FINAL STUDY PLAN - JUNE 2018

A Comparative Insight into the Feasibility and Design of a Methylmercury Control Strategy
Lake Solano, California

Prepared for:
McCord Environmental
Stephen McCord, Ph.D., P.E.

Prepared by:
Kahui Lim
Brooke Ahmed
Lauren Graves

COWPRINTS ENVIRONMENTAL

Executive Summary

Problem Statement

Many reservoirs in California are mercury-impaired. Historic cinnabar mines in the tributary watersheds of Lake Berryessa contribute to mercury contamination downstream at Lake Solano. Mercury contamination leads to the bioaccumulation of methylmercury in fish. The consumption of contaminated fish is detrimental to the health of both humans and wildlife. Because Lake Solano is susceptible to methylmercury contamination, the feasibility of remedial methods should be considered.

Project Goal

The goal of this study is to investigate the feasibility of remedial methods for methylmercury in Lake Solano, California.

Project Objectives

The purpose of this report is to evaluate potential mercury control methods that align with current water resource management objectives and to design a methylmercury control strategy for Lake Solano. Ten potential control methods were ranked according to factors such as compatibility with Lake Solano management, objectives, cost, and aesthetics.

Project Findings

It was identified that aquatic vegetation control by macrophyte harvesting is the most suitable methylmercury control method for Lake Solano. The removal of the floating vegetative mats promotes photodemethylation, removes a substrate for the methylation process, and reduces the formation of local anoxic zones.

Table of Contents

1. Introduction

Mercury contamination is a nationwide and statewide problem. Inorganic mercury is converted by bacteria into methylmercury which is a bioaccumulative toxic pollutant. The consumption of fish with high methylmercury levels can negatively impact the health of both humans and wildlife.[1] This section provides insight into the mechanisms and risks of California's mercury problem.

1.1 The Mercury Cycle

As depicted in Figure 1, the mercury cycle begins as runoff from natural and anthropogenic sources enters a water body.[2] This inorganic mercury is present in low enough doses that it is not harmful to people or wildlife[3]; it is unable to enter organic cells because it has a charge or is attached to a larger molecule.[4] The ability of methylated mercury to bioaccumulate makes it dangerous for both people and wildlife.[3]

While the methylation process is not yet completely understood, it is known that sulfate-reducing bacteria, bacteria that use sulfate (SO_4^{2-}) to respirate, methylate mercury.[5] These organisms reduce sulfate molecules in their respiration processes, leaving negatively-charged sulfur ions (S^{2-}) available for ionic bonding in the water.[4] The mercury cation available in lakes (Hg^{2+}) combines with the reduced sulfur to form mercury (II) sulfide (HgS), a neutral molecule small enough to enter bacterial cells.[5] Once within the bacterial cell, the mercury becomes methylated and is then released into the environment as methylmercury (CH_3Hg).[4]

Methylmercury gets absorbed by phytoplankton as the first stage of bioaccumulation.[4] Methylmercury bioaccumulates to toxic levels in large predatory fish within higher trophic levels.[4] Humans and wildlife often catch and eat these large fish, exposing themselves to health risks associated with mercury poisoning.

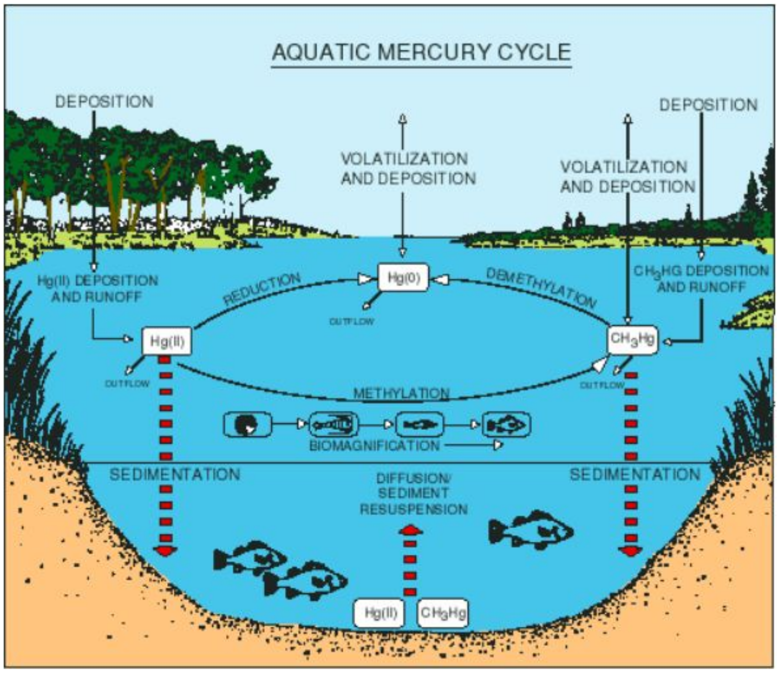

Figure 1: The mercury cycle and the bioaccumulation process.[2]

1.2 Mercury Sources and the Relevance of California Mining History

One hundred and thirty two reservoirs in California are contaminated with mercury[1] due to the state's rich mining history and geology.[6] Gold and mercury mines, erosion of soils and rock, geothermal springs, atmospheric deposition of mercury vapors, manufacturing operations, landfill gas, and incineration all contribute to the release of mercury into the environment.[6] Natural processes such as forest fires and volcanoes are also sources of mercury.[6]

Historically, mercury contamination stems heavily from mining operations. Mercury tailings from both cinnabar and gold mines contributed to the release of mercury into surface water.[7] Cinnabar miners excavated inorganic mercury that was then used in the gold mining operations.[7] Cinnabar, characterized by its bright red color, is a mercury sulfide and is the main ore of mercury in California.[8] The cinnabar is heated to produce mercury vapors, which are then captured and cooled to form liquid mercury, called quicksilver.[8] Drainage from the mercury mines often contains high concentrations of inorganic mercury and sulfate. The presence of the sulfate ion facilitates ideal conditions for the methylation process and explains the high methylation rate of mercury mine drainage.[9]

Mercury was commonly used within gold mining operations to separate gold from the ore. Liquid mercury is poured onto the ore, separating the gold from the rock and creating an amalgam of gold and mercury which settles out during the sluicing process.[10] During sluicing, high-density mercury allows gold and gold amalgam particles to sink and get caught in the troughs.[11] Next, heat is added to the amalgam to evaporate the mercury and leave pure gold.[10] The separation process of the amalgam results in a release of mercury vapors into the atmosphere. Mercury can also remain in the sluice processing water that may be spilled, providing yet another avenue for contamination.[9] Large volumes of turbulent water can cause gold and mercury particles to wash out of the sluice troughs and be transported to downstream waters.[11]

In California, gold mining resulted in the release of over 10,000,000 lbs of mercury, of which, 80-90% was lost in the Sierra Nevadas.[11,12] Between 1850 and 1961, California was the highest producer of mercury in the United States.[6] The extent and prevalence of mercury sources is explained by the large number of mines as shown in the map adapted from Long et al. 1998's study shown in Figure 2.[13] Areas within the Cache Creek watershed, known for its historic cinnabar, sulfur, and gold mining operations, have abandoned mines which also contribute heavily to mercury runoff.[14]

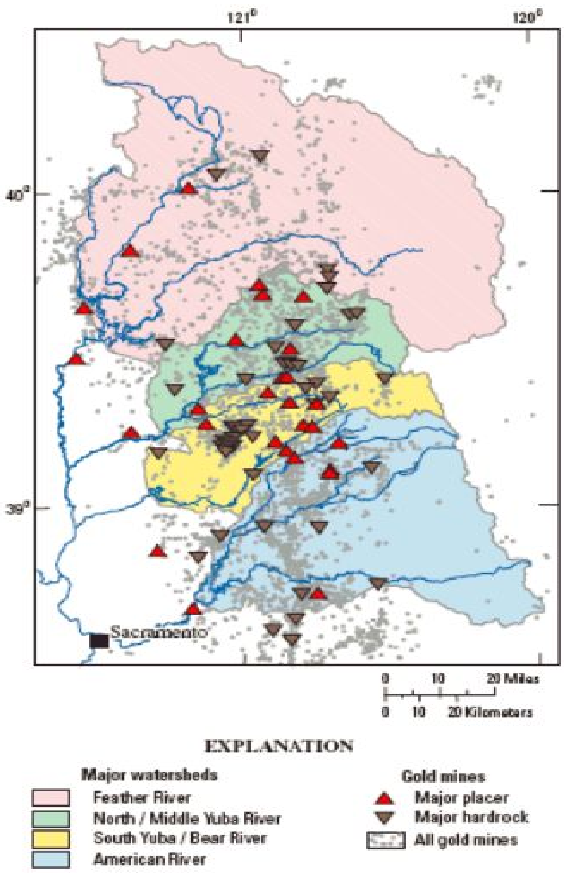

Figure 2: A map of past-producing gold mines in the northwestern Sierra Nevada.[13]

1.2 The Environmental and Health Risks of Methylmercury Contamination

Because the consumption of methylmercury-contaminated fish is hazardous to the health of both humans and wildlife, it is imperative to pilot-test cost-effective control strategies to reduce levels of mercury contamination. Since methylmercury can stunt adolescent brain development,[15] the consumption of contaminated fish may pose a risk to women of childbearing age and children.[7] Therefore, fishing restrictions and eating guidelines have been put in place for contaminated reservoirs.[1] Wildlife also bears the burden of mercury contamination. High trophic level feeders, such as piscivorous birds and mammals, are susceptible to nervous, excretory, and reproductive system damage when methylmercury is ingested from water or prey.[16] Methylmercury contamination also threatens the habitat and health of rare and endangered species.

