DONALD BREN SCHOOL OF
ENVIRONMENTAL SCIENCE & MANAGEMENT
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

STRATEGIES TO CONTROL MERCURY POLLUTION IN THE CACHE CREEK BASIN, NORTHERN CALIFORNIA

2011 Group Project

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Strategies to Control Mercury Pollution in the
Cache Creek Basin, Northern California

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The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

Arturo A. Keller

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ABSTRACT

The Cache Creek Basin in Northern California provides a number of beneficial uses for humans and wildlife alike. Cache Creek is used for a variety of purposes including water for drinking and irrigation, habitat for wildlife, fishing, and recreational activities such as kayaking and rafting. However, these beneficial uses are threatened by high levels of mercury pollution originating from abandoned mine lands within the Basin as well as from natural sources, such as geothermal springs and mercury-enriched soils. This mercury pollution causes adverse health effects for both humans and wildlife in the Cache Creek Basin, and downstream in the Sacramento River, Sacramento/ San Joaquin Delta, and the San Francisco Bay. The Central Valley Regional Water Quality Control Board has established Total Maximum Daily Load (TMDL) requirements for mercury within the Cache Creek Basin; the Bureau of Land Management (BLM), which manages 300 square miles of the Basin, must make efforts to meet these requirements. The objective of this project was to assist the BLM with determining the most effective mercury management strategies to achieve this goal. We have evaluated the effectiveness and costs of various applicable remediation and restoration strategies, analyzed the downstream transport of mercury using watershed modeling software, and presented a policy analysis of the environmental regulations governing the management of mercury pollution in the Cache Creek Basin. We used the combination of these analyses to create a structured approach to assessing a site polluted with mercury and determining the best remediation strategy for that site based on site characteristics as well as decision making priorities, such as cost or effectiveness.

EXECUTIVE SUMMARY

The Cache Creek Basin, located in the Coast Ranges of Northern California, is one of the major contributors of mercury to the Sacramento/ San Joaquin Delta and San Francisco Bay. This is a concern because of the impacts mercury toxicity can have on human health and wildlife. Mercury is a potent neurotoxin that can be especially harmful to developing organisms and children (Alpers et al., 2008; USEPA, 2001). In addition, mercury is able to bioaccumulate within organisms and biomagnify as it transfers to higher trophic levels within food webs. According to Domagalski et al. (2004b), "the bioaccumulation of mercury in fish is one of the most widely recognized environmental problems of the current era."

In order to address the high levels of mercury pollution within the Cache Creek Basin, the U.S. Environmental Protection Agency (USEPA) and the Central Valley Regional Water Quality Control Board (CVRWQCB) have established maximum mercury concentration levels for both water and biota. Currently, these levels are being exceeded within the Cache Creek Basin, and remediation and restoration actions are necessary to meet water quality objectives. The Bureau of Land Management (BLM) manages approximately 300 square miles of the Cache Creek Basin, and has significant interest in controlling mercury diffusion from abandoned mine lands and the mercury that has accumulated in the sediments downstream of these lands. The BLM and other landowners have initiated cleanup efforts of these abandoned mines, but further action will be needed in order to meet water quality objectives. The goals of this project were to aid in bridging gaps in knowledge, to provide a more structured way of analyzing the mercury contamination in the area, and to assess the effectiveness of different remediation techniques.

To aid decision makers as they determine the most effective remediation or restoration option for each site, we developed a series of decision trees. The first tree guides decision makers in determining site specific characteristics that may impact the types of management actions taken at a site or if restoration and remediation efforts should be prioritized at an alternate site. The second decision tree is used to determine possible remediation actions. There are a wide variety of technologies and management options that can be use to control mercury contamination. These range from high impact, high cost technologies, such as excavation, to low footprint, low cost technologies, such as phytoremediation. The third tree guides the decision maker in gathering information about the cost, effectiveness, and time frame for selected management actions.

After the most applicable remediation technologies are determined through the use of the decision trees, the options can be ranked based on relative cost, effectiveness, and timeframe to clean up a site. Ranked scores were adjusted in order to emphasize the varying levels of importance a decision maker may place on these parameters. In order to illustrate the use of the decision trees and ranking system we developed case studies of six sites with varying characteristics. Each applicable option determined by the decision trees was ranked from the perspective of a decision maker that puts more emphasis on health effects, and may choose technologies with higher efficiencies, as well as a decision maker that puts more emphasis on low budget technologies. When management options were ranked with a low budget emphasis, phytoremediation was the most frequently recommended option. Excavation was the most frequently recommended strategy when emphasizing more effective technologies.

In addition to creating a decision-making framework, we used the watershed modeling program Watershed Analysis Risk Management Framework (WARMF), to examine the fate and transport of mercury in the Basin. WARMF can be used to better understand how water quality parameters change through time when actions are taken to reduce contaminant loads from point and nonpoint sources.

The WARMF model allowed us to analyze the daily flow as well as sediment, total mercury, and methylmercury loads for each stream reach in the Basin from 1996-2004. The model also allowed us to analyze the mercury contributions of each mine and thermal spring within the Basin, and examine how those contributions impact mercury concentrations downstream. By removing the mines from the model to simulate cleanup, it was possible to predict the effects of the remedial actions. It was found that mercury loads from the Basin are reduced by 11% with the removal of all mines, indicating there is a significant amount of mercury originating from other sources including legacy mercury in stream sediments along Cache Creek as well as unknown natural sources. The Cache Creek Canyon has been identified as the largest source of mercury in the Basin. It is likely that that there are significant natural sources within the canyon, however confirmation of assertion requires further investigation.

The results of the WARMF model also indicate that previous studies may have overestimated mercury loads originating from the Cache Creek Basin. However, there is considerable uncertainty of this estimate, and more data must be collected to determine mercury loads, especially during high water flows. Prior assumptions made about the linear relationship between mercury concentration and flow are too simple to accurately model the real world and may lead to inaccurate estimations of mercury loads. A watershed modeling program such as WARMF corrects for the complicated relationship between mercury concentrations and flow, and calculates mercury loads with a greater degree of accuracy. In addition to WARMF results, recent flow gauging of the Cache Creek Settling Basin has indicated that it may capture more sediment and mercury than previously thought during low and medium flows, although there must be additional research to determine exactly how much mercury remains in the settling basin.

To decrease mercury loads in the Cache Creek Basin and to meet Total Maximum Daily Load (TMDL) requirements, remediation and restoration actions are essential, as are additional measures to reduce erosion and associated transport of mercury in the Basin. As written in the Water Quality Control Plan for the Basin, it is the duty of the BLM and other responsible parties to reduce mercury concentrations to background levels, even if restoration actions may not meet the water quality objectives in the TMDL due to naturally-occurring high mercury concentrations. As the largest landowner in the mining region, the BLM is in a position to influence the overall management of the area. They can reduce mercury loads while improving the state of knowledge about mercury sources and conditions that contribute to high methylmercury concentrations. The recommendations for the BLM can be grouped into four categories:

1) Actions to take: Remediation and restoration actions as well as best management practices in the region,
2) Additional data collection: More water quality samples to understand mercury sources, as well as continued water quality monitoring before and after remediation and restoration actions,
3) Further research: More research into methylation processes, better understanding of mercury sources and concentrations, and better understanding of remediation and restoration options, including emerging technologies,
4) Partnerships: The BLM can encourage collaborative partnerships with other agencies and entities to help reduce mercury pollution within the Basin and downstream.

Given certain data limitations, our project focused on assisting with decision-making processes relative to remediation and restoration efforts. We developed decision trees and matrices in order to provide a starting point for BLM staff, and others facing similar challenges associated with mercury pollution, to begin the remediation and restoration process. These tools provide a structured approach to addressing a daunting pollution issue, and allow the user to determine a remediation method that best suits the environmental and political parameters of the site as well as other key considerations, such as budget constraints. Mercury pollution is not unique to the Cache Creek Basin, and our trees and matrices are meant to provide a framework that can be applied to other locations with mercury contamination issues.

PROJECT OBJECTIVES

The U.S Environmental Protection Agency (USEPA) and the Central Valley Regional Water Quality Control Board (CVRWQCB) have established maximum mercury concentration levels for both water and biota, which are currently being exceeded within the Cache Creek Basin. The Bureau of Land Management (BLM), which manages approximately 300 square miles of the Cache Creek Basin, has significant interest in controlling mercury diffusion from abandoned mine lands and the mercury that has accumulated in the sediments downstream of these lands. While the BLM and other landowners have initiated significant cleanup efforts at a number of these mine sites, there are areas that require more research and clarity. The objectives of this project were to aid in bridging gaps in knowledge to provide a more structured approach to analyzing mercury contamination in the area and to assess the effectiveness of different remediation techniques. The key areas of focus were:

- Identify ways to conduct mercury remediation and restoration in the Cache Creek Basin
- Develop a method to determine best remediation and restoration options for different site locations
- Evaluate management options through watershed modeling
- Assess legal constraints on management options

PROJECT SIGNIFICANCE

Mercury pollution is one of the most challenging environmental problems to solve, primarily because extremely low concentrations are considered toxic. While all forms of mercury are toxic, organic mercury, or methylmercury, is of highest concern; it is most bioavailable and can increase in concentrations as it moves up the food chain. Mercury has been shown to cause a number of developmental disorders in pregnant women and children; these at-risk segments of the population should restrict or avoid consumption of many types of fish. In several areas of the Cache Creek Basin, historic mining activities have led to high concentrations of mercury in water, fish, and sediment. In addition, the Cache Creek Basin is a major contributor to the elevated mercury concentrations in the Sacramento-San Joaquin Delta and San Francisco Bay, both of which contain active fisheries. Many people that consume fish from these regions are not aware of the mercury pollution problem and consume more fish than the CVRWQCB has determined to be safe. In addition to humans, mercury pollution can be harmful to wildlife, including a number of sensitive species within the Basin.

The CVRWQCB has tasked the BLM and others with taking remediation and restoration steps in order to meet the Total Maximum Daily Load (TMDL) requirements for different parts of the Basin. Identification of the magnitude of different sources of mercury throughout the Cache Creek Basin is necessary in order to prioritize remediation efforts, but has been limited by incomplete sampling and monitoring. In addition to data limitations, there are a number of legal constraints in the Basin, which make remediation efforts more difficult. These policies and restrictions need to be examined when choosing a site for cleanup or a remediation technique. In order to find effective and feasible strategies for mercury cleanup in the Cache Creek Basin and other areas across the globe that are affected by mercury contamination, it is important to assess current remediation strategies and examine emerging technologies. A large quantity of research and resources have been focused on the mercury problems within the Cache Creek Basin; however, the lack of understanding and identification of all the mercury sources as well as the complexities of mercury chemistry have hindered the development of a realistic plan to reduce mercury concentrations to a safe level.

BACKGROUND

Cache Creek

The Cache Creek Basin is located in northern California and occupies 2,978 km^2 (Suchanek et al., 2010) (Figure 1). The upper part of the watershed is within the California Inner Coast Ranges and the lower part of the watershed, downstream of Rumsey, is within the Sacramento Valley. The landscape above Rumsey consists largely of low mountains containing forests of mainly oaks and conifers, shrub lands, grazing lands, and some farmland. Below Rumsey, the majority of the landscape is farmland. Elevations range from a low of 8 meters, at the confluence of Cache Creek and the Yolo Bypass, up to 1,815 meters, with a large majority being between 300 to 800 meters. Precipitation in the region averages 20-40 inches per year and falls primarily between the months of November and April.

