Methylmercury Bioaccumulation in Davis Creek Reservoir

by

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Executive Summary

The objective of this project was to design a cost efficient and monitorable control study that will mitigate methylmercury bioaccumulation in Davis Creek Reservoir (DCR). A literature review was performed to understand the processes of the mercury life cycle in a reservoir, especially its transformation from mercury to methylmercury. These processes were analyzed along with a site analysis of DCR to determine applicable control studies that would effectively mitigate methylmercury bioaccumulation in DCR. The presence of mercury mines in DCR's watershed suggested that controlling the inflow of mercury into DCR would be the ideal solution. Further research showed that because DCR has very little inflow throughout the year, this control study proved to be ineffective. Additionally, stratification of the reservoir promotes conditions for anaerobic methylating bacteria that are the cause of DCR's high methylmercury levels in fish tissue. Based on these findings, it was concluded that the best way to control methylmercury bioaccumulation was to target the reservoir's stratification problem, which resulted in three final control studies: Hypolimnetic Oxygenation, Nitrate Addition, and Artificial Destratification by Aeration.

Due to the high risk of nitrate addition and the difficulty of implementing and maintaining a hypolimnetic oxygenation system at DCR, artificial destratification by aeration was determined as the ideal control study. The artificial destratification system consists of an air compressor and lengths of metal and PVC piping that extend to the bottom of the reservoir. The required air flow was estimated to be 209 cfm using Lanzen and Fast's (1997) empirical model. However, a complete specification of the system design should only be determined by using a model like Davis (1980) and/or Schladow (1992) that takes lake morphology and weather patterns into consideration. In the absence of data to design an aeration system, the capital and operational costs of a small reservoir in New Zealand were examined to show what it would cost to implement and maintain an aeration system. The capital costs and annual costs were estimated at $734,000 and $13,661, respectively, and the annual costs would be cut in half if intermittent operation of the system had been found to deliver the desired results. This cost estimate provides a general idea of the price of a system and shows how the operational costs of an aeration system are highly variable.

The effectiveness of the aeration system can be assessed by monitoring and measuring methylmercury levels in small fish tissue before and after the reservoir naturally destratifies. These levels can then be compared to methylmercury levels in fish tissue after the aeration system is implemented to determine the system's success in preventing methylmercury bioaccumulation. Even if the system is successful, it is important to monitor the reservoir for any changes the reservoir may experience due to altering the lake's dynamic.

Despite not meeting the managerial objective of cost effectiveness, artificial destratification was determined to be the most feasible and monitorable control study that will ultimately mitigate methylmercury bioaccumulation at Davis Creek Reservoir.

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1.0 Introduction

Reservoirs primarily serve to moderate floods, generate hydropower, and supply water for irrigation and urban use. Additionally, reservoirs provide recreation for people and habitat for fish and wildlife. However, the beneficial uses of many California reservoirs are at risk due to harmful concentrations of methylmercury found in fish. According to the California Environmental Protection Agency, over 180 water bodies throughout California are impaired by mercury. The number of reservoirs impaired by mercury will decrease only if significant controls are implemented.

Although mercury is a naturally occurring element in the environment, over 80% of global emissions are from anthropogenic sources (Eagles-Smith, et al. 2012). In California, mercury primarily accumulates in reservoirs from historic mining and atmospheric deposition from fossil fuel combustion (Alpers, et al. 2013). Because there are only four coal powered plants in the state (EPA, 1997), historic mining operations are considered the main source for mercury pollution for many reservoirs in California.

1.1 Project Objective

The objective of this project is to design a cost-efficient and monitorable control study to mitigate methylmercury bioaccumulation in Davis Creek Reservoir (DCR). The control study for DCR is designed to comply with the requirements under the Clean Water Act Section 303(d) list of impaired water bodies. Section 303(d) regulates impaired water bodies throughout California "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters" (33 U.S.C §1251(a)).

1.2 Project Scope

The scope of this project was to design a control study specifically corresponding to Davis Creek Reservoir that controls methylmercury bioaccumulation in fish. The project team used peer-reviewed journal articles to optimize the design of the control study while considering specific characteristics of Davis Creek Reservoir. Additionally, when determining the control study, H_2Yolo considered long-term effects from implementation and created a monitoring plan to ensure the methylmercury bioaccumulation problem is controlled without adding additional problems to the lake.

The remainder of the report includes the background of mercury and methylmercury in California reservoirs, project design objectives, a site description of Davis Creek Reservoir, control studies found in the literature review process, the design process which includes: project development process, data collection, and project constraints, the results of the project, a conceptual model of the preliminary design, monitoring plan, design performance, and design sustainability.

2.0 Background

This section describes the history of mercury and gold mining near DCR, the processes that promote the conversion of mercury into the highly toxic methylmercury, and a site description of Davis Creek Reservoir.

2.1 Historic Gold and Mercury Mining in California

Historic mercury and gold mining operations contribute to the mercury emissions in California. Mercury mining began in 1846 with the discovery of cinnabar ore deposits and continued until 1981. To produce mercury, the cinnabar was coarsely crushed and loaded into large metal kettles. The cinnabar was then heated so the cooling mercury vapors could be collected (Mercury). The heating of cinnabar left tailings, large amounts of contaminated ore, which were often deposited near the mine sites.

In historic gold mining activities, mercury was used extensively in the gold recovery process. Fine particles of gold could be combined with mercury which would cause the gold and mercury to amalgamate. To separate the gold from the mercury, the amalgam would be heated to vaporize the mercury, leaving a gold precipitant behind (Scotia, A. G.). Inefficiencies in the amalgamate process and the leftover tailings deposited large amounts of mercury around mine sites.

2.2 Methylation and Bioaccumulation

Once the inorganic mercury has entered a reservoir, it can be converted to methylmercury through a process called methylation, as seen in Figure 2.1. Methylation occurs in the presence of sulfate reducing bacteria (SRB) and organic carbon (Carrasco et al., 2011). SRB are present in anaerobic conditions, where there is little to no oxygen, which typically occurs at the water-sediment interface. In the anaerobic environment, mercury binds to sulfate, enters the microbe and is bonded together with a methyl group during the reduction of sulfate to sulfide. This new, more toxic methylmercury exits the microbe and has the ability to accumulate in fish in a process called bioaccumulation (Carrasco et al., 2011). As illustrated in Figure 2.2, bioaccumulation increases methylmercury concentrations higher up the food chain, known as biomagnification, which results in the largest methylmercury concentrations found in the largest fish (SWRCB, 2012).

