Phytoextraction to Control Mercury Bioaccumulation in Lake Berryessa

Prepared By:
Adrian Cristobal
Melvin Aquino
Truc Le

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Executive Summary

This goal of this project is to control methylmercury concentrations in Lake Berryessa through the use of phytoextraction. Phytoextraction is a sub process of phytoremediation which works by using plants to absorb elemental mercury. This mercury is absorbed from contacted waters and riverbed sediments. The plant species selected for the phytoremediation process is *Vallisneria spiralis*, more commonly known as tape grass. This species grows underwater on the riverbed, which allows for maximum contact with contaminated water and sediments. This plant is also fast growing and replicates horizontally through the use of underground runners. The proposed remediation site is a 500 meter length of river located upstream of the Upper Putah Creek tributary. Upper Putah Creek was chosen because of its relatively high mercury loading, while the river location was selected due to its shallow, slow moving water.

Vallisneria spiralis will be planted throughout the remediation site in the sediment of Upper Putah Creek and will cover approximately 40,000 square meters. The initial planting phase will involve 500 kg of starter plants and cost approximately $50,000. Labor costs and transportation is estimated to be $5,000. A minimum of 3150 kg of *Vallisneria spiralis* is required to absorb 70% of the daily mercury loading. It will take approximately 6 months for the starter plants to grow and replicate to this amount of biomass. As the plants grow and replicate, a greater quantity of mercury will be absorbed from the environment. When fully matured, the total biomass of the plants are expected to exceed 20,000 kilograms with a density of 0.5 kg per square meter.

Currently, the maximum mercury accumulation capacity of *Vallisneria spiralis* is unknown. As a precaution, the plant biomass will be kept to the 3150 kg minimum biannually after the first year. This is to ensure that the plant does not remove native species. The cutting and disposal process will be done by alternating rows perpendicular to the flow of water. This process will be conducted during the summer months or when water levels are the lowest. The cut plants will be allowed to air dry for several days to reduce their volume and weight. Afterwards, they will be transported to the Napa Recycling and Waste Services for disposal. The total cost for extraction, transportation, and disposal will be $15,206 the first year and $24,225 the sequential years. After removal, the remaining plants in the remediation site will be left undisturbed to repopulate the riverbed for the next cycle. This phytoextraction process is a long term strategy and should be implemented indefinitely to reduce the amount of mercury which enters Lake Berryessa.

Introduction

Mercury bioaccumulation is a high level threat due to its impact on the surrounding ecosystem and human health. California aquatic resources are especially susceptible to mercury contamination from both natural and anthropogenic sources. The Coastal Ranges in California contain a high concentration of mercury within hydrothermal springs. Mercury from this region seeps into surrounding lakes and streams (Mercury 2016). Additionally, the discovery of mercury ore bodies during the Gold Rush accelerated the dispersion of contamination throughout California. Mining activity released an estimate of 220 million pounds of mercury between 1840 and 1960 (Alpers 2005). When the elemental mercury is released into the environment, it is methylated into methylmercury by bacteria, increasing its toxicity to living organisms.

Mercury is introduced into the atmosphere through anthropogenic sources such as coal burning and natural sources such as forest fires displayed in Figure 1. Chemical reactions oxidize the mercury in the atmosphere into its ionic form which dissolves easily into water bodies (Selin 2009). Once in the water, the mercury is absorbed by sediments and settles down to the lakebed. This leaves it susceptible to methylation by sulfate reducing bacteria and converted to methylmercury (Fitzgerald and Lamborg 2007). Sulfate reducing bacteria thrive in anaerobic conditions that are found in the bottom of the lake. To respire, these bacteria need sulfate. Once the sulfate is reduced to sulfide, it combines with the mercury that has settled on the sediment and the bacteria methylate it.

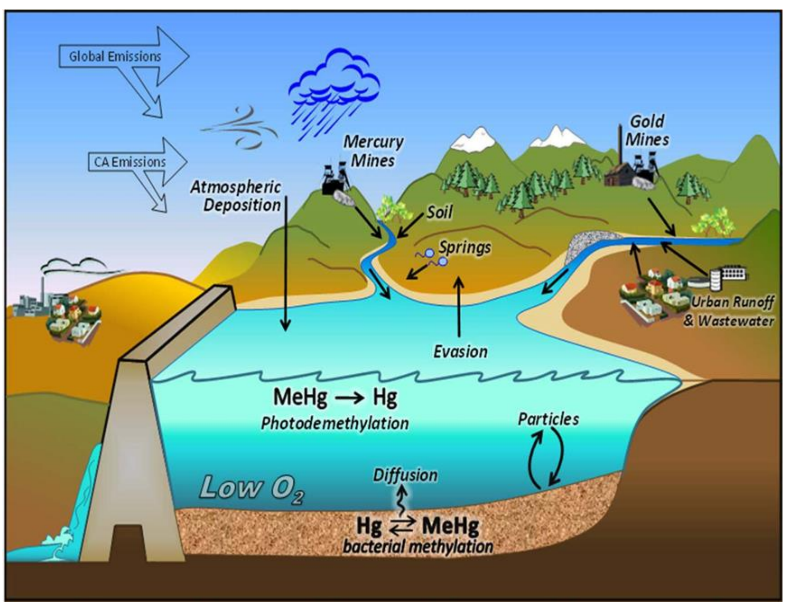

Figure 1. Methylmercury Cycle Diagram (Maven 2016)

