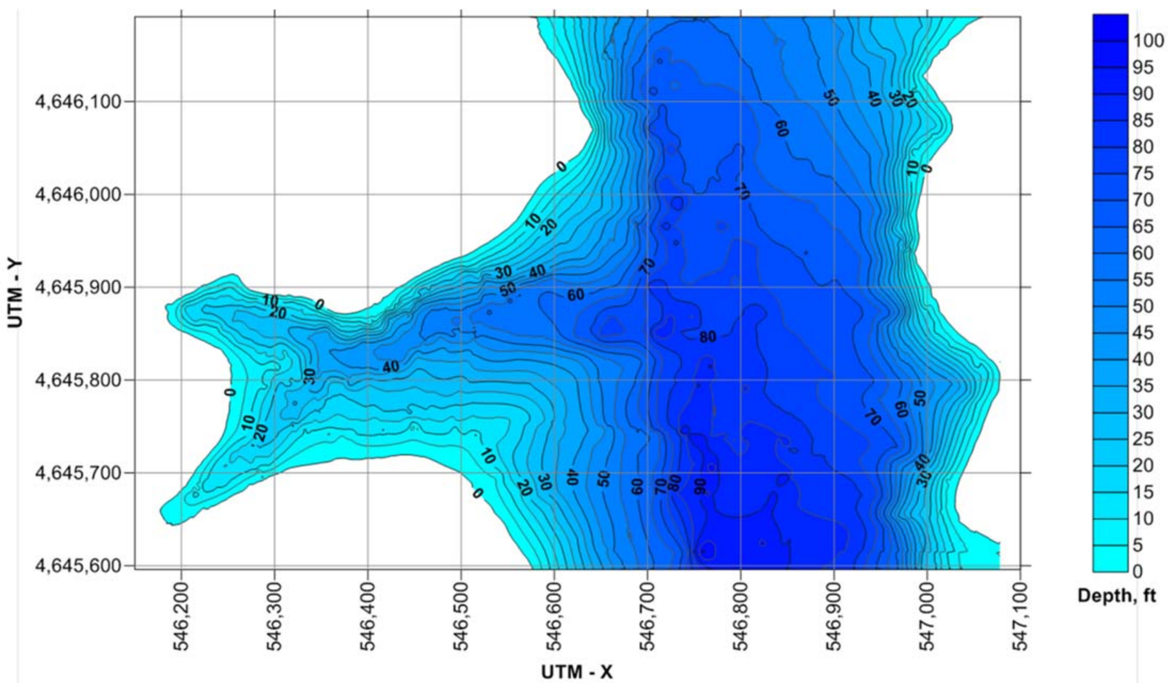


Figure 4. Mirror Cove bathymetry.

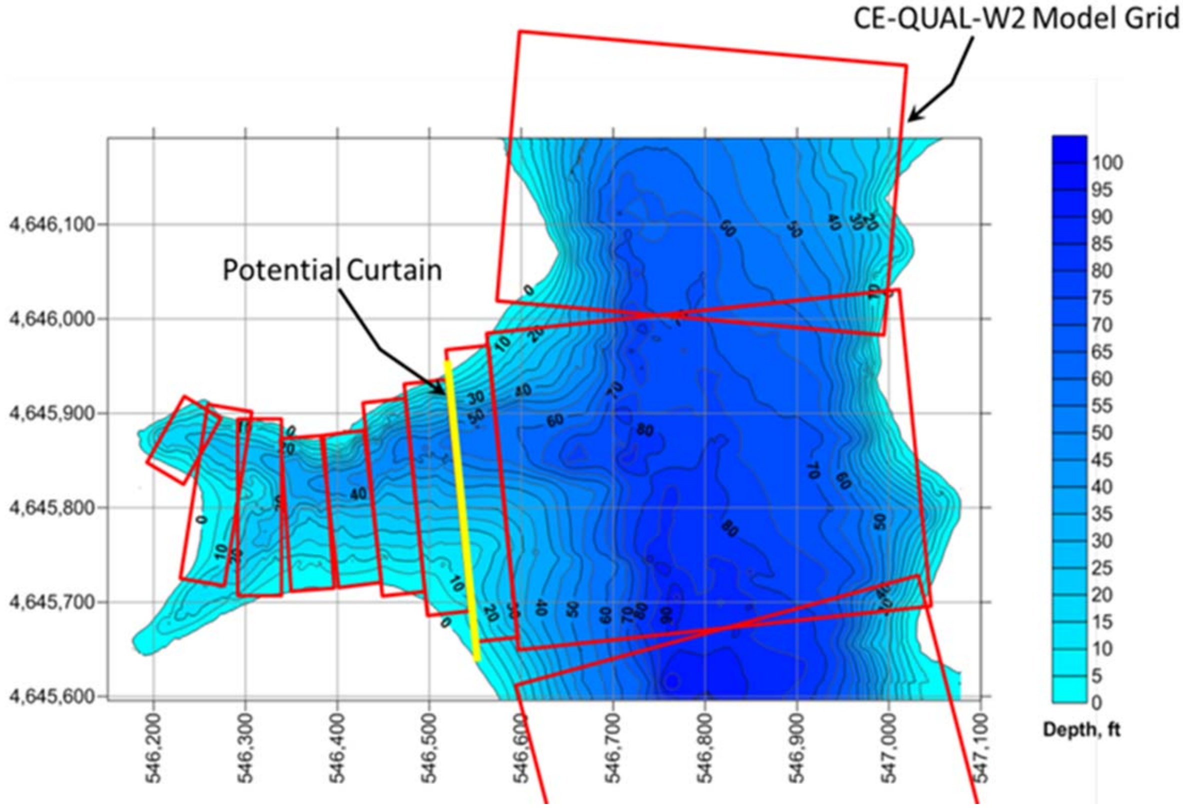


Figure 5. Mirror Cove CE-QUAL-W2 model grid and potential curtain placement.

