Intensive Fishing for Remediation of Mercury Bioaccumulation in Fish at Indian Valley Reservoir, California

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Executive Summary

Mercury is known to be toxic to human and ecosystem health. McCord Environmental, Inc., requests from HXB Corporation to propose a potential control study that can ameliorate the mercury issue in mercury-impaired Indian Valley Reservoir. The objective of this report is to propose a control study to remediate the mercury bioaccumulation in fish.

This report examines fifteen potential control studies and eliminates those not suitable for Indian Valley Reservoir. To determine the most appropriate control study, HXB conducted a site visit and interview with the lake manager, Tim O'Halloran from Yolo County Flood Control and Water Conservation District, to fully understand the physical characteristics, site condition and management objectives of the reservoir. Research, site visit, and interview helped HXB to narrow down one control study that best fit the condition of IVR: intensive fishing.

By collecting a sufficient amount of data from the Department of Fish and Wildlife and General Fish Survey from the Water Resources Control Board, given by Dr. Stephen McCord, HXB proposes two alternative designs to operate intensive fishing operation. Alternative 1 and 2 differ in use of material and cost. Comparing the two alternatives, HXB decides to recommend alternative 2, which has a shorter duration, lower cost, and more incentives.

Introduction

Indian Valley Reservoir

Owned and managed by the Yolo County Flood Control and Water Conservation District (YCFCWCD), Indian Valley Reservoir (IVR), shown in figure 1, is a man-made lake created in 1975 for flood control, irrigation, and water storage. Located in Lake County, California, the six-mile long, one-mile wide reservoir has surface area of 3,975 acres and serves as a warm-water fishery and a home to a number of fish species, including Kokanee Salmon and Rainbow trout. It is situated on the north fork of Cache Creek, and flows through the Capay valley, into Yolo County. Included in IVR's service area are the cities of Woodland, Davis and Winters, and the towns of Capay, Esparto, Madison and other small communities within the Capay Valley. YCFCWCD manages the use of surface and groundwater resources and to provide Yolo County with a "safe and reliable water supply at a reasonable cost" [1]. Because of IVR's creation, the District has a larger water supply and storage to help the recovery of groundwater to protect Yolo County from drought.

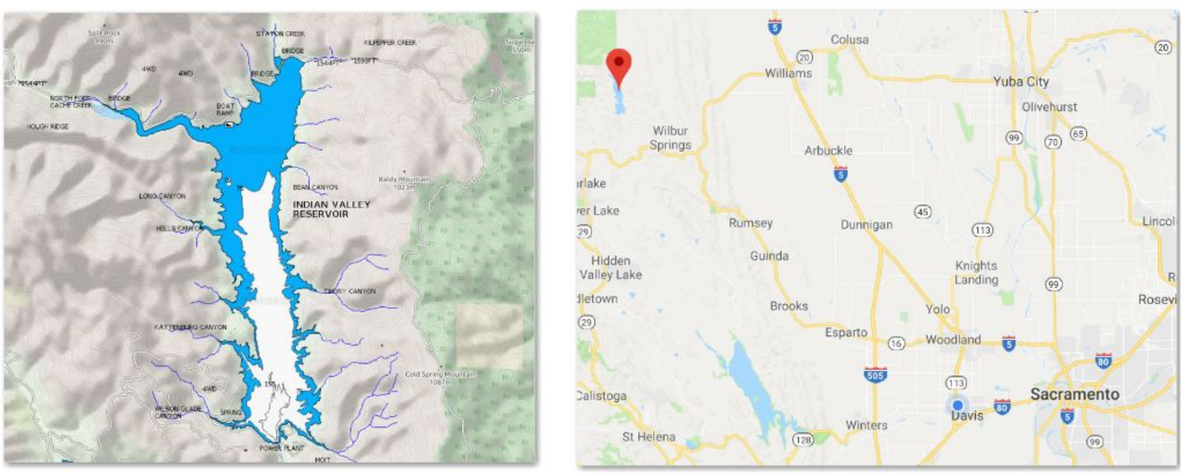

Figure 1: Indian Valley Reservoir Location Relative to Sacramento

In addition to IVR's many services, it also provides energy through a power plant. The 201-foot-high, earthen dam and hydroelectric power plant, shown in figure 2, named the Indian Valley Dam, is "located across the north fork of upper Cache Creek, creating the 301,000-acre-foot capacity"[4]. The hydroelectric facility has a capacity of 3MW and provides 1,998 Net MWh.The catchment area for the reservoir is approximately 121 sq.mi.

Figure 2: Earthen Indian Valley Dam (Left) and Hydropower Plant Pump (Right)

During 1975-1976, Indian Valley Reservoir experienced an extreme drought that led the reservoir to its minimum pool stage [2]. The Department of Fish and Games (DFG) chemically treated the reservoir in 1976 to eradicate carp and other species were transported to other reservoirs. In 1977, they reintroduced rainbow trout, largemouth bass, redear sunfish, white crappie, black crappie, and channel catfish [2].

Recreational Activities

IVR is located on the east of Clear Lake, off of Highway 20, and down Walker Ridge Road. IVR is relatively remote but accessible by a dirt road over traveling over the mountain tops. Although the reservoir is remote and difficult to visit, frequent visitors prefer to keep the dirt roads rather than making an easier route, because they enjoy keeping visitation low.

IVR offers a variety of recreational activities, including camping, fishing, hunting, boating, hiking, bicycling etc. Though often overshadowed by nearby Clear Lake, IVR is visited by sport fishing clubs, such as online communities dedicated to fishing and camping. IVR is popular among its guests for its beautiful clean waters, and sports fishing, with an availability of a number of fish species, including Rainbow Trout and Kokanee Salmon.

Stakeholders

IVR's primary purpose is to provide a reliable water supply for the residents and stakeholders of Yolo County. In addition to its wide range of area, the reservoir is also situated on the north fork of Cache Creek, which flows through the land of the Yocha Dehe Native American reservation. The Yocha Dehe Wintun Nation is a self-governing Native American tribe who have historically inhabited the Capay Valley and are one the largest single stakeholder's dependent on the water for their farms, ranch, and winery.

IVR is heavily relied upon for irrigation, especially for farmers whose livelihoods depend on water for irrigation. Approximately 95% of the overall demand, the water released by IVR is for agriculture and irrigation, which makes farmers the largest stakeholders under the jurisdiction of the YCFCWCD with over 366,000 acres of farmland and a water demand of 866,000 ac-ft. [23]. Urban users follow farming as the second largest users of water, but are relatively minor in comparison to agriculture.

Problem Statement

Similar to many reservoirs throughout California, IVR is subject to the threat of mercury contamination. This reservoir is one of 131 registered mercury-impaired reservoirs throughout California and is susceptible to fish consumption advisories. The issue of mercury contamination threatens the ability of IVR to serve its' purpose.

According to the General Manager of YCFCWCD, Tim O'Halloran, "there are no obvious sources of mercury near Indian Valley Reservoir." However, atmospheric deposition is one of the primary sources of natural mercury contribution. HXB, Inc. aims to find a remedial process for mercury bioaccumulation at a low cost, while considering significant management objects.

Background

Mercury has been an issue affecting the ecosystem and human health for the past few decades. Since the 1950s, mercury contamination in lakes have become a major concern in the western United States. Mercury contamination is a serious issue affecting California's water supply with 131 mercury-impaired reservoirs. Mercury easily enters aquatic ecosystems through different ways shown in figure 4. It cycles through the ecosystem, which makes it difficult to fix mercury bioaccumulation.

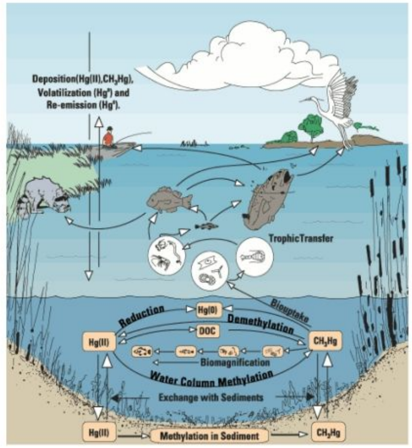

Figure 4: The Mercury Cycle in Aquatic Ecosystems [3]

Mercury Sources from Mining

In the 1850s, hydraulic mining was the most ideal method to extract large amounts of gold. According to "Mercury Contamination from Historical Gold Mining in California", mercury was mostly "used and lost at hydraulic mines than at any other types of mines" [7]. In hydraulic mining, placer would be crushed into a slurry and would flow through sluices and drainage tunnels. Liquid mercury would be poured into the sluices, forming gold-mercury amalgam, a mixture of gold and mercury [7]. The density difference between sand, gravel, gold and mercury caused gold-mercury amalgam to sink, while sand and gravel continue to flow through the sluice [7]. The left-over gold-mercury amalgam would be heated, vaporizing the mercury and leaving the gold behind.

The debris, which consisted of mercury, would stay at the sluices and drainage tunnels where the gold-mercury amalgam flows through. The contaminated debris would flood through downstream and contaminate the water. Also, it was possible that a turbulent water wash through the sluice before the gold-mercury amalgam is actually settled and formed [7]. Therefore, the mercury particles could be washed out and contaminate the water and soil. The mercury vapor would be collected in flasks after it was condensed [12]. It could be also leaked through the smelting process and caused a large amount of mercury released to the atmosphere [13].