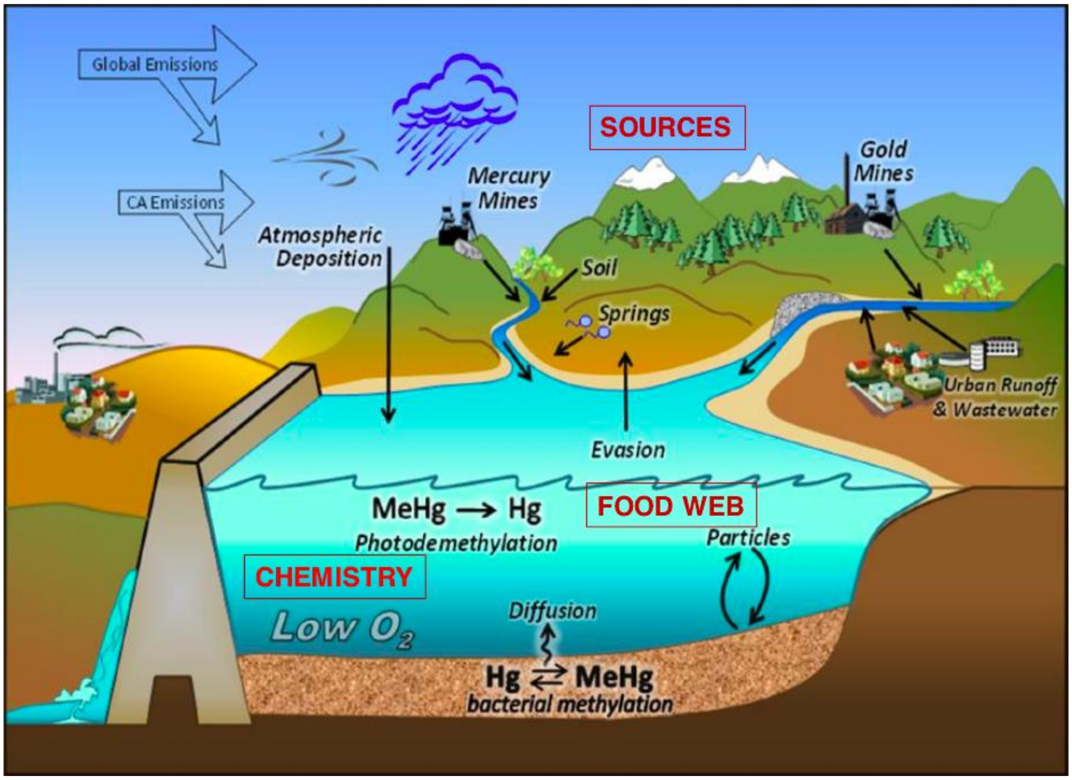

Figure 2.1 - Mercury Life Cycle in Lakes (Source: SWRCB, 2012).

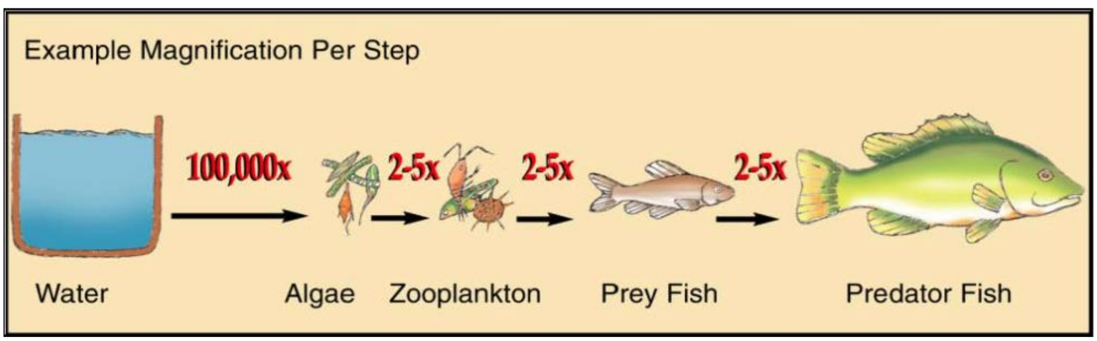

Figure 2.2 - Bioaccumulation and Biomagnification Process (Source: SWRCB, 2012).

The bioaccumulation of methylmercury in reservoir fish poses a risk to humans and wildlife due to the negative health effects associated with its consumption. Fish with high methylmercury concentrations are known to cause birth defects and neurological and chromosomal problems in humans (USGS, 2000). Wildlife are also affected by methylmercury because numerous species rely on fish for food. The ingestion of large amounts of methylmercury can cause deformities in developing animals in the wild (USGS, 2000). The negative health effects consequently impair the beneficial uses of reservoirs by affecting commercial and sport fishing (COMM), wildlife habitat (WILD), and preservation of rare and endangered species (RARE) (SWRCB, 2018).

2.3 Historic Mining in Davis Creek

The discovery of mercury attracted several mining operations in the Davis Creek watershed. Mercury mining began at the Reed mine in 1871 because of its high demand during the industrial revolution (Burleson, 2015). The Reed mine operated periodically until it finally closed in 2002.

In 1984, Homestake Mining Company (Homestake) constructed a dam on the southern reach of Davis Creek forming the Davis Creek Reservoir (DCR) (Burleson, 2015). DCR was initially created as a water source to process gold at the various mining locations surrounding the reserve. Four mines, located along the canyon of upper Davis Creek and DCR, were consolidated and are referred to as the Reed Mercury Mine (Burleson, 2017). Although the mercury mines are now inactive, historic mining operations of the Reed Mine is a major source of mercury contamination in DCR.

In 2001, Barrick Mining Company acquired Homestake (UC Davis, 2009) and are now in the process of conducting a clean up of multiple mercury hotspots near the mine and in upper-Davis creek, DCR's main tributary that connects the contaminated sites to the reservoir. Shortly after the mining operations ceased in 2002, a three-way agreement was established between Barrick, the Regents of the University of California (University), and the Land Trust of Napa County to give the University the exclusive right to manage and use the property surrounding Davis Creek for research and education (UC Davis, 2009). The mine site now serves as a field station for environmental studies.

2.4 Site Description

Davis Creek Reservoir is a tributary of Cache Creek and originates near the Lake County and Yolo County border. DCR has a maximum depth of 25 meters, a storage capacity of 6,000 acre-feet (af), an average depth of 8 meters, and a surface area of approximately 160 acres (UC Davis, 2009). Additionally, the reservoir has a low average inflow of 5,050 af per year, or 7 cfs (UC Davis, 2009), and low outflow rates, suggesting the lake experiences very little elevation change throughout the year.

Since the formation of the reservoir, researchers have found that the sediment in DCR contains high levels of organic matter that contribute to the methylation of mercury (UC Davis, 2009). As a result, high concentrations of methylmercury were found in fish species present in DCR (UC Davis, 2009). Because DCR is closed to the public, humans are unaffected by the methylmercury contaminated fish; however, wildlife surrounding the area are very much affected by the neurological effects of methylmercury.

Because DCR has a relatively small volume compared to its max depth -- 6,000 acre-feet to 25 meters, respectively -- approximately one-third of its volume is subject to anaerobic conditions when the lake stratifies. DCR is a monomictic lake that stratifies during the spring, summer, and most of fall (UC Davis, 2009). When a lake stratifies, the water separates into three distinct regions: the epilimnion, the metalimnion, and the hypolimnion, as seen in Figure 2.3. Because of the distinct layers, the water densities vary, promoting little to no interaction between layers. This limited interaction causes anaerobic conditions in the hypolimnion as oxygen is unable to be replenished when consumed by aerobic microbes.