1.3 Objective, Scope, and Outline

The objective of this report is to design a mercury control method that will be effective for Lake Solano and not detract from current management objectives. To do this, common and field-tested mercury remediation methods are evaluated in the context of Lake Solano. A mercury control study is then developed for Lake Solano.

This project describes the feasibility of a control strategy that ranks highest based on the scoring criteria. The ten scoring criteria chosen were assumed to be important considerations for the support of Lake Solano, its management objectives, and the remediation of methylmercury. The remedial methods ranked in the present study were chosen for their historical effectiveness when implemented in other lakes. A score was assumed for each method by applying the results of past studies to Lake Solano. The cost analysis considers the most substantial factors to demonstrate the feasibility of the design, yet it does not encompass all costs associated with a life cycle analysis of the materials. The times associated with progress monitoring were chosen to reflect the improvement time scale, but might need to be altered based on initial progress findings. Although the scope of the study entails why the chosen strategy is a suitable methylmercury remediation technique, the report in no way intends to serve as a complete guide to its implementation.

This report begins with an explanation of the sources of mercury for Lake Solano and a brief overview of the different types of mercury control methods. Scoring criteria is then given in Section 3 to explain how the remediation techniques are ranked. Section 4 summarizes the ten mercury control methods considered in this study. Justification for the scoring of each control method is given in Section 5. Finally, an explanation of the chosen mercury control method, a cost analysis, and recommendations for implementation are presented in Section 6.

2. Background

The purpose of this section is to provide a brief insight into the sources of mercury for Lake Solano. Lake Solano has several unique characteristics that are considered as part of the study context. Further, a broad summary of mercury remediation techniques is provided.

2.1 Sources of Inorganic Mercury for Lake Solano

The third and fourth largest historic cinnabar mercury mining districts in California, the East Mayacmas and Knoxville Mining Districts, are located within the Upper Putah Creek and Pope Creek watersheds.[6] These watersheds are Lake Berryessa's, a lake just upstream of Lake Solano, largest tributary watersheds.[6] The cinnabar mines within the Upper Putah Creek watershed, shown in Figure 3, illustrate the prevalence of major point sources of inorganic mercury.[17] Although inactive, these mines can still produce mercury runoff and contaminate Lake Berryessa.[9] Because Lake Solano is directly fed by Lake Berryessa, Lake Solano will also accumulate inorganic mercury and be susceptible to methylation.

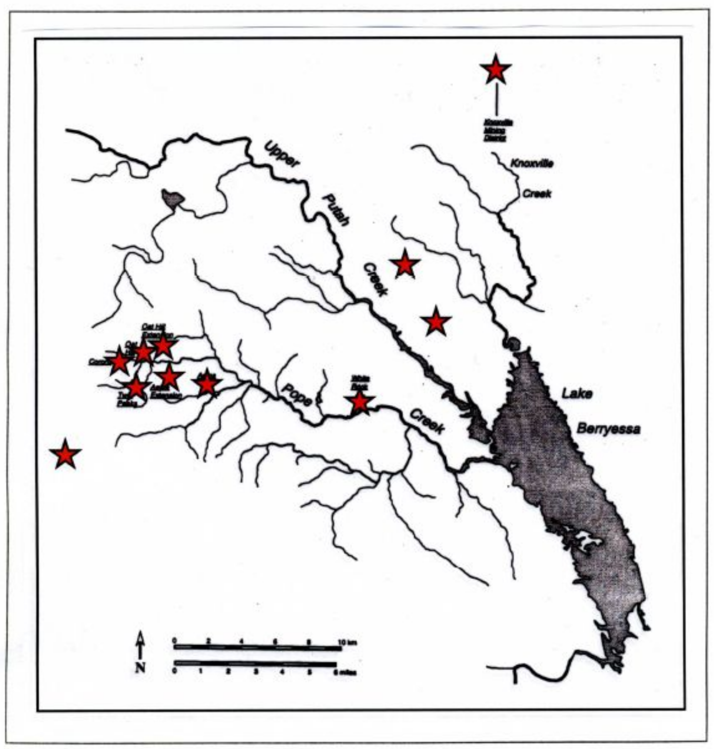

Figure 3: Abandoned cinnabar mines in the Cache Creek watershed.[17]

Lake Solano is a small, shallow reservoir in Solano County, California.[18] It is a slow-moving section of Putah Creek situated downstream of Lake Berryessa, as shown in Figures 4 and 5. It is supplied by Lake Berryessa's cold, highly oxygenated waters.[18] Lake Solano was created by the construction of the Putah Diversion Dam and provides both drinking and irrigation water for Solano County via the Putah South Canal.[19] Lake Solano supports rainbow trout, threespine stickleback, prickly sculpin, Sacramento sucker, a few bluegill, and a few largemouth bass.[20] Currently, the Solano County Water Agency (SCWA) manages the lake while the Solano Irrigation District (SID) operates the Putah Diversion Dam.[19]

Figure 4: Location of Lake Solano. Courtesy: USGS Nationalmap.gov

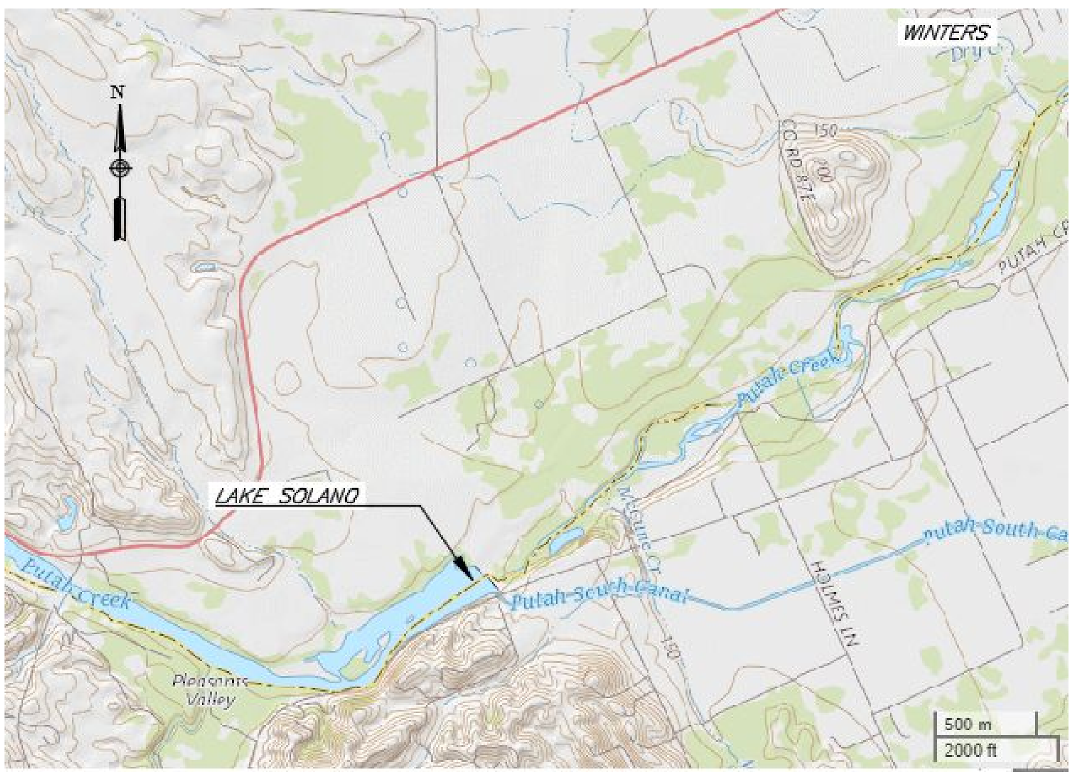

Figure 5: Close-up location of Lake Solano. Courtesy: USGS Nationalmap.gov

Lake management objectives include protecting the natural environment and valuable resources as well as improving the recreation experience for visitors.[21] Lake Solano has public fishing access[19] and provides a hub for habitat conservation and recreation.[21] Personal correspondence with lake managers/engineers revealed the desire to improve lake aesthetics by removing exotic weeds to encourage the growth of California native plants.[19] They also made clear that SCWA would be hesitant to consider cost-prohibitive mercury control methods.[19]