Human activities (Non-Mining Sources of Mercury)

About two-thirds of total mercury emission in the United States comes from anthropogenic activities. [21]. Coal combustion, solid waste incineration and oil combustion are said to be some of the largest sources of mercury from human activity [15]. According to "Gas-phase transformations of mercury in coal-fired power plants", combustion activities are accounted for 87% of mercury emission from anthropogenic activity [16]. The mercury emission of coal combustion was estimated to be 51 tons per year [16] When elemental and oxidized mercury emits into the atmosphere from coal combustion, elemental mercury tends to travel in a longer distance than the oxidized mercury [16]. When mercury deposits on land or water, it will transform into methylmercury once the biochemical reaction occurs. Thus, it will affect the food web and ecosystem health, as well as the human health.

Atmospheric Deposition

Another major source of mercury is atmospheric deposition. Mercury can be emitted into atmosphere through natural and anthropogenic processes. Natural process includes evasion from soil and water, wildfires, vegetation surfaces and more [26]. Anthropogenic mercury sources mostly come from industry. Coal combustion, waste incineration, gold mining and metal smelting are examples of mercury emission from human activity. The major chemical form of mercury released from those two processes is Hg(0), a vapor form, with other chemical forms of mercury, such as dimethyl mercury and inorganic mercury compounds [20]. Anthropogenic source predominates the contribution of mercury emission to the atmosphere for about 70-80% [20]. The nature recycling process allows atmospheric mercury to deposit into water body and soil, and permits the occurrence of methylation in the ecosystem.

According to Tim O'Halloran, the general manager of YCFCWCD, IVR has no obvious point source of mercury. According to the Statewide Mercury Control Program for Reservoirs, Indian Valley Reservoir is located in California emissions hotspot, where "REMSAD (Regional Modeling System for Aerosols and Deposition) attributes more than 50% of atmospheric deposition to California anthropogenic emissions" [22]. The atmospheric mercury deposition around IVR can be seen in figure 3. This image shows that there is a high concentration of atmospheric deposition, which can be used to assume that atmospheric deposition is the main source of mercury.

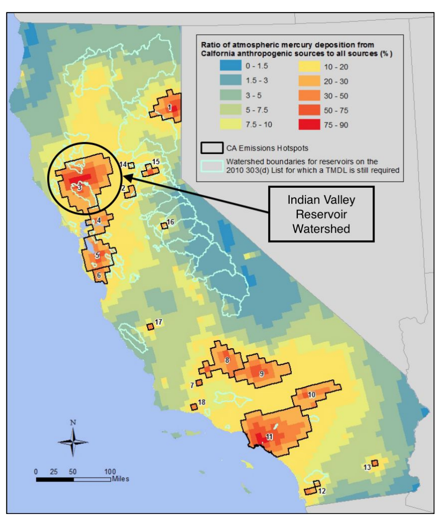

Figure 3: Statewide map showing the ratio of atmospheric deposition attributed by REMSAD to 2001 California anthropogenic emissions to total deposition [22]

Formation of Methylmercury in Aquatic Ecosystems

The formation of methylmercury in aquatic ecosystems is mostly due to sulfate-reducing bacteria (SRB), an anaerobic bacteria, that “obtain[s] energy for growth by oxidation of organic substrate” [6], which is mostly found in the top layer of the aquatic systems. SRBs utilize sulfate to convert sulfate to sulfide [6]: “if mercury is present, [it will be in compounds with] sulfur in the form of Hg(II) compounds… that are then converted to methylmercury.” [3]. According to “Effects of sulfate reducing bacteria and sulfate concentrations on mercury methylation in freshwater sediments,” the process of mercury methylation is related to “sulfate reduction catalyzed by SRB” [6].

Methylmercury is also formed in sediments through microbial species, mercury bioavailability, temperature, sulfur and organic speciation, organic matter, and redox condition [5]. According to the article “Effects of sulfate-reducing bacteria on methylmercury at the sediment–water interface,” microorganisms highly impacted the methylation process in aerobic stages. The microorganisms in aerobic stages demonstrae less methylmercury concentrations where there is a high dissolved oxygen content [5]. The study in the article also concluded that “[t]he order of factors that affect the release of methylmercury is “DO > substrate > weight > pH > temperature” [5].

Mercury Bioaccumulation

According to “The Cycling of Mercury Through the Environment,” mercury tends to be more soluble “in hydrocarbons than in water”, which allows mercury to get into lipid-rich cell membranes of living organisms [8], and forms methylmercury. Methylmercury can bioaccumulate in species.

When predatory fish eats organisms containing methylmercury in their tissues, the predatory fish will be contaminated by methylmercury and obtain a higher toxic level than the eaten organisms. This process is called mercury bioaccumulation. Methylmercury will bioaccumulate up the food chain as fish are consumed by fish-eating birds and human. The issue of methylmercury affects the ecosystem and human health

Effects of Mercury Bioaccumulation

Methylmercury contamination in fish can cause severe health effects on humans and other fish-eating species. Methylmercury is the “only form of mercury that bioaccumulates in humans and wildlife, the only form of mercury that crosses the blood-brain barrier where it causes most of its problems, and the only form that accumulates in human neurological tissues” [3]. Methylmercury can cause health concern on fetal growth, neurologic function, the cardiovascular system, and immune function [14].

Background and Literature Review

Case Studies

Feasibility Tables

HXB reviewed multiple control studies that aim to remediate mercury bioaccumulation in fish. Table 1 is used to compare each control study's feasibility for IVR. Table 1 is the feasibility table, where the costs, design parameters, and effect on environment of each control study is compared to one another. These 15 control studies were considered as a remediation method to fix mercury bioaccumulation.

After meeting with Mr. Tim O'Halloran, the general manager for YCFCWCD, HXB understood that the main concern for choosing a control study to fix mercury bioaccumulation was the application cost. Thus, the team eliminated methods that were high in costs and those that were not feasible for Indian Valley Reservoir based on the design parameters and effects on the environment. They concluded that the top six options were lime addition, selenium addition, biomanipulation, phytoremediation, sediment sealing, and intensive fishing.

Control Study	Cost	Design Parameter	Effect on Environment	Advantage	Disadvantage	References
Adding Limiting Nutrients	Average	• Addition of Nitrate	• Growth dilution on fish • Can lead to a reduced amount of fish • Decreased transparency/clarity • Lower DO levels • Can lead to increased food resources	• Additions of nutrients, such as Nitrogen and Phosphorus, are good for agriculture • Increases growth rate of fish causing dilution of MeHg in the fish	• Increase in primary productivity can lead to increase in greenhouse gas production and anoxia	[33]
Hypolimnetic Oxygenation	High	• Increase oxygen levels in hypolimnion [2]	• Creates cool habitat for fish especially in the summer • Prevents release of iron, manganese, sulfide to the sediments • Higher DO levels to limit amount of mercury	• Reduce SRBs	• Turbulence in layers causes temperature to mix	[2] [34]
Destratification or Vigorous Epilimnetic Mixing	High	• Air injecting diffuser or mechanical axial flow pumps	• Deepening of thermocline and oxycline • Improved dissolved oxygen level, water supply quality	• Benefit coldwater fish • Reduction in phosphorus	• May make lake uninhabitable for cold water fish	[35] [37]
Increase Light Exposure (Photo Demethylation)	High	• Build a shallow pond for water to expose to the sunlight.	• Decrease MeHg concentration in water • Increase water clarity	• No chemical involved in the process	• Can only deal with water portion by portion • Can only affect the downstream	[36] [38]
Intensive Fishing/ Fishing Harvesting	Low	• Removal of 25% of upper trophic level fish biomass	• Reduces mercury levels in fish • Reduced methylmercury for remaining biota	• Fish stocking speeds up process • Reduces	• Does little to affect water or sediment quality • Not a treatment process	[37]
Adding Selenium	Low	• Selenium is put into a biodegradable rubber material suspended from surface solution [39]	• Aquatic organisms can be in high risk of selenium toxicity [39] • Low levels of Selenium will lead to increase MeHg levels in fish [39]	• Effective	• Potential toxicity if Selenium level in the water is high • Water column toxicity at >2ug/L	[39] [33]