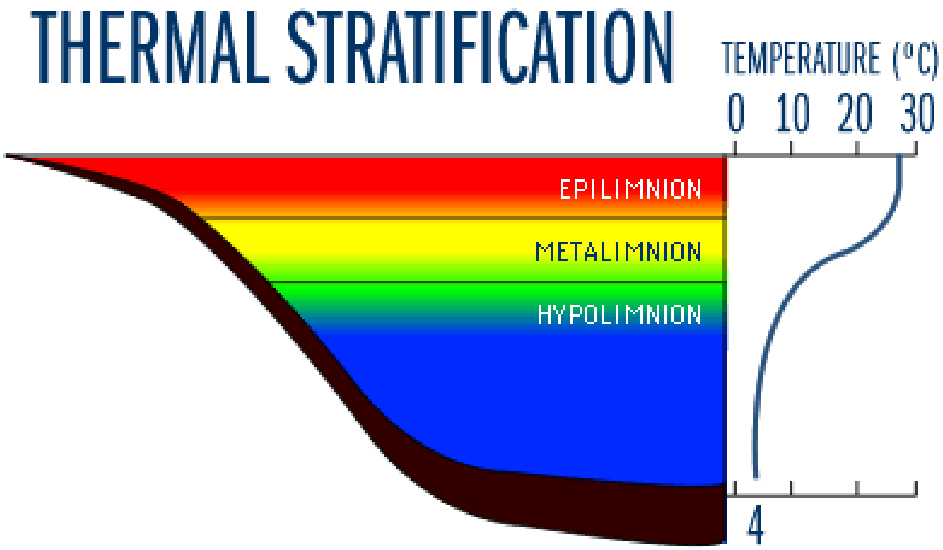

Figure 2.3 - Reservoir Profile of a Thermally Stratified Lake

3.0 Literature Review

There are many reservoir characteristics that promote the conversion of mercury to methylmercury. An extensive literature review was performed to assist in the selection of a proper control study specific to Davis Creek Reservoir. Each control study initially considered is described below and categorized under Biochemical or Physical methods.

3.1 Biochemical Methods

Biochemical methods aim to control methylation by controlling biological or chemical factors affecting methylation in lakes (McCord and Heim, 2015).

Controlling fish population. This control study involves stocking a reservoir with mercury free fish and then harvesting them at a later date. The rationale for this control study is that methylmercury will biomagnify up the food chain so that the harvested fish would typically contain in the order of one millionfold higher concentrations of methylmercury than the reservoir itself. The fish would then be harvested to remove methylmercury from the system. No studies were found to support the viability of this control study (McCord, 2015). Additionally, controlling fish populations do not present a permanent solution to methylation in the reservoir. (Mailman, Stepnuk, et. al, 2006).

Add nitrate. This control study involves adding nitrate to the hypolimnion of the reservoir. This will manipulate the reducing-oxidizing conditions to prevent the presence of SRB, ultimately leading to a decrease in methylation. There are high risks associated with implementation of this control study as increasing nutrient loads in a waterbody can promote algal blooms, potentially leading to fish kills. Consequentially, determining optimum nitrate dosage yields little room for error (McCord and Heim, 2015).

Amend soil with iron. This control study involves adding ferrous iron to reservoir sediments. This decreases mercury solubility and bioavailability and, therefore, net methylation. Further research is necessary to determine the efficiency of this control study. (Mehrotra, Horne, et. al, 2003)

Hypolimnetic Oxygenation. This method involves injecting oxygen into the hypolimnion of a stratified lake to inhibit the presence of SRB. While there are high efficiency rates for this method, there are also high capital and operational costs due to the complexity of the system and the continuous transport of oxygen tanks to the reservoir (Beutel and Horne, 1999).

Artificial Destratification. Artificial Destratification induces mixing by pumping air to the bottom of the reservoir to eliminate the distinct layers of a stratified lake. This control study could have a similar capital cost to hypolimnetic oxygenation, but is typically preferred due to its simplicity and lower maintenance costs. A potential side effect of this method is the reduction of DO levels across the entire lake which would be detrimental to the lake species (Beutel and Horne, 1999).

Phytoremediation. This control study involves adding vegetation to a reservoir's main source of mercury inflow, typically in its main tributary. These plants will uptake heavy metals and limit mercury inflows into the reservoir. However, this method does not address the mercury already present in the reservoir and involves plants non-native to California, which can negatively impact the ecosystem of a lake (Chortek, 2017).

3.2 Physical Methods

Physical methods aim to control mercury methylation through physical processes.

Dredging. Dredging is the removal of sediment layers at the bottom of the reservoir. Removing the mercury contained in the sediment will prevent the mercury from converting to methylmercury. Dredging is extremely expensive and could potentially exacerbate methylmercury bioaccumulation by disturbing the sediment and mobilizing the mercury. (Wanga, Kima, et. al, 2004)

Mine site cleanup. Mine site cleanup involves cleaning mine sites located in the reservoir's watershed. While this method would reduce the amount of mercury flowing into the reservoir, the method does not address the inorganic mercury already present in the system.

Draining the reservoir. This control study involves the complete or partial drainage of a contaminated reservoir using the dam spillway and/or an outlet at the base of the reservoir. However, draining would disturb the fish and wildlife habitat present in the waterbody and could transfer the contaminated waters downstream of a reservoir.

4.0 Methods

This section details the design process of the report, which includes data collection from interviews and selecting optimal control studies that are most appropriate for Davis Creek Reservoir.

4.1 Data Collection

This section will include new information obtained through interviews with DCR managers and UC Davis researchers and DCR limnological data collection.

4.1.1 Interviews

H_2Yolo Engineers met with Catherine Koehler, a UC Davis Reserve representative, and Greg Reller, a Barrick Mining Company representative, to discuss the primary interests of DCR's managers. Although UC Davis and Barrick have different priorities regarding the future of the reservoir, research and profit respectfully, both parties agreed that actions should be taken to control methylmercury bioaccumulation in DCR.

Koehler wants to see DCR serve as a healthy habitat for wildlife near the reservoir. Because DCR is closed to the public, has no hydropower plant, doesn't serve for flood control, draining the reservoir was originally considered for its lack of beneficial uses. However, Koehler also stated that DCR's use as a wildlife preserve is enough of a use to keep the reservoir intact.

Reller shared DCR's role in historic mining activities upstream in the Reed Mine. Additionally, Reller added that Barrick has submitted a proposal to clean up the Reed mine and is looking to begin the project in the near future. This information encouraged H_2Yolo to focus on control studies that target the reservoir itself, rather than the historic mining impacts upstream of the lake.

In addition to meeting with DCR representatives, H_2Yolo met with Dr. Darrell G. Slotton, an environmental and hydrologic researcher, who has performed extensive research on mercury bioaccumulation in DCR since its creation in 1984. This meeting provided the following critical information:

1. When DCR stratifies, anaerobic bacteria inhabit the reservoir in the anoxic zone and methylate. While the reservoir remains stratified, the methylmercury remains in the hypolimnion and does not enter the food chain. As the reservoir

destratifies, the lake mixes and methylmercury is introduced into the food web. Dr. Slotton provided monthly temperature and Dissolved Oxygen (DO) profile data of the lake, shown in Figures 4.1 – 4.3. The data illustrate the transition from a mixed lake (Figure 4.1) to a well stratified lake with its three defined layers (Figure 4.3) (Slotton, 1991).