Lake Solano is unique in terms of its location, low water retention times, and shallow depth. Because it is a shallow reservoir, Lake Solano does not stratify, therefore, sufficient oxygen is available at all depths. Lake Solano has been gathering sediment over time and is decreasing in lake capacity.[22] These sediment deposits contribute to the further growth of vegetation and floating algal mats due to increased sunlight on the lake bottom.[22] Due to areas of inhibited flow, the growth and death of plants may lead to areas of stagnant water and local anoxic zones that promote methylation; yet, the depletion of dissolved oxygen is in local competition with the high rate of oxygen replenishment from Lake Berryessa waters coupled with low lake water retention times.

Much of the water from Lake Solano is treated for use as drinking water, which according to the Safe Water Drinking Act, cannot contain more than 0.002 mg/L of inorganic mercury.[23] At this time, inorganic mercury is not an issue for Lake Solano[19]; the creation and subsequent bioaccumulation of methylmercury is the current concern. There are currently no laws (federal or state) that dictate how methylmercury should be handled. The Food and Drug Administration has placed advisory warnings on the consumption of large predatory fish[24] and the California Sport Fishing Regulations provides a Public Health Advisory, but there are no specific rules regarding methylmercury.[25] Currently, the only motive for lake managers to reduce the amount of methylmercury in their lakes is to protect local wildlife and encourage fishing.

2.2 Summary of Mercury Management Strategies

Since methylmercury poses a threat to the health of both people and wildlife, managers of lakes across the United States have pilot tested many different remediation methods to try to reduce the occurrence of methylmercury in their lake. There are six basic categories of control strategies that have been implemented in mercury impaired areas: 1) reservoir design, 2) source control, 3) exposure reduction, 4) water management, 5) chemical treatments, and 6) biological manipulation.[26] Each category requires certain conditions to be met for it to be effective.

The first category, reservoir design, must be considered before the reservoir is built. Reservoir design incorporates a mercury control strategy into the construction of the reservoir.[26] For example, a lake manager can decide against constructing a reservoir within a watershed that contains unwanted elements like wetlands or abandoned mines. Another example of mercury control through reservoir design is the removal of vegetation in the area to be flooded, through burning or harvesting.[26] This removes a large initial source of carbon within the lake and minimizes the biochemical oxygen demand from decomposing organics that enables the anoxic conditions that promote methylation.[26] These methods are relatively cheap and do not require any chemical additions.

In lakes where runoff is the primary supplier of inorganic mercury, source control of mercury can be an effective remediation technique. Source control may include limiting the amount of mercury released by factories and wastewater treatment plants.[26] In areas of natural mercury abundance, runoff can pick up sediment that contains mercury and transport it into the lake. The focus of a source control based strategy is to either reduce the amount of mercury in runoff by controlling point sources or retain the runoff separately, allowing sediment and attached mercury to settle out before introducing it into the lake.[26]

Water management based mercury control methods involve maintaining a specific water level within the lake and/or reducing residence time.[26] These methods might include adding, mixing, or removing water. During the summer, deep lakes stratify, creating a cooler, lower layer that is relatively stagnant.[27] When this layer becomes low in nutrients like dissolved oxygen and nitrate, methylmercury begins to form.[28] To prevent this, lake managers can mechanically mix the lake, forcing the lake to destratify and introduce oxygen back into the deeper parts of the lake.[26] Managers can also simply remove the water that has high concentrations of methylmercury or low oxygen levels.[26] Another strategy that falls into this category targets the source directly by either placing an impermeable barrier between the sediment and the water or just completely removing the sediment altogether.[29] Water management based strategies can apply to a wide range of lake sizes and locations, but are costly, typically costing tens-of-millions of dollars.[30]

The methylation of mercury can also be controlled by the addition of chemicals and nutrients.[26] Adding specific chemicals to the lake can inhibit methylation, raise pH, shift the redox state to disfavor methylation, and flocculate mercury containing solids.[26] Nutrients can also be added to the lake to impede methylation. Though these methods are relatively expensive, they do a thorough job of reducing mercury levels in impaired lakes. Chemical addition methods are often suitable in large, deep lakes that stratify.[27]

Biological methods of controlling methylmercury focus on the fish and plants that reside within the lake. Adding fish from uncontaminated lakes or removing the top predator in the lake can alter the food web and reduce the amount of fish with large levels of bioaccumulated mercury.[26] In some lakes, planting vegetation along the sides of the lake can filter runoff and stabilize sediment.[26] Vegetation in the lake are sources of carbon, can create anoxic zones, and block sunlight, promoting the methylation of mercury or blocking the demethylation of it.[28] Mercury control techniques that increase light exposure and reduce dissolved organic matter within the lake can increase photodemethylation rates.[30]

Exposure reduction control methods do not work to reduce the amount of methylmercury created, but rather focus on limiting people’s exposure to the mercury.[26] These methods involve placing restrictions on the size of fish people can take home and educating the public on methylmercury, why it is harmful, and how to avoid it.[26] Focusing on education leaves the system to rely on the naturally-occurring rates of demethylation, which may be effective in systems that do not have high concentrations of methylmercury.[9]

3. Methods for the Ranking of Potential Methylmercury Control Strategies

3.1 Project Development and the Scoring Criteria of Control Method Viability

In order to identify a suitable methylmercury remediation technique for Lake Solano, ten possible control studies were ranked by eight different criteria as shown in Table 1. Each criterion was weighted to represent its importance. The categories were ranked based on the control method's relationship to Lake Solano.

Table 1: Rating Criteria for Potential Methylmercury Control and Remediation Techniques in Lake Solano

Criteria	Weighting Factor	Rating Details					
		Negative		Neutral	Positive		Weighted Score
		1	2	3	4	5	
Suitable for Lake Solano	3	Characteristics of lake are incompatible with control method		Characteristics of lake are somewhat compatible with control method	Characteristics of lake are highly compatible with control method		=3 x Score
Compatibility with lake management objectives	3	Incompatible or limited compatibility		Compatible	Meets objectives and beyond		=3 x Score
Multiple benefits	3	Potential or certainty to detract from other benefits		No additional benefits	Potential or certainty of enhancing other benefits		=3 x Score
Cost (Capital+ O&M)	2	High cost		Moderate cost	Little to no cost		=2x Score
Aesthetics	2	Park closures and or onsite facilities		No change in aesthetics	Some aesthetic enhancement	Beautification of area	=2 x Score
Failure risk	1	Certain Failure	Probable Failure	Moderate	Low risk	No risk	=1 x Score
Improvement time scale	1	>3 years		1-3 years	<1 year		=1x Score

* Table adapted and modified based on Stillwater Science's 2012 Study[31]

The suitability of the methylmercury control method for Lake Solano was weighted heavily because specific lake characteristics can be a predictor of control strategy effectiveness. For example, hypolimnetic oxygenation, nitrate injection, and mechanical mixing require the lake to stratify to be effective.[32,33,34] Methods that involve removing sediment for treatment would not work in very large lakes due to the sheer volume of sediment that would be involved.[9]

It was also important to consider whether a control method would be in agreement with lake management objectives, because if a control method disagreed with current management objectives, it is unlikely to be implemented by lake managers. Therefore, it was important to ensure that the mercury control method chosen and designed met management objectives. For example, if a lake supplies drinking water, lake managers may be hesitant to inject nitrate as it is a drinking water contaminant.

Some mercury control methods can have benefits outside of mercury control. For example, dredging has the added benefit of increasing lake capacity and mechanical mixing can increase fish habitat by producing a larger warmed layer.[9, 34] The presence of multiple benefits can help incentivize lake managers to implement a specific mercury control technique.