Once the methylmercury is exerted by the bacteria, it is bioaccumulated by species in the lowest trophic levels of the food web. Animals like phytoplankton are some of the first organisms the contaminant is exposed to. When these organisms are consumed by smaller fish, the methylmercury within the phytoplankton is transferred and absorbed in the tissues of the predator. As more methylmercury contaminated prey are consumed, the mercury concentrates within the organic tissue of the animal (Rickert 2018). This process is known as mercury bioaccumulation. Species higher up in the food chain tend to have higher levels of mercury contamination. This correlation is a result of biomagnification. At sufficiently high concentrations, water bodies become uninhabitable and may collapse local aquatic ecosystems (Rickert 2018). Methylmercury is a hazardous substance to living things and its presence in the environment must be minimized to protect humans and the ecosystem. When humans consume fish with high mercury concentrations, the mercury enters the body and can accumulate in vital organs. This may result in a wide range of adverse effects ranging from mercury poisoning to permanent damage of the central nervous system. Methylmercury is also a hazard to the natural ecosystem.

Once mercury concentrations in the blood get to a level of above 10 micrograms per liter in, the mercury contamination is considered above average (Thornton 2011). Levels at or above 15 milligrams per cubic meter are considered an immediate threat to human health. Mercury mainly enters the system through inhalation of elemental mercury, or through consumption of seafood previously contaminated with methylmercury (Thornton 2011). Elemental mercury is especially dangerous in its gaseous state. Symptoms are evident in workers who are exposed to elemental mercury in the air at levels greater than 20 micrograms per cubic meter (Mercury 2017). The effects of inhaling mercury can result in symptoms showing within hours of initial exposure. Symptoms include malaise, a dry cough, and shortness of breath. Chronic exposure to mercury in the air can result in lung disease. When mercury is ingested in the form of methylmercury, symptoms show in the gastrointestinal tract, the central nervous systems, and the renal systems (Mercury 2017). Severe symptoms include intention tremors, nausea, fatigue, rashes, and renal dysfunction (Thornton 2011). The effects of mercury exposure are amplified in both children and fetuses. The mercury affects the development of a child through cognitive, spatial, and motor skill impairment (Mercury 2017).

The goal of this project is to minimize methylmercury concentrations within Lake Berryessa at an affordable price. The most cost effective method to achieve this goal is to limit the amount of elemental mercury which enters the lake. Lake Berryessa is a reservoir formed in 1958 after the completion of the Monticello Hydroelectric Dam. With a surface area of 20,700 acres, Lake Berryessa is the 7th largest reservoir in California. It has a max depth of 275 feet and an estimated total volume of 1.6 million acre feet. Lake Berryessa is fed by headwaters of the Putah Creek Watershed and the three major tributaries: Upper Putah Creek, Pope Creek, and Eticuera Creek. Water from Lake Berryessa and Electricity from the Monticello Dam supplies the cities of Vacaville, Suisun City, Vallejo, and Fairfield. Lake Berryessa serves as a recreational hub for camping, swimming, recreational fishing, and boating. Campsites and hiking trails are located in the surrounding woodlands while resorts and boat docks can be found on the shoreline. Lake Berryessa serves about 9 million visitors annually and is a valued part of the local community.

Figure 2. Overhead Image of Lake Berryessa (Google Maps, 2018)

Lake Berryessa is stratified by temperature into three distinct layers as depicted in Figure 3. The epilimnion is the uppermost layer of the lake and is characterized by warm temperatures during the summer, presence of sunlight, and oxygenated water. Because this water is warmer and has a lower density than the deeper, colder waters, it floats to the top and remains in the upper layer. This separation occurs year round, but is most pronounced during the summer months where temperatures are the highest (Chortek 2017). Deeper down is the metalimnion which acts as the transition zone between the upper and lower layers. The thermocline is located in this layer and is characterized by rapid temperature change with depth. The hypolimnion is the deepest layer of the lake where the coldest and densest water resides. Little to no mixing occurs in this layer and visible light is significantly reduced. Oxygen is able to diffuse into the uppermost layer of the lake but is unable to penetrate to the deeper layers. As a result, there is usually little to no dissolved oxygen in the hypolimnion. These conditions promotes the growth of methylating bacteria and allows for mercury methylation to occur. The effects of mercury bioaccumulation can be minimized if the formation of methylmercury is inhibited. In the following section, several methods are discussed which can reduce the effect of mercury bioaccumulation in Lake Berryessa (Chortek 2017).