2. From experience, Dr. Slotton provided that when measuring methylmercury levels, it is important to use young fish. Because of the way methylmercury enters the food web described in point 1, these small fish will have a distinct spike in methylmercury levels right after the fall turnover - a spike that might not show in larger fish that have been accumulating methylmercury throughout their lives. By comparing methylmercury levels in young fish tissues, better correlations can be made between methylmercury bioaccumulation before and after a control study is implemented.

4.1.2 DCR Stratification Data

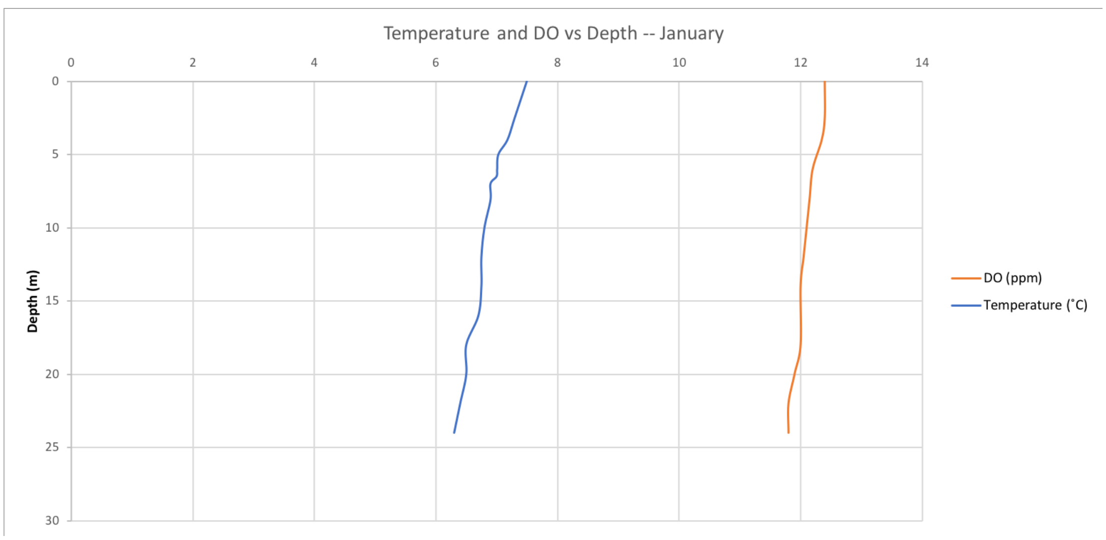

Figure 4.1 - Temperature and dissolved oxygen levels in DCR in January, 1981. (Slotton, 1991)

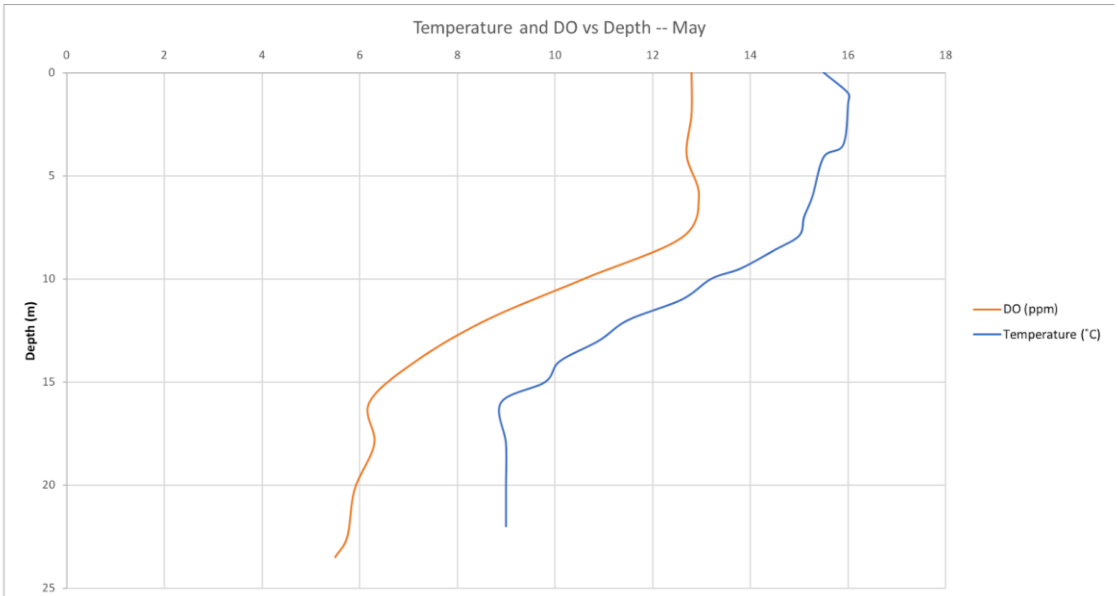

Figure 4.2 - Temperature and dissolved oxygen levels in DCR in May, 1981. (Slotton, 1991)

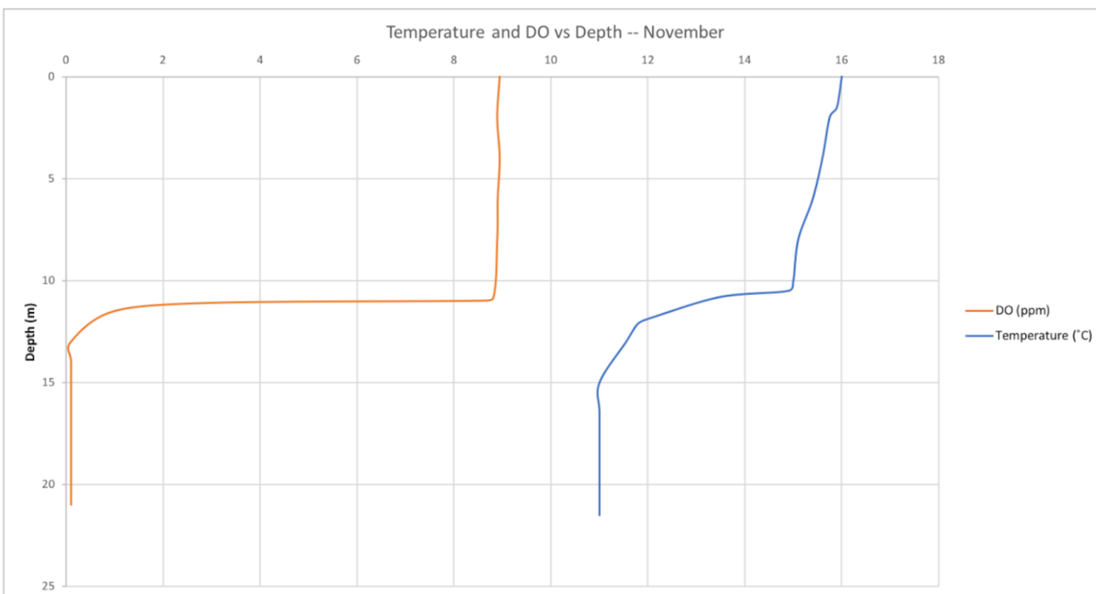

Figure 4.3 - Temperature and dissolved oxygen levels in DCR in November, 1981. (Slotton, 1991)

4.2 Project Development Process

The original Request for Proposal (RFP) included an analysis of 132 mercury impaired reservoirs and choosing suitable control studies for each. This was going to be done by creating a matrix of groups of reservoirs and assigning each group to a control study. At the halfway mark of the project timeline, the scope was drastically changed from 132 reservoirs to 1 specific reservoir to meet time constraints. The first half of the project allowed H_2Yolo to analyze mercury dynamics in water bodies around the world and encouraged a broad scope to the methylmercury problem in California. This research was then applied to DCR in the latter half to determine its most suitable control study given the characteristics present in the reservoir.