Capital and operation and maintenance (O&M) costs are also important aspects to consider, as low cost is often preferred by lake managers and cost-prohibitive strategies are less likely to be carried out. For lakes that cater to the public, aesthetics are important to consider. Methods that require lake closure or the building of on-site facilities can negatively impact aesthetics and cause lake managers to lose money while spending more.

The risk of adverse effects or method failure was also considered within the scoring criteria. Methods such as capping or dredging have a higher risk factor than macrophyte harvesting because of the potential exposure of mercury-bearing sediments.[20] Methods that require on-site facilities, such as mechanical mixing and oxygenation, risk power outages or malfunctions.

Finally, the last criterion considered was the improvement time scale, or the amount of time it would take to observe a noticeable difference in methylmercury concentrations. The methylmercury concentrations would be observed biologically, within the tissue of fish at high trophic levels, to quantify a decrease in toxicity.

3.2 Data Collection

To properly prescribe a suitable methylmercury remediation technique for Lake Solano, it is critical to first understand the unique characteristics of the lake. Interviews and other forms of personal correspondence were performed with experts from SCWA, the California Department of Fish and Wildlife (CDFW), and the University of California, Davis. These experts helped to illuminate the current management objectives and available budget for any mercury remediation. An internet search for past strategies implemented at Lake Solano was also performed to elucidate the management objectives.

A sufficient understanding of the unique characteristics of Lake Solano and feasible methylmercury remediation strategies was necessary to propose an appropriate remediation method. A comprehensive literature review was conducted to identify a list of methylmercury remediation techniques that were feasible based on the unique characteristics of Lake Solano.

Multiple site visits were also conducted to observe the current conditions of the lake; characteristics such as water levels and the presence of vegetation were verified. Maps were obtained from the USGS National Map archive and Google Earth to supplement photographs taken from site visits.

3.3 Project Constraints

An interview and field visit led by Alex Rabidoux, P.E. from SCWA elucidated the importance of the aesthetics, budget, and adherence to water resource objectives within a design. Because a multi-million dollar project is not feasible for SCWA, a significant weight was placed on cost considerations in the scoring process of the study. Further, it is important that the design does not detract from the recreational and aesthetic objectives of Lake Solano because the lake is popular with fishermen and tourists alike. Because methylmercury is not a drinking water hazard, the proposed design must illustrate benefits beyond methylmercury control to further incentivize lake managers to consider addressing the methylmercury problem.

4. Possible Remediation Techniques

A list of potential management methods considered all possible viable approaches. Strategies suggested by local experts were included. A list of proven, common, and innovative mercury remediation techniques are summarized in Table 2, as shown in the following pages. The mercury remediation methods were then scored based on criteria described in Table 1. Methods that the present study deems viable will be discussed later in the Design section of this report.

Table 2: Summary Table of Potential Mercury Control Techniques (continued on the following pages).

Remediation Method	Summary	Development Status	Pros	Cons	Cost Factors	Aesthetics	Source
Thermal Treatment	Using heat and reduced pressure to volatilize Hg and condense it into liquid elemental forms	Full scale and field tested, typically in industrial applications	High removal efficiency of mercury from contaminated mediums	High capital cost; Requires emission control and specialized facility such as rotary dryer, thermal oxidizer, and acid gas scrubber	Specialized facility capital cost, O&M, disposal of captured mercury, and hauling	Will require construction of treatment facilities	USEPA (2007)
Dredging	Removal of sediment from water body using excavation techniques	Minamata Bay, Japan saw 600 mg/kg reduced to 5 mg/kg after dredging	Effective in heavily contaminated sites	Expensive remedial method; Disposal method may require trucking; Risk of sediment resuspension and oxidation change	Use of heavy machinery	Little to no effect after treatment, but may result in construction closures of park	Wang et al. (2004)
Capping	In situ: Placement of an impermeable liner between the sediments and the overlying water column of a lake or reservoir	Implemented effectively at approximately 15 EPA Superfund (CERCLA) sites throughout the United States	Low cost; Suitability for multiple contaminants; Low environmental impact	Possible disturbance and resuspension of contaminated sediment by benthic organisms or hydrodynamic currents	Capping material and placement	May limit vegetation growth on the treated area, but may impact wildlife activity in the direct area of cap	Stillwater Sciences (2015)

Table 2: Summary Table of Potential Mercury Control Techniques Continued:

Remediation Method	Summary	Development Status	Pros	Cons	Cost Factors	Aesthetics	Source
Natural Attenuation	Allowing natural processes such as photoremediation and microbial methylmercury reduction to remediate mercury	Bellingham, Washington, source control and natural attenuation reduced from 4.5 mg/kg to 0.5 mg/kg	Little to no cost; May be best option for less contaminated sites; No site disturbance; No adverse impact on benthic layer	Uncertainty in treatment length; Improper source management may lead to increase in mercury levels	Little to no cost	Little to no effect	Wang et al. (2004)
Hypolimnetic Oxygenation	Bubbling oxygen up from tube(s) on the lake floor to reduce anoxic zones	In Twin Lake, Washington, MeHg levels went from 0.2 to 0.1 ng/L after 17 days of oxygenation	Not operated year-round; Reduces accumulation of ammonia and sulfide as well; Decrease in internal nutrient loading; maintains thermal stratification; Increase drinking water quality	Energy intensive; Only works in lakes that stratify	Installation of piping, building of facility, oxygen, and O&M	Little to no effect on lake, on-shore oxygen facility must be built	Beutal et al. (2014)
Nitrate Injection	Injecting a liquid calcium-nitrate compound into the hypolimnion to decrease the mobilization of MeHg	The addition of nitrate decreased MeHg by 94% in Onondaga Lake, New York	Non-intrusive; Cheaper than oxygen; Not operated year-round	May increase algae growth; Must be carefully regulated in reservoirs that supply drinking water; Labor intensive	Calcium-nitrate compound, boat, and dosing tube (PVC)	Little to no effect	Matthews et al. (2013)

Table 2: Summary Table of Potential Mercury Control Techniques Continued:

Remediation Method	Summary	Development Status	Pros	Cons	Cost Factors	Aesthetics	Source
Mechanical Mixing	Mix the layers of a stratified lake to prevent the bottom layer from becoming anoxic	Santa Clara Valley Water District: Two circulators had no effect on MeHg levels in the reservoirs but in the lake, MeHg levels went from 70 ng/L to 10 ng/L.	Not done year-round; Can reduce nutrient cycling; Has the potential to reduce algae	Only works in lakes that stratify; Must be perfectly placed and sized	Mixer(s) and O&M	Little to no effect; mechanical mixers may be visible at surface	Drury (2009)
Biomanipulation	Stocking of sport fish to increase the population of piscivorous fish in a waterbody to create a change in the food web	Colorado State University saw northern pike mercury concentrations reduced by up to 50% within 50 days.	Can be combined with other long-term management techniques to reduce methylmercury production and bioaccumulation, such that its use can be curtailed over time.	Fish at risk of escaping water body and/or competing with native species; Mercury concentrations may rebound when stocking ceases	Purchase of fish, transportation of fish, and stocking	Little to no effect	Stillwater Sciences (2015)
Phytoremediation	Uses the inherent potential of naturally occurring plants and microbes to clean polluted sites. Helps in preserving the natural state of environment	In lab research stage. No mercury hyperaccumulating plant species has yet been identified	Process is effective with respect to the surface area covered	May take years to see decrease in mercury concentrations; Harvested plants may be considered hazardous waste; Wildlife may eat foliage that uptakes mercury	Vegetation removal and planting of new species, hauling, and disposal	Allows for incorporation of California native flora	USEPA (2000), Sood et al. (2012)
Macrophyte Harvesting	Mechanically remove Hg-accumulating plants/weeds naturally growing in the lake, or harvest plant material from floating islands installed and maintained in the lake.	Pilot tests have been done for Putah South Canal	Remove anaerobic zones; Allow for more sunlight for demethylation, Halt bioaccumulation of methylmercury	High average cost; Disruption of bottom sediment; Increase in floating weed fragments; Regular maintenance and removal of vegetation may be required	Regular harvesting intervals, harvesting tools and equipment, hauling, and disposal labor	Non-intrusive on recreational activities; landscaping techniques can improve aesthetics	McCord (2018), Northwest Hydraulic Consultants (2010)

5. Scoring Results of Potential Methylmercury Remediation Techniques

The potential methylmercury control methods were scored. The results are shown in Table 3.