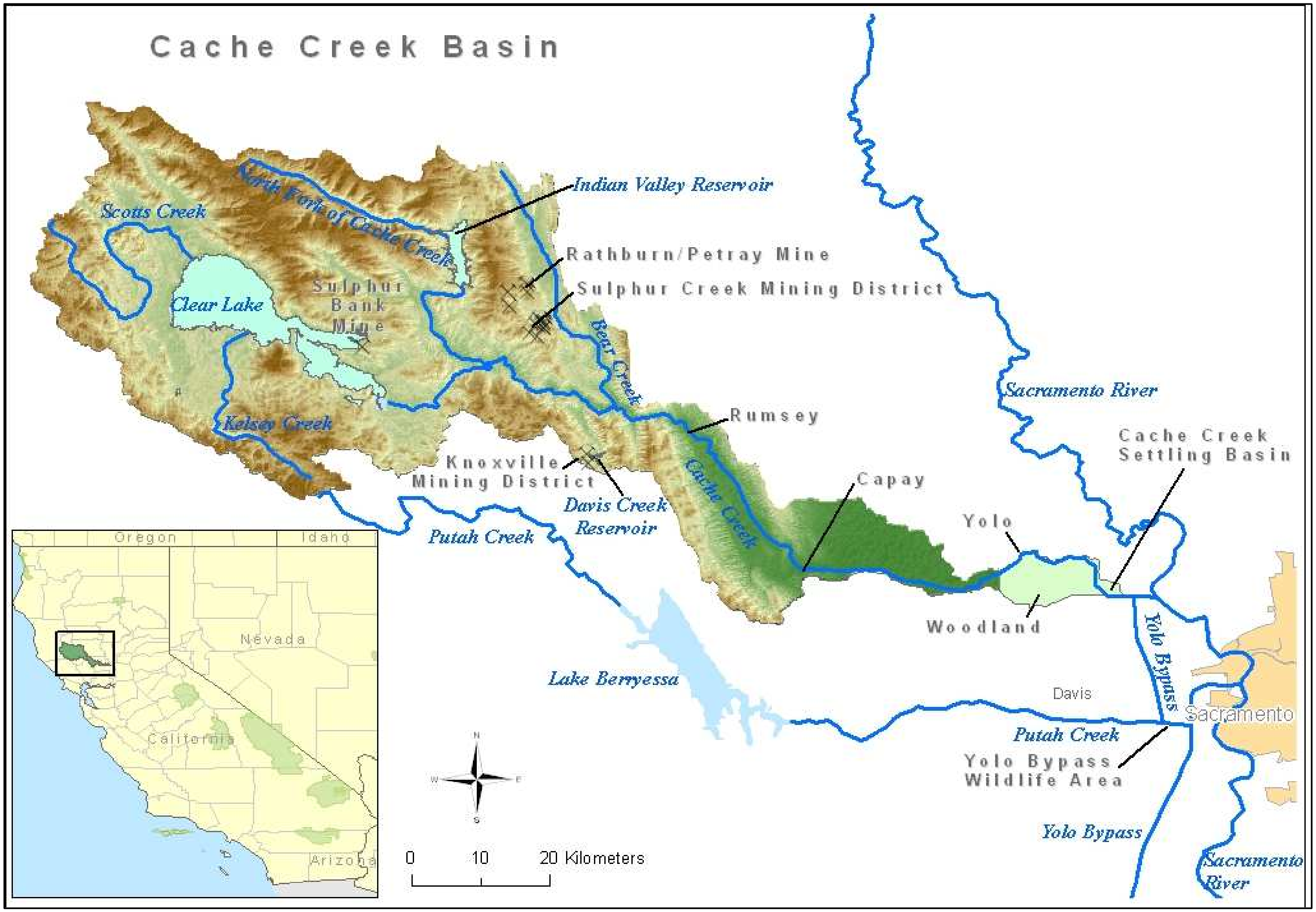


Figure 1: Cache Creek Map with Mining Districts

Nearly half of the watershed drains into Clear Lake, which is the source of the Main Fork of Cache Creek. Clear Lake is the largest natural freshwater lake entirely in California and is fed by a number of smaller creeks, including Kelsey Creek and Scotts Creek. Clear Lake contains a small dam built in 1914, which adds an additional 270,000 acre-feet of storage and helps regulate flow throughout the year to benefit agricultural irrigation in the Sacramento Valley (Lake County, 2009). In addition to Clear Lake, the Basin contains Indian Valley Reservoir on the North Fork of Cache Creek with a capacity of 300,000 acre-feet (CDEC, 2010), as well as the much smaller Davis Creek Reservoir. The Cache Creek Basin provides Lake and Yolo Counties with drinking and irrigation water, and a variety of recreational activities to locals and tourists alike. There are several noteworthy regional, state, and national fishing tournaments held at Clear Lake. A resort and spa are also located at Wilbur Springs, which makes use of the local hot springs. Lake County is emerging as one of the newest wine regions in California; the number of vineyards, wineries, and tasting rooms is increasing rapidly in the area. Several state parks that surround Clear Lake are used for wildlife viewing and camping. During summer months, Cache Creek and the North Fork of Cache Creek are commonly used for kayaking and other river activities.

The wide range of landscapes within the Cache Creek Basin provides many different uses to the area's landowners. These landowners vary from private trusts and corporations to government agencies. One such owner is our client, the U.S. Department of the Interior, Bureau of Land Management (BLM), The BLM's mission is to "sustain the health, diversity, and productivity of the public lands for the use and enjoyment of present and future generations" (BLM, 2008); it does so in managing archaeological and cultural resources, land exchanges, rangelands, minerals, national monuments, recreation, special status plants, wild horses and burros, wildlife, and wilderness areas (BLM, 2008). In October of 2006 President George W. Bush created the Cache Creek Wilderness (BLM, 2011), a 110 km^2 wilderness area located in Lake

County (Figure 2). The BLM manages 26 percent of the lands within the Cache Creek Basin, including the Cache Creek Wilderness (Figure 3).

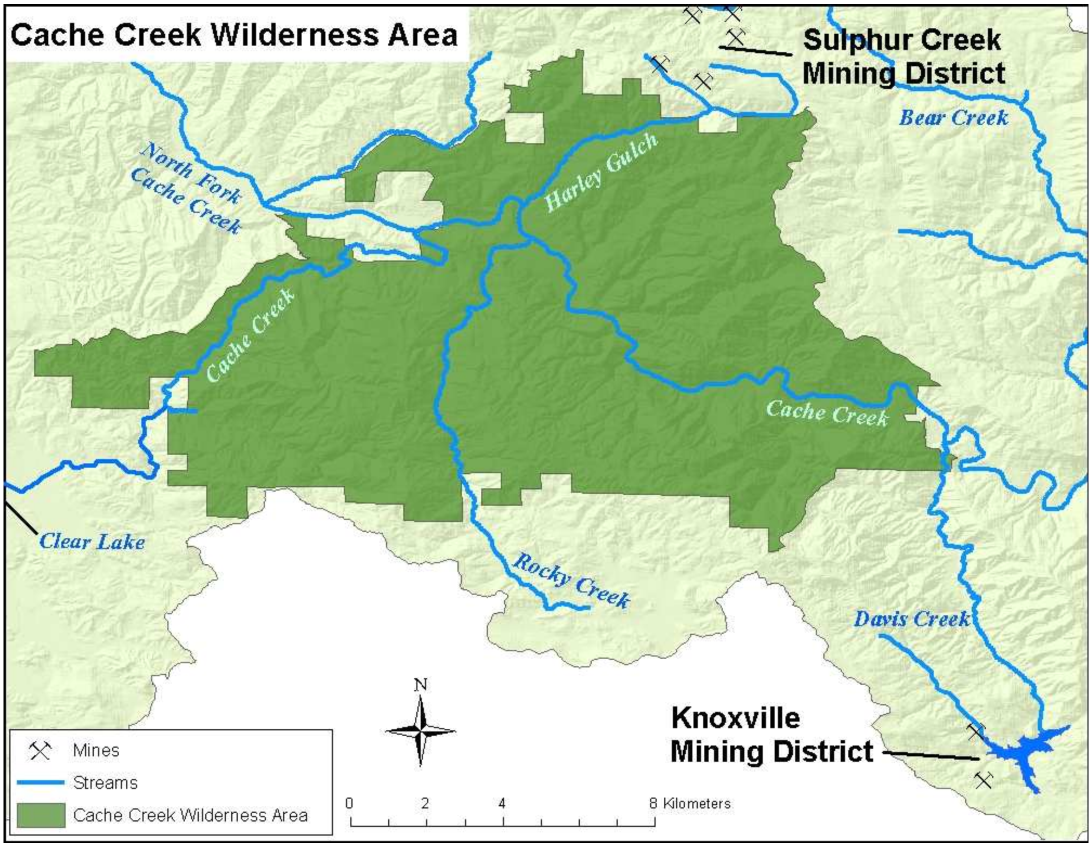


Figure 2: Cache Creek Wilderness Area

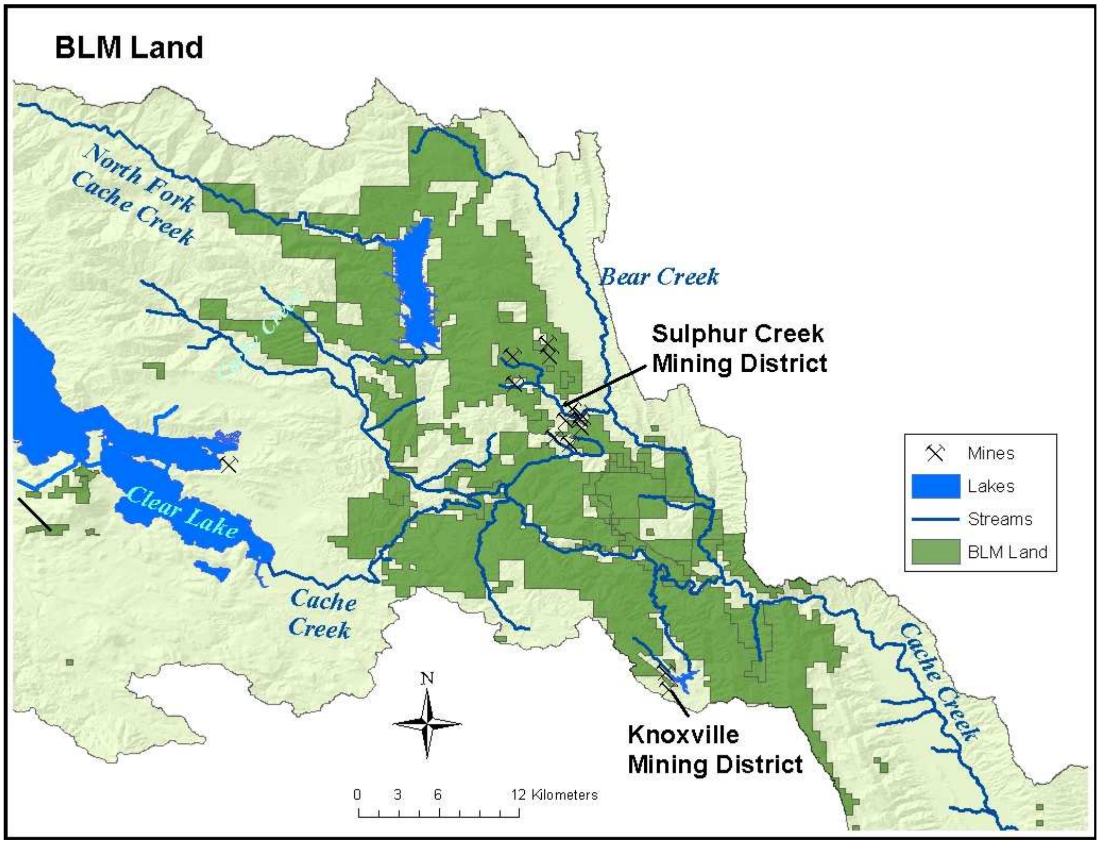


Figure 3: BLM Land

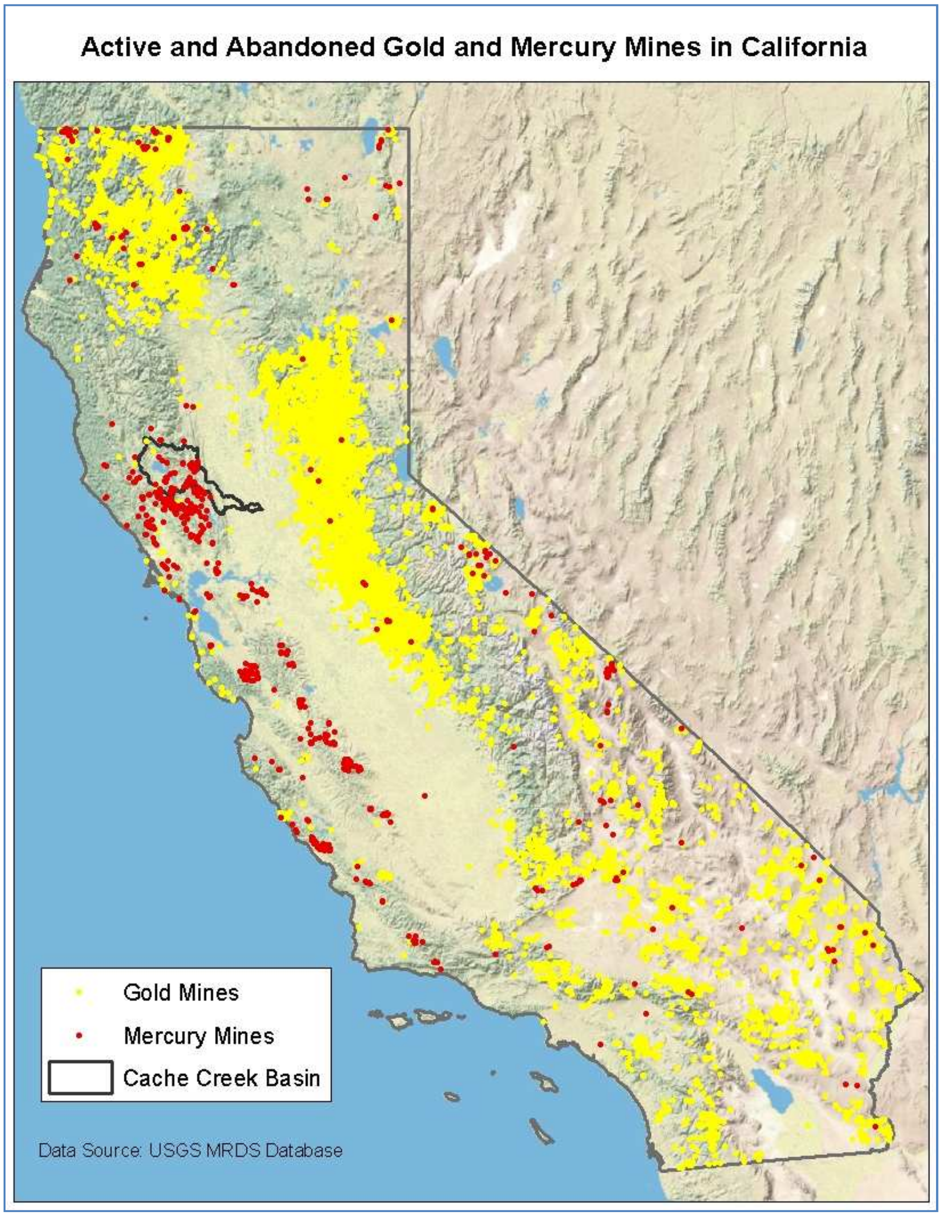
As a large landholder in the Basin, the BLM is one of many responsible parties for maintaining water quality and preventing the discharge of pollutants into Cache Creek. Responsible parties are required to address cleanup orders and meet the Total Maximum Daily Load, or TMDL, of a specific pollutant for the rivers or tributaries on their land as required by the Central Valley Regional Water Quality Control Board (CVRWQCB). A cleanup order is given to a responsible party when beneficial uses of a water body are affected by pollution and water quality objectives are not being met. As with most California water quality directives and standards, cleanup orders are issued by a Regional Water Quality Control Board (Board) to achieve water quality standards required under the U.S. Clean Water Act. In the case of the Cache Creek Basin, the CVRWQCB has issued cleanup orders for several abandoned mines because they are polluting the water with mercury. To date, the BLM has received three cleanup orders. The Rathburn-Petray Mine cleanup order was issued in