After choosing artificial destratification as the ideal control study for Davis Creek Reservoir, an additional literature review was conducted to design an artificial destratification system. When designing a bubble plume system, the most important parameter that defines it is the amount of air needed to destratify a lake. Because the design is heavily dependent on this value, researchers at H_2Yolo focused on reviewing published mathematical models for calculating the required airflow for the destratification of Davis Creek Reservoir.

4.2.1 Mathematical Models for Calculating Destratification Air Flow

<u>Lorenzen and Fast (1997) Model</u>

The Lorenzen and Fast (1997) model was derived based on empirical performances of airflow rates in many different reservoirs. Lorenzen and Fast concluded that an airflow rate of 9.2 $m^3/min/km^2$ would be sufficient to destratify most storages (Kelly, 2015). Their estimation of this airflow rate per unit surface area is shown in Figure 4.4 and is based entirely on existing data.

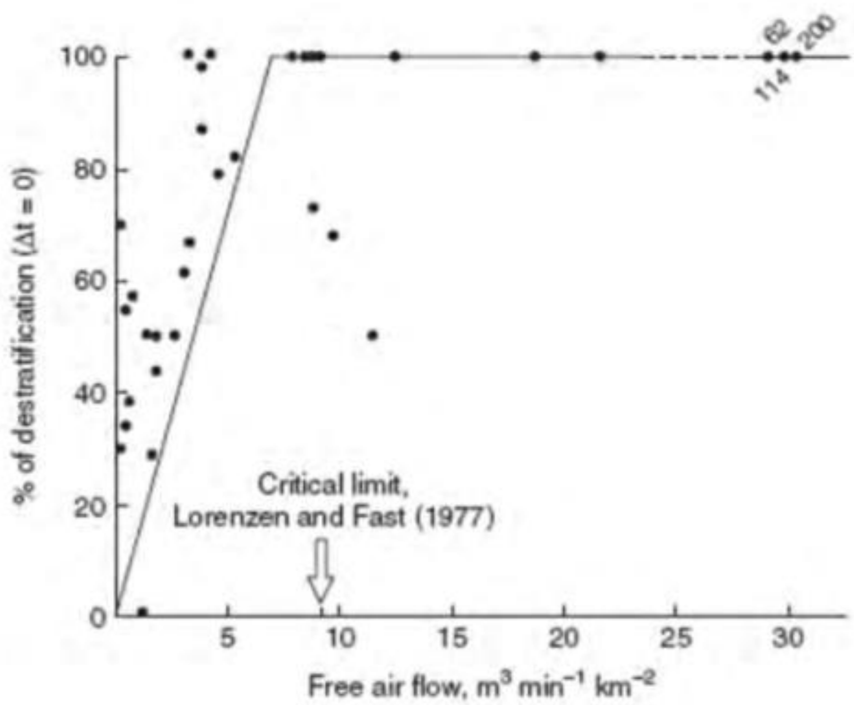

Figure 4.4: Lorenzen and Fast (1997) correlation between bubble plume air flow and the proportion of destratification in reservoirs (Kelly, 2015).

This model does not take lake morphology and other environmental factors into account and is reminiscent of how aeration systems were implemented in the past, with design and operation being largely improvised and not based on scientific principles (Schladow, 1992).

Davis's (1980) Model

A more recent and arguably more accurate design methodology was produced by Davis (1980) and takes the lake morphology into account when calculating the required airflow rate for destratification. The steps in Davis's method include the calculation of reservoir stability as well as morphological information. The stability of a reservoir is the difference between the potential energy of the stratified reservoir and the potential energy of the reservoir when it is completely mixed (Kelly, 2015). Davis (1980) calculated the stability of a reservoir as:

$$S = g \sum_{i=1}^{n} \rho_{im} V_i h_i - g \sum_{i=1}^{n} \rho_{is} V_i h_i \tag{1}$$

Where S = Stability, [Joules]; g = acceleration due to gravity, m/s^2; p_i = density of layer i, kg/m$^{3;}$ V_i = volume of layer i, m^3; h_i = height of centroid of layer i, m; m = mixed, i = stratified.

The destratification energy is calculated by:

$$E = S + R - W \tag{2}$$

Where S = stability, R = heat input, and W = wind energy, all in joules.
To provide the necessary airflow rate for destratification, Bowersox (2002) writes that:

$$Q = \frac{0.196E}{Yln\left(1+\frac{D}{10.4}\right)} \tag{3}$$

Where E = energy input required, T = time to achieve destratification, D = depth of diffuser, 10.4 = depth of water equivalent to a pressure of 1 atm.

Bowersox (2002) states that the volume of air in the bubble column released by the diffuser pipe can be calculated with the following equation:

$$V_e = 0.486LT\left(\frac{gQ}{L}\right)^{1/3}\left(1+\frac{D}{10.4}\right)^{-1/3}\ln(1+\frac{D}{10.4}) \tag{4}$$

Schladow's (1992) Method

This method is based on "the fluid dynamics of bubble plumes ascending through stratified water" (Lemckert et al. 1992) and has been described as the most efficient method at determining the required destratification air flow rates. Similar to Davis (1980), the first step is to use equation 1 to calculate the potential energy required to destratify the reservoir. The PE per unit area can then be calculated (J/m^2), and the linear buoyancy frequency can then be calculated, as described by Lemckert (1992):

$$N_e = \left(\frac{1/2\rho_B g h^2 - PE_A}{1/3\rho_B h^3}\right) \tag{5}$$

Where p_b is the water density at the diffuser depth and h is the water height above the diffuser.

Qm, Qp, and Qr can then be calculated, where (Lemckert 1992):

$$Q_M = \frac{4\pi\alpha^2 h^3{}_S}{g},\ Q_P = \frac{N^3h^4}{g} \text{ and } Q_R = \frac{Q_P}{Q_M} \tag{6}$$

Where a = entrainment coefficient ~0.083, N = buoyancy frequency, rad/s, v_s = slip velocity of the bubbles relative to the rising water plume ~0.3, m/s.

Qb, the air flow rate from a single diffuser at depth, can then be calculated:

$$\frac{N^3h^4}{Q_B^* g} = 10^{\left[0.16\log(Q_R)+(2.1H_R - 0.55H_R^2)\right]} \tag{7}$$

Where $H_r = h/H_t$, where H_t is the total pressure at diffuser depth in meters of water.