Control Study	Cost	Design Parameter	Effect on Environment	Advantage	Disadvantage	References
Sediment Dredging	High	• Remove bottom layer of sediment	• Reduce the concentration of contaminant in sediment	• Dredged sediment can be sold	• Destruct the existing benthic ecosystem • Increase turbidity of water • No practical for large reservoir • Require accurate site characterization	[33] [39]
Sorbent Amendments	High	• Apply Activated Carbon (AC) to the bottom of sediment layer.	• AC binds with contaminant particles, and thus, reduces the bioavailability uptake of benthic organisms. • Reduce the contaminant diffusive flux from sediment to water	• Effect on where legacy contaminiantion is found • Opportunity for efficient resource utilization for AC • Minimize carbon footprint	• Potential toxicity of AC to benthic organisms • Reduce the uptake bioavailability, but not reduce the actual contaminant concentration in sediment	[33]
Adding Lime for pH control	Low	• Depending on the volume, pH level, targeted pH, and water salinity • Add calcium carbonate	• If reservoir is acidic, can help neutralize pH [6]	• Easy application • Efficient implementation of selected technique can reduce expenses	• Effective only in short term • The calculation on deciding amount of lime added varies and not lead to accurate liming results	[40] [41]
Water Level Control	High	• Control the maximum/minimum volume of the reservoir • Control the outflow during drawdown and refill	• Reduce the exposure rate of sediment during the critical spring and summer growing seasons	• Stable lake level will improve shoreline for humans • Reduction in Fish total Hg occurring from 3 to 12 years after reservoir impoundment	• Less fluctuation restricts primary uses of flood control and hydropower • Effects on Oxygen levels, pH levels, and nutrients level	[42]
Selective Withdrawal		• Discharge of poor quality water with undesirable features (anoxia, algae)	• Potential for resuspension and capture in discharge/intake • Potential loss of hypolimnion, stratification, need to treat discharge for downstream	• Removes target water efficiently • Works well with other techniques that use drawdown or aeration	• May reduce water level if summer flows not substantial • May result in poor water quality downstream • Bad for cold water fish	[33]

Control Study	Cost	Design Parameter	Effect on Environment	Advantage	Disadvantage	References
Education and Outreach	Low	• Educate people who closely relate with Hg, such as fishermen, medical professionals and high risk populations • Propose fish consumption advisory	• Reduce human exposure to Hg	• Wildlife is not affected • Based on sites and fish species	• Not as effective • Not a popular method • Based on voluntary of people and cannot regulate what other people are doing	[33]
Biomanipulation	Average	• Manipulation of trophic structure • External nutrients loading need to be reduced prior to biomanipulation	• Increase the piscivorous fish (fish who eats fish), and thus, reduce planktivorous fish (fish who eats plankton), then results in increasing the amount of herbivorous zooplankton with consequence of algae reduction	• Improve water clarity • Improve algae condition	• Decrease in nutrient (Nitrogen and Phosphorous) concentration that will affect the water condition for irrigation	[17]
Phytoremediation	Average	• Use of genetically engineered plants to absorb contaminants through natural processes and demethylate organic mercury	• Improves overall water quality in addition to targeting contaminants	• Potential use of native plants • Improved habitat • Natural look	• Increased cost due to removal and disposal of plants • Potential adverse effects to wildlife if eaten	[43]
Sediment Sealing	Low	• Sediment containment by placing a layer of isolating sediment (usually sand) between contaminated sediment and water	• Low adverse environmental effects •	• Suitable for wide range of contaminants • Absorbs or contains mercury in capping material • Low cost	• Not a treatment process but containment • Not long term solution • Potential for capping material to be uplifted by hydrodynamic flow, recreation activity...	[44]

Liming Addition for pH Control

Mercury bioaccumulation occurs more in lakes that have low pH or are acidic [1]. Lake acidification is mostly due to “burning of different fossil fuels… [and] acidifying substances” [1]. Acidic lakes have other toxic effects to aquatic species aside from mercury bioaccumulation and the addition of lime to control the pH level in the lake. This control study aims to neutralize acidic lakes by adding limestone, also known as calcite or calcium carbonate ($CaCO_3$), to control the pH level and mercury bioaccumulation rate. According to Virginia Tech, liming has many advantages: “inexpensive, available, non-toxic, natural mineral, easy to distribute, [and easily] dissolves in water” [1].

Liming requires about 1-2 tons of lime per surface acre and reliming is only necessary based on the size and acidity of the lake. The most common and inexpensive way to apply lime is by throwing limestones “into the wake (prop wash) of a moving powerboat” [1]. Another way is to mix limestone and water and “pumping the mixture into the lake”, which increases the dissolution by 25% [1]. When applying limestone, it should be spread out the whole surface area of the lake. As mentioned before, purchasing lime is cheap (about $10-50 per ton) because of the easily accessible material. Most of the cost for this control study is mainly due to “transport, labor, and the application equipment” [1]. The cost is also dependent on how often application is necessary. Annual treatments only require a smaller dosage than the first one.

Selenium Addition

Similar to mercury, selenium (Se) also bioaccumulates up the food chain. However, selenium instead assists the remediation of aquatic ecosystems affected by methylmercury; there are studies that show that “organism Se concentrations are inversely correlated to organism Hg levels” [23]. Sodium selenite is carried by a rubber material in a sack to have a controlled release when it is added to the water about 1-2 meters deep. One negative about selenium addition is that it requires multiple applications but requires a smaller dosage after the first application. The application of selenium is dependent on how uniform the selenium presence in the lake. Adding selenium improves “biological functions involved in antioxidant defense, immune responses, thyroid function and muscle metabolism” [23]. Selenium competes with mercury in the organism’s tissue; thus, an increase in selenium will reduce the amount of mercury in aquatic species’ tissues.

Biomanipulation

Biomanipulation aims to reduce the amount of algae in the water body in small reservoirs. The primary goal of biomanipulation is to reduce the amount of planktivorous fish that eat zooplankton and phytoplankton in the reservoir, which will increase the amount of herbivorous zooplankton. The consumption rate of phytoplankton will increase based on the faster growth rate of zooplankton; hence, the amount of algae is consumed at a faster rate. One of the main advantages of this specific method is that the algae problem and water clarity of the water will be improved.

Furthermore, biomanipulation can also reduce the nutrient level in the lake. Nutrient concentrations of nitrogen and phosphorus has been observed to decrease after two years of applying this control study [16]. The study speculated that the reduction of nutrient levels may be due to the "increased formation and sedimentation of fecal material after bioaccumulation" [24]. In addition, biomanipulation is less expensive for treating algae than other methods and has a shorter duration: it is expected to last for two years when the reservoir's food chain is maintained with "planktivore , piscivores, and benthivores [24]."

Phytoremediation

Phytoremediation is a method of mercury remediation that takes advantage of the natural ability of plants to reduce the mercury content in aquatic systems. Plants can remediate mercury through a variety of natural methods, including Phyto-stabilization or Phyto-degradation, which are natural processes that plants undergo to convert or break down pollutants [43]. However the limitations of natural plant life include their inability to detoxify methylmercury. Natural plant life is also limited in the capacity that certain species have for tolerating mercury.

The solution to this issue is to develop genetically engineering plant species to have a greater capacity for the removal and volatilization of methylmercury in aquatic systems. Genetically engineered plants can be manipulated to include two specific enzymes, MerA and MerB, to help increase the capacity of plants in remedying the issue of methylmercury. The enzyme MerB is used to convert methylmercury (MeHg) to ionic mercury (Hg^{2+}), and the MerA enzyme is used to further convert the ionic mercury (Hg^{2+}) to elemental mercury (Hg), which then volatilizes [43]. This method has been applied towards a number of plant species, including tobacco, yellow poplar, and a variety of wetland species.

One of the advantages of Phytoremediation is the possibility of a permanent in-situ remediation process. Once placed, the plants will perform their natural processes and do not need to be monitored as closely compared to other methods. Secondly, this method does not interfere with reservoir management objectives due to its natural aesthetic. Finally, phytoremediation comes at a relatively low cost, making it significantly cheaper than other possible methods.

Sediment Sealing

Sediment sealing is the process of placing a layer of finer-grained sediments, usually sand or clay, over the bottom of the reservoir to block or absorb mercury within sediments in the reservoir bottom. The finer-grained sediments form a physical barrier that prevents mercury from being suspended into the water column. Sediment sealing also has the effect of lowering methylmercury production and bioaccumulation rates. Sediment sealing has the advantage of having a low cost and is relatively effective in reducing the introduction of mercury to overlaying water. Sediment sealing also blocks other contaminants existing in the lower sediments, such as cadmium, lead, or other heavy metals. It is important to consider that in shallow or fast-moving waters, the sealing layer could be disturbed, which will reduce effectiveness. Activities such as swimming or boating also easily disturbs the sealing layer.

Intensive Fishing

Intensive fishing is a method of reducing mercury levels in fish through the removal of a large portion of fish biomass. To be effective, intensive fishing requires 25% or more of the fish biomass removed from the reservoir. There are multiple mechanisms that explain how intensive fishing is successful; however, there is no dominant explanation [28]. A few hypotheses explain the mechanism behind intensive fishing and the resulting lower mercury levels in fish.

The hypothesis behind intensive fishing is that "by removing an important part of the fish biomass from a lake, a significant amount of methylmercury can be eliminated, therefore reducing the mercury available to the remaining biota" [29]. While this method will not reduce overall mercury levels in the reservoir, it aims to reduce the bioaccumulation available to fish; thus, intensive fishing dilutes mercury concentration in fish. The drawback of this method is that the duration of this method ranges per application. However, it is safe to assume intensive fishing will take at least 8 years to be effective, taking four years for the mercury concentrations in fish to reach their lowest, and another 4 years for the mercury concentrations to rebound.

Methods

Project Development Process

This subsection explains the development process of the design. The processes of researching available control studies on mercury remediation and collecting data on IVR are described in detail below. After conducting research and collecting data, HXB utilized all the known information to narrow down the control studies. The process of choosing the most feasible control study is discussed in this subsection.