December 2005 and the Clyde Mine and Elgin Mine cleanup orders were issued in August 2009. In addition to the cleanup orders directed to the BLM, several others have been issued to the owners of the Central, Cherry Hill, Empire, Manzanita, Elgin, and Wide Awake mines.

In addition to cleanup orders, a TMDL is issued by the Board when a water body is not meeting water quality objectives stipulated in the U.S. Clean Water Act. The goal of the TMDL program is to maintain the beneficial uses of individual water bodies. Each water body in California has a number of beneficial uses that have been determined by the Board; a TMDL is ordered when a pollutant interferes with sustaining the beneficial uses of a water body. A typical TMDL report provides details about the pollutant that is in violation, the desired water quality standards, and provides a method in which the water body will be brought back into compliance. In the Cache Creek Basin, a TMDL report was issued for Clear Lake in 2002, for Cache Creek, Bear Creek, and Harley Gulch (as one report) in 2004, and for Sulphur Creek in 2007.

Historical Mercury Mining in the Cache Creek Basin

Mercury mining in the region began in the mid nineteenth century in order to assist gold extraction from ore in the booming gold mining industry located in the foothills of the Sierra Nevada (Domagalski et al., 2004). Across California there is a large number of historical mercury and gold mines, which have been documented by U.S. Geological Survey (USGS, 2005) (Figure 4). In the Cache Creek Basin there were several large gold mines and mercury mines as well as mines that produced both gold and mercury.



Data Source: USGS MRDS Database

Figure 4: Active and abandoned gold and mercury mines in California

The Cache Creek Basin contains three mercury mining areas: the Sulphur Bank Mine, the Knoxville Mining District, and the Sulphur Creek Mining District (Figure 5). The Sulphur Bank Mine has contributed large quantities of mercury to Clear Lake. The mine was declared a Superfund site in 1990, and initial cleanup efforts have significantly reduced the flow of mercury into the lake (Sulphur Bank Mercury Mine, 2010). The Knoxville district is in the Davis Creek watershed and is comprised of the

Harrison, Manhattan, and Reed Mines (Foe & Bosworth, 2008). The Sulphur Creek Mining District is comprised of 12 mines located within the watersheds of Sulphur Creek, Bear Creek and Harley Gulch. The mines in the Sulphur Creek watershed include: Elgin, Clyde, Empire, Manzanita, West End, Central, Cherry Hill, and Wide Awake; the Rathburn and Petray mines are within the Bear Creek watershed; and the Abbott and Turkey Run mines are within the Harley Gulch watershed (Cooke, et al., 2004) (Figure 6). Because Sulphur Creek drains into Bear Creek, the mines within the Sulphur Creek watershed impact the water quality of both streams and eventually the main stem of Cache Creek.

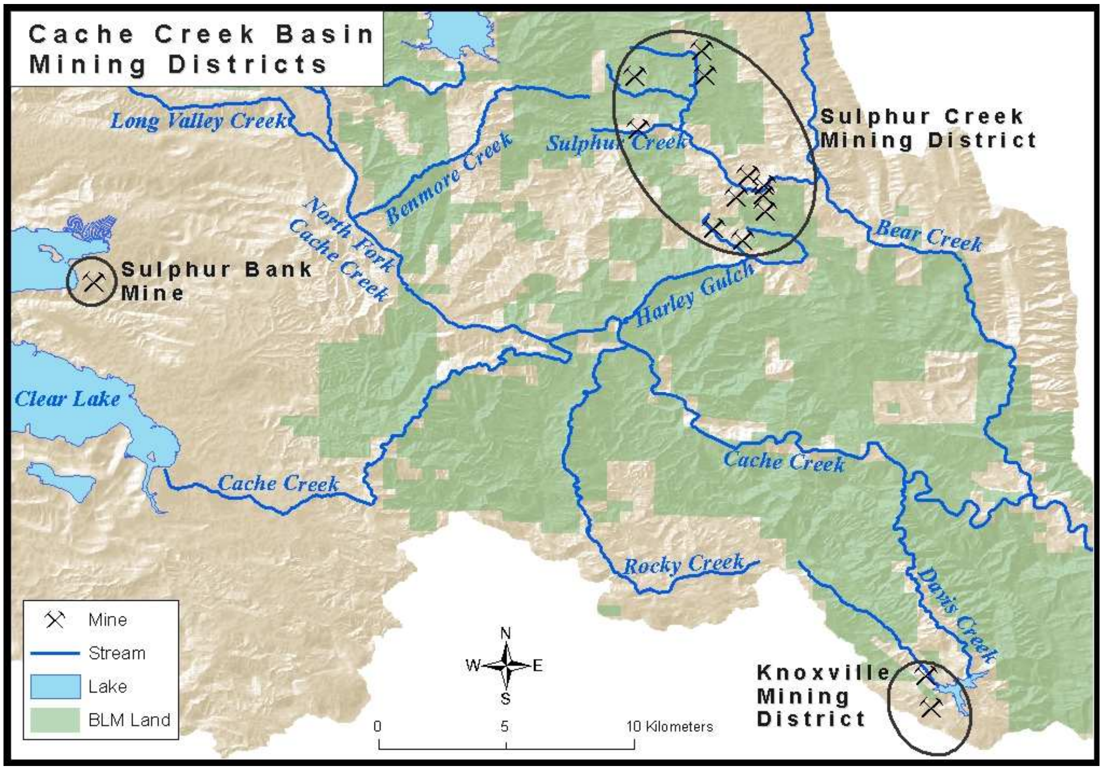


Figure 5: Cache Creek Mining Districts

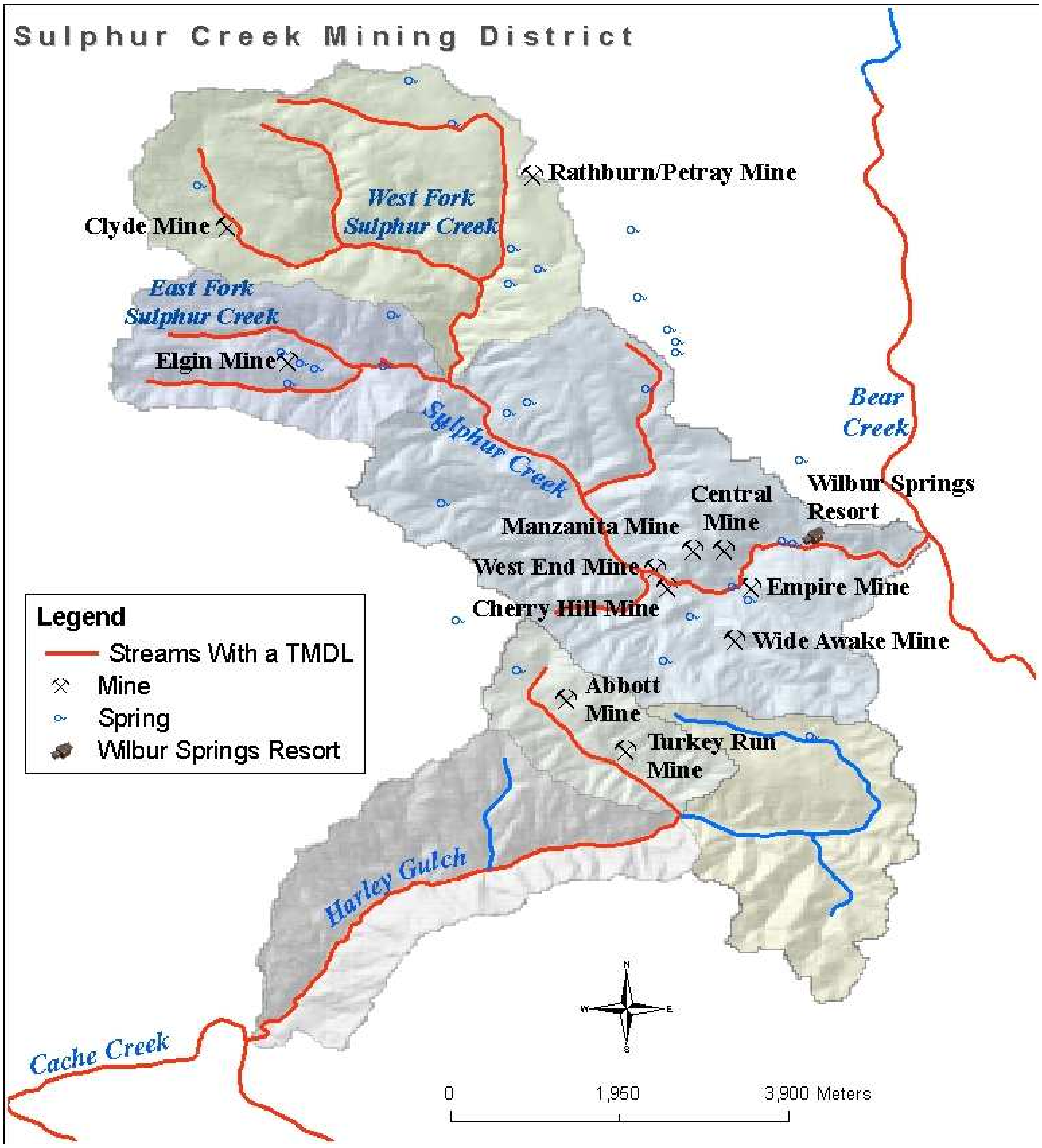


Figure 6: Sulphur Creek Mining District

Mercury Chemistry

Mercury (Hg) is found in the environment primarily in three classes: elemental mercury (Hg^0); divalent salts of ionic mercury (Hg^{2+}) which include mercury chloride ($HgCl_2$), mercury hydroxide ($Hg(OH)_2$), and mercury sulfide (HgS); and methylmercury (CH_3Hg^+ or MeHg) (Schroeder and Munthe, 1998). In the Cache

Creek Basin, the largest quantity of mercury is HgS, otherwise known as cinnabar (trigonal HgS) or metacinnabar (cubic HgS). Cinnabar ore, which is the mineral sought by the mercury miners, can contain concentrations of mercury as high as 15 percent (Pearcy and Peterson, 1990). Hg^{2+} itself is not a concern because it is not readily absorbed into plant and animal tissue, but it can be transformed to MeHg, the most toxic form of mercury, by biotic and abiotic processes (Marvin-DiPasquale and Agee, 2002). The primary method of methylation is conducted by sulfur reducing bacteria that live in the top layers of sediment in wetlands. The methylation of Hg^{2+} is particularly rapid in anaerobic conditions. Methylation can also occur abiotically when fulvic and humic acids are available, but, absent of acidic conditions, biotic processes will dominate (Nagase el al., 1982). Methylation is counterbalanced by biotic and abiotic processes that demethylate MeHg (Hudson et al., 1994). These processes tend to dominate in aerobic conditions which receive direct sunlight. Demethylation converts MeHg to Hg^0, which will quickly volatilize into the atmosphere. Figure 7 shows mercury cycling in freshwater ecosystems.