Qb can then be used to calculate M_H, the source strength compared to a water depth pressure, using the following equation (Lemckert 1992):

$$M_H = \frac{gQ_B}{4\pi\alpha^2 h v_s^3} \tag{8}$$

Qt can then be determined using the following equation (Lemckert 1992):

$$Q_f = 0.56\left(\frac{(Q_B^* g)^3}{N_E^5}\right)^{1/4} M_H^{0.11} \tag{9}$$

m*, the number of diffuser ports required, can then be calculated using the following equation (Lemckert 1992):

$$T_V = \frac{\Delta PE}{m^* Q_f^*} \tag{10}$$

Where Tv is the time to destratify the reservoir in seconds. The required airflow rate can then be calculated by multiplying the airflow rate per diffuser by the number of diffusers required. Selecting a short destratification time requires a more compressed airflow, while a longer destratification time requires a less compressor airflow (Kelly, 2015).

4.3 Project Constraints

The selection of a proper control study was constrained by the management objectives of Barrick and UC Davis, the ten weeks available to complete the project, and the limited resources available. While UC Davis and Barrick have their own respective goals for DCR, it was clear that there are financial constraints to the implementation of any control study. The accuracy of the design is also constrained by the data found in the literature review and the lack of initial knowledge regarding contaminants in large bodies of water and limnology.

Furthermore, because the first half of the project followed a different scope, the man-hours available to conduct the final project were essentially halved. The limited timeframe rushed the literature review process and data collection of Davis Creek Reservoir. With more time, DCR could have potentially shared more data with the project team and researchers at H_2Yolo could have met with other researchers in industry and academia, namely Dr. S. Geoffrey Schladow, a professor at UC Davis who derived the most accurate method for determining artificial destratification system requirements.

Another constraint was the limited communication between DCR lake managers and H_2Yolo. This lack of communication hindered data collection and provided a limited understanding of DCR's uses. Aside from the initial site visit, DCR maintained little to no dialogue with the research team and failed to answer questions that would potentially lead to better results.

5.0 Results

This section details three control studies most appropriate for DCR and the factors that were considered in the final selection of the Artificial Destratification system. This section also outlines the design process for the Artificial Destratification system, which includes a description of the factors considered in the preliminary design and cost estimates.

5.1 Selecting a Control Study

After analyzing the reservoir data and interviews from DCR representatives, it is concluded that stratification is the leading cause of methylation in the reservoir because it promotes anaerobic conditions in the hypolimnion which encourages the growth of sulfate reducing bacteria. Consequentially, the literature review was narrowed to three final control studies that directly attack this problem: Hypolimnetic Oxygenation, Nitrate Addition, and Artificial Destratification.

5.1.1 Hypolimnetic Oxygenation

The Hypolimnetic Oxygenation System (HOS) is a technology that injects oxygen in the hypolimnion of a stratified lake. In the hypolimnion, there is little to no oxygen, which allows the SRB to dominate, later converting mercury to methylmercury through the methylation process. HOS prevents anoxic conditions in the hypolimnion, which consequently prohibits the methylation process by preventing the domination of SRB at the water-sediment surface. The advantages of HOS are the high solubility and higher system transfer efficiencies of pure oxygen (Beutel and Horne, 1999). The advantages reduce the size of mechanical devices and recirculation rates needed to deliver pure oxygen. The reduced recirculation rates cause less turbulence in the hypolimnion which results to minimized levels of induced oxygen demand and high levels of dissolved oxygen (DO) concentration (Beutel and Horne, 1999). Additionally, HOS has a low destratification potential because the system does not disturb the thermal gradient when the lake is stratified during the spring and summer. A low destratification potential is important to preserve the temperature of the lake for fishery habitat that survive in either warm or cold waters.

However, some oxygenating system designs can be very complex and include multiple pumps for oxygen and water, leading to high energy usage and high maintenance demands. Because of DCR's rural location, the power output to the reservoir is considered dirty and unreliable, with each additional power requirement. Additionally, because an oxygenation system requires continual oxygen pumping for large periods of time, oxygen tanks must be transported to the reservoir once the current oxygen tanks are emptied. Because of DCR's rural location, it has very little accessibility with just two roads reaching the reservoir. As a result, the transport of oxygen to the reservoir is unideal. After considering all aspects of the control study, it was concluded that Hypolimnetic Oxygenation is considered infeasible to DCR.

5.1.2 Nitrate Addition

Nitrate addition aims to manipulate the reducing-oxidizing conditions in a lake to prevent methylation of mercury (McCord and Heim, 2015). During its metabolic process, microorganisms actively consume compounds that have the highest free energy charge available to metabolize organic compounds. Because oxygen has one of the highest free energy charges, microorganisms tend to consume oxygen first in a lake. Additionally, once this oxygen is fully consumed to depletion, anaerobic microbes outcompete aerobic microbes due to the lack of oxygen and first consumes nitrate. Once nitrate is depleted, microbes move down the sequence of highest free energy charges, until they reach sulfate, which is reduced to hydrogen sulfide. These bacteria are responsible for the methylation of mercury into methylmercury. By adding nitrate to the water, the depletion of nitrate is prevented within the lake to prevent the presence of sulfate reducing bacteria, ultimately leading to a reduction in methylmercury bioaccumulation (McCord and Heim, 2015)

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5.1.3 Artificial Destratification

Artificial destratification involves bubbling air from the bottom of the reservoir (Beutel and Horne, 1999). This method does not aim to oxygenate, but rather to destratify the reservoir and introduce oxygenated water to the hypolimnion. Stratification occurs in the spring and summer months when the sun warms the upper layer of the reservoir. This warmer and less dense water does not mix with the colder, denser layer at the bottom of the reservoir and does not mix until the fall season when the upper layer cools down. When air is released at the bottom of the reservoir, the column of bubbles generates a vertical current that brings the water from the hypolimnion to the surface (Beutel and Horne, 1999). Once the cold water reaches the surface, it radially diverges and sinks below the warm surface water.

Because of its simple design, artificial destratification systems require less maintenance and operation compared to that of hypolimnetic oxygenation, and is less of a risk than nitrate addition.

5.2 Designing the Aeration System

This section details the components of an aeration system and the necessary steps needed to design an effective system. A preliminary estimate of airflow for DCR is given, and the system's costs are estimated by presenting the capital and operational costs of an artificial destratification system for a similar sized reservoir.

5.2.1 Determining aeration system components

The design and layout of an aeration system depends on a number of components including:

- The size and type of air compressor
- Pipe sizes and materials
- Configuration of piping and orifices

Air Compressor. The air compressor is placed above the reservoir, similar to the placement in Figure 5.1, and pumps air down to the hypolimnion. Lorenzen and Fast's (1997) empirical model was used to estimate that DCR would require a destratification airflow of 209 cfm. This is an acceptable value for an estimate, but it is purely empirical and an accurate value is highly dependent on lake morphology and weather. For example, East Sidney Lake in New York has a storage capacity six times greater than DCR but only requires 50 cfm of air to achieve destratification (Meyer, 1992). If the necessary site data is acquired, air flow should be determined using the models of Davis (1980) or Schladow (1997). In addition to the required air flow, the proper compressor will be determined based on the discharge pressure requirements, which will depend on the reservoir's strength of stratification. Finally, the appropriate compressor will be decided based on the availability of electrical power. Electrical power is the most efficient way of producing compressed air because they require less maintenance, have fewer mechanical problems, and create less noise than fuel operated compressors (Toetz, 1972).