Table 3: Ranking List of Potential Methylmercury Control Methods

Remediation Method	Score							
	Suitable for Lake Solano	Compatability with lake management	Multiple benefits	Cost (Capital+ O&M)	Aesthetics	Failure Risk	Improvement Time Scale	Weighted Score
Macrophyte Harvesting	5	4	4	3	5	3	2	60
Natural Attenuation	5	5	3	5	3	3	1	59
Biomanipulation	3	4	3	4	3	4	4	52
Phytoremediation	3	3	3	4	4	3	2	48
Capping	3	1	3	1	1	3	5	33
Dredging	3	1	4	1	2	3	5	38
Thermal Treatment	3	1	3	1	2	3	5	35
Mechanical Mixing	Disqualified							
Hypolimnetic Oxygenation								
Nitrate Injection								

Notably, because Lake Solano is a uniquely shallow lake, commonly-used remediation techniques that target the redox reaction ladder associated with the methylation process are not applicable. These strategies include mechanical mixing, hypolimnetic oxygenation, and nitrate injection. Because the lake does not stratify, has a low water retention time, and is constantly supplied with highly oxygenated water,[19] the development of methylmercury-promoting anoxic conditions is not a risk in Lake Solano. These redox modifying techniques are not applicable. Therefore, they were disqualified from the scoring process and will not be considered.

Methylmercury control techniques that require heavy machinery, specialized treatment facilities and other aesthetically and habitat invasive remediation methods also tended to score low overall. Furthermore, processes such as capping and dredging, while proven to be effective treatment methods, often cost tens-of-millions of dollars.[31] The prohibitive cost of techniques such as capping and dredging is often incompatible with the budget of small agencies such as

SCWA. The use of heavy machinery and treatment facilities would also detract from the aesthetics of the lake. Because Lake Solano attracts many recreational users, aesthetics are an important consideration. Since its creation in 1957, Lake Solano has been steadily losing water storage capacity due to sediment build-up; its volume has already been reduced by 50%.[19] Therefore, even if the soil was removed, cleaned, and replaced or even completely removed, new, contaminated sediment would quickly cover it.

Instead, remediation techniques that were aesthetically pleasing, affordable, and habitat preserving tended to score higher. Macrophyte harvesting, natural attenuation, biomanipulation, and phytoremediation scored the highest.

The ranking process identified phytoremediation as a possible mercury control method for Lake Solano. Phytoremediation involves introducing plants into the environment to absorb methylmercury. By then removing the plants, the methylmercury is subsequently removed from the food web.[35] Although phytoremediation is one of the more cost effective methods,[36] the present study discounts phytoremediation because the lake managers have determined that aquatic weeds are impeding dam flow and planting new vegetation might make the problem worse.[19]

Although biomanipulation is a competitive remediation option, there is a strenuous permitting process associated with fish stocking.[31] The California Department of Fish and Wildlife holds jurisdiction, as authorized by Section 6401 of the Fish and Game Code, for issuing permits for fish stocking in waters of the state of California. Under CDFW's regulations, a permit may be issued once CDFW has determined that the proposed stocking is in agreement with the department's fisheries management objectives. Also, it is necessary to confirm that the stocking would not introduce any diseased or parasitized fish into California waters.[31] The permitting application, Form 749 from the CDFW, requires the species, number, and size of fish to be stocked as well as the name of the registered aquaculturist from whom the fish will be obtained.[37] The 2018 application currently costs about $63.[37] George Neillands, environmental scientist from the CDFW, stated that stocking the lake with new fish may cause competition with existing fish populations.[38] Further, Dr. Peter Moyle, professor of Fish, Wildlife, and Conservation Biology at the University of California, Davis, stated that stocked clean predatory fish in the presence of predatory mammals and birds might be eaten by those mammals and birds and would not work to dilute lake mercury concentrations.[20]

After the ranking process, it was determined that macrophyte harvesting and natural attenuation are accessible and applicable for Lake Solano. Macrophyte harvesting would also address the problem of dam impedance caused by vegetative overgrowth. The present study proposes an "enhanced natural attenuation" that utilizes techniques associated with macrophyte harvesting, aquatic vegetation control, and photodemethylation.

6. A Discussion on the Suitability of Macrophyte Harvesting as the Proposed Remediation Method

Due to factors such as low habitat impact, reasonable costs, aesthetics, and agreement with lake management objectives, macrophyte harvesting scored the highest in the ranking analysis and is proposed as an appropriate methylmercury remediation technique in Lake Solano.

6.1 Scoring and Design Performance of Macrophyte Harvesting

Macrophyte harvesting is proposed to be the primary method of methylmercury formation control in Lake Solano. Relative to control methods such as dredging and capping, the low cost of macrophyte harvesting is compatible with lake management objectives. Also, the shallow depth of Lake Solano allows a large amount of sunlight to reach the bottom the lake, which causes unwanted vegetation growth. Macrophyte harvesting is therefore proposed as an effective, non-invasive strategy to control methylmercury formation in Lake Solano.

Macrophytes are aquatic plants that grow in or near water and are either emergent, submergent, or floating, as shown in Figure 6. Macrophytes include helophytes, plants that are partly submerged in marshy waters and grow from buds below the water surface.[39] Recent site visits have identified dense macrophyte growth in Lake Solano, as shown in Figures 7 and 8. These vegetative mats are made of algae and other kinds of plants. Macrophyte harvesting would remove this vegetation from Lake Solano.

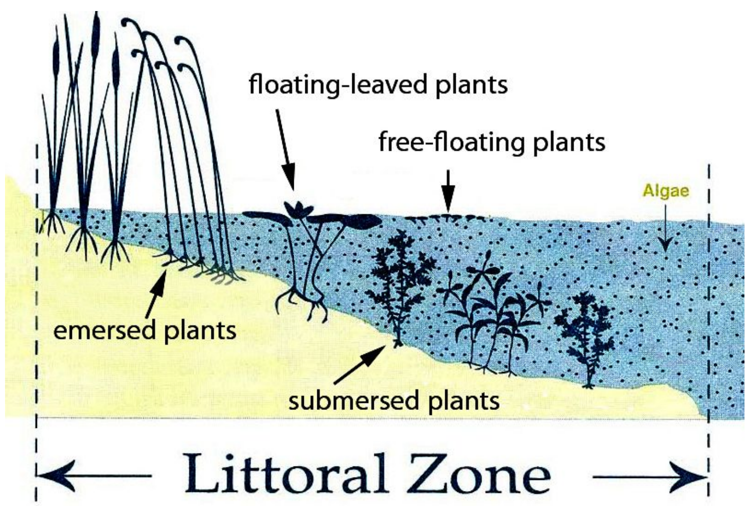

Figure 6: Depiction of macrophytes.[40]

Figure 7: Vegetative mats covering lake surface of Lake Solano. Photos taken in May, 2018.

The primary mechanism relating macrophyte harvesting and methylmercury reduction is photodemethylation. During this process, UV light from the sun converts methylmercury back to inorganic mercury, which is insusceptible to bioaccumulation unlike its organic counterpart.[41] In Lake Solano, the vegetative mats occupy a large surface area of the lake and inhibit photodemethylation by preventing sunlight from reaching the bottom of the lake. The submerged plants also impede the penetration of sunlight necessary for photodemethylation. Macrophyte harvesting would further enable photodemethylation in Lake Solano by removing the inhibiting plants.