Although there are well-defined processes that convert Hg between the three different classes, the equilibrium conditions are complex and thus make it difficult to predict the form in which mercury will be found; a high concentration of Hg^0 or Hg^{2+} does not necessarily imply a high concentration of MeHg. However, methylation and demethylation rates are proportional to their concentration in the water and sediment and other environmental conditions which exist, such as dissolved oxygen concentration, sulfate concentration, and pH (Xun et al., 1987). Methylmercury is the only variety of mercury that bioaccumulates and is regularly found in fish; the insertion of a covalent bond between the mercury and carbon atoms during methylation enables MeHg to penetrate cell membranes more rapidly (Baldi, 1997), resulting in higher levels of toxicity than those associated with either Hg^0 or Hg^{2+}. Therefore, methylmercury is the variety that must be limited to a larger extent to reduced exposure and potential harm to humans and ecological receptors. MeHg concentrations in fish are a function of MeHg concentration in the water, trophic level of the fish, and age of the fish (Back et al., 2002).

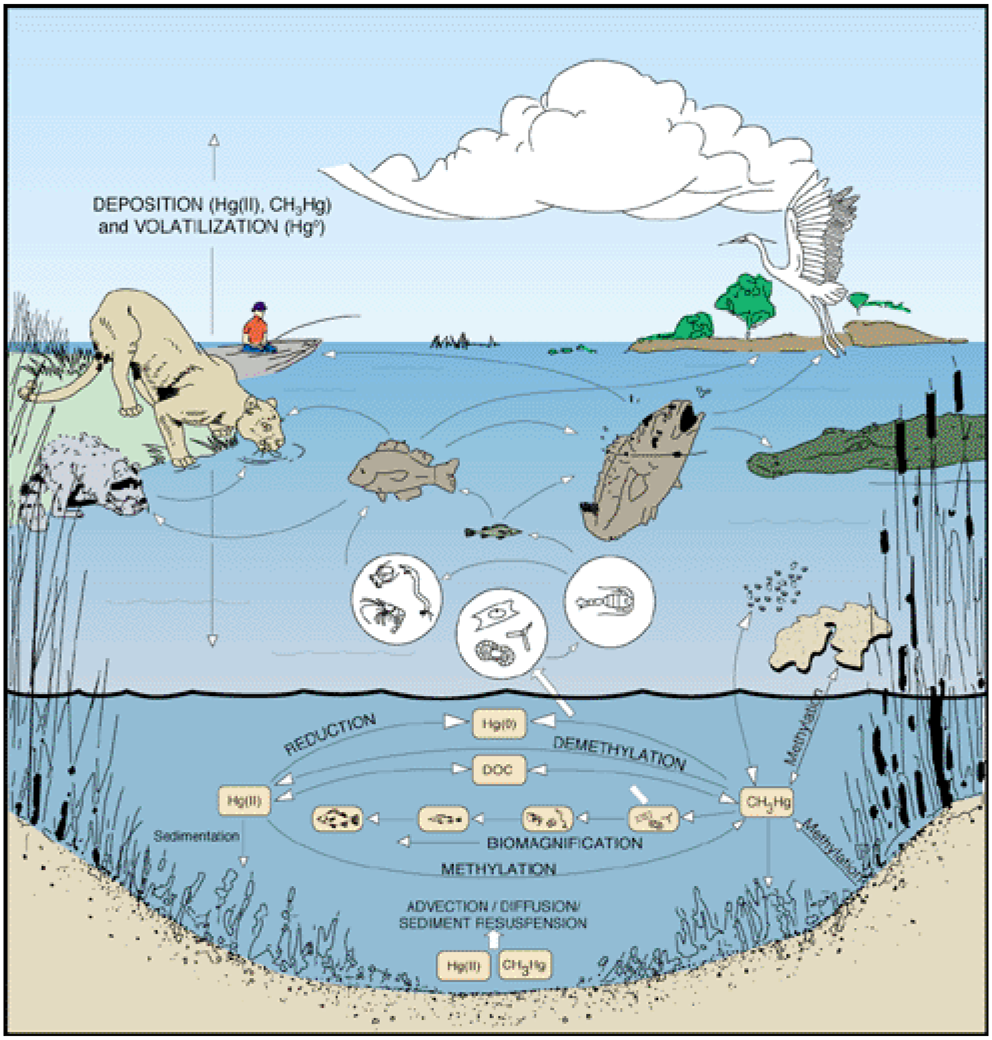


Figure 7. Mercury cycle in freshwater ecosystems (USGS, 2000)

All three varieties of mercury have a very high soil adsorption coefficient (K_d), which means mercury has a high affinity for adsorbing onto both suspended and settled sediments (Lyon et al., 1997). This is critical in understanding the transport of mercury, as it implies that if the flux of total suspended sediments from a mining region is limited, the flux of mercury will also be limited. As suspended sediment settles out of water, like it does in the Cache Creek Settling Basin, it has very high concentrations of Hg^{2+} and is prone to methylation during the anaerobic conditions prevalent in the dry season.

Ecological Effects of Mercury Contamination

Cache Creek Basin provides a number of beneficial uses from recreation to habitat for wildlife (Cooke and Morris, 2005; Cooke et al., 2004). There have been over 154 species of birds observed, including peregrine falcons and the southern bald eagle (Schwarzbach et al., 2001). A number of game and non-game fish including channel catfish, brown trout, smallmouth bass, Sacramento pike minnow, Sacramento sucker, and California roach also inhabit the watershed (Cooke and Morris, 2005). While the watershed provides valuable habitat for a number of wildlife species, high mercury levels threaten these uses. Increased mercury levels can lead to a number of adverse effects on wildlife and human health. In the Cache Creek Basin it is particularly important to manage mercury at a safe level to avoid transport of mercury into the Sacramento/ San Joaquin Delta and San Francisco Bay as well as to protect humans and wildlife that eat fish from the area (Cooke and Morris, 2005).

One reason mercury is of concern is due to its ability to bioaccumulate within organisms and to be magnified as it transfers to higher trophic levels within food webs. According to Domagalski et al. (2004b), “the bioaccumulation of mercury in fish is one of the most widely recognized environmental problems of the current era.” Organisms can accumulate mercury from multiple sources including water, sediment, and other organisms. However, “before mercury can bioaccumulate, the inorganic form must be converted to the organic (methylmercury CH_3Hg^+) form” (Domagalski et al., 2004b). Methylmercury is the most common form of organic mercury in natural systems (Nichols et al., 1999). In its methylated form, mercury becomes more bioavailable because it is more soluble in water than its inorganic form (Alpers et al., 2008). Methylmercury is also able to cross cell membranes allowing it to be more easily accumulated within organisms (Alpers et al., 2008). Alpers et al. (2008)

explains that methylmercury has the ability to form strong bonds with biological proteins making it easier for organisms to retain and transfer the mercury to other organisms. Thus, concentrations become magnified as they move up trophic levels to predatory organisms like piscivorous fish and birds (Domagalski et al., 2004b). In the Cache Creek Basin, correlations have been found between the concentrations of methylmercury in lower trophic level organisms and adult sport fish (Alpers et al., 2008). Studies in the San Francisco Bay-Delta Estuary have shown that bioaccumulation trends can also be linked to seasonal fluctuations of methylmercury (Alpers et al., 2008).

The primary target of methylmercury is the central nervous system (Nichols et al., 1999). As a result, methylmercury contamination causes a number of neurological effects. Wildlife including invertebrates, fish, birds, and mammals experience adverse effects when exposed to elevated levels of mercury. In the Cache Creek Basin and the San Francisco Bay-Delta, this is a concern because many studies have measured mercury concentrations in wildlife above recommended thresholds (Alpers et al., 2008; Domagalski et al., 2004b). As of 2005 there had been no studies directly linking the adverse effects of mercury exposure to wildlife; however, it can be difficult to detect non-lethal effects of mercury in organisms like fish (Cooke and Morris, 2005). Therefore, elevated mercury levels are still a concern because piscivorous fish in the watershed are estimated to exceed safe levels for consumption by humans and wildlife (Cooke and Morris, 2005). Slotton et al. (2004) found that piscivorous fish in Bear Creek had levels of mercury mainly between 2 and 4 µg/g and detritivorous fish also showed elevated levels of mercury well above the 0.3 µg/g standard established by the TMDLs.

Fish are exposed either by consuming contaminated benthic macro-invertebrates or other contaminated fish. Lower trophic level fish can become contaminated by consuming invertebrates and detritus; higher level predatory fish are exposed when they consume other fish. Decreased reproductive success, altered behavior, and impaired developmental growth are among some of the effects that fish can experience from exposure to an increased level of mercury (Alpers et al., 2008).

Predatory birds and mammals are also at risk in the watershed when they consume fish with elevated levels of mercury. Both mammals and birds have been shown to experience “impaired neurological development and learning behaviors” when exposed to mercury (Alpers et al., 2008). According to Cooke and Morris (2005), behavioral effects such as “impaired learning, reduced social behavior and impaired physical abilities have been observed in mice, otter, mink, and macaques exposed to methylmercury.” In the Cache Creek Basin, river otters may be at risk of contamination (Alpers et al., 2008). Of most concern are the peregrine falcon and the southern bald eagle that inhabit the watershed. Nesting and wintering bald eagles have been observed preying on large forage fish that may have elevated levels of mercury, especially from November to March (BLM, 2004).

Amphibians are another group of organisms that can be negatively impacted by increased levels of mercury in aquatic environments. One sensitive species found in the Cache Creek Basin is the Foothill Yellow Legged Frog (BLM, 2004). These organisms are affected because they prey on invertebrates and live in areas where even fish may not find the habitat suitable (Hothem, 2008). As a result, they may experience effects such as reduced survival, growth inhibition, behavioral modification, impaired reproduction, and malformations of larvae (Hothem, 2008).

Humans are primarily exposed to methylmercury by eating contaminated fish (Alpers et al., 2008; USEPA, 2001). Cache Creek is fished year round mainly for sport fish such as Channel Catfish and Smallmouth Bass (Alpers et al., 2008; Cooke and Morris, 2005). Much of the knowledge about mercury toxicity in humans comes from poisoning events that occurred in Minamata, Japan from contaminated fish as well as in Iraq, Guatemala, and Pakistan from grain contaminated with mercury (Alpers et al., 2008). These events showed how neurotoxicity is the biggest concern for humans and that developing organisms and children are most susceptible (Alpers et al., 2008; USEPA, 2001). Some of the signs and symptoms from methylmercury poisoning in humans are lowered immune system response, decreased reproduction, hearing, vision, and speech impairements, coma, and death (Batten and Scow, 2003). However, these effects were observed from extreme events and are not likely to occur with lower levels of mercury exposure that might occur from eating contaminated fish caught in Cache Creek (Alpers et al., 2008).

Mercury Sources

Sources of mercury to the Cache Creek Basin include geothermal springs, erosion of natural mercury-enriched soils, atmospheric deposition, sediment enriched with legacy mercury, as well as waste rock and tailings from historical mines. Unlike many other regions of the country, atmospheric deposition of mercury in the Cache Creek Basin is relatively small compared to the contributions from other sources (Churchill and Clinkenbeard, 2003). It is more likely that the region is a larger source of atmospheric mercury rather than a site of significant deposition. Soils that contain naturally elevated levels of mercury are common in the Basin, especially in mining regions. Weathering of bedrock is enhanced by the hydrothermal processes in the area, contributing to elevated mercury concentrations (Suchanek et al., 2010). It is believed that the largest sources of mercury are from geothermal springs, mine materials and sediment in the banks and beds of the streams below mining areas (Figure 8).

The Cache Creek Basin is geologically complex with multiple faults, extinct volcanoes, and many different types of soil and bedrock (Suchanek, 2010). The rock types include: quaternary deposits, volcanic rocks, Great Valley sequence, Coast Range ophiolite, and the Franciscan Complex. The high heat flow associated with volcanism deposited high concentrations of mercury, gold, and silver in the area. Even without human disturbance, concentrations of mercury in Cache Creek would be relatively high.

Many hot and cold springs exist in the area, and contribute various amounts of mercury and other minerals, depending on their chemical makeup. Additional parameters are important to take into account in considering mercury and methylmercury contributions of particular locations. For example, high levels of sulfur are known to increase the methylation of mercury by sulfur reducing bacteria. In addition, unknown springs may exist, especially in creek beds, making it difficult to quantify mercury contribution from those springs (Suchanek et al, 2010). Springs often form a black precipitate that contains a variety of metals including mercury that will accumulate during the dry season. The first large rain event of the wet season flushes this precipitate into the creek. Although mining activities are often associated with acid mine drainage, the springs and the creeks in the area have a pH that is moderately basic, indicating that acid mine drainage is not an issue in the Basin (Churchill & Clinkenbeard, 2003).