## 3.2 Calculation of Turbulent Diffusion

Huisman et al. (2004) determined that sufficiently increased values of vertical turbulence and eddy diffusion produce unfavorable conditions for growth and surface blooms of *Microcystis* (Figure 2). Eddy diffusivity values were calculated as another means of assessing the ability of management actions to destabilize the water column in Mirror Cove to potentially manage *Microcystis* populations.

Eddy diffusivity values were calculated from the modeled changes in temporal and spatial distribution of heat in the cove based on the method of Jassby and Powell (1975) and Benoit and Hemond (1974). This is a method that incorporates the vertical energy distribution of the water column, vertical solar energy input, and sediment heat flux in the water body according to the following equation:

$$\rho C_p K_z(z) \frac{dT}{dz}\Big|_z^{z_{max}} F(z) = -\int_z^{z_{max}} \frac{dT}{dt} F(z)dz + R(z)F(z) - \int_z^{z_{max}} H(z)l(z)dz$$

Where:

- $K_z(z)$ = turbulent diffusion coefficient [square centimeters per second ($cm^2/s$)]
- z = depth [centimeters (cm)]
- $z_{max}$ = maximum water depth (cm)
- ρ = water density [grams per cubic centimeter ($g/cm^3$)]
- g = mass [grams (g)]
- $C_p$ = specific heat of water [Joules per degree Celsius per gram g ($J/^oC{\cdot}g$)]
- T = water temperature [degrees Celsius ($^oC$)]
- t = time [seconds (s)]

F(z) = water body surface area at depth z [square centimeters ($cm^2$)]
R(z) = solar (short-wave) radiation at depth z [watts per square centimeter ($W/cm^2$)]
H(z) = sediment heat exchange [Joules per square centimeter second ($J/cm^2 \cdot s$)]
l(z) = sediment area at depth z ($cm^2$)

Solving for the turbulent diffusion coefficient ($K_z(z)$) yields:

$$K_z(z) = \left[-\int_z^{z_{max}} \rho C_p \frac{dT}{dt} F(z)dz + R(z)F(z) - \int_z^{z_{max}} H(z)l(z)dz\right] \cdot \left[\rho C_p \frac{dT}{dz} F(z)\right]^{-1}$$

Simulated vertical temperatures were employed assuming a time step of 1 second to minimize large changes and to represent $K_z(z)$ for a specific thermal profile. Bathymetry of the cove was used to determine planar surface areas and sediment areas at specific depths.

### 3.3 Assessment of Potentially Applicable Mixing-Circulation Technologies

Model simulations (Section 4) and turbulent diffusion calculations (Section 3.2) were used to determine effective mixing/circulation requirements of the cove using the theoretical foundations discussed previously as a guide (see Section 2). Once the mixing requirements had been identified, applicable commercially-available mixing/circulation systems were identified that would be capable of providing the required turbulent diffusion and advection in Mirror Cove. The assessment of potentially applicable mixing/circulation systems is contained in Section 5 below.

## 4.0 Results

### 4.1 Model Simulations

To complete simulations of Mirror Cove, the entire reservoir model was applied and results from the Mirror Cove branch and nearby Camp Creek arm (Figure 1) were assessed as distinct outputs. Model year 2004 was used as the base condition for all simulations, and an existing conditions simulation was completed as a baseline scenario against which simulated alternative management scenarios could be compared.

Mirror Cove generally widens and deepens as it approaches the main reservoir, which leads to open and direct water exchange with the main reservoir. Initial modeling indicated that a barrier or curtain would be needed to isolate Mirror Cove from the Camp Creek arm of Iron Gate reservoir (Figure 5). Because of cove morphology, without a curtain water quality conditions from the body of the reservoir tended to overwhelm conditions in the cove. For different cove morphologies, a curtain may not be needed.

To isolate Mirror Cove in the CE-QUAL-W2 model, a curtain was placed at a model grid boundary near the Camp Creek arm (Figure 5). The curtain was modeled as being 10 m (32.8 ft) deep. The model was tested to ensure that Mirror Cove results were consistent with previous modeling and effectively represented stratification conditions in nearby Camp Creek arm. Three simulations were completed as an initial trial: (1) Existing Conditions (baseline without any curtain or mixing measures); (2) Curtain Only (imposed on existing conditions); and (3) Curtain with Internal Mixing and Circulation (imposed on existing conditions). Simulations were completed for the calendar year. Each of these scenarios was assessed for July 8 (early July) and July 28 (late July). These days were chosen because they illustrate a period when the lake experienced the transition toward the reservoir's annual peak in surface water temperature and thermal stratification.

### 4.1.1 Existing Conditions Simulation

The existing conditions simulation illustrates how the cove and the main reservoir experience similar baseline conditions (Figures 6 and 7; top plots of both figures). The epilimnion thickness is approximately 3 m (10 ft) coincident with the typical summer period photic zone depth in Iron Gate reservoir. The temperature gradient between the surface and 10 m (32.8 ft) for early and late July is approximately 6$^{o}$C and 10$^{o}$C, respectively. A small creek is assumed to add 0.001 cubic-meters per second (cms; 0.03 cfs) to Mirror Cove in the most upstream model segment (furthest left segment on Figure 5); this inflow has no influence on the results and is assumed to occur in all model simulations.