1. Research Control Studies

A literature review was conducted to find possible control studies to mitigate the effect of mercury in aquatic systems. Based on known information about IVR and remediation processes, 15 possible mercury remediation studies were chosen to be further researched. Each method was listed in a feasibility table, shown in table 1, to compare characteristics that would affect the improvement of mercury bioaccumulation in fish.

2. Data Collection

HXB conducted an interview and site visit with Mr. Tim O'Halloran, the general manager of YCFCWCD. The site visit served to further clarify IVR's physical location, biological features, and management objectives, and the interview clarified the management practices and perspective towards the remediation of mercury contamination in the reservoir.

Mr. O'Halloran provided further information on IVR's pH level, fish population, and physical characteristics. In addition, the team was given a compiled set of data by the project sponsor, Dr. Stephen McCord. This data set provided information from the Water Resources Control Board about the mercury concentration, length, and weight of collected fish, which greatly assisted HXB in their design process.

3. Establish Management Objectives

The next step was to establish the management objectives of IVR based on the site visit, interview and background of the reservoir. Establishing the management objectives of the reservoir is important in designing a control study that is most applicable to IVR. The management objectives that HXB considered are listed below:

> Cost
> IVR has a limited budget. In order to provide water to customers at a low cost, IVR must keep overall costs low to maximize the benefits of the stakeholders.
>
> Ecosystem
> In addition to its other management objectives, protection of the ecosystem is important to the management of IVR. The ecosystem includes wildlife and the surrounding environment that are dependent on IVR. The surrounding vegetation aids in erosion control and water quality of the reservoir, while the surrounding wildlife plays an important role in the ecosystem.
>
> Irrigation
> Agriculture is integral to the economy or Yolo County, which makes farmers one of IVR's largest and most significant stakeholders. IVR was created for the purpose of providing a reliable water supply for irrigation to Yolo County.
>
> Recreational Activities
> IVR provides an area for recreational activities, such as camping, fishing, boating, and hiking. The purpose of the recreational activities is to bring enjoyment and pleasure to visitors.

4. Rank management objectives based on importance

The next step was to rank the management objectives based on importance to the reservoir's purpose. Ranking management objects is a vital step to choose a control study that serves the management's objectives. Without meeting their objectives, the control study will not be implemented knowing that it would harm IVR's services to Yolo County. The following management objectives are ranked in order of importance based on a site visit, interview, and background information.

1. Cost

Cost is the most important management objective, which will be the main concern in deciding a control study. If the cost extends beyond IVR's limited budget, the study will not be implemented. IVR does not have the funds to attempt a control study that has a high cost unless there is a cost-effective benefit to the reservoir; thus, choosing a control study that is economically feasible for the management is the most important objective to focus on.

2. Irrigation

After determining whether a control study was within IVR's budget, the second thing HXB considered was irrigation, which is the primary service of the reservoir. Nearby farmers rely on IVR to distribute water sources to their crops. Therefore, the chosen control study should not affect the quality of the water to prevent any negative impact on nearby agriculture. Thus, any control studies that interfere with the irrigation supply should not be considered.

3. Recreational Activities

Recreational Activities must also be considered as an important management objectives. IVR has many visitors throughout the year, and maintaining the reservoir's ability to serve as a place of enjoyment for visitors is important to consider. Any control studies that may negatively affect visitors of IVR, such as studies that require unsightly heavy equipment or affect the clarity of water around the shorelines, must be considered.

4. Ecosystem

The state of the surrounding ecosystem was the next management objective to consider when eliminating control studies. It is important that any control studies considered do not interfere negatively with the ecosystem. Any damage to the environment could result in a larger problem for the reservoir's ecosystem or water quality, and could negatively affect wildlife that rely on the reservoir, and so needs to be considered

5. Narrowing Down Control Studies

Taking into account IVR's main concern, HXB narrowed the possible control studies down based on costs and the requirements of the control study. Knowing the difficulty of traveling to the reservoir, specifically the dirt, narrow road, HXB removed the control studies that required heavy equipment. Focusing on the cost of each method, the company narrowed it to 6 studies, described in “Case Studies” section, that could possibly be a suitable option to fix mercury bioaccumulation in fish in Indian Valley Reservoir. After further research, HXB looked into certain requirements and precautions that were necessary for those 6 control studies. With this knowledge, HXB was able to narrow down to one method that was the most suitable for Indian Valley Reservoir.

Selenium addition was one of the top six choices that were chosen as a method to fix mercury bioaccumulation in fish because of its easy application and low cost. However, according to IVR’s Water Management Plan, there is a high level of selenium in the water already. One of the main precautions of selenium addition was the possibility of selenium toxicity in fish. Thus, selenium addition was not an option for IVR to avoid an excess of selenium concentration in the water.

Another possible method was biomanipulation, which focuses on the consumption of algae to prevent mercury bioaccumulation. However, IVR does not have an algae issues, biomanipulation is not a suitable option to fix mercury bioaccumulation for IVR.

Phytoremediation was another considered option; however, due to the unreliability of IVR’s water levels, the flooding or receding shoreline could damage the plants, making the fluctuations in the water level unsuitable for this method. If this method were to be used, stable water levels would be needed throughout the year.

One thing HXB could possibly control was the water, and lime addition for pH control neutralized the acidity in the water. However, one of the requirements of lime addition was that the lake had to be highly acidic, and IVR’s pH level ranges from 7 to 8.5. Thus, lime addition is not a suitable option for Indian Valley Reservoir.

In addition, the sediment sealing was also a possible option to reduce the amount of mercury in the water by containing the soil. However, since there are no obvious source of mercury, it is reasonable to believe IVR does not have any history of high mercury contamination in the sediment layer. Thus, focusing on soil to control mercury bioaccumulation was not the best option.

HXB believes that although there is uncertainty in mercury contamination source, atmospheric deposition is assumed to be the primary source of mercury in IVR. After speaking with knowledgeable personnel from YCFCWCD, HXB understood that mercury bioaccumulation in fish was an issue because visitors mainly come to IVR to fish in the reservoir. Thus, with a purpose of preventing people from eating contaminated fish, intensive fishing is the most feasible control study to remediate mercury bioaccumulation in fish for Indian Valley Reservoir at a low cost.

Data Collection

HXB, Inc. met with Mr. Tim O'Halloran for an interview and a site-visit. Before driving to the reservoir, Mr. O'Halloran explained how YCFCWCD uses the software Supervisory Control and Data Acquisition (SCADA) to remotely monitor the reservoirs they manage. The drive took about 1 hour and 30 mins from YCFCWCD's office (located in Woodland, California) to IVR. This site visit aimed to get a better understanding of the reservoir's characteristics and services.

HXB was shown different facilities around IVR during the tour with the lake manager. The Indian Valley Dam is secured by an emergency electric generator, shown in figure 5, in case of experiencing electricity shut down. The emergency electric generator provides energy for the areas around the reservoir in case there is no electricity.

IVR has a earthen dam that generates hydropower electricity, shown in the introduction figure 2. There is an underground pipe, shown in figure 6, that pumps water from the reservoir to the hydropower and releases the water at the north fork of Cache Creek, shown in figure 7.

Figure 5: Emergency Electric Generator

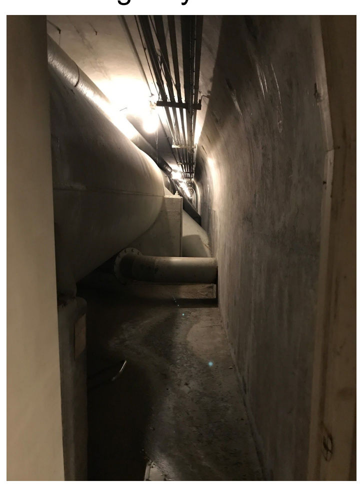

Figure 6: Underground Pipe Connecting Reservoir to the North Fork of Cache Creek

Figure 7: Release of Water to the North Fork of Cache Creek

Another part of IVR is an emergency spillway. The spillway is used when the reservoir reaches its capacity. The spillway gates, shown in figure 8, is lifted in three ways. One way the spillway can be activated is by rising up using electricity. Another way is a set of chains that pull the spillways up allowing the water to flow out of the reservoir. Lastly, as a precaution, if there is no electricity or man that would help pull up the spillway, the spillway will end up floating when the water reaches a certain depth. The spillway releases water into Cache Creek, shown in figure 9, where the pipe from hydropower dam also releases water.

Figure 8: Spillway Gates

Figure 9: Spillway released into North Fork of Cache Creek

Project Constraints

The primary constraint on the selection of a control study is the cost. The cost of a control study will determine whether it is worth considering. YCFCWCD has a limited budget, and their primary objective is to provide water for their customers at affordable rates. Therefore, expensive control studies are not considered.

Another limitation that must be considered before implementing the study is IVR's accessibility. The reservoir is located in a relatively remote area and is not as easily accessible as other reservoirs. The road to IVR is a 12-mile long, bumpy, narrow, dirt road traveling along the mountain tops, which would prove difficult for heavy equipment and machinery to access the site.

The water level of IVR is dependent on rainfall and irrigation outflows and will fluctuate from season to season. The water demand for irrigation will decrease during the winter season when less water is needed and increase during the summer when crops need more watering. As a result, the fluctuating water level will limit the effectiveness of certain control studies which require steady water levels throughout the year.