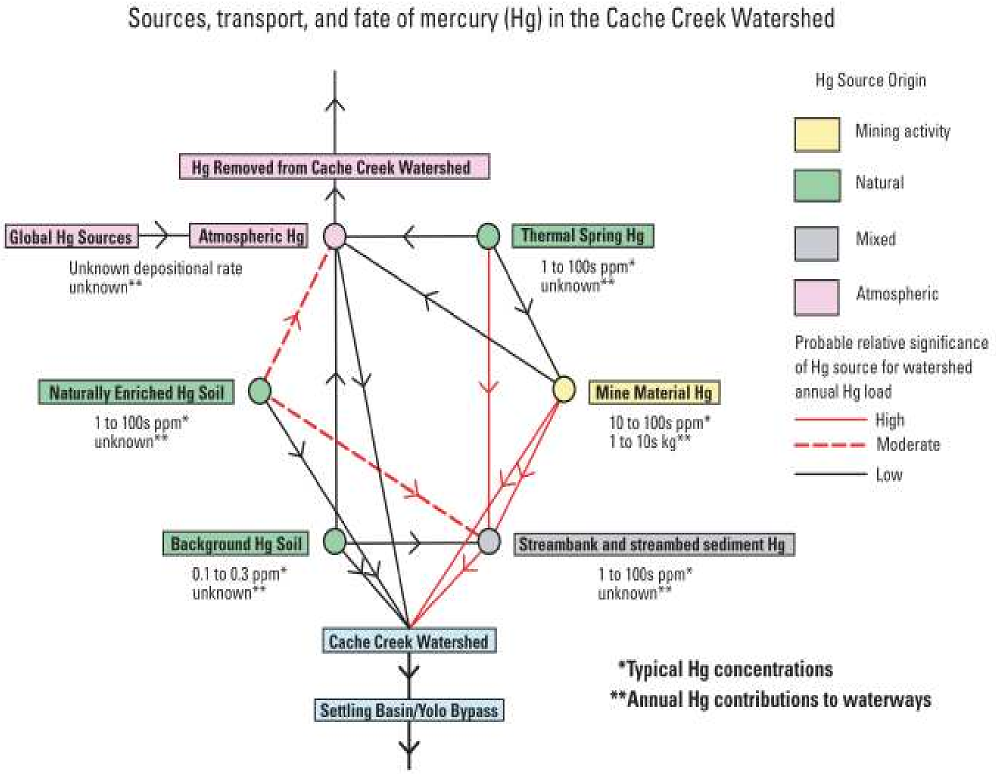


Figure 8: Sources, transport and fate of mercury in the Cache Creek watershed (Domagalski et al., 2004b)

Many of the mines had their ore processed at neighboring facilities, and as a result not every mine contains tailings. The last mercury mine in the Basin closed in 1971, around the same time many environmental regulations began. Before this time there was little understanding of the toxicity of mercury at the mines and processing facilities. Therefore, waste rock and tailings that contain high concentrations of mercury were left behind after those facilities closed. These tailings are often on steep slopes and are highly erodible. As the location of most of these mines is very close to tributaries of Cache Creek, rainfall and resulting erosion lead to much of the tailings ending up as sediment in creek beds, with some eventually washing into the Sacramento River and Sacramento-San Joaquin Delta. Pre-mining mercury concentrations in sediment in San Francisco Bay were estimated at around 0.06 mg/kg, whereas post-mining sediment mercury concentrations in the same area are between 0.2 and 0.5 mg/kg (Holloway, 2009). The contaminated sediment can remain in creek beds and in flood plains for long periods of time, and will likely be re-suspended in subsequent years, especially during high flow events. Although some remediation efforts, such as the removal of mining waste and erosion prevention measures, have taken place in the last couple of decades, a great deal of mercury is still eroding into the streams from the exposed rock left over from these abandoned mines.

Approximately half of the mercury exported from the Cache Creek Basin is retained in the Cache Creek Settling Basin (CCSB) while the remaining half is exported downstream to the Yolo Bypass and eventually the Sacramento-San Joaquin Delta (Foe & Bosworth, 2008). The CCSB is a 3,600 acre reservoir built by the United States Army Corp of Engineers (USACE, 2003) that serves to limit the amount of sediment entering the Yolo Bypass and maintain flood conveyance past Sacramento (Division of Safety of Dams). During large winter storms, the majority of water from the Sacramento River is diverted into the Yolo Bypass, and because Cache Creek Basin naturally exports very large amounts of sediment, the USACE built the CCSB to prevent this sediment from settling in the Yolo Bypass. An average of 340 acre-feet of sediment is trapped per year in the CCSB, which results in the need to periodically dredge the stored sediment to maintain the CCSB’s settling efficiency (USACE, 2003).

The majority of the mercury that reaches the Settling Basin is from sources upstream of Rumsey. From 1996 - 2000 it was found that about 400kg/yr of mercury was transported past Rumsey and 369 kg/yr was measured further downstream at Yolo (Cooke, et al., 2004). There does not appear to be any major source of mercury between Rumsey and Yolo, and the decrease in mercury is most likely due to irrigation diversions at Capay or sediment deposition (Cooke, et al., 2004). Although some of the sources of mercury upstream of Rumsey have been identified, such as those associated with the mines, they do not account for all of the mercury found downstream (Table 1 and Table 2). Sites of mercury input to Cache Creek that have been identified and studied are Harley Gulch, Sulphur Creek, Bear Creek, Davis Creek and Clear Lake. Each of these locations has been impacted by historical mining activities. Cooke, et al. (2004) note that mercury loads from unknown sources increase during years with high levels of precipitation. This indicates that the unknown sources are likely from ephemeral streams or from additional erosion of sediments in the streambed which are not usually wetted enough for scour.

Table 1: Cache Creek Total Mercury Budget (kg/yr) for Water Years 1996 thru 2000 (Cooke et al., 2004)

Water Year	Cache Creek: Clear Lake to North Fork	North Fork Cache Creek	Harley Gulch	Davis Creek	Bear Creek	Sum of inputs upstream of Rumsey	Unknown Sources Above Rumsey	Cache Creek at Rumsey	Atmospheric Deposition	Ag Diversions	Sum of Inputs & Diversions Upstream of Yolo	Erosion/Deposition btwn Rumsey and Yolo	Cache Creek at Yolo	Settling Basin Outflow	Deposition in the Cache Creek Settling Basin
1996	9	17	7		8	41	332	373	0.02	-31	343	-110	233	135	42%
1997	11	23	8		9	51	456	507	0.02	-36	471	-38	433	269	38%
1998	24	22	13		39	98	809	907	0.02	-42	865	159	1024	643	37%
1999	6	16	5		8	33	108	143	0.02	-32	112	7	119	65	46%
2000	3	11	4	0.04	9	27	41	68	0.02	-40	28	9	37	19	50%
Avg	**10**	**18**	**7**	**0.04**	**15**	**50**	**349**	**400**	**0.02**	**-36**	**364**	**-5**	**369**	**226**	**39%**

Table 2: Cache Creek Sediment Budget (kg/yr) for Water Years 1996 through 2000 (Cooke et al., 2004)

Water Year	Cache Creek: Clear Lake to North Fork	North Fork Cache Creek	Harley Gulch	Davis Creek	Bear Creek	Sum of inputs upstream of Rumsey	Unknown Sources Above Rumsey	Cache Creek at Rumsey	Ag Diversions	Sum of Inputs & Diversions Upstream of Yolo	Unknown Sources btwn Rumsey and Yolo	Cache Creek at Yolo	Settling Basin Outflow	Deposition in the Cache Creek Settling Basin
1996	41	81	0.02		4	125	249	374	-46	328	193	521	306	215
1997	41	110	0.02		4	154	336	490	-55	435	171	906	553	352
1998	41	102	0.03		16	159	711	870	-63	807	1316	2123	1304	819
1999	44	73	0.01		4	121	35	156	-48	108	174	282	160	122
2000	65	53	0.01	0.02	4	122	-33	89	-60	29	67	96	52	44
Avg	**46**	**84**	**0.02**	**0.02**	**6**	**136**	**260**	**396**	**-46**	**350**	**436**	**786**	**475**	**311**

Harley Gulch

The largest historical mining operation in the Sulphur Creek Mining District, the Abbott-Turkey Run complex, drains into Harley Gulch making it an area of significant concern for mercury contamination. Between one and two miles of underground tunnels exist there, and at least 1.8 million kg of mercury were extracted from the two mines. The rest of the mines in this mining district are small in comparison, with a cumulative 200,000 kg of mercury mined; however, their contributions to mercury pollution are also significant because of the high rates of erosion at these locations. As of 2003, it was estimated that 267,000 tons of tailings were present at the Abbott-Turkey Run complex (Churchill & Clinkenbeard, 2003). A cleanup effort was initiated by El Paso Merchant Energy-Petroleum Corporation and the USEPA in 2006. It included the removal and off-site disposal of several tons of mine tailings (Larson, 2007). The large tailings pile at the Abbott Mine was re-graded, capped with clean soil, and re-vegetated to minimize erosion and transport of sediment. Although the remedial actions were completed in 2007, is unclear how effective these efforts have been, but it is assumed the cleanup resulted in a large reduction in mercury transport originating from Harley Gulch.

Prior to the cleanup effort, the remnants of the Abbott-Turkey Run complex led to mercury contamination within Harley Gulch as well as in the downstream areas of Cache Creek. An 8 to16 fold increase in mercury concentrations was found in sediments below the confluence of Harley Gulch and Cache Creek, compared to levels upstream (Foe & Bosworth, 2008). It is strongly believed the elevated levels of mercury found in sediment in the seven miles between Harley Gulch and Crack Canyon is from the historical mining of Abbott and Turkey Run. Foe and Bosworth (2008) were unable to find evidence of any other source of mercury that would explain the increased mercury in that reach of Cache Creek. Although two-thirds of the flow in Harley Gulch is from the East Branch, studies have determined that over

90 percent of mercury leaving Harley Gulch originates from the West Branch, which flows from within the mine complex (Cooke, et al., 2004; Suchanek, et al., 2004).

Other characteristics of this watershed may promote the methylation of mercury, which is important in addressing the TMDL requirements. Cooke, et al. (2004) determined that most of the methylmercury in Harley Gulch is produced in a wetland area downstream of the Abbott-Turkey Run complex. This may be due to the elevated sulfate levels in this area from a thermal spring at the Turkey Run Mine. The spring contributes about 50,000 to 160,000 kg/yr of sulfate and total mercury and methylmercury concentrations in the water increase when mine site materials interact with the water from this spring (Churchill & Clinkenbeard, 2003; Rytuba, 2000). As noted above, sulfate reducing bacteria are suspected to be the primary route of mercury methylation under these conditions.

While the cleanup efforts at the Abbott-Turkey Run complex have likely helped to minimize future inputs of mercury into Harley Gulch, the mercury that is already in the soils and sediments in and around Harley Gulch and the downstream reaches of Cache Creek will continue to be an issue. It is estimated that 855 kg of mercury are in depositional piles along Cache Creek between Harley Gulch and Crack Canyon, and an additional 15-20 kg of mercury are in the alluvial fan at the confluence of Harley Gulch and Cache Creek, commonly called the Harley Gulch Delta (Foe & Bosworth, 2008). It is strongly believed that a major source of mercury within Cache Creek Basin is the re-suspension of mercury from sediments in the creek beds (Cooke, et al., 2004). During dry years, Harley Gulch was found to be a small contributor of mercury to Cache Creek (Domagalski, et al., 2002b); sediment disturbance and transport only occurs with sufficiently elevated stream flows, and therefore would be of smaller magnitude during years with less rainfall. Since Harley Gulch, an ephemeral stream that flows primarily from October to June, typically has lower flows, it would be more affected by large increases in precipitation.

The 2004 TMDL report (Cooke, et al., 2004) found that Harley Gulch contributes approximately 7kg of mercury and 1.0g of methylmercury annually to Cache Creek. These estimates were done over a range of years in an attempt to account for both relatively wet and dry years. The requirement of the TMDL (Cooke, et al., 2004) is to reduce the total mercury load from Abbott and Turkey run mines by 95 percent of the existing load at the time of publication of the report and methylmercury of the entire stream by 84 percent, and to reduce concentrations of methylmercury to below 0.14 ng/l (Table 3).