Pipe Sizes, Materials, and Configuration. A length of piping will extend from the compressor to the bottom of the reservoir, shown in Figure 5.1. Due to the high air temperatures leaving the compressor, the pipe connected to the compressor will be composed of iron, steel, and another temperature-resistant material. PVC pipe will connect to the temperature resistant piping and extend to the hypolimnion of the reservoir. The length of piping depends on the location of the air compressor and the location where the air needs to be released to generate maximum circulation. The perforation size and configuration of the PVC piping will depend on the necessary exit velocity of the air stream to overcome stratification. The depth of the diffusers will also need to be considered. Diffusers placed too close to the bottom of the reservoir will mobilize the sediment, while diffusers placed at a great distance from the reservoir's base will leave an area of unmixed hypolimnion that will allow methylation to occur.

Power Supply. When visiting the site, there were no noticeable power facilities near the reservoir. However, at a water body near the reservoir, there was an evaporation operation taking place that employed a large amount of power which indicated that power could be supplied to the site. If the destratification power requirements are found to be low enough, solar panels could be installed at the site to power the system. This would cut down the potentially high power costs described in section 6.2.3.

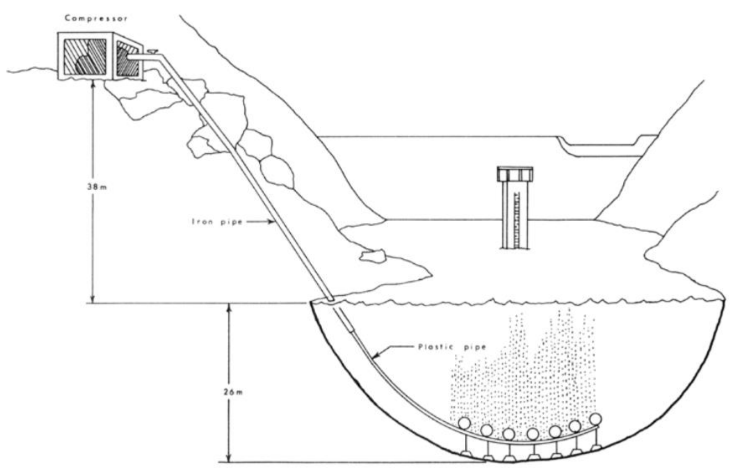

Figure 5.1 - Components of an aeration system installed in El Capitan Reservoir (Fast, 1968)

5.2.2 Estimation of Destratification Air Flow Requirement

Because of the limited morphology and weather data available, Lorenzen and Fast's (1997) empirical model (5.2.2.1) was used to estimate the required destratification air flow for DCR. Lorenzen and Fast concluded that an airflow rate of 9.2 $m^3/min/km^2$ would be sufficient to destratify most storages. Based on this relationship between the air required and the reservoir surface area, it is estimated that DCR would require 209 cfm to achieve destratification.

5.2.3 Destratification System Cost Estimate

An accurate cost estimate cannot be given until the proper components of the system are determined. Although the air flow rate was estimated as 209 cfm, the size and power output of the compressor still depends on the pressure output and availability of electrical power. Until the necessary data is acquired, the cost of an aeration system in DCR can be assumed to be similar to the cost breakdown of a 2015 aeration system for a small reservoir in New Zealand shown in Table 5.1. A comparison of DCR and the Maitai reservoir is presented in Table 5.2. It is important to note that the air flow for DCR was determined using Lorenzen and Fast's (1997) empirical model, while the required airflow for Maitai reservoir was determined using Schladow's (1992) model.

Table 5.1 – Reservoir comparison

Reservoir	Average Depth (m)	Max Depth (m)	Volume (acre-feet)	Surface Area (acres)	Air Flow (cfm)
Davis Creek	8	25	6,000	160	209*
Maitai Reservoir	7.8	36	3250	80	70

*** = estimate**

Table 5.2 – Cost breakdown for a small New Zealand Reservoir (Kelly, 2015)

Parameter	Cost (US Dollars)
Site preliminaries & general construction	$ 12.6 K
Compressor building	$ 47 K
Compressors	$ 112 K
Feed pipework & associated equipment	$ 39 K
Air distribution pipework & fittings	$ 39 K
Electrical works	$ 22 K
Sub Total	**$ 450 K**
Contractor overheads & profit	$ 83 K
Project management	$ 23 K
Base Cost	$ 565 K
Contingency	$ 169 K
Total Capital	**$ 734 K**

The operational costs depend on how consistently the system will run for and how much of the year the system will operate. Based on a six month per year usage of the system, the estimated annual operating costs at Maitai reservoir converted to US dollars were:

- $2,550 annual costs for mechanical maintenance
- $1,586 annual costs for electrical maintenance
- $9,526 annual costs for electrical power

Electrical power costs would be greatly reduced if it was found that intermittent operation of the system could deliver the desired results. Intermittent power costs at Maitai reservoir were estimated to be $1,905 annually, if the system operated 6 weeks per year based on the rate of $0.13 per kWh (Kelly, 2015).

The capital and operational costs of installing an artificial destratification system in DCR will depend on a site analysis and the outcomes of Davis (1980) and Schladow's (1997) models. Until these are performed, the cost breakdown of Maitai reservoir serves as an excellent benchmark on what capital and recurring costs should be expected.

6.0 Discussion/Interpretation

This section discusses the Design Performance, Design Sustainability, and Further Design Modeling. Design performance details the steps and considerations that should be taken when implementing the proposed control study and how the results meet the project's objectives. Design Sustainability discusses the possible effects artificial destratification can bring by altering the natural dynamic of a lake. Further Design Modeling describes two methods that can be used to determine an accurate estimation of destratification air flow requirements.

6.1 Design Performance

The design performance of the proposed aeration system describes the implementation plan, how the design is consistent with the project objectives, and how to improve the accuracy of the proposed system.

6.1.1 Implementation Plan

To meet the project objectives, the following steps should be taken to implement the proposed aeration system:

1. The current effects of stratification on methylmercury bioaccumulation should be measured before the system is installed. This can be done by measuring methylmercury levels in young fish tissues before and after the reservoir destratifies. It is important that young fish are used for these measurements because methylmercury levels of young fish will be influenced more heavily by a single season than larger fish will. This means the methylmercury spike due to stratification or the lack of a spike due to an aerated reservoir will be more noticeable in young fish.
2. After the destratification system is implemented, methylmercury levels in small fish tissues will be measured again before and after the reservoir would have historically stratified. The measured methylmercury levels can be compared to the data before the aeration system was implemented to determine the effect of artificial destratification on methylmercury bioaccumulation.