The most important goal of IVR is to provide reliable water source to its respective farms. Therefore, it is the best if the control study can avoid any impacts on farming. If the control study includes adding unwanted chemicals into the water, it could interfere with farming. Hence, control studies which are effective on reducing mercury concentration but harmful to farming irrigation will need to be considered carefully for IVR reservoir.

Results

Design Process of Intensive Fishing Based on Published Study

Intensive Fishing Explanation

Although, there are many possible mechanisms to explain how intensive fishing reduces mercury concentration in fish, many articles indicate intensive fishing as a successful mercury bioaccumulation remediation. Some mechanisms relate the removal of methylmercury from the water supply to biodilution, however there is no conclusive evidence on a dominating mechanism controlling the decrease in mercury concentrations.

The first mechanism behind intensive fishing relates to the natural flow of contaminants in biological systems by removing methylmercury in the reservoir. By removing an important part of the fish biomass from the reservoir, a significant amount of methylmercury can be eliminated from the system. The result is a reduced overall amount of mercury in remaining biota. The method does not affect the amount of elemental mercury in the reservoir but acts toward removing the amount of methylmercury in the system, thereby removing it from the flow of contaminants in the biological system.

The second mechanism behind intensive fishing involves biodilution. As higher trophic level species are removed from the system through intensive fishing, the smaller, lower trophic level species are able to grow and increase in population. The amount of methylmercury in the system however does not change. By increasing the population, the same amount of methylmercury in the system will be distributed through a larger amount of fish, meaning each fish has less methylmercury in their system. The distribution of mercury over a larger population effectively dilutes the mercury concentrations in fish.

Characteristics of Indian Valley Reservoir's Fish Population

Provided by Dr. Stephen McCord, a data set from the Water Resources Control Board was used to look into the fish mercury concentrations in IVR. There were information on the following caught fish: Channel Catfish (CHC) , Largemouth Bass (LMB), Common Carp (CC), Redear Sunfish(RS), and Pumpkinseed Sunfish (PS) [30]. The data set also included significant information on each caught fish: trophic level, mercury concentration, average length, minimum length, maximum length, and average weight [30].

Since the fish population in IVR is unknown, YCFCWCD's Mr. Tim O'Halloran provided Indian Valley Reservoir's General Fish Survey collected by the Resources Agency of the Department of Fish and Wildlife in 2013, which provides information to estimate the fish population of those known mercury-impaired fish species [31]. Pumpkinseed Sunfish is not considered for this design due to its low mercury concentration and unavailable population information. Based on the Fish Survey, CHC, LMB, CC and RS are 1%, 31%, 21% and 12% of caught fish population, respectively [31]. Table 2 summarizes fish characteristics from these two sources.

Fish Name	Trophic Level	Percentage of Total Population	Average Weight/fish (g)	Average Hg Concentration (mg kg^{-1})	Above EPA Mercury Safe Standards (0.3)?
Pumpkin Sunfish (PS)	TL3	N/A	59	0.27	NO
Channel Catfish	TL4	1%	669	0.4	YES
Largemouth Bass	TL4	31%	446	0.77	YES
Common Carp	TL3	21%	1752	0.46	YES
Redear sunfish	TL3	12%	58	0.28	NO

Table 2: Summary of Fish Characteristics [30], [31]

Moreover, based on the given data from Dr. McCord, the calculated average mercury concentration in CHC, LMB, CC and RS: 0.4, 0.77, 0.46, and 0.28 mg kg^{-1}, respectively. Fish species that contained an average mercury concentrations lower than the EPA safe standard of 0.3 mg kg^{-1} were removed as an option for intensive fishing: thus, the redear sunfish is not an option for removal in intensive fishing. Because CHC has the second lowest mercury concentration and had a small population percentage between the four species, Largemouth Bass and Common Carp were targeted for intensive fishing due to their high mercury concentration and high population percentage.

Calculation of Fish Biomass Removal

After deciding which fish species to target for intensive fishing, HXB needed to decide on a numerical target of fish biomass to remove. As mentioned before, for intensive fishing to be a successful remediation option for mercury bioaccumulation, 25% of the total fish population biomass needs to be eradicated from the reservoir.

In the article, "Effects of intensive fishing on the perch population in a large oligotrophic lake in eastern Finland," a study of intensive fishing was conducted in Lake Hoytiainen, which has an area of 293 km^2 and average depth of 11.8 m [32]. Intensive fishing is only applied to one section of the lake that is 3850 hectares and has a similar water depth as Indian Valley Reservoir [32]. Based on the design parameters of intensive fishing in Lake Hoytiainen, the fish biomass removal in IVR will be similar since there is unknown information about the fish population and requires further detailed examination by a biologist.

The surface area of examined section of Lake Hoytiainen is 3850 ha, which is 2.39 times larger than the IVR's surface area of 1608 ha. The total amount of caught fish from year 2001 to year 2004 of Lake Hoytiainen is 79,473 kg with average of 19,868 kg per year [32]. Thus, the amount of caught fish in IVR is determined by reducing the average amount of caught fish of Lake Hoytiainen per year by the size factor of 2.39, resulting in 8,313 kg.

The Indian Valley Reservoir General Fish Survey provided a table with a population percentage and average weight of the caught fish species. The population percentage is used as a basis to calculate the total fish population in IVR. The table in the fish survey includes fish species stated or not stated in McCord's dataset. During the calculation, for fish species given in sponsor's dataset, HXB uses the calculated average weight of the fish species to calculate the fish population, and for fish species not included in the dataset, HXB uses the average weight in the table given by the general fish survey.

Assuming the 25% fish biomass to be removed per year is approximately 8,313 kg, HXB calculated the total fish biomass in IVR to be 33,252 kg. Using the population ratio of the fish species listed in the fish survey report, equation 1 will be used to calculate the total fish population. In the calculation, the total fish population is set to be unknown, X.

Equation 1:

$$Total\ Fish\ Biomass = \sum_{i\,=\,types\ of\ fish\ species} (Population\ Percentage)_i \ast (Average\ Weight)_i \ast (Total\ Fish\ Population,\ X)$$

From the sponsor's given data, average mercury concentration is calculated with units of mg/kg. The mercury concentration of a given fish specie is calculated as Equation 2. The removed Hg concentration is calculated Equation 3:

Equation 2:

$$\begin{aligned} &Mercury\ Concentration\ of\ Given\ Fish\ Species \\ &\quad = Average\ Mercury\ Concentration\ of\ Given\ Fish\ Species \ast Given\ Fish\ Biomass \end{aligned}$$

Equation 3:

$$\begin{aligned} &Removal\ Mercury\ Concentration\ of\ Target\ Fish\ Species \\ &= Removal\ Fish\ Biomass\ of\ Target\ Fish\ Species \ast Average\ Mercury\ Concentration\ of\ Given\ Fish\ Species \end{aligned}$$

Using the equations above, fifty percent of calculated caught fish biomass from LMB and CC will be removed, which result in the removal of 4,157 kg of LMB and 4,157 kg of CC. Ratio of caught fish between fish species can be adjusted after a further sample analysis in IVR.

Based on the Indian Valley Reservoir General Fish Survey, the population of each fish species can be estimated. After calculation, the populations of CHC, LMB, CC, and RS are: 447, 13,868, 9,394, and 5,368, respectively. After the first year of intensive fishing, 9,320 LMB and 2,372 CC, are removed from the reservoir. The population of fish after removal of CHC, LMB, CC and RS is: 447, 4548, 7022, 5368, respectively. A summary of the fish population before and after intensive fishing can be seen in Table 2. The total amount of Hg removed from the reservoir after first year application is estimated to be 5,112.54 mg kg^{-1} .The fish biomass and mercury concentration before and after intensive fishing can be seen in Table 3, which demonstrates that intensive fishing can be successful, if done correctly.

	Fish Population Before Removal	Fish Population to Remove	Fish Population After Removal
Channel Catfish	447	0	447
Largemouth Bass	13868	9320	4548
Common Carp	9394	2372	7022
Redear	5368	0	5368

Table 2: Fish Population During Intensive Fishing

	Before		Removal		After		After	Before
	Fish Mass (kg)	Total Hg(mg)	Fish Mass (kg)	Total Hg(mg)	Fish mass (kg)	Total Hg(mg)	Hg Concentration in Fish	Hg Concentration in Fish
Channel Catfish	299.28	119.71	0.00	0.00	299.28	119.71	0.54	0.50
Largemouth Bass	6185.14	4762.56	4156.54	3200.53	2028.60	1562.02		
Common Carp	16459.11	7571.19	4156.54	1912.01	12302.57	5659.18		
Redear Sunfish	311.36	87.18	0.00	0.00	311.36	87.18		

Table 3: Fish Biomass Before and After Intensive Fishing and Effects on Mercury Concentration

Alternate Ways to Apply Intensive Fishing

In this report, HXB proposes two alternatives of the operational process of intensive fishing in IVR to achieve the suggested design. These two alternatives will be different in material used and overall cost.