Table 3: Allocation of Methylmercury Loads to Cache Creek (Cooke, et al., 2004)

Tributary Watershed	Current load of MeHg (gm/yr)	MeHg Load Reduction	Acceptable MeHg Load (gm/yr)
Clear Lake Outflow	36.8	70%	11.0
North Fork Cache Creek	12.4	0%	12.4
Harley Gulch	1.0	84%	0.1
Davis Creek	1.3	50%	0.7
Bear Creek	21.1	85%	3.2
Net within channel production & ungauged tributaries, upper basin to Yolo	53.1	85%	7.4
Total	125.7	72%	34.8

Bear Creek and Sulphur Creek

Large portions of Sulphur Creek and the lower portion of Bear Creek are managed by the BLM; mercury and methylmercury loading to Cache Creek from this area is of great concern. Sulphur Creek drains into Bear Creek, which is a major tributary of Cache Creek. The 2004 TMDL (Cooke et al., 2004) found that 4 percent of total mercury and 17 percent of methylmercury in Cache Creek originates from Bear Creek. The elevated mercury levels in soils and sediments in and around Sulphur Creek contribute largely to Bear Creek exceeding water quality standards for mercury. According to the CVRWQCB's report on Bear Creek, only 22 percent of the total mass of bed sediment in Bear Creek is downstream of the Sulphur Creek confluence, but this sediment contains 85 percent of the total mercury mass in all

Bear Creek sediments (CVRWQCB, 2009b). This report also found a 4 to 9 fold increase in mercury concentrations in Bear Creek sediment found downstream of the confluence with Sulphur Creek, as compared to the upstream portion of Bear Creek. The Sulphur Creek TMDL (Cooke & Stanish, 2007) finds that on average, Sulphur Creek directly contributes 48 percent of mercury and 41 percent of methylmercury to Bear Creek. The remaining mercury and methylmercury is from sediments within Bear Creek that originated from Sulphur Creek.

There are multiple historical mines found in the Sulphur Creek Mining District. With the exception of the Abbott-Turkey Run complex discussed above, all mines in this district drain into Sulphur or Bear Creeks. The mines, combined with geothermal springs and naturally mercury-enriched soil, create high mercury concentrations in local streams. Several of the hot springs near Wilbur Springs in the Sulphur Creek watershed contain high concentrations of mercury and methylmercury. Although hot springs in this area contribute to the mercury issue, the Sulphur Creek TMDL (Cooke & Stanish, 2007) states that the majority of the mercury in Sulphur Creek comes from the mines. A more recent study, which examined the chemical make-up of surface soils in Bear Creek, also concluded that mercury-rich sediment in this area is derived from mine tailings and calcines (Holloway, et al, 2009). The Sulphur Creek TMDL outlines a reduction plan, which mainly focuses on reducing mercury loads from mines in order to meet the specified levels of mercury and methylmercury. This plan would require the reduction of loads from inactive mines by 95 percent (Table 4). According to Holloway, et al. (2009) these mining areas still have exposed tailings and have undergone little to no remediation.

Due to the sulfate-rich water from the geothermal springs, a great deal of mercury is methylated in-stream. Therefore, the TMDL (Cooke & Stanish, 2007) focuses on the reduction of total mercury loads from sources such as mines, since this will result in a reduction of methylmercury as well. The 2004 TMDL (Cooke, et al., 2004) found that Bear Creek contributed 21.1g of methylmercury to Cache Creek annually. The report states that an 85 percent reduction is necessary, which, combined with reductions from Harley Gulch, Davis Creek, Clear Lake and other sources, would lead to a reduction in the annual methylmercury load reaching Yolo from 122.1g to 39g.

In addition to reducing mercury loads from the mines, the 2007 TMDL (Cooke & Stanish, 2007) also focuses on controlling erosion of stream sediments and soil that contain high concentrations of mercury. The report found that erosion from sediments and soil with concentrations greater than 0.4 mg/kg weight can be a significant source of mercury (Cooke & Stanish, 2007). Similar to Harley Gulch, storm events lead to more erosion and re-mobilization of mercury in Sulphur and Bear Creeks, which results in larger mercury loads moving downstream. The high mercury and methylmercury concentrations in Bear Creek are a larger problem for Cache Creek after the irrigation season when Clear Lake and Indian Valley Reservoir stop releasing water (Cooke, et al., 2004). At that time, Bear Creek, a perennial stream, becomes a larger source of downstream water and the elevated mercury levels have a greater impact.

Table 4: Sulphur Creek Total Mercury Budget by Source Type and Load Limits based on data collected in 2000-2004 (Cooke & Stanish, 2007)

Source	Current Load (kg/yr)	Load Reduction	Future Load based on current load estimates, kg/yr
Geothermal springs	1.4	0%	1.4
Non-mine site erosion	1.2	15%	1.0
Clyde Mine	0.4	95%	0.02
Elgin Mine	2.7	95%	0.13
Wide Awake Mine	0.8	95%	0.04
Lower Watershed Mines plus contaminated stream bed	5.3	95%	0.3
Atmospheric Deposition	0.03	0%	0.03
Total	11.8	75%	2.9

Davis Creek

Another notable source of mercury to Cache Creek is Davis Creek, which contains the Knoxville Mining District. The Knoxville District includes the Reed, Harrison, and Manhattan mercury mines; the district produced between 2.4 and 2.8- million kg of mercury during its operation from 1860 to 1978, making these mines more productive than all the mines in the Sulphur Creek Mining District (Foe & Bosworth, 2008). Yet, studies show that Davis Creek is a much smaller source of mercury to Cache Creek than either Sulphur Creek or Harley Gulch (Domagalski et al., 2004b). We acknowledge, however, that there is a distinct lack of data in the literature to support this assertion.

A large portion of the Knoxville District was purchased by Homestake Mining Company in 1984. Soon after, they built Davis Creek Reservoir to assist with nearby gold processing operations, but only used the reservoir for a few years. Homestake has made efforts to clean up the mining areas, and remedial actions have included covering the tailings with clean soil and extensive re-vegetation (Holloway, et al., 2009). Despite these efforts, annual monitoring from 1993 to 2002 showed that an average of 72 kg of mercury was detained annually by the Davis Creek Reservoir from the mining district (Foe & Bosworth, 2008). It is unknown where this mercury is coming from, or how much mercury is being exported out of the reservoir. There is no record of the amount of mercury reaching Davis Creek prior to the remedial efforts, so no conclusions can be drawn about the impact of remediation. Holloway, et al. (2009) surveyed this area and reported that there was still at least one exposed mining pit as of 2005, which could be a source of mercury rich sediment to Davis Creek. Additionally, was found that naturally occurring mineralized ultramafic rock and soils in the region have mercury concentrations ranging from 34 - 290 mg/kg (Holloway, 2009).

The 2004 TMDL for Cache Creek (Cooke, et al., 2004) concluded that while there are elevated concentrations of mercury and methylmercury in Davis Creek's water and sediment, its minimal flow rate keeps it from being a more significant contributor of mercury to Cache Creek. This report found that Davis Creek contributes about 1.3g of methylmercury annually to Cache Creek. The mandate is to reduce this load by 50% percent in order to reach an acceptable level of 0.7g/yr (Table 2). However, there have been very few samples taken of Davis Creek both above and below the reservoir during high flows, and it is not possible at this time to know exactly how much mercury or methylmercury Davis Creek contributes to Cache Creek.

Clear Lake

Sulphur Bank Mercury mine contributed a significant amount of mercury to Clear Lake, which has resulted in additional loading to Cache Creek. In 1990 the mine area was listed as a Superfund site by the USEPA. As a result, the USEPA has removed mine wastes from multiple residential areas and performed numerous studies in order to fully assess the sources and extent of mercury contamination in the area. These efforts have lowered Clear Lake's mercury contribution and it is now less of a concern than the other sites, although it continues to be monitored and assessed. Foe & Bosworth (2008) found that the majority of the mercury from Sulphur Bank mine is being detained in Clear Lake and only small amounts are moving downstream. It can be seen from Table 3 that Clear Lake contributes an average of 36.8gm/yr to Cache Creek, making it a far greater source of mercury than any of the other mining areas. Wetlands surrounding Clear Lake, especially Anderson Marsh, are suspected of fostering very high levels of mercury methylation.

Summary

Much effort has gone into identifying and characterizing the sources of mercury in the Cache Creek Basin. As outlined above, anthropogenic sources from historical mining activities have been identified and studied in Harley Gulch, Sulphur Creek, Bear Creek, Davis Creek and Clear Lake. However, there is a significant amount of mercury observed downstream from unknown sources. It is speculated that these sources are a combination of natural sources, increased erosion during times of high precipitation, and the re-suspension of mercury enriched sediment. In order to be able to successfully meet the TMDLs for the area, further analysis is necessary to determine the magnitude of each of these unknown sources in order to address them effectively.

Regulatory Framework

BLM Management, Water Board, and Basin Plan Background

The BLM must adhere to a number of regulations during the process of remediating contamination and restoring public lands like those found within the Cache Creek Basin. In addition to following state and federal regulations to restore and remediate the Basin, they must also follow the guidelines of the Federal Land Protection Management Act (FLPMA). Under FLPMA, the BLM’s responsibility is to "provide the public the opportunity to use and appreciate significant cultural and natural resources while protecting and conserving them" (BLM, 2008). As a result of this responsibility, BLM has developed the management goal to "maintain the health of the land and, to the best of its ability, to restore or replace resources that are harmed by pollution" (BLM, 2008). This management goal is important to the Cache Creek Basin because of its damaged water resources which affect the Basin’s ecosystem.

The U.S. Clean Water Act (CWA) requires each state to identify all beneficial uses of water bodies within its boundaries. Managers of waters that are not meeting water quality standards set by the USEPA, as required under the CWA, must implement cleanup measures to achieve these standards (CVRWQCB, 2009a). To accomplish this goal, California's water code created the State Water Resources Control Board and nine regional offices under the Porter-Cologne Water Quality Control Act. Each Board is tasked with setting standards and ensuring compliance. The Cache Creek Basin is under the jurisdiction of the Central Valley Regional Water Quality Control

Board (CVRWQCB). To meet the standards set in the CWA, the CVRWQCB outlined their management goals in the Water Quality Control Plan ("Basin Plan") for the Sacramento River and San Joaquin River basins. The Basin Plan describes beneficial uses and water quality objectives for the area and gives recommendations for implementation of surveillance and monitoring programs for impaired water bodies (CVRWQCB, 2009c). The Basin Plan also provides information about financing, individual discharges, and action recommendations (CVRWQCB, 2009c).

The Cache Creek Basin has its own section in the Basin Plan titled the "Cache Creek Watershed Mercury Program" ("Program") (IV-33.12) (CVRWQCB, 2009c). The Program describes the amount of total mercury and methylmercury in Cache Creek, as well as its tributaries and outlines acceptable loads of methylmercury within the Basin (Table 5) (CVRWQCB, 2009c). In addition to setting goals for acceptable levels of methylmercury, mining sites were identified that require a 95 percent annual load reduction of total mercury (Table 6) (CVRWQCB, 2009c). The Program also outlines monitoring protocols, erosion control, and road construction and maintenance (CVRWQCB, 2009c).

Table 5: Cache Creek Basin methylmercury allocation (CVRWQCB, 2009c)

Source	Existing Annual Load (g/yr)	Acceptable Annual Load (g/yr)	Allocation (% of existing load)
Cache Creek (Clear Lake to North Fork confluence)	36.8	11.0	30%
North Fork Cache Creek	12.4	12.4	100%
Harley Gulch	1.0	0.04	4%
Davis Creek	1.3	0.7	50%
Bear Creek at Highway 20	21.1	3.0	15%
Within channel production and ungauged tributaries	49.5	32.0	65%
Cache Creek at Yolo	72.5	39.0	54%
Cache Creek Settling Basin Outflow	87.0	12.0	14%

Table 6: Cache Creek Basin inactive mines that require 95 percent total mercury load reduction (CVRWQCB, 2009c)

Mine	Average Annual Load Estimate (kg Hg/year)
Abbott and Turkey Run Mines	7.0
Rathburn and Rathburn-Petray Mines	20.0
Petray North and South Mines	5.0
Wide Awake Mine	0.8
Central, Cherry Hill, Empire, Manzanita, and West End Mines	5.0
Elgin Mine	3.0
Clyde Mine	0.4

There are a number of beneficial uses for water bodies in the Cache Creek Basin that are identified in the Basin Plan. Some of these uses include: municipal and domestic water supply; industrial process and service supply; contact and non-contact water recreation; irrigation; and warm and cold freshwater spawning and wildlife habitat (CVRWQCB, 2009a). To maintain these uses, the state established Water Quality Objectives (WQOs) and implementation policies to achieve these objectives. WQOs are numeric targets that use standards, such as maximum contaminant levels (MCLs), TMDLs, odor, and color to determine water quality (CVRWQCB, 2009a). Cleanup orders are created when beneficial uses of a water body are being affected by polluted water and WQOs are not being met (CVRWQCB, 2009a). Many tributaries in the Basin are not meeting water quality standards due to mercury pollution from abandoned mines. In particular, mercury is affecting municipal and domestic water supply, recreation, and wildlife habitat (Cooke & Morris 2005).

The BLM manages a large portion of the Cache Creek Basin, and is therefore considered one of the responsible parties for maintaining water quality and preventing ongoing discharge of pollutants. The BLM is liable for cleanup on its property in the Basin even though they were not the perpetrators of the initial discharge of pollutants (CVRWQCB, 2009a). As a part of this responsibility, the BLM must comply with cleanup orders issued by the CVRWQCB to achieve the targeted TMDLs. As stated in the California Water Code and the Basin Plan, wastes must be cleaned up to background levels or, if this is not achievable, to the most stringent level that is the most technologically and economically feasible (CVRWQCB, 2009a). However, the cleanup order is an enforcement action required by a regulatory agency and can be considered a minor action to mitigate the release of hazardous waste; therefore, the order is exempt from the California Environmental Quality Act (CEQA) (CVRWQCB, 2009a).