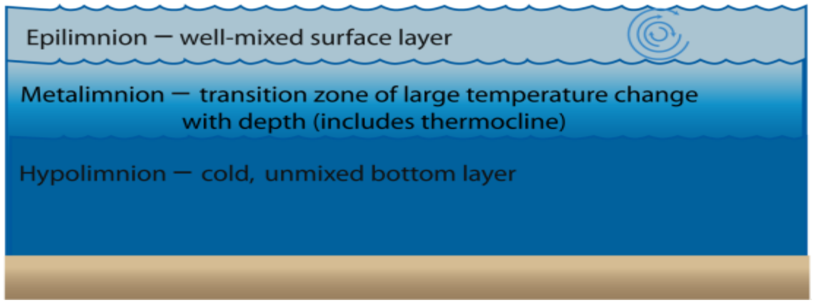

Figure 3. Lake Stratification (Coastal 2018)

Literature Reviews

The team conducted a literature review to understand current methods of controlling methylmercury. Each paragraph below describes the process of preventing accumulation of mercury. The different variables for each method were taken into account when deciding the most viable option for Lake Berryessa. Seven potential mitigation strategies for Lake Berryessa are described below.

Sulfate Stimulation

Previous studies have shown the process of methylation occurs in sulphate reducing bacteria. Sulfate stimulation aims to block the methylation pathway without inhibiting the reduction of sulphate to sulphide. By allowing the reduction of sulphate to continue, the carbonate produced from the reduction buffers the lake from acidification and low pH. Sediment tests were conducted in Quabbin Reservoir in Massachusetts to demonstrate the effects of molybdate on the sulphate reducing bacteria in anoxic waters. Based off of the results of this study, molybdate was successful in preventing the process of methylation. Methylmercury concentrations were inversely related to the addition of inhibitors. While the methylation pathway was blocked, sulfate conversion enhanced in the presence of the sodium molybdate (Gilmour 1992). This method of mercury control would have inconclusive results in Lake Berryessa. Due to its size, molybdate would have to be added on a large scale, and the side effects of adding molybdate in large amounts are unknown.

Photoremediation

Studies on photoremediation describe a method of mercury control by utilizing energy from the sun to break apart the methylmercury compound. High levels of methylmercury in winter are attributed to low solar radiation, low wind speed, and temperature conditions. Industrial and residential runoff especially had the highest recorded values for methylmercury. This specific study described a lab experiment which measures rates of methylmercury degradation by exposing contaminated waters to sunlight, and comparing these to contaminated water kept in the dark. To test the effectiveness of photo demethylation, methylmercury was added to both river water and deionized water. One set of river and deionized water were exposed to simulated sunlight, while another set was kept in the dark. Little to no degradation of methylmercury occurred in both the deionized water. Very little degradation occurred in the absence of sunlight due to microbial demethylation of methylmercury. Photodegradation rates increased when the sample was exposed to fulvic acid, nitrate, and with ferric iron, all of which are contaminants found in discharge (Pan et. al).

Phosphorus Additions

Some remediation methods use chemicals such as phosphorus to induce algal blooms to reduce the mercury concentrations in fish. The concept behind this method is that increasing the number of algae will decrease the uptake of mercury by plankton. Assuming the mercury concentration in a water body is constant, the mercury would be distributed amongst a greater number of algae (Pickhardt et al. 2002). This may reduce methylmercury concentrations per unit mass. Inducing algal blooms using phosphorus additives may also change the diet of aquatic life in the water body. An increase in the algae population may increase the value of this species as food for fish (Mailman et al. 2006) . As a result, the mercury accumulation per unit of food would be less for the predator compared to other diets (Mailman et al. 2006).

Reduce Carbon Sources before Flooding

The goal of this remediation method is to remove organic matter such as standing trees so that it limits the organic fuel for microorganisms to methylate mercury (Mailman et al. 2006). By controlled burning, the high temperatures cause the ionic mercury to enter its gaseous phase and organic carbon to mineralize (Mailman et al. 2006). Lower organic carbon concentrations may inhibit the colonization of methylating microorganisms or decrease their rate of metabolism. Mineralization of the organic matter minimizes decomposition and anoxia (Mailman et al. 2006). This is to be done prior to flooding and is a one-time process. The issue to this method is that is it inapplicable to existing reservoirs and lakes (Mailman et al. 2006).

Hypolimnetic oxygenation

Hypolimnetic oxygenation is a remediation process which introduces oxygen into the hypolimnion layer of lakes and reservoirs. The goal of this strategy is to inhibit or reduce mercury methylation from sulfate reducing bacteria and other anoxic bacteria. These types of bacteria thrive in the hypolimnion because there is little to no dissolved oxygen in this layer. Since the water is deep, natural processes like photosynthesis or atmospheric diffusion will not restore oxygen levels in this area. Oxygen is added to the hypolimnion so that the environment would be unsuitable for these mercury methylating bacteria. These conditions would promote the growth of aerobic bacteria in the hypolimnion that do not methylate mercury as a natural biological process. Because methylation is being reduced, mercury bioaccumulation would also decrease (Chortek 2017).