3. An operational protocol can be determined manually by measuring temperature differences at different elevations, but thermistors should be used to monitor the stratification process and schedule the operation of the compressor.

The following should be considered while the system is running:

1. DO levels and temperature profile data need to be monitored at all sections of the reservoir while the system is operational. Air inflow should be adjusted to ensure all parts of the reservoir remain aerobic. Look for algae blooms, any other side effects that could result from increased movement of nutrients.
2. The temperature of the air compressor should be monitored during operational periods. Continuous power usage in direct sunlight could overheat and damage the system.

Important notes:

1. Daily run time during the system's operational months will be largely determined by empirical means.
2. DO and temperature need to be monitored consistently for a number of seasons. DCR currently has no algae blooms, but the movement of nutrients could change this or alter the food web in another way. Algal bloom life cycles could work against the aeration system and contribute to methylmercury spikes.
3. If methylmercury spikes do occur, it may be necessary to reimagine the PVC piping layout to induce mixing in all areas of the reservoir.
4. The system should be operated at least once a month during the off-season to prevent biological growth and sediment deposits in the holes of the diffuser (Davis, 1980).

6.1.2 Meeting Project Objectives

The objective of this project is to design a feasible, cost efficient, and monitorable control that would limit methylmercury bioaccumulation. The literature review was performed to obtain a list of a few control studies that could be successful in limiting methlymercury bioaccumulation. These control studies were then compared to determine their feasibility, monitorability, and cost effectiveness. The selection of artificial destratification meets the project requirements for feasibility, monitorability, and potential for success, but possibly not cost effectiveness. The costs would be reasonable if aeration would allow Barrick Gold to use the reservoir for profit, but $700,000 in capital and $13,661 in operational costs might be too much for Barrick to pay with no benefit except for DCR being removed from the 303(d) listing of impaired reservoirs. Barrick Gold's next steps will most likely be influenced by contrasting the costs of a implementing a control study with the cost of fines they would accrue by not taking action on methylmercury levels.

6.2 Suggested Aeration System Modeling

Because of the lack of information on DCR, the Lorenzen and Fast (1997) model was used to estimate the required destratification airflow. To properly design an aeration system, air flow requirements should be based on models that take into account the amount of energy stored in the density stratification of DCR, and the energy provided by the addition of a bubble plume (Kelly, 2015).

6.3 Sustainability

When considering a control study that will alter the dynamic of a lake, unexpected outcomes must be considered and planned for. One outcome of artificial destratification is isotropic conditions throughout the lake, causing changes in the ecosystem of cold-water fish. If a reservoir contains a cold-water hatchery, artificial destratification is unideal because cold-water fish will not be able to survive in these altered conditions. Fortunately, DCR has no cold-water fish, so isotropic conditions are allowable.

The most significant potential problem is the system failing due to under design. The existence of models like Schladow (1992) and Davis (1980) allow for accurate airflow estimates but don't guarantee success. The project's objectives require DCR to be completely mixed; in the case where mixing does not occur, measurements for methylmercury bioaccumulation cannot be taken and the project goals will not be achieved (Toetz, 1972). To avoid this problem, reservoir managers should carefully carry out the implementation plan.

Another potential problem could arise if the aeration system causes DCR to turnover rapidly. Rapid mixing could cause the entire lake to become anaerobic which would be lethal for DCR's aquatic species. To mitigate this risk, caution should be exercised when initially destratifying the lake and the process should resemble that of a natural turnover (Toetz, 1972). Even so, aeration can still produce serious deficiencies in DO for the first year or so of mixing (Toetz, 1972). Thomas (1996) aerated Lake Pepper, Switzerland, and found that the absolute mass of DO in the lake was much lower after aeration than before (Toetz, 1972). This indicates that mixing could have caused the lake to become eutrophic and/or the loading of organic matter had been accelerated. In most cases, artificial destratification causes increased DO levels in what used to be the hypolimnion and decreased DO levels in the former epilimnion. This decrease in DO is usually attributed to the introduction of water with a high oxygen demand, but could be due to a reduction in the rate of photosynthesis (Toetz, 1972).

6.3.1 Stakeholder Interests

The main stakeholders of DCR are Barrick Gold, UC Davis, and the fish and wildlife that use DCR as habitat.

Barrick Gold. An aeration system that successfully mitigates methylmercury bioaccumulation would help Barrick Gold to comply with Section 303(d) that regulates impaired water bodies “to restore and maintain the chemical, physical, and biological integrity of the Nation's waters"(33 U.S.C §1251(a)). The reservoir can offer no public uses, so controlling methylmercury levels will not result in any profits for Barrick Gold. They will suffer financial losses every year the system is running.

UC Davis. UC Davis has used the reservoir since its conception as a way to study mercury dynamics in large bodies of water. Installing an aeration system that successfully destratifies the reservoir and prevents methylmercury formation would affect current projects UC Davis is working on and change how research will be performed in the future. This change could be beneficial, as researchers could use the system to shift their research from mercury dynamics to methylmercury bioaccumulation control and prevention.

Fish and Wildlife. An aeration system that is successful in preventing the methylation process would benefit all fish and wildlife that use it. Studies have shown that fauna surrounding a contaminated lake are negatively impacted by consuming fish present in the reservoir. However, certain species could be affected by the noise of the air compressor. This impact is dependent on the chosen power source, with an electric compressor making substantially less noise than a fuel powered one (Toetz, 1972). The possibility of low DO levels discussed earlier would also have a negative effect on all wildlife that live in the reservoir.

7.0 Conclusions

In Davis Creek Reservoir, the presence of SRB thrive in the hypolimnion during the spring and summer months when the reservoir is stratified, which allows for the conversion from mercury to methylmercury to occur. Inhibiting the methylation process will deter the ability for methylmercury to exist, ultimately mitigating the mercury bioaccumulation in DCR fish. The methods used to design the control study for DCR consisted of a literature review, gathering available data, performing interviews, and finally narrowing down potential designs most appropriate to the reservoir, which align with reservoir manager goals. The methods used to design the control study may be considered in future studies in methylmercury bioaccumulation in lakes and reservoirs to address mercury impairment.

Artificial destratification, hypolimnetic oxygenation, and nitrate addition were considered to determine the optimal control study for the conditions in DCR. Based on the available data and interviews, artificial destratification is the most simple, yet efficient method for DCR. If implemented and monitored accordingly, artificial destratification can assist the reservoir to comply with the Clean Water Act, and most importantly, protect the wildlife living in the reservoir.

Using Lanzenz and Fast’s (1997) empirical model, it was estimated that an airflow of 209 cfm is required to destratify DCR. The lengths, configuration, and perforation of the piping will be entirely dependent on site characteristics. A bathymetric survey of DCR needs to be completed to acquire the data necessary for Davis's (1980) and Schladow's (1992) models. The cost of an aeration system was estimated by observing the capital and operational costs of a similar sized reservoir in New Zealand. The capital costs and annual costs were estimated at $743,000 and $13,661, respectively. The annual costs could be reduced if intermittent operation of the system can deliver the desired results. The cost estimate provides a general idea of the price of a system for DCR and shows how the operational costs of an aeration system are highly variable and will be known only after the system is in place.

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