### 4.1.2 Curtain Only Simulations

This simulation assumes a curtain is located at the downstream end of Mirror Cove (Figure 5) which restricts the mixing of water from the Camp Creek arm of Iron Gate reservoir into the cove. Without exchange with the main reservoir, the cove is slightly cooler at the surface but consistently warmer at middle depth than existing conditions (Figures 6 and 7; middle plots of both figures). The temperature gradient between the surface and 10 m (32.8 ft) is approximately 4$^{o}$C for both early and late July. This indicates that the presence of the curtain results in reduced thermal stratification as compared to existing conditions.

As a comment on a draft of this report, the Karuk Tribe (in a letter from Susan Corum to the IMIC dated May 17, 2016) indicated that it is not clear why curtain-only simulations show reduced thermal stratification in the cove. The Karuk Tribe assumes the cove under curtain-only simulations would be prone to less mixing, shorter wind fetch, and presumably more stagnant, surface-warming conditions. There are two main explanations for why curtain-only simulations show reduced thermal stratification in the cove. First, wind mixing does not abate simply because the cove is isolated. The cove has an area of about 18 acres, a mean depth of about 7 meters, and a fetch length of 500 meters. Isolated bodies of water (e.g., small lakes) of this size and depth tend to be more-readily mixed (Fischer et al. 1979). Near-surface velocity vectors in the curtain-only simulations indicate response to wind shear in near surface waters (Figures 6 and 7). As heat energy enters the system via the air-water interface, even modest winds can mix the relatively shallow water column. Second, the curtain acts to cut off the cove from the relatively large thermal mass and associated stratification of the main lake, which otherwise affects vertical temperature gradients in the cove. Without the connection with this relatively large stratified mass, temperature gradients in the cove are much less stable and diminish, leading to the generally isothermal structure in the cove.

### 4.1.3 Curtain Combined with Mixing and Circulation Simulation

This simulation also assumes a curtain is located at the downstream end of Mirror Cove as discussed previously (Section 4.2.2). In addition, this simulation assumes a mixing and circulation system that pumps water at a rate of 1 cms (35.3 cfs) from a location in the cove upstream of the curtain (in segment 46 of the model) to near the head end of the cove (in segment 41 of the model). This simulation illustrates that pumping this volume of deeper water to the upstream end of the cove results in mixing the entire cove inside the curtain to a near isothermal state (Figures 6 and 7; bottom plots of both figures). This mixing also imposes circulation within the cove that includes a vertical component. The mixed cove is effectively separated from the lake, and the temperature gradient between the surface and 10 m (32.8ft) is less than 1$^{o}$C for both the early and late June cases. The deepest waters adjacent to the curtain do not mix upwards into the cove because they are notably cooler and denser than the water in the cove.