Phytoextraction

Phytoextraction is a process in which mercury and other heavy metal contaminants are removed from the environment through the use of plants. These plants act as accumulators and absorb the constituents into their biomass. After the growing cycle is complete, the contaminants are then removed from the ecosystem by cutting and disposing of the plants (Chortek 2017). The process of phytoextraction begins by selecting the most suitable plant species for the site conditions. The species chosen for this task must be capable of absorbing mercury and tolerating high levels of mercury in its system. This species should also be non-invasive to the region and grow quickly to maximize the rate of mercury extraction. Once a species has been selected, these plants are then cultivated along the coastlines or riverbeds. At the end of the growth cycles, the plant biomass is then removed and disposed of. This process removes mercury from contacted water and from the surrounding sediments. Phytoextraction is a lengthy process that can take years or even continue indefinitely (Chortek 2017). However, this method is significantly cheaper and less invasive than other strategies such as sediment dredging. When implemented correctly, the process of phytoremediation prevent mercury from spreading throughout the lake, and confine it only to the extracting plants.

Addition of Selenium

Methylmercury embeds itself within organisms by binding to organic tissue. This method of mercury control introduces sodium selenium into the benthic food web and allows it to bioaccumulate, similar to the pathway of methylmercury. The selenium then competes with methylmercury for the available binding sites in the body. A rubber matrix loaded with sodium selenium is lowered into the lake to release the selenium into the food web. Selenium was added at about 100 micrograms per liter in order to show these changes in the lake. Remediation starts at the benthic levels of the food chain, where net plankton start to accumulate the selenium in the water. The selenium shows significant changes in pike and perch found in Lake Oiterjam in Sweden (Paulson and Lundbergh 2003). This method might be possible for Lake Berryessa. However, the size of the lake and the amount of additions will increase the cost significantly.

Project Development Process

To determine the best solution for Lake Berryessa, the team initially conducted literature reviews. We relied primarily on scholarly journal articles, published reports, and government papers, compiling a list of common practice remediation strategies. Each method was evaluated on criteria such as costs, secondary impacts, and limitations. Similar control studies of methods conducted on Californian water bodies were also taken into account to evaluate their applicability to Lake Berryessa. To better understand the lake characteristics and its water flows, the team organized a site visit to the Western coast of Lake Berryessa and Monticello Dam with the lake manager. From our site visit, we obtained additional sampling data from 2015-2017 and water discharge information. Using this information, we developed management practices and recommendations for the remediation strategies we thought most applicable for Lake Berryessa. The team investigated each strategy based on the following list of criteria:

- Installation and Operating Costs
- Environmental and Secondary Impacts
- Constraints and Limitations
- Water Quality and Human Health Concerns
- Impact on Stakeholders
- Advantages and Disadvantages

Methylmercury can be controlled in aquatic systems by inhibiting the process of methylation or by preventing elemental mercury from entering the environment in the first place. Methods such as dredging control methylation by disposing of sediment high in mercury. However, for Lake Berryessa, this is not a viable option because of the cost constraints. The process of dredging is one of the most expensive methods and also highly impacts the aquatic ecosystem. The overall depth of the lake and its remote location make the process of dredging and waste disposal costly. Methods such as dredging also disturbs the sediment, which facilitates methylation. From the lake manager’s perspective, dredging is too costly and is not in the current budget for SCWA.

Chemical additions such as in sulfate stimulation and phosphorus addition inhibit the conversion of elemental mercury into methylmercury. Although these methods are cheaper than dredging, they may alter the water chemistry of the entire lake and pollute the drinking water. The waters of Lake Berryessa are used for recreational purposes, agriculture, and drinking water. Because of this, chemical additions were not considered because of their impact on the lake and ecosystem. Lime addition was also not considered because of the given pH value of the lake. Adding limestone to the sediment prevents the accumulation of methylmercury by helping neutralize an acidified lake. The provided pH data showed that Lake Berryessa has a pH of 6 or above year round, and so lime addition wasn’t considered.

Hypolimnetic oxygenation is an alternative that is effective for mercury concentrated sediment, but is costly to apply. During our site visit, the lake manager has expressed that while aerating the sediment would be a good design for the mercury problem in Lake Berryessa, the lake is too deep for this method to be cost effective. The design must take into consideration the length and cost of the pipe system, the cost of the pumping system to get water oxygenated, the energy cost needed to run the system, and the maintenance cost. These costs are outside the interest of the lake manager. This is why this method was not chosen for the final design.

Phytoremediation was concluded to be the optimal solution for Lake Berryessa. Rather than preventing the methylation of mercury, it was determined that a better alternative was to control the inflow of elemental mercury into Lake Berryessa. To achieve long term mercury control, it is essential to limit the amount of mercury which enters the lake. A summary of impacts are listed in the feasibility attached below. The project team also provides their rationale as to how applicable different methods are to Lake Berryessa.

Data Collection

Data was collected from a site visit, internet sources, and scholarly papers. The information was used for determining the best remediation method for Lake Berryessa, as well as for designing the parameters of the recommended control.