In addition to requiring the BLM to take action, the cleanup orders require the creation of technical and monitoring reports (CVRWQCB, 2009a). Reports required in the cleanup order include: Mining Waste Characterization Report; Mining Waste Characterization Work Plan; Surface and Ground Water Monitoring Plan; and Site Remediation Work Plan (CVRWQCB, 2009a). Cleanup of the site must continue until the Executive Officer determines the site has had sufficient contaminant reductions to fully comply with the order (CVRWQCB, 2009a). The BLM has received cleanup orders for Rathburn-Petray Mine, Clyde Mine, and Elgin Mine. The Rathburn-Petray Mine order was issued in December 2005 and the Clyde Mine and Elgin Mine orders were issued in August 2009.

Another challenge for cleanup of the Cache Creek Basin is finding funding sources for remediation and restoration actions. Although the BLM is the principal responsible party for cleanup of its lands, it is not the sole financier of all cleanup projects; the BLM collaborates with the USEPA and the CVRWQCB to fund remediation efforts. In addition, the USEPA is considering approving the Cache Creek Basin as a Superfund site (Weigand, 2010). If the Cache Creek Basin is classified as a Superfund site, this would significantly change how cleanup actions are financed and managed. Until a decision is made, the BLM needs to find ways to fund the restoration and/or remediation of their contaminated lands in the Basin. One way to do this is through the BLM Natural Resource Damage Assessment and Restoration (NRDAR) process.

The NRDAR assessment is a litigation-based process designed to identify all parties responsible for degradation of a natural resource in order to get restoration of that resource financed and underway. The Trustee of the resource, in this case the BLM, seeks damages from the polluting party to compensate for the cost of the loss of ecological services. These damages are then used to fund restoration of the affected site.

It is important to note that NRDAR is a funding mechanism for restoration, whereas a Superfund designation would require remediation of the affected site (see Box 1 for definitions of restoration and remediation). This is particularly relevant in the case of the Cache Creek Basin, as many of the polluted areas are on public land downstream of the mine sites. Restoration under NRDAR would allow the BLM to use funds acquired through the litigation process to restore ecological functioning at a site downstream of that which is directly affected by the pollutant. The effectiveness of restoration could be maximized by choosing a site that is not constrained geographically or politically by the wilderness designation. Further research must be done in order to determine an appropriate valuation method for assessing damages to ecosystem services in the Cache Creek Basin.

Box 1. Restoration versus Remediation.

The difference between restoration and remediation must be understood before any cleanup efforts can be initiated. Restoration addresses the downstream effects of the pollutant, whereas remediation addresses the source of the pollutant, in this case abandoned mercury mines (Weigand, 2010). This distinction clarifies which policies and regulations apply to the cleanup actions. Though TMDLs do not specifically state how to achieve water quality standards, it is important to know whether cleanup efforts

Applicable Regulations, Policies, and Laws

The BLM must identify and consider various regulations and laws that relate to restoration and remediation of the Cache Creek Basin (Table 7). These regulations can determine what remediation or restoration options can be undertaken at a particular site. They can also affect the way in which cleanup is implemented. Some of the regulations impacting cleanup actions are federally driven and others are state driven; however, state laws typically build upon federal standards or are based on federal requirements. While a wide range of applicable regulations, policies, and laws will be discussed below, we do not present an exhaustive list, only those we consider the most relevant regulations for the Cache Creek Basin. Ecology and Environment, Inc (2008) includes a more extensive list of applicable regulations; however, it does not mention the Wilderness Act, California Toxics Rule, or the Antidegradation Policy.

Table 7: Regulations, policies, and laws that BLM will have to consider for any remediation and/or restoration project

Law, Policy, Regulation	Citation	Description
Antidegradation Policy	23 CCR § 2900 and 40 CFR§ 131.12	Part of water quality standards in the Clean Water Act. States must establish a 3-tier system to ensure water is not degraded
California Cultural and Paleontological Resources	Document 33.4	State-level protection for cultural and paleontological resources via the Antiquities Act of 1906 and CEQA
California Mining Waste Regulations	27 CCR § 22470-22510	Establishes three different groups of mining waste that is required for all mining sites (active or inactive) and is administered by the RWQCB
California Preservation Laws	Administrative Code, Title 14, Section 4307	Protection for objects of paleontological, historical, or archeological interest and/or value

Table 7 *continued*: Regulations, policies, and laws that BLM will have to consider for any remediation and/or restoration project

Law, Policy, Regulation	Citation	Description
California Surface Mining and Reclamation Act of 1975	Office of Mine Reclamation Article 9 Title 14; § 3703, § 13704, § 3705, § 3706, § 3710, § 3711, § 3712, § 3713	Protection and performance standards for wildlife habitat; backfilling, regrading, slope stability and recontouring; revegetation; drainage, diversion structures, and erosion control; stream protection; topsoil salvage, maintenance, and redistribution; tailing and mine waste management; and closure of surface openings
California Toxics Rule	40 CFR Part 131.38	Clean Water Act numeric criteria for priority toxic pollutants for State waters
Closure Criteria for Municipal Solid Waste landfills	40 CFR Part 258.60(a)(1-3)	Design criteria for caps
Design and Siting under California Water Code (re: California Mining Waste Regulations)	Section 13172	State regulations for the design of mine waste disposal sites for the different mine waste groups
Endangered Species Act	16 USC § 1531 (h) through 1543	The preservation and conservation of endangered species and critical habitat
Historic Sites, Buildings, and Antiques Act and Executive Order 11593	16 USC 461 et seq.	Federal agencies must consider the existence and location of landmarks on the National Registry of Natural Landmarks
Porter-Cologne Water Quality Act	CWC, Division 7: Water Quality, Water Code Section 13000-13002	All State waters must be protected for the use and enjoyment by the people of the state
Regional Basin Plan for Central Valley	RWQCB Basin Plan	Sets TMDL limits and establishes location-specific beneficial uses
The Historic and Archeological Data Preservation Act of 1974	16 USC 469; 40 CFR 6.301	Procedures to preserve historical and archeological data that may be destroyed during a federal construction project or licensed activity or program
Water Rights	23 CCR § 880-969	The allotment of the use of water either through the riparian doctrine or prior appropriation doctrine
Wilderness Act of 1964	43 CFR Part 6300	Areas of land preserved for the permanent good of the whole people and for other purposes in a state that is unimpaired for future use and enjoyment

Antidegradation Policy

The Antidegradation Policy is part of the water quality standards in the Clean Water Act. Each state has its own antidegradation policy standards. In California, the policy is incorporated into all regional water quality control plans (SWRCB, n.d.). Therefore, the antidegradation policy should be considered for the TMDLs and other water quality control issues in the Cache Creek Basin. The federal antidegradation policy requires states to establish their own three-tiered antidegration program based on the following tiers: Tier 1 maintains and protects existing uses and water quality conditions necessary to support such uses; Tier 2 maintains and protects "high quality" waters; and Tier 3 maintains and protects water quality in outstanding national resources waters (ONRWs) (USEPA, 2009b). California's antidegradation policy applies only to high quality waters and requires that existing high quality water be maintained to the "maximum extent possible", but the tiered federal policy is applied where relevant (SWRCB, n.d.). Water quality targets can be lowered if the change is "consistent with maximum benefit to people of the state and does not unreasonably affect beneficial uses" and if waste discharge does not allow pollution or nuisance (SWRCB, n.d.). California currently has no federal Tier 1 designations and does not use a Tier 2 designation; however, it applies Tier 2 protection per pollutant by comparing the current water quality to the particular water quality objectives for the pollutant (BLM, n.d.) If the water is in Tier 1, California must protect existing in-stream uses (SWRCB, n.d.). For Tier 2 protection, California uses a qualitative approach to determine if an activity will lower water quality (SWRCB, n.d.), which was suggested for the Capay diversion dam apron retrofit project (SWRCB, 2010a). For Tier 3, California has 2 ONRWs – Lake Tahoe and Mono Lake – for which protect is mandated (SWRCB, n.d.).

California Mining Waste Regulations

The California Mining Waste Regulations (CMWR) (27 CCR § 22470-22510; CalRecycle, 2010) were promulgated by the State Water Resources Control Board and is administered by a Regional Water Quality Control Board (RWQCB). These regulations apply in the Cache Creek Basin because all mining sites must comply with the siting and construction requirements, whether or not the mines are active. There are three different waste group classifications under the CMWR that are determined by the risk of water quality degradation from the waste. These classifications were created under the California Water Code, which requires California to adopt regulations to address the management of mining waste. Each waste is to be classified as Group A, Group B, or Group C by the RWQCB. Group A includes mining wastes that are considered hazardous waste. Group B includes mining wastes that either contain or consist of a hazardous waste or contain nonhazardous soluble pollutants that would degrade water quality and prevent water quality objectives from being met. Group C includes mining wastes that are in compliance with water quality objectives when discharged (other than turbidity). The California Water Code (CWC § 13172) stipulates certain design and siting regulations for these three groups: all mining units must be protected from flooding; containment structures must be designed by a registered civil engineer and construction shall be supervised and certified by a registered civil engineer or a certified engineering geologist; liner regulations must be followed (e.g., permeabilities shall be relative to the fluids, clay liners have to be at least two feet thick with a compaction of at least 90 percent, etc); and Group B drainage facilities shall be designed to withstand one 10 year, 24 hour storm. In addition to these requirements, water quality monitoring is mandatory at all mining sites.

Though mercury is typically considered a hazardous waste (Group A) mercury mine tailings are considered a Group B waste. Mining waste may contain and/or consist of mercury (a hazardous waste by the Group A definition), but is not considered a hazardous waste itself because it can be removed as an ore (Tetra Tech, 2003). This classification is important because if the mine tailings and waste were considered Group A, this would immediately eliminate the ability to cap the waste (e.g., create a municipal solid waste landfill) because hazardous waste cannot be put in a municipal solid waste landfill (40 CFR Part 258.60(a)(1-3)). In addition, Resource Conservation and Recovery Act (RCRA) regulations would have to be followed for the handling of hazardous waste, requiring special training and permits (Tetra Tech, 2003). Overall, if mercury mine waste was classified as a hazardous waste, it would significantly increase the cost of and limitations on the removal of any mine waste from the Basin.

California Surface Mining and Reclamation Act of 1975

California Surface Mining and Reclamation Act (CSMARA) of 1975 contains several regulations that are pertinent to the Cache Creek Basin; however, these regulations will only be relevant if a reclamation plan had not been approved prior to January 15, 1993 (TetraTech, 2003). There are several regulations in the CSMARA that may be applicable to the Basin regarding performance standards for: wildlife habitat (14 CCR § 3703); backfilling, regarding, slope stability, and re-contouring (14 CCR § 3704); re-vegetation (14 CCR § 3705); drainage, diversion structures, waterways, and erosion control (14 CCR § 3706); stream protection (including surface and groundwater) (14 CCR § 3710); topsoil salvage, maintenance, and redistribution (14 CCR § 3711); tailing and mine waste management (14 CCR § 3712), and closure of surface openings (14 CCR § 3713). These performance standards will not be discussed in this paper, but details can be found accordingly in each section of the CSMARA and should be considered if deemed appropriate.

California Toxics Rule

One of the regulations of concern for meeting TMDL limits is the California Toxics Rule (CTR). The Clean Water Act requires states to adopt numeric criteria for the priority of toxic pollutants if they could be expected to interfere with the designated use(s) of the state's waters (USEPA, 2009a). California had set numeric criteria for priority toxic pollutants in the Inland Surface Water Plans and Enclosed Bays and Estuaries Plans in April of 1991, but a California State court ordered the state to rescind the water quality control plans in 1994 (USEPA, 2009a). In April of 2000, the USEPA promulgated numeric water quality criteria for priority toxic pollutants for the State of California (USEPA, 2009a). The USEPA created the water quality criteria because the Administration was determined to protect California human health and environment (USEPA, 2009a). A criterion was created for human standards, but does not include standards for any aquatic life (USEPA, 2009a). The National Marine Fisheries Service (NMFS) and the Fish and Wildlife Service (FWS) did not accept that the criteria would sufficiently protect federally listed species and, as a result, should not be promulgated (Federal Register, 2000). Therefore, the criterion listed by the USEPA has a narrower focus than the original rule. For mercury, the CTR has a water quality criterion of 0.05 µg/l total recoverable mercury for freshwater sources of drinking water (Cooke & Morris 2005). In the Cache Creek Basin, because of the naturally high sediment concentrations in many creeks, CTR criterion is often exceeded even in creeks that have no mercury mines upstream.