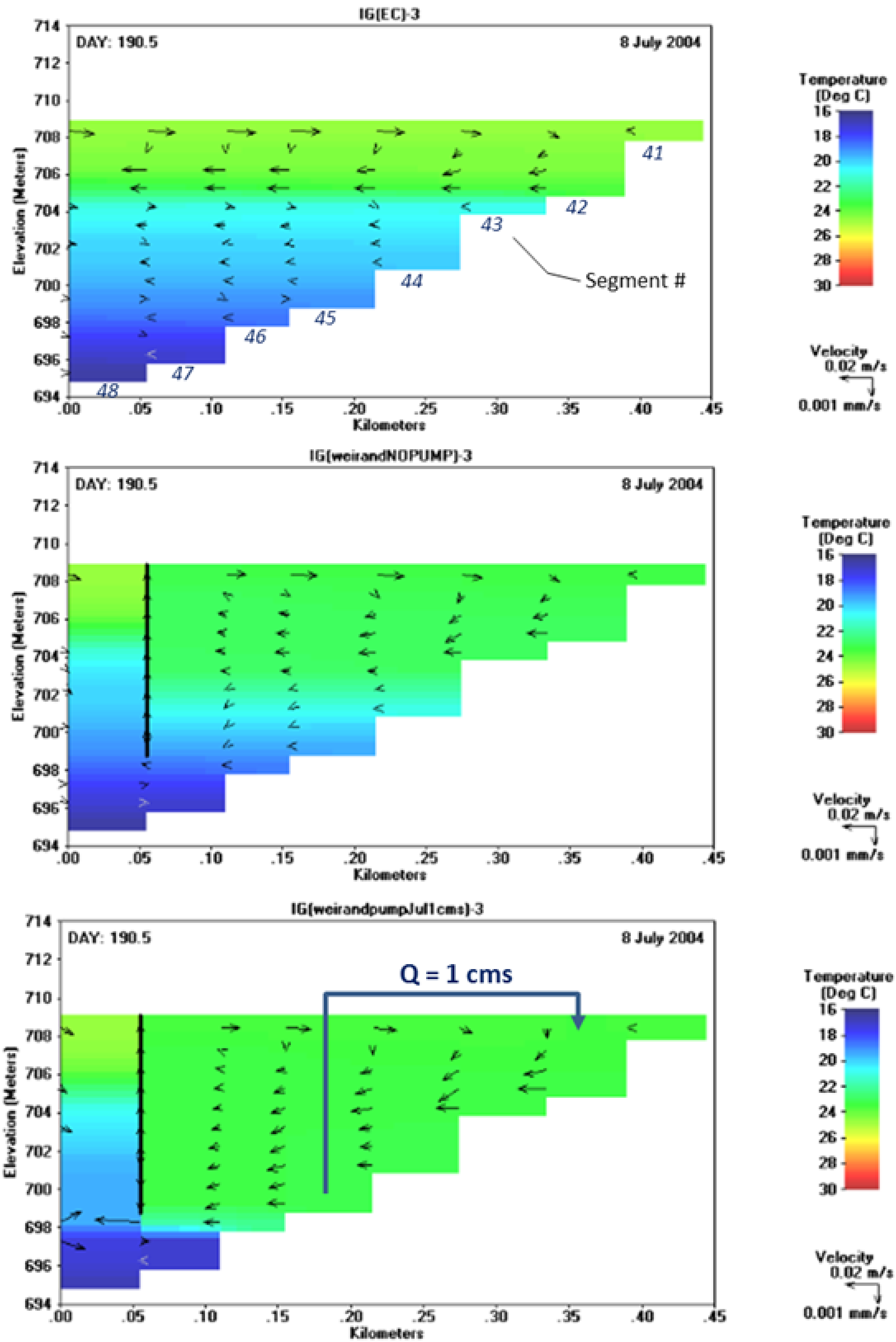


Figure 6. Mirror Cove CE-QUAL-W2 simulations for July 8, 2004 for Existing Conditions (top plot), Curtain Only (middle plot), and Curtain with Internal Mixing and Circulation (bottom plot).

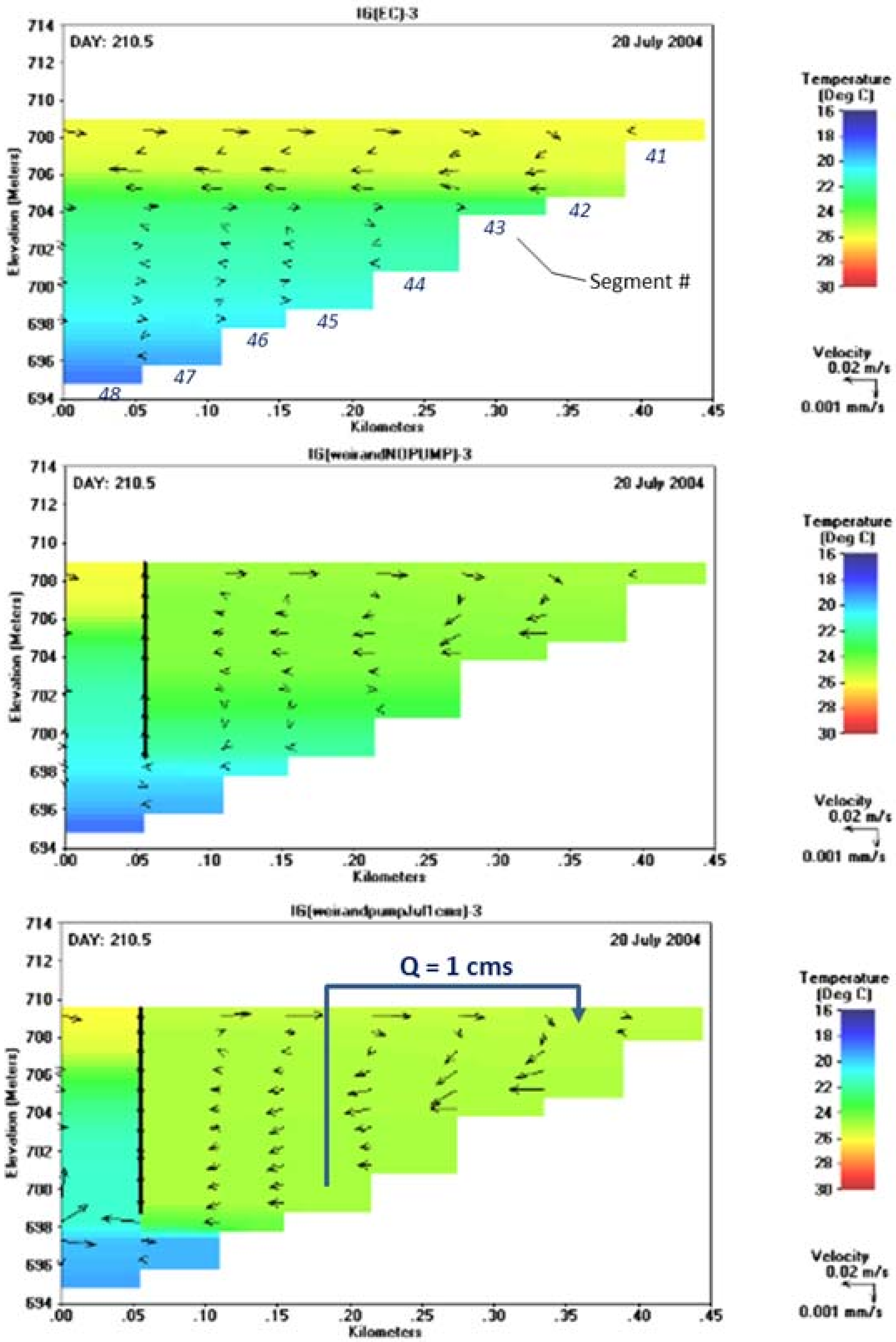


Figure 7. Mirror Cove CE-QUAL-W2 simulations for July 28, 2004 for Existing Conditions (top plot), Curtain Only (middle plot), and Curtain with Internal Mixing and Circulation (bottom plot).

## 4.2 Turbulent Diffusion Values

Temperature gradients commonly occur in the epilimnion of lakes that have direct implications on the stability of the water column and vertical turbulent mixing (Cooke et al. 2005). This stability favors conditions that can lead to the formation of cyanobacterial blooms, notably of *Microcystis.* Because of this, destabilizing this area through turbulent mixing is a direct way to potentially manage and reduce the growth and accumulation of *Microcystis*.

Vertical turbulent mixing is generally characterized through eddy diffusivity (also known as an eddy diffusion coefficient) that represents the vertical advection in a water column and characterizes the stability of the water column as a function of depth. Huisman et al. (2004) determined that sufficiently increased values of vertical turbulent eddy diffusion leads to two desirable management outcomes: (1) less favorable conditions for growth and surface blooms of *Microcystis*; and (2) and dominance by other more-beneficial algae (e.g., diatoms and green algae more supportive of lake food webs).