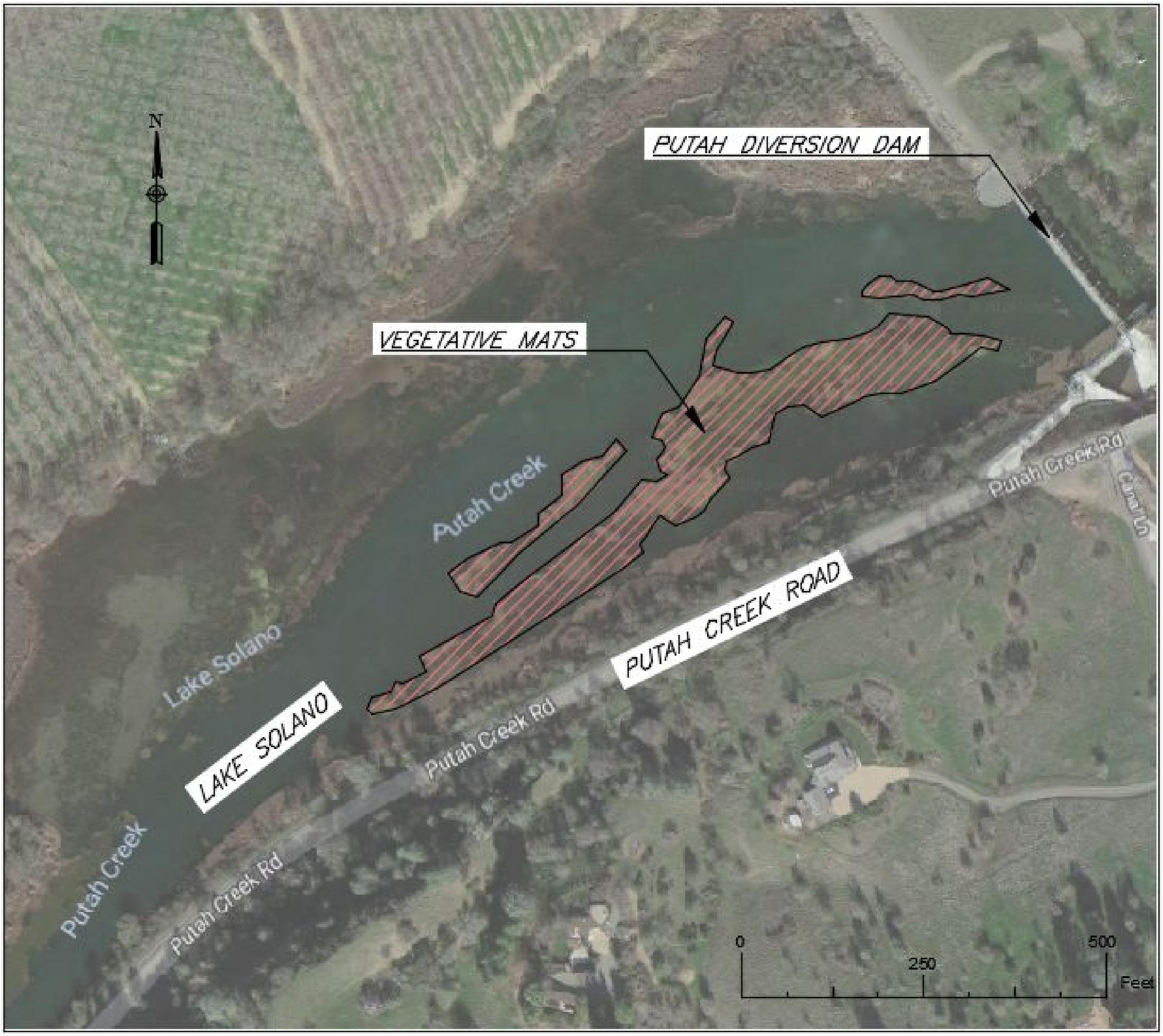

Figure 8: Proposed vegetative mat removal areas.

The benefits, implementation, and cost considerations of macrophyte harvesting are discussed in the following sections.

6.2 The Benefits of Aquatic Vegetation Control

Besides the inhibition of photodemethylation, there are several other problems associated with the presence of aquatic vegetation in Lake Solano. Vegetation is often mercury-accumulating and subsequently allows for further bioaccumulation of methylmercury. Vegetation also periodically impedes dam flow, a recurring problem discussed by dam operators.[19] Also, densely vegetated areas formed by tall grasses on the sides of the lake may inhibit flow and promote areas of oxygen-depleted, stagnant water.[28] Correspondingly, dead aquatic vegetation may settle to the lake bottom and create localized zones of increased biological oxygen demand due to microbial decomposition.[28] The increased oxygen demand also promotes conditions of oxygen depletion. These anaerobic conditions promote mercury methylation. Further, the dead aquatic vegetation serves as a substrate for mercury methylation. Detritus that settles to the bottom of the lake provides a source of organic carbon necessary for the methylation process.[30]

Macrophyte harvesting can solve these problems. This strategy can simultaneously meet management objectives and prevent the formation and bioaccumulation of methylmercury. Lastly, harvesting can remove trash and any other unwanted debris from the lake.[42]

6.3 The Implementation of Macrophyte Harvesting

During the first year of the study, the aquatic vegetation would be monitored to determine the types of vegetation present and their growth rates. Seasonal growth would be monitored, and the dates of weed death would be recorded. The non-native species would be targeted prior to their death. The first-year monitoring would indicate how often harvesting would need to be performed to be effective. Harvesting would be performed most likely 1-3 times a year.[22]

Solano County Water Agency would have the choice to perform the task themselves, or hire an outside mechanical harvesting company to do the work. If SCWA chooses to perform the work, the harvester would be purchased and operated. It would also be cost-effective to hire a long-term contractor to do the work.

One type of harvester that might be appropriate would be an Aquamarine H5 Harvester. The Aquamarine H5 Harvester was used in the Putah South Canal as a pilot test.[22]

Figure 9: An Aquamarine H5 Harvester in action.[45]

The harvester would need to be small enough to fit on the boat ramp at the lake. Aquamarine harvesters work like lawnmowers for the surface of the water.[42] They are hydraulically-driven by one person and use knives to cut the vegetation, which is then transferred to a conveyor system on the closed deck barge.[42] The storage containers hold the plant matter until it can be unloaded off-shore into a dump truck.[42] Although one harvester is probably enough for the lake size and shape, multiple may need to be used if there are significantly varying lake dimensions.

6.4 Economic Performance and Cost Considerations of Aquatic Vegetation Control

While traditional methylmercury techniques such as capping and dredging are often cost-prohibitive, costing millions of dollars, macrophyte harvesting is an economically-sensible remediation technique. Macrophyte harvesting requires little equipment and only entails a small operations and maintenance cost. A cost estimation of macrophyte harvesting and aquatic vegetation control is discussed in this section.

Personal correspondence with Northwest Aqua, an aquatic vegetation harvesting contractor, led to the conclusion that it would take roughly $4500 and one eight-hour work day to harvest a 2-acre area estimated by the hatch in Figure 8.[43] On the other hand, if SCWA is to perform the aquatic weed harvest themselves, they would need to purchase their own harvester. The H5 Aquatic Weed Harvester is priced $50,000 new.[44] Assuming a crew of three people paid $30/hr each and assuming that 2 acres can be harvested in a work day, it would cost approximately $50,720 for the first harvest, and $720 for any subsequent 2-acre harvests. These economic analysis assumptions are summarized in Table 4, and are used to perform a break-even analysis between contractor pricing and in-house costs as shown in Figure 10. The estimate of two acres of aquatic vegetation was made from both site visits and satellite imaging, as shown in Figure 8. These resources helped to identify the size of the densest areas of the lake. If, however, the lake contains more than two acres worth of aquatic weeds, the costs would be further increased.

Table 4: Cost Analysis Assumptions of Macrophyte Harvesting.

SCWA: In-House Labor		
Item	**Value**	**Units**
H5 Harvester [43]	50000	$
Crew Size	3	Crew
SCWA Crew Labor	30	$/hr
Work Day Period	8	hours
One Harvest: Total Cost	50720	$
Each Subsequent Harvest	720	$
Short-Term Contractor		
Item	**Value**	**Units**
One Harvest :Total Cost [44]	4500	$

As shown in Figure 10, the break-even analysis concluded that while it would initially be cheaper to hire a contractor, it would be more economically sensible for SCWA to purchase their own harvester. Because aquatic weeds will regrow, regular harvesting should be performed. Based on Figure 10, it would take thirteen harvests for the purchasing the harvester to be a better investment than it would be to hire a contractor. While it would be cost-effective in the long run for SCWA to purchase an aquatic weed harvester, a contractor should be hired for the first two or three years as fish tissue samples are collected. At this time, it would be sensible to initially verify the effectiveness of the harvesting technique in reducing biological methylmercury concentrations, as discussed in Section 5.7.