Literature Review

Current remediation strategies were researched using the UC Davis Library database and Google Scholar. The different studies came from a multitude of sources. Based off of the constraints, the most applicable methods for Lake Berryessa were hypolimnetic oxygenation, phytoextraction, and selenium addition.

Site Visit

On May 2nd, the team conducted a site visit to the Monticello Dam alongside Alex Rabidoux, Solano County Water Agency's supervising water engineer. Before the visit, a list of questions regarding management practices and reservoir characteristics were prepared for Alex Rabidoux. During the interview process, a list of constraints was compiled and is shown in Table 1. The team learned that no controls are currently being implemented because the Solano County Water Agency does not consider mercury contamination to be a high priority issue. Although mercury contamination data is not measured by Solano County Water Agency. However, he provided a two year old study on pH levels and dissolved oxygen levels in the reservoir. Alex stated that most of the mercury is contributed by the inflow from the tributaries.

Table 1. Constraints Summary

Constraint	Reasoning
Costs (initial costs, O&M costs, etc.)	SCWA requested that the control study is cost effective.
Technical Feasibility	The natural landscape of Lake Berryessa must not inhibit the implementation and maintenance of the control study.
Environment Impact	The control study must not directly harm wildlife or water quality in the region.
Stakeholders	The control study must be compliant to the beneficial uses of stakeholders.

Methylmercury in Three Tributaries - Genevieve Sparks

A copy of Genevieve Spark's master's thesis was recommended to us by Stephen McCord. The thesis included the daily discharge rates and mercury loading values for the three main tributaries that feed into Lake Berryessa. Data for Upper Putah Creek, Eticuera Creek, and Pope Creek were provided. The contribution of mercury contamination was most significant in Upper Putah Creek, and so the design mainly focuses on this tributary only. The discharge and mercury concentration values for this creek were used to calculate how much plant biomass is needed to reduce the mercury to a target level.

Navionics

The Navionics website provides data on the depths of Upper Putah Creek at any given point. The website also provides distances between two points set by the user. This source was used to find an ideal spot along the creek that was shallow and narrow to support phytoextraction. The distance measuring tool helped in estimating the cross sectional area and wetted perimeter for the design calculations.

Results

The mercury loading through Putah Creek was calculated by multiplying the average water flow with the average mercury concentration. The volume of water which flows through Putah Creek is approximately 217 million liters per day with an average total mercury concentration of 3.96 ng/L (Sparks 2017). These values equate to a daily mercury loading of 0.859 grams per day into Lake Berryessa. The mercury uptake rate of *Vallisneria spiralis* is dependent on the concentration of mercury in the water and the contact time. A previous study examined the varying uptake rates of *Vallisneria spiralis* in different mercury concentrations. This data was plotted, as shown in Figure 4, and used to extrapolate the uptake rate in mercury concentrations conditions similar to Upper Putah Creek (Gupta and Chandra 1998). The absorption rate at 3.96 ng/L was calculated to be approximately 391.4 $\frac{\text{ng Hg}}{\text{g Plant}}/\text{day}$ These calculations are shown in Appendix A.

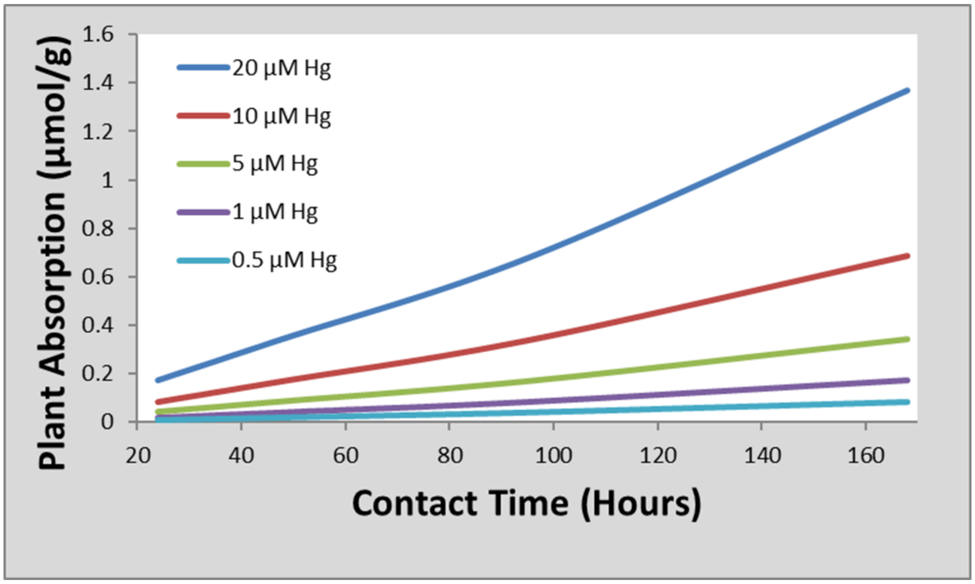

Figure 4. Plotted *Vallisneria spiralis* Uptake Rates in Varying Concentrations of Mercury (Gupta and Chandra 1998)

The proposed remediation site was selected after examining topographic data obtained from Navionics. This location had a waterway which was wide, shallow and had a relatively flat riverbed. These characteristics maximize the riverbed surface area, allowing more *Vallisneria spiralis* to be planted. The length of the river at the remediation site is 500 meters and has an average width of 80 meters. Using the topographical data, the average cross sectional area of the river at the remediation site was estimated to be 1,170 square meters. The volume of water within the site was calculated to be 1.88 million cubic meters. The estimated flow velocity of 0.00215 meters per second was obtained after dividing the river's flow rate by the cross sectional area. The water retention time of the remediation site was calculated by dividing the volume of water by the flow rate. This yielded an average retention time of 208 hours, or 8.66 days. A summary of the characteristics of the proposed design site is given in Table 2 below.