Based on the work of Huisman et al. (2004, Figure 2) and assuming a fully-mixed condition over a depth of 10 m (32.8 ft), a target turbulent diffusion value greater than 2.0 $cm^2/s$ (0.0022 $ft^2/s$) would be an appropriate target for reducing *Microcystis* dominance for Mirror Cove . Turbulent diffusion values calculated for existing conditions in Mirror Cove (based on simulated vertical temperature profiles) are mostly less than 2 $cm^2/s$ (0.0022 $ft^2/s$). Under existing conditions, water column stability is generally favorable to *Microcystis* growth, and thermal stratification yields sufficiently strong density differences to impede diffusion and limit mixing (Figure 8).

Turbulent diffusion values calculated for the Curtain Only scenario are similar to existing conditions (Figure 8). The turbulent diffusion values are higher at depths of 6 m (19.2 ft) or less, which indicates that the reduced thermal stratification (compared to existing conditions) caused by the presence of the curtain (see Section 4.1.2) results in more turbulent diffusion at these depths. However, despite this increase in turbulent diffusion, water column stability for the Curtain Only scenario is still generally favorable to *Microcystis* growth and accumulation (Figure 8).

Turbulent diffusion values for the scenario of curtain combined with internal mixing and circulation are generally greater than 2 $cm^2/s$ (0.0022 $ft^2/s$), particularly over the shallower portion of the water column between the surface and a depth of about 9 meters. This is important because this area comprises the photic zone where most algae are found (Figure 8). This scenario's vertical distribution of turbulent diffusion values indicates that a curtain with internal mixing and circulation in the cove could suppress *Microcystis* and instead favor diatoms and green algae (Figure 2). Presence of the curtain coupled with active mixing results in a near isothermal condition in the top 9 m (29.5 ft) of the cove. This active mixing leads to turbulent diffusion values that exceed 2 $cm^2/s$ and reach as much as about 40 $cm^2/s$ at the water surface.

To our knowledge, the application of the Huisman et al. (2004) turbulent diffusivity criteria to CE-QUAL-W2 modeling is novel. At the outset of this study, the intent was to modify CE-QUAL-W2 to provide a means of explicitly modeling the dynamics of cyanobacteria blooms, including buoyancy compensation; however, this has proved to be a complex and challenging task that will require more work and testing. Nonetheless, the application of the Huisman et al. (2004) turbulent diffusivity criteria to CE-QUAL-W2 output provides a method to evaluate changes in hydrodynamic conditions that could control *Microcystis* blooms. This approach uses the strong hydrodynamic features of the CE-QUAL-W2 model as forcing functions that can simplify in a realistic and straightforward manner the complex ecosystem dynamics of cyanobacteria blooms. These results provide strong supporting evidence to assess and identify effects of engineered turbulent diffusivity for cove algae management.

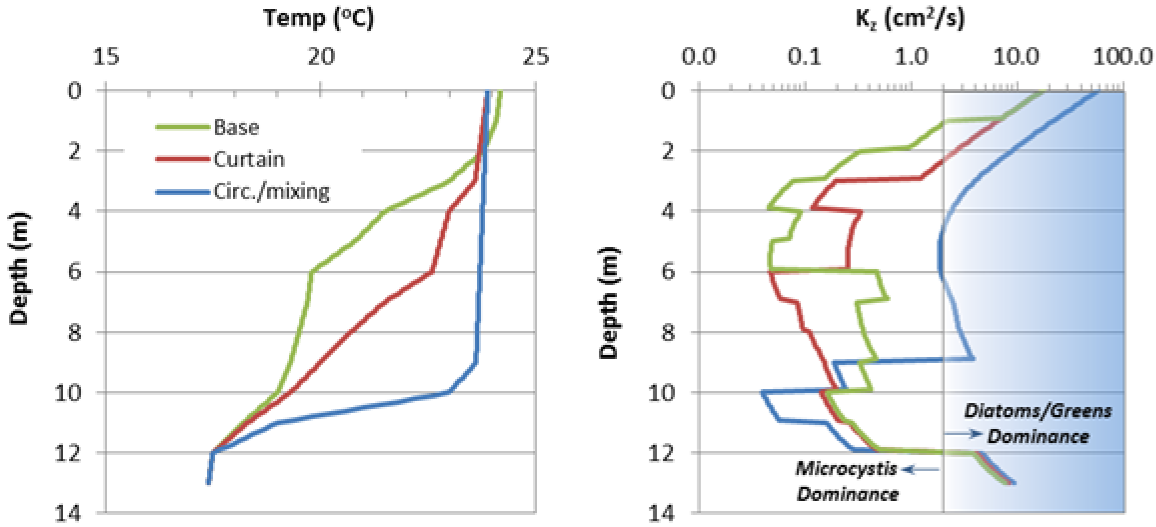


Figure 8. Vertical profiles of water temperatures (left) and turbulent diffusion values (right) for July 28 model simulations for Existing Conditions (green lines), Curtain Only (red lines), and Curtain with Internal Mixing and Circulation (blues lines). The shaded region representing greater than 2 $cm^2/s$ (right plot) represents the region of turbulent diffusion where *Microcystis* would yield dominance to diatoms and green algae (per Huisman et al. 2004).