For both suggested methods, fishermen and a biologists are needed during the intensive fishing process. Fishermen are expected to be knowledgeable of fishing to effectively catch fish and to classify LMB and CC. Biologists are needed to estimate the fish population to calculate the fish biomass before fish removal begins and to sample fish tissue to know the mercury concentration before the process begins and after every application. In the study of Lake Hoytiainen, the effectiveness of intensive fishing can be examined in about four years. The intensive fishing process is going to take about four years total, so the process will need to be completed every year.

Alternative 1:
One method of conducting intensive fishing is by fishing twice a year. The design of alternative option 1 is based on the study in Lake Hoytiainen mentioned above. Fishing will conduct during the fall and spring seasons to align with the spawning season. Every season, fisherman will need to take out approximate of 4,156 kg of fish. The seine net with bag and seine net without

bag account for 84% and 16% of caught fish biomass, respectively, assuming that only these two types of fishnets are used during the operation.Therefore, fishermen will take about five days with an approximately 700 kg of caught fish biomass using a seine net with bag and 133 kg using a seine net without bag for each day operation, shown in figure 10.The design of alternative option 1 is based on the study in Lake Hoytiainen mentioned above.

Figure 10: Seine Net with Bag (Left) and Seine Net without Bag (Right)

With each year, fishermen need a rental boat, which will cost approximately $1,490. The caught fish will be disposed into Yolo County Central Landfill, assuming the are not considered toxic, and are allowed to place into landfill. A truck is also needed to transport the caught fish from IVR to the landfill with roundtrip of 180 miles. The material specification and cost are listed in Table 4.

Table 4: Cost Estimation Table for Intensive Fishing Operation for Alternative 1

Expenses and Materials	**Unit Cost**	**Amount**	**Cost**
Seine Net with Bag (Reusable) Net size: ● Length: 500 m ● Mesh Size: 30 mm ● Height: 4 m Bag Size: ● Mesh size: 25-30 mm ● Height: 4 m	$11,190/net	1	$ 11,190
Seine Net without Bag (Reusable) ● Length:500 m ● Mesh Size: 3 mm ● Height: 4 m	$11,000/net	1	$ 11,000
Disposal Fee of Fish	$54/ ton	9.16 ton	$ 494.64
Rental Boat Cost	$149/full day	10 days/ year	$1490
Rental Truck Cost	$19.95 start up price $ 0.69 / mile	● 180 miles roundtrip ● 10 days/year	$ 1441.5

Total Cost in first year (including everything discussed in the cost table)	$ 25616.14
Total Cost after first year (not including the fishnet cost)	$ 3426.14
Total operational cost for four years	$ 35894.56

Alternative 2:
The second alternative for intensive fishing operation is using recreational fishermen. This alternative would offer incentives to fishermen by giving them a reward. In the study of Lake Hoytiainen mentioned before, the average caught fish by recreational fishermen is about 4,391 kg per year. Based on this rate, fishermen need to catch at least 3,922 kg of fish in IVR. Since fish traps mainly catch fish in the upper water level, the use of fishermen aim to replace the use of seine net without bag, which will reduce the cost of fish nets compared to Alternative 1, with the assumption of the fishermen having their own fish trap. Seine net with bag are used to catch 3,922 kg of lower level fish . Assuming at least 700 kg per day is caught using the seine nets, six days will be needed every year or three days per season.

Fishermen will be given a reward for catching a certain amount of fish, which will be established by the Department of Fish and Game or the management; however, for the design proposal, the fishermen will receive at least $20 for every 50 kg of fish, which will result in $1,756.40 cost to reward the fishermen. Similar to alternative 1, a rental boat and truck is needed with a cost of $894 and $864.90 per year, respectively.The disposal distance for alternative 2 will be the same as alternative 1, with a cost of $494.64. Material and costs are presented in Table 5.

Because IVR does not want the fishermen to eat the mercury contaminated fish, they will buy back the fish that are caught, which will be dependent on the decision of the DFW and IVR.

Table 5: Cost Estimation Table for Intensive Fishing Operation for Alternative 2

Expenses and Materials	**Unit Cost**	**Amount**	**Cost**
Seine Net with Bag (Reusable) Net size: • Length: 500 m • Mesh Size: 30 mm • Height: 4 m Bag Size: • Mesh size: 25-30 mm • Height: 4 m	$11,190/net	1	$ 11,190
Disposal Fee of Fish	$54/ ton	9.16 ton	$ 494.64
Rental Boat Cost	$149/full day	6 days/ year	$894
Rental Truck Cost	$19.95 start up price	• Roundtrip miles/day:	$ 864.9

	$ 0.69 / mile	180 miles ● 6 days/ year	
Reward Money Cost	$20	50 kg of fish	$ 1756.4
Total Cost in first year (including everything discussed in the cost table)			$ 15199.94
Total Cost after first year (not including the fishnet cost)			$ 4009.94
Total operational cost for four years			$ 27229.76

Comparing Alternatives Based on Costs

The total operational cost for a four-year period for the application of alternative 1 is $35,894.56, with a first year cost of $25,616.14 and following years cost of $3,426.14. The total operational cost for alternative 2 for four-year period is $27,229.76, with a cost of $15,199.94 for the first year and $4,009.94 for the following years.

The total operational cost of four years of alternative 2 is less than the total cost of four years of alternative 1 with $8,664.8 difference. However, the operational cost application after first year of alternative 2 is higher than alternative 1 with a difference of $583.8.

Therefore, by calculation, the breakeven point (the cost of alternative 1 and 2 will be the same, and once exceeding the breakeven point, the cost of alternative 1 will be less than alternative 2) for the cost of these two alternatives happens in year 15. If IVR sees the intensive fishing method to be effective and tends to continuously operate for more than a 15-year time frame, it is better to choose alternative 1. If IVR only wants to apply this control study for less than 15 years, it will be appropriate to choose alternative 2.

Discussion

Design Performance

HXB recommends performing intensive fishing to reduce mercury bioaccumulation in fish after comparing its advantages and disadvantages. After doing an extensive amount of research on intensive fishing, there was still an issue of finding sufficient explanation on how intensive fishing reduces mercury bioaccumulation in fish. Many of the scholarly articles also lacked detail about their methods and process, which left HXB to make inferences.

For intensive fishing to be successful, 25% of biomass needs to be removed from the reservoir. HXB had trouble attaining accurate information of fish population data, which led them to make interpretations using the Fish Survey done in 2013 by the Department of Fish and Game. In addition, the only fish that were considered in the design process were the species listed in Dr. McCord's given data, which listed out each fish's mercury concentration.

To make a more accurate interpretation, biologist are needed for the estimation of fish population and analysis of mercury concentration on fish tissue in the reservoir before the study and during the application. Without knowing the fish population and biomass, it is hard to target the amount of fish removal. Thus, making it difficult to know if intensive fishing is effective. Knowing the mercury concentration in fish before applying the study will be also useful for future analysis. Biologist can examine the trend of mercury in fish before and after the study and can assist IVR to determine whether intensive fishing is an effective study for the reservoir.

Advantages

One advantage of intensive fishing is the relatively low cost. The total cost of the project is estimated to be $35,894.56 for alternative 1 and $27,229.76 for alternative 2 depending on IVR's choice on the application method. Alternative 2 will take advantage of recreational fisherman, while alternative 1 will be solely operated by IVR. The remaining repeat treatments after the first treatment for alternative 1 and 2 would cost $3,426.14 and $4,009.94, respectively, which indicate maintenance cost would remain relatively low after the initial capital costs.

The design of the control study has low involvement in the reservoir. The design for alternative 1 is scheduled to have intensive fishing occur for only five days twice a year, which result in a total of 10 days of involvement per year. On the other hand, the design duration for alternative 2 is estimated to be three days twice a year for a total of 6 days a year. The duration of both alternatives have little interference and involvement of the design with the operations of IVR. Furthermore, by performing the intensive fishing during the week, the study can avoid interfering with weekend visitors when visitation is higher than during the weekdays.

Intensive fishing targets the food web, and so avoids any chemical additions that might disrupt the chemical balance of the reservoir. Because the reservoir is man-made and artificially stocked with fish, the alteration of the food web will have little impact on the surrounding ecosystem.

Disadvantages

As for the cons of the study, there are a few issues with the assumptions made leading to our design. One issue affected by the assumptions was the lack of data on IVR. Because of the lack of data, our group had a difficult time selecting a control study and making decisions on how to move forward. Assumptions were made to expedite the process but need to be considered before this project is actually implemented and should be researched more in depth to assure this methods' success.

One area where we lacked data was concerning the fish population data. IVR lacks any actual fish population data. The only fish data publicly available were annual fishing reports by the Department of Fish & Wildlife (DFW). These reports consisted of a report of fish caught over short period of time by a small group of fishermen. The reported results are not representative, and due to the lack of actual fish population data, an assumption had to be made based on percentages of fish species caught. These values from the fishing reports were used to model the species partitioning of the total fish population in the reservoir. This became one of the primary assumptions made in the estimations of the fish population for IVR. The issue with this assumption however is that the DFW annual fishing reports had small sample sizes, which adds uncertainty to the assumptions, thus making the estimations for the fish population uncertain and unreliable. The assumption for the fish population may be acceptable for a preliminary design, but before performing an actual control study, a more reliable fish population estimation must be made to reduce the uncertainty in the assumption, and to reduce the impact of the uncertainty.