Table 2. Remediation Site Characteristics

Length	500 m
Average Width	80 m
Volume	1,880,000 m^3
Velocity	0.00215 m/s
Retention Time	208 hours

The desired mercury concentration reduction is 70%. To achieve this level of mercury reduction, at least 3150 kg of *Vallisneria spiralis* plant matter will be required, distributed throughout the riverbed of the remediation site. The initial setup will require 500 kg of starter plants which will cost a total of $50,000. These initial plants will mature and begin to proliferate through the use of underground runners. A minimum plant biomass of 3150 kg will be achieved after approximately 6 months, and a maximum density of 19850 kg will be achieved after 12 months. An illustration of the proposed design is modeled in Figure 5 below, and the specifics of the mercury loading and the associated plant biomass needed is listed in Table 3. Currently, it is unknown how much mercury *Vallisneria spiralis* is able to safely accumulate, so as a precaution, 3150kg of the plants should be maintained while the remaining amount is cut and disposed of every 6 months after the first year. Future studies should be conducted to determine the capacity of the plant so that cutting cycles can be optimized to reduce expenses.

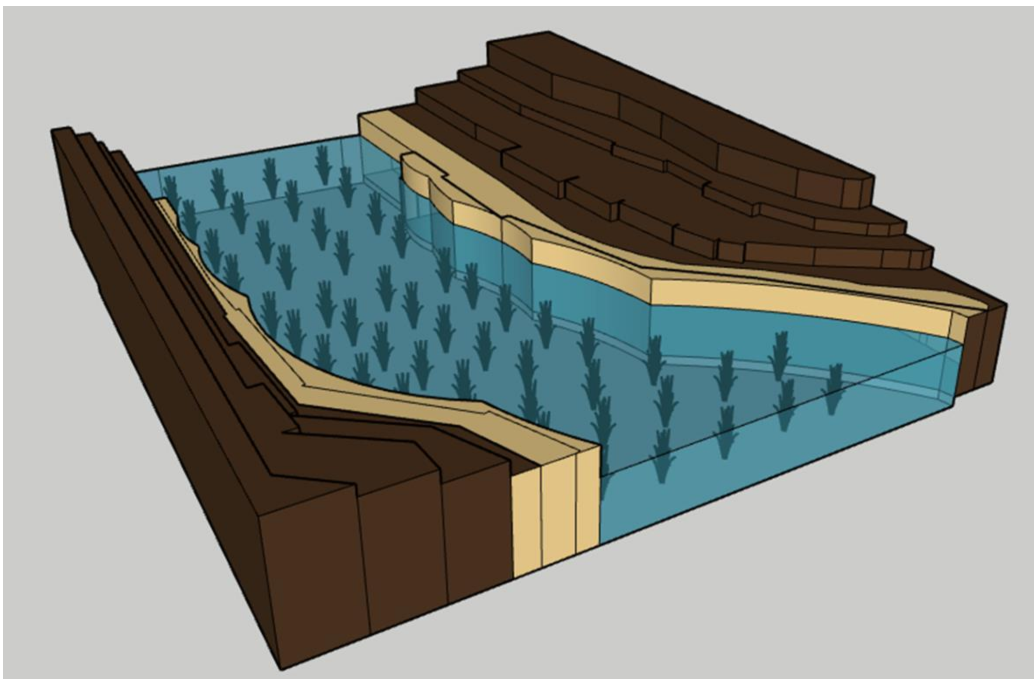

Figure 5. Sketched Model of Proposed Design Site

Table 3. Mercury Loading Summary

Average Flow	217 million liters
Average Mercury Concentration	3.96 ng/L
Daily Loading (Hg)	0.859 g/day
Plant Absorption Rate	391.4 ng Hg/(g Plant * day)
Plant Biomass for 70% Removal	3150 kg

Plant removal should occur during the summer or when the water levels are lowest. This will make the plants more accessible and reduce the costs of extraction. Plant removal can be done manually by hand or with specialized rakes dragged across the river. The entire plant, including its roots, must be removed during this process. Only 3150kg of plant biomass should remain in the remediation site, while the rest should be removed during the cutting cycle every six months after the first year of implementation. The plants will be removed in an alternating row pattern to allow the remaining plants to reproduce for the next cutting cycle. Afterwards, the extracted plants will be left to air dry for several days. This will reduce the weight and volume of the plants to reduce transportation and disposal expenses. The dried plants will then be transported by truck to Napa Recycling and Waste Services, located 39 miles away and disposed of. The cost of removal, transportation, and disposal is estimated to be $815 per ton. In the first year the plants are grown, the total cost for extraction, transportation, and disposal of 16,700kg after 12 months will be about $15,206. Every 6 months after that, 13,550 kg must be removed, which equates to $12,112. Outside of the cutting and disposal phase, the remediation site will require little to no maintenance and occasional monitoring.