## 4.3 Hydraulic Residence Times

The growth rate of cyanobacteria is typically much lower than that of many algal species (Mur et al. 1999). For example, at 20°C and light saturation, *Microcystis* achieves average growth rates of 0.2-0.33 doublings per day (i.e., a doubling time of 3 to 5 days), while diatoms reach 0.8-1.9 doublings per day and growth rates of up to 1.3-2.3 doublings per day have been observed for single-celled green algae (Imai et al. 2009; Lürling et al. 2013; Wilson et al. 2006). Slow growth rates require long water retention times to enable a bloom of cyanobacteria to form; therefore, cyanobacteria do not bloom in water with short retention times (Mur et al. 1999).

Decreases in lake or reservoir hydraulic retention time (HRT) is a well-reported technique to decrease cyanobacteria blooms where control of HRT is possible (Cooke et al. 2005; Takeya et al. 2004; Welch 1978). For significant reduction or washout of algal cells to occur, the water exchange rate must approach the algae growth rate (Cooke et al. 2005; Welch 1978). Huisman et al. (2004) determined the maximal specific growth rate of *Microcystis* to be 0.008 per hour (doubling time of 5.2 days) in a natural mixed species phytoplankton assemblage. Imai et al. (2009) report the growth rate of *Microcystis* to be 0.20 per day (doubling time of 5 days) at a water temperature of 20°C. Wilson et al. (2006) documented variation in the maximum population growth rates of 32 *Microcystis* strains, ranging from 0.13 to 0.46 per day (doubling times of 5.2 to 1.5 days, respectively), with an average growth rate across all strains of 0.33 per day (doubling time of 3 days). On the basis of above information, we assume significant reduction or prevention of *Microcystis* blooms in the cove will occur as HRT is decreased to about 5 days or less (equivalent to a water exchange rate of 20 percent of the volume per day or greater).

Based on the bathymetry and modeling of Mirror Cove, an estimate of cove residence time (flow rate/volume) under mixed conditions was calculated. Using a flow rate of 1 cms (35.3 cfs) as assumed in the simulation of the mixing and circulation system (as described in Section 4.1.3), the HRT in Mirror Cove is calculated as 3 to 4 days. Therefore, the HRT of Mirror Cove with the assumed mixing and circulation system likely would be short enough to disrupt and prevent *Microcystis* blooms and accumulation in the cove. This finding provides additional support to the previous conclusion (as described in Section 4.2) that the turbulent diffusion caused by mixing and circulation system would help to reduce or prevent *Microcystis* blooms.

# 5.0 Mixing and Circulation Systems for Potential Use in the Reservoir Coves

This section describes potential mixing and circulation technologies that would be capable of providing enough turbulent diffusion and advection to achieve improved conditions in reservoir cove/s (e.g., Mirror Cove). The technologies are evaluated in relation to the theoretical foundations (Section 2) and assessed by modeling and calculations (Section 4). Fundamentally, an appropriate and effective system must increase turbulent diffusion (mixing intensity) uniformly in the water column.

## 5.1 Common Surface Mixing Systems

There are many commercially available surface mixing devices. In general practice, surface mixing systems have been relatively commonly applied in lake and reservoir settings. However, in the reservoir coves (e.g., Mirror Cove), such systems are expected to have significant limitations because these mixing systems would not mix sufficiently to meet the criteria set forth by Huisman et al (2004). Two examples are discussed below.

An example of one of these systems is SolarBee®, a common solar-powered surface mixing technology that is based on a hydrodynamic concept of establishing a low intensity laminar flow to promote mixing (for more information on SolarBee® technology see website at: http://lakes.medoraco.com/). The theory behind this technology is that water pumped from deeper depths travels laterally for large distances, thereby mixing cyanobacteria downward. However, the low-energy laminar flow provided by these units likely would not impart sufficient mixing energy and intensity to suppress and control cyanobacteria growth and accumulation in the reservoir coves.

In 2008, PacifiCorp conducted study where 12 SolarBee® circulators (Model SB10000v12) were deployed in the upper portion of Copco reservoir (including within or near coves) from April through October (Carlson and Foster 2009). The main objective of this study was to assess whether the circulators act to improve water quality in the upper portion of Copco reservoir where the circulators were installed relative to other areas without circulators. The focus was on reducing blooms and accumulations of cyanobacteria. Monitoring results showed that the circulators did not act to improve water quality conditions, particularly in reducing blooms and accumulations of cyanobacteria and it was concluded that the units' low-intensity laminar flow mixing was simply overridden by the relatively stronger influence of the reservoir's background hydrodynamics (Carlson and Foster 2009).

In another study on a hypereutrophic lake in central Minnesota, CH2M assessed the performance of SolarBee® units in a shallow (3.7 m) isolated bay with strong cyanobacteria blooms (Austin et al. 2014). No suppression of cyanobacteria was noted in 2 years of study. Velocity transects were measured radially outward from the edge of the SolarBee® unit that was pumping water at a nominal rate of 10,000 gpm (0.63 m3/s). This data indicated that horizontal surface velocity dropped to less than 1 mm/s within 10 m. Monitoring of the area around the SolarBee® units could not find evidence of density effects from water temperature differences on circulation or water quality.

The hydrodynamic opposite of the SolarBee® technology is the higher-energy WEARS mixing unit (for more information on this technology see website at: http://www.wears.com.au/). The concept behind the WEARS technology is that warm surface water is pushed to the bottom through a draft tube allowing the buoyant surface water to mix the reservoir. However, while the WEARS mixing unit can provide higher-intensity deep mixing, its effectiveness can be limited spatially (particularly laterally) when the influence of the plume of rising water is confined to a small, local area centered on the mixer (Lawson and Anderson 2007). For application to Mirror Cove, the degree of destratification that occurs simply with installation of the barrier makes the vertically-dominated mixing of a WEARS unit unnecessary.