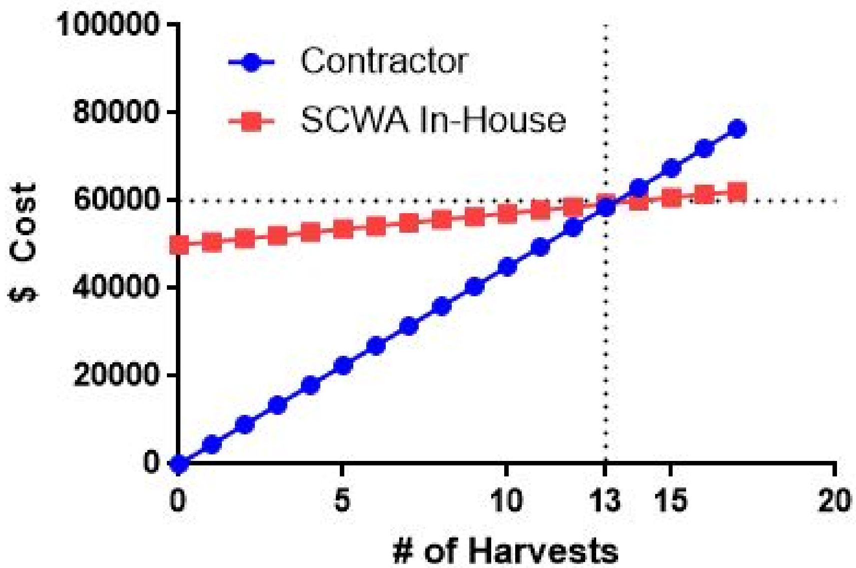

Figure 10: Comparative cost analysis of contract vs. in-house harvesting.

6.5 Design Performance

This report evaluated ten common and field tested mercury control methods to decide which control method would work best for Lake Solano. An extensive literature review was performed to thoroughly analyze every option. Once a feasible control study was identified, an implementation strategy was designed with help from experts on methylmercury, contractors, and macrophyte harvesting case studies.

While the benefits of removing macrophytes are clear, there are several limitations and risks associated with macrophyte harvesting. Care must be taken to not disrupt the sediment bed during the plant removal process. The sediment most likely contains buried mercury deposits, and uprooting vegetation could resuspend inorganic mercury.[45] Therefore, any disturbance to the lake bottom, including that induced by the removal of bottom or lakeside aquatic vegetation, may exacerbate the mercury problem. Subsequently, sediment disruption may increase turbidity and iron levels in the water that might slightly exceed drinking water standards.[22] However, the impacts would most likely not be a health issue for the public.[22] The removal of certain types of aquatic vegetation, notably bottom or side vegetation, could adversely impact habitat for fish, especially the threespine stickleback.[20] Lastly, periodic maintenance is needed since the plants will continually be in a cycle of growth and death; it is likely that the lake will need to be harvested 1-3 times a year.

6.6 Design Sustainability

Because macrophyte harvesting will produce large quantities of biomass per harvest, lake managers should consider creating a designated compost area. Composting would minimize the greenhouse gas emissions and hauling costs associated with transportation of waste material. Compost could also be used as a fertilizer for park maintenance.

6.7 Progress Tracking of Improvements

Progress monitoring should be performed regularly to minimize unnecessary macrophyte harvests and to verify a decrease in biological methylmercury concentrations.

Fish tissue samples will be collected biannually and sent to a laboratory to measure total mercury as an indicator of progress for the selected treatment method. Gill nets for small (5−15 cm full length, trophic level 3) prey and sport fish will be placed at designated sampling sites located at various depths and vegetative conditions.[36] Fish will be captured, retained, measured, weighed, grouped by species and size, and stored for future laboratory analysis per U.S. Environmental Protection Agency's (EPA) Quality Assurance Project Plan (QAPP).[46]

The tissue section analyzed will be fish fillets as the fillet is the portion of the fish commonly consumed by humans. All fish tissue samples will be analyzed by thermal decomposition, amalgamation, and/or atomic absorption spectrophotometry per EPA method 7473.[47] Since methylmercury typically accounts for more than 80% of the total mercury concentration, total mercury is recommended as a conservative monitoring parameter.[48]

7. Conclusions and Recommendations

Lake Solano is a unique in that it is shallow, has a low water retention time, and is relatively small. Because the lake does not stratify, commonly used methylmercury remedial techniques such as hypolimnetic oxygenation and nitrate injection are not suitable for the lake. Furthermore, because Lake Solano is a recreational hub for fishermen and other tourists, invasive techniques such as dredging, capping, and thermal treatment are similarly inappropriate choices for the lake. Instead a method that is inexpensive, aesthetically pleasing, non-invasive, and does not require the extensive and prolonged use of heavy equipment is more appropriate.

Following a ranking analysis of ten common remediation methods, macrophyte harvesting was identified as the most appropriate choice for the lake. The removal of aquatic vegetation associated with macrophyte harvesting allows sunlight to stimulate photodemethylation, removes a substrate for methylation, and reduces the formation of local anoxic zones within the lake.

Macrophyte harvesting also yields multiple benefits. In addition to decreasing methylmercury concentrations in the lake, the regular harvesting of aquatic weeds would prevent the impedance of dam flow caused by the dense vegetative growth-- a problem cited by SCWA engineer Alex

Rabidoux. An economic analysis indicated that it would be cheaper in the long term for SCWA to purchase a harvester and use in-house labor to remove the aquatic weeds. However, it is recommended that a contractor is hired for the first two to three years of harvesting to ensure that the prescribed remedial technique is effectively decreasing biological methylmercury concentrations. Progress monitoring would be performed by fish tissue sampling.

Macrophyte harvesting would not only help to solve the mercury problem, but would also meet current water resource objectives. Macrophyte harvesting is low-cost and aesthetically-pleasing, and also helps to improve dam flow. Finally, macrophyte harvesting might benefit other mercury-impacted lakes similar to Lake Solano in vegetative content and hydraulic lake characteristics.

Acknowledgements

Cowprints Environmental would like to thank Stephen McCord, Ph.D., P.E., Professor Jeannie Darby, Ph.D., P.E., and Alex Sweat, for their unwavering support throughout this senior design project and for providing resources and their own expertise. Cowprints Environmental would also like to thank Alex Rabidoux from SCWA for sharing his knowledge of Lake Solano and the surrounding watershed.

References

[1] California Water Board: State Water Resources Control Board. (2017). Statewide Mercury Control Program for Reservoirs. Retrieved from: https://www.waterboards.ca.gov/water_issues/programs/mercury/reservoirs/docs/summary_april_2017.pdf

[2] Mercury Cycling in the Environment. (2013). *US Geological Survey.* Retrieved from: http://wi.water.usgs.gov/mercury/mercury-cycling.html

[3] Park, J., and Zheng W. (2012). Human Exposure and Health Effects of Inorganic and Elemental Mercury. *Journal of Preventive Medicine & Public Health*. Retrieved from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3514464/

[4] Winner, C. (2010). How Does Toxic Mercury Get into Fish. *Oceanus*. Vol. 48. Retrieved from: https://www.whoi.edu/oceanus/feature/how-does-toxic-mercury-get-into-fish

[5] National Center for Biotechnology Information. PubChem Compound Database; CID=26623. Retrieved from: https://pubchem.ncbi.nlm.nih.gov/compound/Mercuric_ion#section=Top

[6] Sparks, G. C. (2016). Mercury and methyl mercury related to historical mercury mining in three tributaries to Lake Berryessa, Upper Putah Creek watershed, California. Retrieved from: http://csus-dspace.calstate.edu/handle/10211.3/171301

[7] State of California Office of Environmental Health Hazard Assessment. (2013). Mercury in Fish Caught in California: Information for People Who Eat Fish. Retrieved from: https://oehha.ca.gov/media/downloads/fish/fact-sheet/hgfactsheet.pdf

[8] State of California: Department of Conservation. (n.d.) Mercury. Retrieved from: http://www.conservation.ca.gov/cgs/minerals/hazardous_minerals/mercury

[9] Wang, Q., Kim, D., Dionysiou, D. D., Sorial, G. A., & Timberlake, D. (2004). Sources and remediation for mercury contamination in aquatic systems-a literature review. *Environmental Pollution*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S026974910400051X

[10] Extracting the Gold. (n.d.) Retrieved from: http://novascotiagold.ca/theme/exploitation_de_lor-mining/extracting_the_gold-extraction_de_lor-eng.php

[11] Alpers, C.N., Hunerlach, M.P., May, J. T., & Hothem, R.L. (2005). Mercury Contamination from Historical Gold Mining in California. *U.S. Geological Survey*. Retrieved from: https://pubs.usgs.gov/fs/2005/3014/

[12] Churchill, R.K.. (2000). Contributions of mercury to California's environment from mercury and gold mining activities-insights from the historical record. *Proceedings: Assessing and Managing Mercury from Historic and Current Mining Activities*. 33. 33-36. Retrieved from: https://www.researchgate.net/publication/298431904_Contributions_of_mercury_to_California's_environment_from_mercury_and_gold_mining_activities-insights_from_the_historical_record