Discussion

Design Performance

The design of this project is to minimize the methylmercury concentrations within Lake Berryessa. The metrics of success for this project is the amount of mercury prevented from reaching Lake Berryessa and the amount of mercury prevented from methylation by bacteria. To measure the success, a baseline must be established before the project design is implemented. The total elemental mercury will be recorded in the water of the tributary and in the sediment of Upper Putah Creek. Methylmercury concentrations will also be recorded in the tissue of 1 year old fish within Lake Berryessa. These monitoring tests will continue annually for the duration of the project. Additionally, samples of the plant tissue must also be taken to determine the levels of elemental mercury uptake. After conducting these four tests, success will be determined by these following criteria:

1. Elemental mercury is detected in the leaf and root tissues of *Vallisneria spiralis*, indicating that plant absorption is occurring.
2. There is a reduction in elemental mercury concentrations in remediation site sediment.
3. The concentration of methylmercury in Lake Berryessa fish is reduced.

Achieving these three criteria indicate that the project goals are successful. More frequent monitoring must be conducted when the results are unsuccessful. One limitation of the design is that there are two other sources of daily elemental mercury loading. The mercury from Pope Creek and Eticuera Creek can still bioaccumulate within the food web of Lake Berryessa, thus causing the change in methylmercury in fish tissue to be almost insignificant in the first few years. Methylmercury that is already present with the food web prior to the installment of the plants will also affect monitoring data of organic mercury within the fish tissue. Therefore, the monitoring of mercury contamination in fish tissue must continue over a span of years to observe significant changes in methylmercury levels.

Cost Analysis

The breakdown of the cost required in both the first year and the following years are summarized in Table 4 and Table 5. The costs to this control study can be split into the following:

Table 4. Cost Analysis (First Year)

Cost Type	Amount ($)
Initial Cost (Plants + Labor)	55,000
Extraction Cost	13,400
Transportation Cost	1,380
Disposal Cost	426
Total Cost	70,206

Table 5. Cost Analysis (Sequential Years)

Cost Type	Amount ($)
Maintenance Cost	21,280
Extraction Cost	2250
Disposal Cost	695
Total Cost	24,225

1. Initial Costs

The initial expenses include the cost of 500 kg of *Vallisneria spiralis* as well as the labor hours required to plant them in Upper Putah Creek. The cost of 1 kg of the plant is 100 US dollars. Therefore, it will cost $50,000 for 500 kg of plant. It was assumed that the hours it will take to plant will be 250 worker-hours. The average wage of a gardener is $20. So the cost of labor is $5,000. By adding the cost of the plant and the cost of labor, the total initial costs will be $55,000.

2. **Extraction**

The cost for extraction is based on how often the plants will need to be extracted. It has been determined that 16,700 kg of the plants will have to be removed for the first year. Removing this amount will still provide the theoretical 70 percent removal rate since 3150 kg of the plant will remain. It was assumed it will take 670 worker-hours for a gardener to extract the plant mass at a rate of 25.4 kg per hour. Using the average gardener wage, the cost of maintenance for the first year is $13400. This process does not require heavy machinery, so there are no additional costs.

For the following years, maintenance will occur bi-yearly so the plants will not overgrow and dominate native species. The total biomass every 6 months will be 16,700 kg. To keep a 70 percent removal rate, 13,550 kg of *Vallisneria spiralis* must be extracted. Using the plant extraction rate per hour, it will take 532 worker-hours to accomplish this task. This will cost $10,640 per 6 months, meaning $21,280 per year.

3. **Transportation**

The extracted plants will be allowed to air dry for several days to reduce their weight and volume. The dried plants will then be loaded onto a truck and transported to the Napa Recycling and Waste Services located 39 miles away. The cost of transportation is $75 per ton. For the first year, this project will generate 16,700 kg of waste, which equates to 18.4 tons of waste. Thus, the cost for transportation is $1380 for the first year of implementation. The sequential years will generate 27,100 kg of plant biomass per year, which is about 30 tons of waste. The cost for transportation for the following years will then be $2250.

4. **Disposal**

Once the waste is brought to the Napa Recycling and Waste Services, it will be properly disposed at the rate of $23.14 per ton of waste. The first year will require $426 to dispose the 18.4 tons of waste. The following years will cost $695 to dispose 30 tons of plant waste.