Another issue with intensive fishing is that it is not a permanent solution for mercury remediation. While intensive fishing works well for reducing mercury levels in fish in the short term, it does not prevent mercury from finding its' way into the system, meaning that it cannot work as a long-term solution. The effective time frame for intensive fishing is approximately eight years. It takes four years for the mercury concentrations in fish to reach their lowest level, and another four years for the mercury concentrations to arrive at their original pre-intensive fishing levels. This indicates that in order for the reservoir to keep benefitting from intensive fishing, the process would have to be repeated every eight years. In the short term, intensive fishing does well at reducing mercury levels, but it is not a permanent solution.

The issue with intensive fishing is that it aims at reducing the mercury levels in fish. The target of this method is fish. Although, it does not prevent mercury from entering the system. It only works to reduce bioaccumulation but not atmospheric deposition, a possible mercury source for IVR.

Potential Food Web Disruptions

One thing to consider when implementing intensive fishing is its effect on the food web. Removal of fish species higher on the food chain results in a population increase of lower trophic level fish. However, it is important to consider that a change in the food web could have unforeseen results in terms of affecting the lower species on the food chain. Small fish feed on small organisms such as zooplankton, which feed on phytoplankton, such as algae and cyanobacteria. Thus, as a result of overfishing higher trophic species, the increase in smaller fish population could result in a decrease of zooplankton resulting in algal blooms. The impacts of increased algae could result in a decline of water quality, introduction of potential toxins, and anoxic conditions in the reservoir.

Effects on Stakeholders

Intensive fishing has the benefit of not interfering with irrigation for farming, IVR's largest stakeholders. The removal of fish has no effect on the volume of water supply and does not require any restrictions on water outflows, meaning irrigation will not be interrupted and farming can continue as usual. In terms of the size of the different stakeholder groups, irrigation and farming is the largest, and should not be affected by intensive fishing.

The other large stakeholder group is recreational fishermen. Intensive fishing could have a negative impact on recreational fishermen due to the removal of fish, meaning there is less fish available for fishermen. However, with proper use of incentive programs, the control study could satisfy recreational fishermen, for example, by providing free fishing licenses. With proper incentive programs, recreational fishermen can be appeased and the study can avoid having a negative impact on key stakeholders.

Design Sustainability

One primary societal benefit of intensive fishing is that with alternative 2, the study provides a place for fishermen, by offering an incentive, which would draw more visitors to IVR. On the other hand, alternative 1 ignores the contributions of recreational fishermen. Fishermen lose certain species of fish due to intensive fishing. By providing incentives to fishermen in alternative 2, a portion of the fishing can be done at a lower price, which increases the economic benefit from intensive fishing and provides an improved societal service for visitors by potentially attracting more visitors.

Intensive fishing also has a larger applicability on a global scale. The first intensive fishing studies were done in Nordic countries, such as Sweden and Finland, but has spread in Canada and Brazil. An advantage of intensive fishing is that it is easily applicable in all parts of the globe. Intensive fishing takes advantage of the trophic levels between species and can be easily applied anywhere where there is an abundance of fish. Intensive fishing designs vary dependent on the local conditions and water quality; however, the same biological principles apply to fish throughout the world, and with small changes to the process, intensive fishing can be applied throughout the world to remediate mercury bioaccumulation in fish.

Conclusion and Recommendations

HXB suggests that IVR should conduct intensive fishing to reduce mercury concentrations in fish. HXB proposes two alternatives processes for conducting intensive fishing operation in Indian Valley Reservoir.

Alternative 1 suggests using the seine net with bag to target lower level fish and the seine net without bag to catch upper level fish. Alternative 1 is expected to operate for five days for spring and fall seasons in a year, and to remove the designed amount of fish biomass. The total cost of alternative 1 for a four-year operation is $35,894.56. The high cost is mainly due to purchasing the fish nets but are expected to be reused every year.

The cost of alternative 2 for a four-year operation is $27,229.76. Similarly to alternative 1,the operational period of alternative 2 is also expected to be in the spring and the fall season each year; however, the operation only takes three days for each season. The difference in cost is mainly due to using only the bottom trawl net while rewarding fishermen to catch more fish.

After comparing the pros and cons of alternative 1 and 2, HXB recommends alternative 2 for Indian Valley Reservoir to do the intensive fishing operation. The total cost of alternative 2 is $8664.80 less than alternative 1 with same caught fish amount. Alternative 2 also provides incentives to recreational fishermen by giving cash reward for the fish they catch and attracts more visitors to fish at Indian Valley Reservoir.

References

[1]“District Infrastructure.” *Yolo County Flood Control & Water Conservation District*, www.ycfcwcd.org/infrastructure.html.

[2]*DFG PLAN FOR INDIAN VALLEY RESERVOIR*(pp. 1-20, Rep.). (1991). CA: Lake County Region 3.

[3] Krabbenhoft, David P. “Methylmercury Contamination of Aquatic Ecosystems: A Widespread Problem with Many Challenges for the Chemical Sciences.” *Water and Sustainable Development: Opportunities for the Chemical Sciences: A Workshop Report to the Chemical Sciences Roundtable.*, U.S. National Library of Medicine, 1 Jan. 1970, www.ncbi.nlm.nih.gov/books/NBK83731/.

[4] “The Indian Valley Dam.” *The Indian Valley Dam | Restore/Restory*, www.restorerestory.org/timeline/indian-valley-dam.

[5] Zeng, Lingxia, et al. “Effects of Sulfate-Reducing Bacteria on Methylmercury at the Sediment–Water Interface.”*Journal of Environmental Sciences*, Elsevier, 20 June 2016, www.sciencedirect.com/science/article/pii/S1001074216301851?via%3Dihub.

[6] Shao, Dingding, et al. “Effects of Sulfate Reducing Bacteria and Sulfate Concentrations on Mercury Methylation in Freshwater Sediments.” *Science of The Total Environment*, Elsevier, 22 Mar. 2012, www.sciencedirect.com/science/article/pii/S0048969711010436.

[7]Alpers, Charles N., et al. “Mercury Contamination from Historical Gold Mining in California.”*Mercury Contamination from Historical Gold Mining in California*, USGS, Nov. 2005, pubs.usgs.gov/fs/2005/3014/.

[8] Gavis, Jerome, and John F Ferguson. “The Cycling of Mercury Through the Environment.”*Science Direct*, Elsevier Ltd. , 21 Mar. 1972, ac.els-cdn.com/004313547290053X/1-s2.0-004313547290053X-main.pdf?_tid=37b47cc7-7b46-4c35-b28b-9551399efb51&acdnat=1525039372_df4707804e6d483eb655bc9734f1e74d.

[9] Won, Jong Hyun, et al. “Mercury Emissions from Automobiles Using Gasoline, Diesel, and LPG.” *Science Direct*, Elsevier Ltd. , 18 May 2007, ac.els-cdn.com/S1352231007004992/1-s2.0-S1352231007004992-main.pdf?_tid.

[10] Youngs, L. (n.d.). Map of California Historic Gold Mines [Map]. In *California Department of Conservation*. Retrieved April 30, 2018, from http://www.conservation.ca.gov/cgs/geologic_resources/mineral_production/Documents/big_au map.pdf

[11] Li, Ping, et al. “Mercury Pollution from Artisanal Mercury Mining in Tongren, Guizhou, China.” *Egyptian Journal of Medical Human Genetics*, Elsevier, 3 May 2008, www.sciencedirect.com/science/article/pii/S0883292708001728.

[12] A. Ordóñez, et al. “Risk Assessment of Soils Contaminated by Mercury Mining, Northern Spain.” *RSC Advances*, The Royal Society of Chemistry, 28 Oct. 2010, pubs.rsc.org/-/content/articlehtml/2011/em/c0em00132e.

[13] Pirrone, N, et al. “Global Mercury Emissions to the Atmosphere from Anthropogenic and Natural Sources.” *Global Mercury Emissions to the Atmosphere from Anthropogenic and Natural Sources*, 2 July 2010, doi:https://www.atmos-chem-phys.net/10/5951/2010/acp-10-5951-2010.pdf.

[14] Karagas, Margaret R., et al. “Evidence on the Human Health Effects of Low-Level Methylmercury Exposure.” *Advances in Pediatrics.*, U.S. National Library of Medicine, 24 Jan. 2012, www.ncbi.nlm.nih.gov/pmc/articles/PMC3385440/.

[15] Feng, Xinbin, et al. “OCCURRENCE, EMISSIONS AND DEPOSITION OF MERCURY DURING COAL COMBUSTION IN THE PROVINCE GUIZHOU, CHINA.” *OCCURRENCE, EMISSIONS AND DEPOSITION OF MERCURY DURING COAL COMBUSTION IN THE PROVINCE GUIZHOU, CHINA*, 3 Dec. 2001.

[16] Senior, Constance L, et al. “Gas-Phase Transformations of Mercury in Coal-Fired Power Plants.” *Science Direct*, Science Direct , 20 Sept. 1999, ac.els-cdn.com/S0378382099000971/1-s2.0-S0378382099000971-main.pdf?_tid=317903a8-5fb9-4d4e-b9dd-f670445aa377&acdnat=1525759982_1d55ebd31520c451f6673a90c4e87771.