## 5.2 Aeration-based System

A destratification aeration-based system would be the most effective technologic approach in the reservoir coves (e.g., Mirror Cove). This conclusion is not based on a comprehensive comparative assessment of various mixing and circulation methods, but is rather a logical conclusion that comes from straightforward identification of the only commercially-available mixing technology that would be practical and effective at providing comprehensive turbulent entrainment of water in the cove.

Destratification aeration operates by turbulent entrainment of water by an air bubble plume and then lateral shedding (detrainment) of water at micro-density gradient scales (Figure 9). This mechanism of destratification itself increases turbulent diffusivity throughout the water column. Consequently, it creates the hydrodynamic conditions to support the theoretical foundation based on Huisman et al. (2004) as described in Section 2.1. In practical terms, the aeration intensity for destratification of the cove is small.

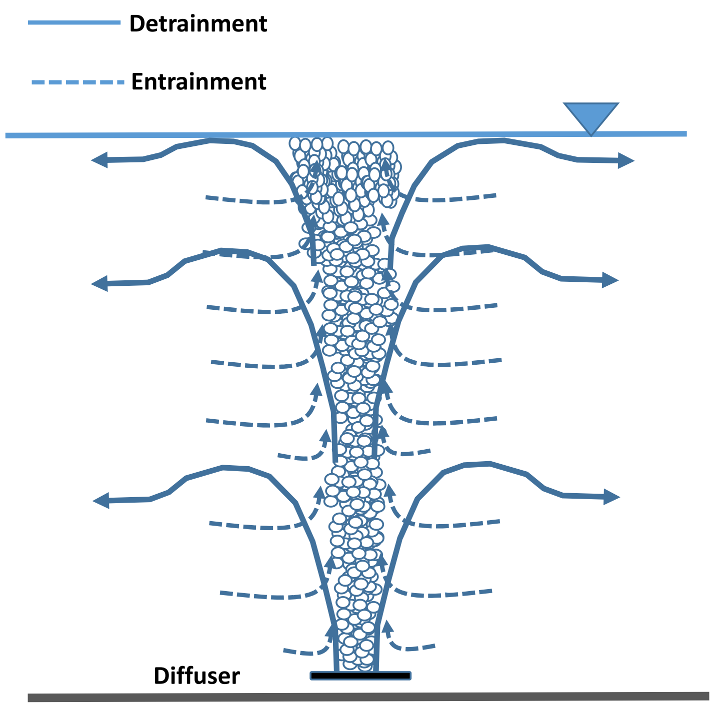


Figure 9. Entrainment and detrainment of water at micro-density scales with destratification aeration systems (Adapted and redrawn from Schladow and Fisher 1995).

A time-tested default aeration rate for a destratification aeration system is 9.2 cubic meters per hour per square kilometer ($m^3/h/km^2$) (1.3 standard cubic feet per minute per acre) (Cook et al. 2005). This default aeration rate may not in and of itself be sufficient to ensure turbulent diffusion to meet the Huisman et al. (2004) criteria. Consequently, additional infrastructure may be necessary to strengthen destratification and ensure adequate mixing intensity in the cove. The additional infrastructure would include a curtain (such as assumed in the modeling as described above) and an ancillary pump-based horizontal mixing system. As such, the system would comprise the following components:

1. Exclusion Curtain. This would consist of a curtain across the mouth of the cove similar to those previously deployed by PacifiCorp at Long Gulch Cove and upstream of the Iron Gate reservoir intake tower. As previously discussed, the curtain itself acts to promote some amount of destratification and would make mixing more efficient by separating the cove water mass from the main body of the reservoir.

2. Destratification Aeration Diffuser. This component would entail setting an aeration diffuser array at the same depth as the bottom of the exclusion curtain. Destratification aeration would ensure attainment of the isothermal conditions as simulated in the model (see Section 4.1.3). Destratification aeration alone is probably sufficient to meet model conditions without an ancillary pump-based horizontal mixing system (described below). However, the combination of destratification aeration and pump-based horizontal mixing are mutually reinforcing and provide process redundancy. Both are advisable to provide a high level of confidence of mixing intensity that will meet the criteria of Huisman et al. (2004) for vertical mixing and displacement of cyanobacteria (notably *Microcystis*) from the surface photic zone. It is important to note that destratification aeration is probably mandatory if there is to be boat passage section with a gap allowed at the curtain top. The destratification system would counteract the potential for outside algae material or warm water to flow in through such a gap.

3. Ancillary Pump and Conduit Horizontal Mixing. This component would use a pump-and-conduit system near the head end of the cove that would pump deeper water (from below the photic zone) into the shallow end of the cove. This component is similar in concept to the method employed for hydraulic flushing of coves for HAB mitigation in Lake Granbury, Texas (Roelke and Pierce 2011; Roelke et al. 2013). This system also would incorporate the theoretical foundation (see Section 2.2) for horizontal advective mixing and displacement of HABs from the coves.

Destratification aeration systems of the kind recommended above are commercially available. For example, Mobley Engineering, Inc. (MEI) offers linear aeration diffuser systems that can be manufactured on site and then floated to location, sunk by means of a ballast pipe, and then floated again as necessary for maintenance (see MEI website for additional information and examples; http://mobleyengineering.com/).

The typical linear aeration diffuser offered by MEI may be larger than needed for the cove. Therefore, an alternative is to explore the pond diffuser market for diffuser systems placed from the surface. An example of a diffuser potentially applicable to the cove is the MixAir Twister™ TB16 (https://www.greatlakesbiosystems.com/consumers/mixair-tech/diffusers/mixairtech-twistertm-tb16-diffuser). Note that this diffuser and the MEI diffusers both use sintered rubber hose diffuser technology. Moreover, both have shield orifices where the hole through which air flows is not in direct contact with the water. In combination, these air-delivery features tend to prolong diffuser life in environmental (non-wastewater) settings. Time between diffuser cleanings for this technology is on the order of 10 years.