[13] Long, K.R., DeYoung Jr., J.H., and Ludington, S.D. (1998). Database of significant deposits of gold, silver, copper, lead, and zinc in the United States. *U.S. Geological Survey Open-File Report*. Retrieved from: https://pubs.er.usgs.gov/publication/ofr98206AB

[14] Domagalski, J. L., Slotton, D.G., Alpers, C.N., Suchanek, T.H., Churchill, R., Bloom, N., . . . Clinkenbeard, J. (2004). Summary and synthesis of mercury studies in the Cache Creek watershed, California. *US. Geological Survey*. Retrieved from: https://pubs.er.usgs.gov/publication/wri034335

[15] Health Effects of Exposures to Mercury. *US Environmental Protection Agency.* Retrieved from: https://www.epa.gov/mercury/health-effects-exposures-mercury#methyl

[16] Wolfe, M.F., Schwarzbach, S., & Sulaiman, R.A. (2009). Effects of mercury on wildlife: A comprehensive review. *Environmental Toxicology and Chemistry.* Retrieved from; https://setac.onlinelibrary.wiley.com/doi/full/10.1002/etc.5620170203

[17] Lee, G. F., & Jones‐Lee, A. (2009). LEHR superfund stormwater runoff and putah creek mercury issues. *Remediation Journal*, *19*(2), 123-134. Retrieved from: https://onlinelibrary.wiley.com/doi/pdf/10.1002/rem.20207

[18] Gassel, M., Klasing, S., Brodberg, R.K., & Roberts, S. (2006). SafeEating Guidelines for Fish and Shellfish from Lake Berryessa and Putah Creek Including Lake Solano (Napa, Yolo, and Solano Counties. *California Environmental Protection Agency*. Retrieved from: https://oehha.ca.gov/media/downloads/advisories/062206lbpc.pdf

[19] Rabidoux, A. Personal communication. May 1, 2018.

[20] Moyle, P., Ph.D. Personal communication. May, 2018.

[21] Hermsmeyer, S., & Alvarez, M. (2006). Lake Solano Regional Park Master Plan. *Solano County Regional Parks.* Retrieved from: https://www.solanocounty.com/civicax/filebank/blobdload.aspx?BlobID=21777

[22] Assessment of Issues and Concerns Regarding Aquatic Vegetation in Putah South Canal. (2010). *Northwest Hydraulic Consultants.*

[23] National Primary Drinking Water Regulation Table. (2009). Environmental Protection Agency. Retrieved from: https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations#Inorganic

[24] Eating Fish: What Pregnant Women and Parents Should Know. (2017) *United States Food and Drug Administration*. Retrieved from: https://www.fda.gov/Food/ResourcesForYou/Consumers/ucm393070.htm

[25] 2018-2019 California Freshwater Sport Fishing Regulations. (2017). *California Department of Fish and Wildlife.* Retrieved from: http://www.eregulations.com/wp-content/uploads/2018/03/18CAFW_LR.pdf

[26] McCord, S. (2018). Mercury Management Strategies.

[27] Lake Stratification and Mixing. (n.d.). *Illinois Environmental Protection Agency.* Retrieved from: http://epa.state.il.us/water/conservation/lake-notes/lake-stratification-and-mixing/lake-stratification.pdf

[28] McCord, S. Personal communication. May 1, 2018.

[29] Treatment Technologies for Mercury in Soil, Waste, Water. (2007). *U.S. Environmental Protection Agency*. Retrieved from: https://www.epa.gov/remedytech/treatment-technologies-mercury-soil-waste-and-water

[30] Jeremiason, J.D., Portner, J.C., Aiken, G.R., Hiranaka, A.J., Dvorak, M.T., Tran, K.T., & Latch, D.E. (2015). Photoreduction of Hg(II) and photodemythylation of methylmercury: the key role of thiol sites on dissolved organic matter. *Environmental Science: Processes & Impacts*. Retrieved from: http://pubs.rsc.org/-/content/articlelanding/2015/em/c5em00305a#!divAbstract

[31] Stillwater Sciences. (2015). Soulajule Reservoir & Arroyo Sausal Methylmercury Control Study. Retrieved from: http://marinwater.org/DocumentCenter/View/3384/Soulajule-Final-Study-Plan_09_10_2015

[32] Beutal, M., Dent, S. Reed, B., Marshall, P., Gebremariam, S., Moore, B., . . . Shallenberger, E. (2014). Effects of hypolimnetic oxygen on mercury bioaccumulation in Twin Lakes, Washington, USA. *Science of the Total Environment*. Retrieved from: https://www.researchgate.net/publication/264090987_Effects_of_hypolimnetic_oxygen_addition_on_mercury_bioaccumulation_in_Twin_Lakes_Washington_USA

[33] Matthews, D.A., Babcock, D.B., Nolan, J.G., Prestigiacomo, A.R., Effler, S.W., Driscoll, C.T., . . . Kuhr, K.M. (2013). Whole-lake nitrate Addition for control of methylmercury in mercury-contaminated Onondaga Lake, NY. *Environmental Research, 125*. Retrieved from: https://www.sciencedirect.com/science/article/pii/S001393511300073X

[34] Drury, D.D. (2009). Methylmercury production and control in lakes and reservoirs contaminated by historic mining activities in the Guadalupe River watershed. *Santa Clara Valley Water District.*

[35] Sood, A., Uniyal, P.L., Prasanna, R., & Ahluwalia, A.S. (2011). Phytoremediation Potential of Aquatic Macrophyte, Azolla. *Ambio, 41*. Retrieved from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3357840/

[36] Introduction to Phytoremediation. (2000). *United States Environmental Protection Agency*. Retrieved from: https://nepis.epa.gov/Exe/ZyNET.exe/30003T7G.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1995+Thru+1999&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C95thru99%5CTxt%5C00000016%5C30003T7G.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL

[37] California Department of Fish and Game. (2018). *Information Leaflet No. 6 APPLICATION FOR PRIVATE STOCKING PERMIT Pursuant to Section 6401, Fish and Game Code*

[38] Neillands, G. Personal communication. May 18, 2018.

[39] Hickey, M.; King, C. (2001). The Cambridge Illustrated Glossary of Botanical Terms. *Cambridge University Press*.

[40] Minnesota Department of Natural Resources (n.d.). *Littoral Zone.* [Infographic]. Retrieved from: https://www.dnr.state.mn.us/shorelandmgmt/apg/wheregrow.html.

[41] Klapstein, S. J., Ziegler, S. E., Risk, D. A., & O'Driscoll, N. J. (2017). Quantifying the effects of photoreactive dissolved organic matter on methylmercury photodemethylation rates in freshwaters. *Environmental Toxicology and Chemistry*, *36*(6), 1493-1502. Retrieved from: https://setac.onlinelibrary.wiley.com/doi/pdf/10.1002/etc.3690

[42] Welcome to Aquamarine. (n.d.) *Aquamarine.* Retrieved from: http://www.aquamarine.ca/why-mechanical-harvesting/

[43] Aquamarine. Personal communication. May 25, 2018.

[44] Northwest Aqua. Personal communication. June 4, 2018

[45] Marovich, R. Personal communication. May, 2018.

[46] Herger, L.G. (2016). Assessment of Mercury in Fish Tissue from Pacific Northwest Lakes. *United States Environmental Protection Agency.* Retrieved from: https://www.epa.gov/sites/production/files/2016-03/documents/assessment-mercury-fish-tissue-pnw-lakes-report.pdf

[47] Method 7473: Mercury in Solids and Solutions by Thermal Decomposition, Amalgamation, and Atomic Absorption Spectrophotometry (1998). *United States Environmental Protection Agency.* Retrieved from: https://www.epa.gov/sites/production/files/2015-12/documents/7473.pdf

[48] Sun, J., et al. (2006). Analysis of total mercury and methylmercury concentrations in four commercially important freshwater fish species obtained from Beijing markets. *Wei Sheng Yan Jiu Journal of Hygiene Research* 35.6: 722-725

Cover Photo Citations:

https://www.usgs.gov/media/images/usgs-scientist-collecting-a-water-sample-boulder-creek-colorado
https://rattsalad.wordpress.com/2011/09/19/lake-solano/
https://pubs.usgs.gov/fs/2012/3146/
https://fisheries.org/2016/12/environmental-dna-effectively-monitors-aquatic-species-populations/