[17] Shapiro, Joseph, and David I Wright. “Lake Restoration by Biomanipulation:Round Lake, Minnesota, the First Two Years.” *Wiley*, Wiley, 29 Sept. 1983, www.bing.com/cr?IG=478BF393DE4D46DEAC90C2F674619A3C&CID=348F5AC2E76C6DE12A345128E6C36C1E&rd=1&h=EuFTwCSips7lKafxLIEA_nBFiCra1S5g1CFjkUbIdUE&v=1&r=http%3a%2f%2fonlinelibrary.wiley.com%2fdoi%2f10.1111%2fj.1365-2427.1984.tb00161.x%2freferences&p=DevEx.LB.1,5504.1.

[18] Ghosh, Upal, et al. “In-Situ Sorbent Amendments: A New Direction in Contaminated Sediment Management.” *ACS Publications* , Environmental Science & Technology, 1 Jan. 2011, pubs.acs.org/doi/pdf/10.1021/es102694h.

[19] Schroeder, W., & Munthe, J. (1998). Atmospheric mercury—An overview. *Atmospheric Environment,32*(5), 809-822. doi:10.3897/bdj.3.e5361.

[20] Mason, R. P., Fitzgerald, W. F., & Morel, F. M. (1994). The biogeochemical cycling of elemental mercury: Anthropogenic influences. *Geochimica Et Cosmochimica Acta,58*(15), 3191-3198. doi:10.3897/bdj.4.e7720.

[21] Cleaner Power Plants. (2017, June 12). Retrieved June 11, 2018, from https://www.epa.gov/mats/cleaner-power-plants

[22] Staff Report for Scientific Peer Review (April 2017). (2017, April). Retrieved June 10, 2018, from https://www.waterboards.ca.gov/water_issues/programs/mercury/reservoirs/docs/peer_review/03_staff_report_figures.pdf

[23] Økelsrud, Asle, et al. "Biomagnification of Mercury and Selenium in Two Lakes in Southern Norway." *Advances in Pediatrics.*, U.S. National Library of Medicine, 1 Oct. 2016, www.ncbi.nlm.nih.gov/pubmed/27236625.

[24] Shapiro, Joseph, and David I Wright. "Lake Restoration by Biomanipulation:Round Lake, Minnesota, the First Two Years." *Wiley*, Wiley, 29 Sept. 1983, www.bing.com/cr?IG=478BF393DE4D46DEAC90C2F674619A3C&CID=348F5AC2E76C6DE12A345128E6C36C1E&rd=1&h=EuFTwCSips7lKafxLIEA_nBFiCra1S5g1CFjkUbIdUE&v=1&r=http%3a%2f%2fonlinelibrary.wiley.com%2fdoi%2f10.1111%2fj.1365-2427.1984.tb00161.x%2freferences&p=DevEx.LB.1,5504.1.

[25] Ghosh, Upal, et al. "In-Situ Sorbent Amendments: A New Direction in Contaminated Sediment Management." *ACS Publications* , Environmental Science & Technology, 1 Jan. 2011, pubs.acs.org/doi/pdf/10.1021/es102694h.

[26] Simoneau, M., Lucotte, M., Garceau, S., & Laliberte, D. (2005). Fish growth rates modulate mercury concentrations in walleye (Sander vitreus) from eastern Canadian lakes. *Environmental Research,98*(1), 73-82. doi:https://doi.org/10.1016/j.envres.2004.08.002

[27] Lindqvist, O., Johansson, K., Aastrup, M., Andersson, A., Bringmark, L., Hovsenius, G., . . . Tim, B. (1991). MERCURY IN THE SWEDISH ENVIRONMENT - RECENT RESEARCH ON CAUSES, CONSEQUENCES AND CORRECTIVE METHODS. *Water, Air and Soil Pollution,*1-264.doi:10.3897/bdj.4.e7720.figure2f
https://link.springer.com/content/pdf/10.1007%2FBF00542429.pdf

[28] Masson, S., & Tremblay, A. (2003). Effects of intensive fishing on the structure of zooplankton communities and mercury levels. *The Science of the Total Environment,304*, 377-390. doi:10.1107/s0108768104030617/bs5012sup1.cif

[29] Surette, Céline & Lucotte, Marc & Tremblay, Alain. (2006). Influence of Intensive Fishing on the Partitioning of Mercury and Methylmercury in Three Lakes of Northern Quebec. The Science of the total environment. 368. 248-61. 10.1016/j.scitotenv.2005.09.038.

[30] McCord Environmental, Inc. (2018) Appendix. Z [Microsoft Excel Sheet]. 2018: UC Davis Box Folder. Available from: https://ucdavis.app.box.com/file/290975910548 [5/11/2018]

[31] Ewing, Ben. “Indian Valley Reservoir General Fish Survey .” *California Department of Fish and Wildlife* , California Department of Fish and Wildlife , 2013, www.bing.com/cr?IG=1553656EB9204D03A3E4EBE16B0BCBD1&CID=262C3B3731876E471F26373C307A6FCD&rd=1&h=OMjjPjd8y6Xrx5aauAzzPf09KTCOBHVrphR4paqLO8w&v=1&r=https%3a%2f%2fnrm.dfg.ca.gov%2fFileHandler.ashx%3fDocumentID%3d74964&p=DevEx.LB.1,5560.1.

[32] Haakana, Helena, and Hannu Huuskonen. “Effects of Intensive Fishing on the Perch Population in a Large Oligotrophic Lake in Eastern Finland.” *Science Direct*, Science Direct, 15 Nov. 2007, www.bing.com/cr?IG=B52160939B94428198C42896435D358C&CID=2A21BF6A42886A372A24B36143756BCD&rd=1&h=vTtpnvnvOJdBpTuL5oo8fyuLStkzDNX5fcz1Ug_fm64&v=1&r=https%3a%2f%2fwww.researchgate.net%2fpublication%2f229194930_Effects_of_intensive_fishing_on_the_perch_population_in_a_large_oligotrophic_lake_in_eastern_Finland&p=DevEx.LB.1,5067.1.

[33] Mailman, Mariah, et al. “Strategies to Lower Methyl Mercury Concentrations in Hydroelectric Reservoirs and Lakes: A Review.” Science of The Total Environment, Elsevier, 15 Dec. 2005, www.sciencedirect.com/science/article/pii/S0048969705006637.

[34] Chortek, Emily, "Remediation Strategies for Mercury Contaminated Lakes and Reservoirs Within the State of California" (2017). Master's Projects and Capstones. 691.https://repository.usfca.edu/capstone/691

[35] Beutel, Marc W., and Alex J. Horne. “A Review of the Effects of Hypolimnetic Oxygenation on Lake and Reservoir Water Quality.” Lake and Reservoir Management, www.tandfonline.com/doi/pdf/10.1080/07438149909354124.

[36] Li Y B, Cai Y. Progress in the study of mercury methylation and demethylation in aquatic environments. Chin Sci Bull, 2013, 58: 177185, doi: 10.1007/s11434-012-5416-4

[37] Hudson, H., & Kirschner, B. (1997). Lake Aeration and Circulation. *Lake Notes, Illinois Environmental Protection Agency*.

[38] Seller, P., Kelly, C. A., Rudd, J. M., & MacHutchon, A. R. (1996). Photodegradation of methylmercury in lakes. *Nature,380*, 694-697. doi:10.1038/380694a0

[39] Ghosh, Upal, et al. “In-Situ Sorbent Amendments: A New Direction in Contaminated Sediment Management.” *ACS Publications*, ACS Publications, pubs.acs.org/doi/pdf/10.1021/es102694h.

[40] Diwekar, Urmila M., and Yogendra N. Shastri. “Green Process Design, Green Energy, and Sustainability: A Systems Analysis Perspective.” Computers & Chemical Engineering, Pergamon, 20 Feb. 2010, www.sciencedirect.com/science/article/pii/S0098135410000530.

[41] Helfrich, Louis A., et al. “Liming Acidified Lakes and Ponds.” Virginia Cooperative Extension, Virginia Cooperative Extension, vtechworks.lib.vt.edu/bitstream/handle/10919/23440/VCE420_254_2001.pdf?sequence=1.

[42] Madison, Wisconsin, and Virginia Alexandria. “Managing Lakes and Reservoirs .” *U.S. Environmental Protection Agency* , U.S. Environmental Protection Agency , 2001.

[43] Andrew C. P. Heaton, Clayton L. Rugh, Nian-jie Wang & Richard B. Meagher (2010) Phytoremediation of Mercury- and Methylmercury-Polluted Soils Using Genetically Engineered Plants, Journal of Soil Contamination, 7:4, 497-509, DOI: 10.1080/10588339891334384

[44] Wang, Qianrui, et al. “Sources and Remediation for Mercury Contamination in Aquatic Systemsda Literature Review.” *Science Direct*, Elsevier Ltd. , 30 Jan. 2004, www.bing.com/cr?IG=F270C507B0BE4A63A49761F122BD020F&CID=277418CBE8F461C3208614C0E909604E&rd=1&h=fJRqtdkz7kitV4xc7CadYnCTljgX9lZebxxJgEXZE8s&v=1&r=https%3a%2f%2fwww.sciencedirect.com%2fscience%2farticle%2f&p=DevEx.LB.1,5236.1.