# 6.0 Conclusions

Mirror Cove in Iron Gate reservoir was analyzed using a CE-QUAL-W2 model to assess management strategies to control cyanobacteria. Bathymetric measurements were completed and the existing Iron Gate reservoir CE-QUAL-W2 model was modified to add on the Mirror Cove branch. Model simulations were completed to test the model grid and explore management strategies. Barrier curtain and mixing scenarios were simulated to assess potential effectiveness of different management approaches. Simulated thermal conditions were subsequently used to calculate turbulent diffusion values.

Turbulent diffusion values generated from the various scenarios were compared with a criterion of 2 $cm^2/s$. This value was chosen because it would result in diatom and green algae dominance over cyanobacteria (e.g., *Microcystis*) according to the theoretical foundation criteria developed by Huisman et al. (2004). The modeling results indicate that implementation of a curtain with mixing would create conditions that met the turbulent diffusion threshold under typical stratification found during the summer. Finally, the hydraulic residence time within the cove was calculated as 3 to 4 days based on this circulation regime. These results indicate that a combined barrier curtain and mixing system could be used to control cyanobacterial growth and accumulation in reservoir coves like Mirror Cove.

On the basis of the results of modeling and calculations, a combined system incorporating a curtain, aeration, and pumping would result in a mixed cove and suppression of cyanobacterial blooms. Elements of an effective destratification aeration-based mixing system are possible in this location, including for the rates of aeration and pumping that would be needed, and the provision of a barrier curtain. All needed equipment is commercially available and can be configured to site-specific conditions and the performance specifications necessary to be effective. Consequently, such a system is technically feasible and could be considered for further design development and testing.

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# Appendix A: IMIC Comments and Responses on Draft Report

| PacifiCorp Responses to IMIC Comments on the Draft Technical Report for Activity 6 – Study of Algal Conditions Management Within a Reservoir Cove Using Physical Measure | | |
|---|---|---|
| **Commenter** | **Comment** | **PacifiCorp Response** |
| USFWS/ Hamilton - 1 | At this time we have no comments on the report | Comment noted. |
| Karuk/Yurok - 1 | The initial simulations included simulations for a curtain only (the curtain across the downstream end of the cove is intended to restrict mixing of water from the main body of Iron Gate reservoir into the cove) and a curtain combined with mixing and circulation. Although curtain only simulations show that the curtain results in reduced thermal stratification in the cove due to lower exchange, it is not clear why this would be the case considering the now more isolated cove would be prone to less mixing, shorter wind fetch, and presumably more stagnant conditions which would allow surface waters to warm. | There are two main explanations for why curtain-only simulations show reduced thermal stratification in the cove. First, wind mixing does not abate simply because the cove is isolated. The cove has an area of about 18 acres, a mean depth of about 7 meters, and a fetch length of 500 meters. Isolated bodies of water (e.g., small lakes) of this size and depth tend to be more-readily mixed (Fischer et al. 1979). Near-surface velocity vectors in the curtain-only simulations indicate response to wind shear in near surface waters (Figures 6 and 7). As heat energy enters the system via the air-water interface, even modest winds can mix the relatively shallow water column. Second, the curtain acts to cut off the cove from the relatively large thermal mass and associated stratification of the main lake, which otherwise affects vertical temperature gradients in the cove. Without the connection with this relatively large stratified mass, temperature gradients in the cove are much less stable and diminish, leading to the generally isothermal structure in the cove. |
| Karuk/Yurok - 2 | While simulated results indicate that turbulent diffusion values may achieve levels where *Microcystis* dominance might diminish, this is based on the premise that the curtain coupled with active mixing results in near isothermal conditions in the top 9 m of the cove. While theoretically possible, no information is provided as to the feasibility of mixing from economic or logistical perspectives. Coves where *Microcystis* accumulates tend to be isolated from infrastructure that could provide power, and the cost of curtains, mixing equipment[2], and power would likely be exorbitant to achieve the desired results. Moreover, costs would recur on an annual basis. Thus, even if possible technically (and this would have to be further tested using pilot studies), the use of such considerable funds to provide limited recreational opportunities to a very limited number of people is misguided when other longer-term solutions such as nutrient reduction via wetlands, algal harvesting, and watershed restoration (among others) are likely to contribute to the long-term health of the basin and its fisheries. | Comment noted. PacifiCorp disagrees that reservoir management technologies that can directly and immediately benefit water quality conditions in Project reservoirs are less feasible and more expensive than nutrient reduction measures. |

[2] For example a system that pumps water from a location in the cove upstream from the curtain to near the head end of the cove

| PacifiCorp Responses to IMIC Comments on the Draft Technical Report for Activity 6 – Study of Algal Conditions Management Within a Reservoir Cove Using Physical Measure | | |
|---|---|---|
| **Commenter** | **Comment** | **PacifiCorp Response** |
| Karuk/Yurok - 3 | Finally, although the report provides a helpful technical and theoretical review of mixing effects on *Microcystis* and includes innovative modelling and simulation we strongly disagree with the concluding statement: "Elements of an effective destratification aeration-based mixing system are practical and attainable in this location, including for the rates of aeration and pumping that would be needed, and the provision of a barrier curtain." Given that the report provided no information on the practicality (e.g., no initial costs or operations and maintenance costs are included) or attainability (see above logistical considerations) of employing any of the mixing and circulation systems described, this statement is wholly unsupported. We recommend replacing the phrase "practical and attainable" with "theoretically possible". | The report has been modified in response to this comment to describe such as system as "possible". |

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