Risk Analysis

There are associated risks when *Vallisneria spiralis* interacts with the surrounding environment because of the mercury that the plants uptake. For example, by planting the *Vallisneria spiralis* along the waterway, it is susceptible to being reintroduced into the food web through herbivores. However, the elemental state would not be as harmful to the organisms that consume it. Since the mercury is not in its organic form, it is less likely to bioaccumulate within the food chain. The elemental mercury that is accumulated by the plants is not significantly harmful when consumed.

The location of the plants along the river bed also makes the plants susceptible to being uprooted during high flow events and transported into Lake Berryessa. If these plants with absorbed elemental mercury decay at the bottom of the lake, the mercury within the roots and leaves of the plant are vulnerable to methylation. If this happens, the mercury load absorbed by the plant will be reintroduced to the system. Despite the high flow rates, the velocity of the water isn't quite as fast at the riverbed than it is at the surface. The friction slows the water to prevent the uprooting at the lowest level of water. The design is not guaranteed to keep all of the plants in place, but losing a few to the flow is a minor risk.

There is also an associated risk with introducing a nonnative plant species into the ecosystem. Since it is not native, there is a possibility of *Vallisneria spiralis* pushing out other plant species in the area. If the plant is not properly maintained, the plant can continue to grow further upstream. To prevent the plant from travelling upstream, the plant must not be allowed out of the specified site of 500 meters. This can be maintained with the biannual extraction. Along with extracting the plants within the design site, any plants outside of the site must be extracted as well.

Design Sustainability

To prolong the life of the project, sustainable practices were implemented into the design. In this case, sustainable practice is defined by the EPA as, "Maintaining the natural resources in the environment to sustain present and future generations" (Learn 2016). The design reflects the goals of sustainability in its extraction plan. Each year, only a portion of the plants are extracted, while some of the plants are left untouched on site. Reproduction is the main method for restoring the missing plant mass from extraction. Since reproduction is dependent on the plants already present, more plants do not have to be bought and planted at the site. This method reduces the resulting yearly waste of natural resources.

Recommendation

If this study is proven to be successful, the design can be further improved to reduce methylmercury contamination in Lake Berryessa. The uptake rate of the site is largely dependent on the water level and the velocity of the flow in the tributary. Since these values differ from year to year, the required amount of plant biomass can be adjusted accordingly. Further studies can also be conducted to determine the maximum capacity of mercury each plant can hold. By doing so, the design can operate at maximum efficiency without planting or extracting more *Vallisneria spiralis* than needed.

If the *Vallisneria spiralis* is proven effective in absorbing the mercury in the flow, then the project team recommends that a similar design be implemented in the other two main tributaries. Pope Creek and Eticuera Creek contribute a total mercury loading of 2.19×10^{-7} mg per day and 7.74×10^{-8} mg per day respectively. Based on the data of mercury uptake rates of the plant, the amount of plant biomass needed for 70% removal in the other two creeks can be found. Monitoring would have to be continued to make sure the mercury contamination is successful in the other two tributaries as well.

Currently, the design calls for disposal of the plants at a landfill site in Napa County. Rather than disposing the plants at a landfill site, the extracted plants could be converted to biofuel or compost. These alternate disposal methods require extra processes to separate the mercury from the plant. These methods are more environmentally sound since the mercury is isolated and handled appropriately as hazardous waste material (Kucharski 2003). Further studies can take into account these disposal methods and incorporate into the project's overall costs.

Another recommendation is to include other effective mercury removal plants along the side banks of the creek. One aspect of the design that can be improved for further use of this method in California is finding a native plant with similar properties. One possibility is a variation of the *Vallisneria* species, which is *Vallisneria americana.* Although, this plant is native to California, no research was available for its uptake rates. Further studies would have to be conducted to find the associated uptake rate. Another possibility that was researched was the Arroyo Willow, a sandbar shrub that has shown evidence of mercury absorbed in its roots. These plants can be planted along the banks of the stream where it will have contact with the upper levels of the water. Introducing these California native plants to the water can further increase the removal rate and decrease the daily mercury loading into Lake Berryessa. Additional testing could be performed to determine the uptake rate of the Arroyo Willow, and having the combination of the Arroyo Willow and *Vallisneria spiralis* would be optimal for Lake Berryessa's conditions. Doing so can improve increase the success of the phytoextraction design.

Conclusion

From the available methods of mercury control and the site constraints, phytoextraction was the best option for remediation at Lake Berryessa. A total of 3150 kg will be planted on a 500 meter stretch of riverbed to achieve 70% removal in Upper Putah Creek. Each year during the dry season, the plant biomass will be brought back to 3150 kg for the 70 percent removal. The following years, the plants will be extracted biannually to keep them from overgrowing. Reproduction will restore what was extracted. This design will cost $70,206 the first year and $24,225 the following years.

To transition from the project design to implementing it onto the design site, permits have to be acquired before any action is taken. For example, the EPA must approve *Vallisneria spiralis* to be introduced into the habitat. Also, since the plants will increase the friction along the riverbed of the tributary, a permit will need to be acquired since the flow will be altered. Once all the permitting is completed, laborers will have to be hired to both plant the *Vallisneria spiralis,* as well as follow the extraction plan for disposal of the waste.

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