Historical and Archaeological Data Preservation Act of 1974

The Cache Creek Basin contains many different tribal lands and areas with historical significance. The protection of these lands is established under the Historic and Archaeological Data Preservation Act of 1974 (16 USC 469; 40 CFR 6.301), which outlines a procedure to provide for preservation of historical and archaeological data that might be destroyed through federal projects, activities, or programs. In addition, California has its own version of the federal law, the California Preservation Law (Administrative Code 14 § 4307), thereby creating two levels of protection on all archaeological, historical, and/or culturally significant sites. Due to these laws, historically, culturally, and/or archaeologically sensitive sites may not be impacted during cleanup of the Cache Creek Basin (Weigand, 2010). This act may prove to be a significant barrier for most remediation and restoration projects bordering or affecting historical, archeological, and cultural sites.

Municipal Solid Waste Landfills

One possible way to contain mercury in the Cache Creek Basin is to place a containment cap of clay over contaminated areas. This would be considered a landfill (i.e., creating a landfill, disposing the mercury mine waste within it, and covering the landfill) and regulations must be followed for a municipal solid waste landfill (MSWLF) (40 CFR Part 258.60(a)(1-3)). Water quality concerns relative to the design of a MSWLF are leachate and run-off. The run-off control system must collect and control, at minimum, the water volume resulting from a 24 hour, 25-year storm. The final cover of the landfill must be designed to minimize infiltration and erosion with the following criteria: maintains a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present or a permeability no greater than $1x10^{-4}$ cm/s (whichever is less); minimizes infiltrations through the closed MSWLF by use of an infiltration layer that contains a minimum 18 inches of earthen material; and minimizes erosion of the final cover by the use of an erosion layer that contains a minimum 6 inches of earthen material that is capable of sustaining native plant growth. (FedCenter, 2010)

Species of Concern

An area of concern for all restoration and remediation efforts is whether endangered or threatened plants and/or animals will be affected. There are no state or federal endangered or threatened species which inhabit the Cache Creek Basin (the American peregrine falcon was delisted both by the state and federal government in recent years (CDFG, 2010)). However, there are two List 1B plants in the Basin: the Hall’s harmonia (*Harmonia hallii*) and the adobe lily (*Fritillaria pluriflora*). List 1B plants are categorized by the California Native Plant Society (CNPS) as “rare, threatened, or endangered in California and elsewhere” (CNPS, 2010). The CNPS Lists (1B and 2) are not a formal state or federal listing, but the California State Director of the BLM conferred sensitive status upon all List 1B plants in California. As a result, the BLM recognizes these plants as "Special Status Plants" and must treat them as if they are federally- or state-listed endangered and/or threatened plant (BLM, 2010). Hall's harmonia has been primarily documented directly east of Indian Valley Reservoir and the adobe lily has been found to the east of Indian Valley Reservoir and southeast of Clear Lake. Although the Cache Creek Basin has two List 1B plants, it is believed these plants do not reside in areas that would be considered for remediation and/or restoration efforts (Weigand, 2010). However, a species inventory should be performed prior to the initiation of every project to ensure that no endangered or threatened plants or animals will be affected.

Water Rights

For various restoration and remediation options, water rights must be considered within the Cache Creek Basin. California has a "dual system," which means it recognizes the riparian and prior appropriation doctrines (BLM, 2001). California is the only western state that recognizes riparian rights, which adds a layer of complexity to "water issues" as compared to other states (SWRCB, 2010b). The BLM will be required to ensure that any remediation and restoration efforts do not decrease or negatively affect any owners of water rights downstream. This will be most applicable in situations where water bodies are diverted or filled (e.g., building a new settling basin). In addition, any streambed alterations or water projects will need extensive permitting to ensure water quality is maintained (SWRCB, 2010b).

Wilderness Act of 1964

Similar concerns of the Historic and Archaeological Data Preservation Act are addressed in the Wilderness Act of 1964. The purpose of the Wilderness Act was to create a land preservation system for the permanent good of the people (43 CFR Part 6300). The Cache Creek Wilderness Area is over 27,000 acres and most of this acreage is on BLM land (16 U.S.C. 1131). No mines are within the wilderness, but contaminated sediments in Harley Gulch and Cache Creek lie within the wilderness. The wilderness area poses an interesting problem for remediation and restoration because the act does not allow for permanent or temporary roads, use of motor vehicles, motorized equipment or motorboats, landing of aircraft, any other form of mechanical transport, or installation of structures within the area. This essentially limits any remediation and restoration efforts to places easily accessible by kayak, raft, horseback, or foot and technologies that do not require any motorized equipment. This act and the Historic and Archaeological Data Preservation Act are the two most restrictive Acts for the BLM in terms of implementing restoration actions in the Basin and would require a significant amount of permitting for any disturbances in the wilderness; however, there is an allowed exception of the prohibitions for an action that is "necessary to meet minimum requirements for the administration of the wilderness area" (43 CFR § 6303.1). Therefore, the BLM could make an argument that mercury cleanup is necessary for the betterment of the wilderness area and the wildlife habitat and recreation benefits it provides. Despite the fact that the BLM could get an exemption to clean up the wilderness area, for our analysis we have considered these regulations too stringent for effective restoration to take place within the wilderness area. We have limited our discussion of cleanup measures to those areas outside the wilderness.

Remediation/ Restoration Technologies & Management Options

Many strategies and technologies can be implemented to remediate mine sites contaminated with mercury and to restore stream banks and sediments downstream of mining areas. According to Pepper et al. (2006) there are three major categories or types of remedial actions:

1) Containment, where the contaminant is restricted to a specified domain to prevent further spreading;
2) Removal, where the contaminant is transferred from an open to a controlled environment;
3) Treatment, where the contaminant is transformed into a nonhazardous substance.

There are also a number of emerging technologies that are still in development and have not been tested extensively in the field. A full list of remediation and restoration technologies can be found in Table 8 with estimates of cost, effectiveness, and expected time frame to show progress toward reducing mercury contamination at impacted sites.

Table 8: Remediation option descriptions

Remediation Option		Effectiveness	Cost	Time
Do Nothing (Natural Attenuation)		Not effective[1,7]	Low[7] – Requires Monitoring	Long[7]
Institutional Controls		Not effective[1]	Low[1]	N/A
Excavate and contain waste on site		High[1]	Medium-High[2,3] ($300-510 per metric ton)	Short
Excavate and transport waste to an offsite treatment facility		High[1]	High[2,3] ($300-500 per metric ton)	Short
Erosion Controls/Bank Stabilization (Place barriers between material and waterway, recontour/regrade, revegetate, redirect storm runoff or geotextiles)		Medium[1]	Low-High[1**]	Short
Containment	A) Cap	Medium-High[1**]	Low-Medium[2,3**]	Short
	B) Solidification and Stabilization	High[6]	Medium-High [3, 6 **] ($50-330 per m^3)	Short
	C) Physical barriers	High[3]	High [3, 4] ($870-$1200 per m^2)	Short
Chemical Treatment (Soil)	A) Soil washing	High[6]	Medium-High [2, 3**] ($70-187 per m^3)	Short
	B) Acid extraction	High[6]	Medium-High [2, 3**] ($358-1,717 per m^3)	Short
	C) Alkaline leaching	Uncertain[1]	Medium-High [2**]	Short
	D) Soil Flushing	Uncertain[14]	High [3, 14*] ($14-37 per m^3)	Medium[14]
Chemical Treatment (Water)	A) Adsorption	Medium[1]	High[3,6*,**] ($63-90 per m^3)	Short
	B) Precipitation and Coprecipitation	High[12]	High[3], [6*] ($4.5-10.8 per m^3)	Short

Table 8 *continued*: Remediation option descriptions

Remediation Option		**Effectiveness**	**Cost**	**Time**
In-situ Thermal Desorption		Low-High[5, 6]	High[1, 3, 5]	Short
Vitrification		High[6***]	High[1,3] (\$349 per m^3)	Short
Phytoremediation		Low-Medium[8]	Low [3, 8] (\$0.18-0.63 per m^2)	Medium[8]
Settling Basin Modifications	A)Expand existing settling basin	Low-High[1, 7]	High[2]	Short
	B) Create new settling basins	Low-High[1, 7]	High[2]	Short
	C) Redirect thermal springs to settling basins	Low-High[1, 7]	High[2]	Short
Air stripping		High[3, 9]	Medium[3,6*] (\$0.1-0.5 per m^3)	Short
Nanotechnology – Developing		High[6, 10]	Low[13]	Short
Bioremediation – Developing		Medium-High (in lab studies) [4]	Uncertain[**]	Short

1: Tetra Tech, 2003
2: Tetra Tech, 2003 – Total cost will vary based on the size of the site
3: FRTR, 2002
4: Wood, 2003
5: Kunkle et al., 2006
6: USEPA, 2007
7: Cooke and Morris, 2005
8: Cabrejo, 2010
9: Looney, 2001
10: Mattigod, 2003
11: Pepper et al., 2006
12: USEPA, 1997
13: PNNL, 2009
14: Kahn et al., 2004
* Low operational costs, but high capital costs to construct infrastructure
** Depends on materials used
*** May be influenced by concentrations of mercury

Containment Technologies

There are several types of containment technologies that have been used to address mercury-contaminated sites. Generally, containment technologies work by "controlling the flow of fluid that carries the contaminant or directly immobilizing the contaminants" (Pepper et al., 2006). Examples of containment technologies that can be used to address mercury contamination include physical barriers, solidification/ stabilization, and containment caps. The advantage of these types of technologies is they can contain mercury in a relatively short amount of time; however, these technologies can be costly depending on the size of the site and the types of materials used for containment. There are also possible risks that containment technologies can be washed away during large storm events. Soil capping and stabilization have been applied in at least two sites in North America, including Clear Lake in California and Oakridge in Tennessee (Turner and Southworth, 1999).

Physical barriers

A physical barrier to groundwater is used "to control the flow of water to prevent the spread of contamination" (Pepper et al., 2006). Barriers are most effective when they are "installed in front and down gradient of the contaminated zone" (Pepper et al., 2006). A typical barrier consists of a vertically excavated trench that is filled with slurry (Figure 9). According to the Federal Remediation Technology Roundtable (FRTR) (2002) "the technology has demonstrated its effectiveness in containing greater than 95% of the uncontaminated ground water" and "most slurry walls are constructed of a soil, bentonite, and water mixture. Slurry walls are typically placed at depths up to 30 meters and are generally 0.6 to 1.2 meter thick." This technology was used at the Onodoga Lake superfund site to prevent the spread of contaminated materials including mercury (USEPA, 2010e).

While this technology is effective at containing contaminated groundwater, there are some disadvantages. Not only will the slurry wall have a high cost (estimated $870-

$1200 per m^2) but there is a possibility that it could degrade, reintroducing contamination into the area (FRTR, 2002).

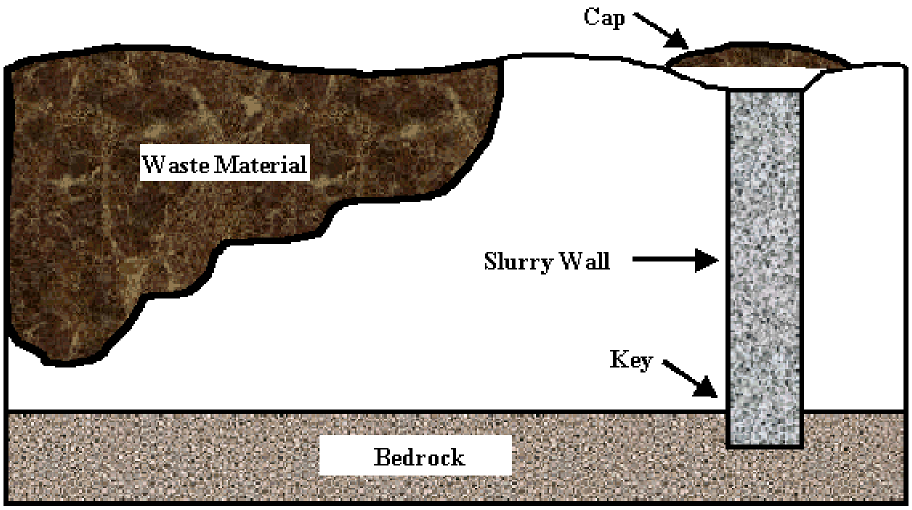


Figure 9: Physical containment of a groundwater contaminant plume with use of a slurry wall (FRTR, 2002)

Solidification/Stabilization (In-situ encapsulation)

In-situ encapsulation is accomplished by injecting a solution containing a compound that will solidify the contaminated area into the soil. For example, "cement or a polymer solution can be added, which converts the contaminated zone into a relatively impermeable mass encapsulating the contaminant" (Pepper et al., 2006). This technology is frequently used to meet regulatory cleanup levels and is commercially available (Otto and Bajpai, 2007). Another advantage of this strategy is that it may limit the release of contaminant particles into the atmosphere (DTMC & SRWP, 2002).

This technique is used frequently, but a major factor to consider before implementing this strategy is the cost to treat large amounts of waste as well as the potential that the solid matrix may degrade and the possibility that contaminants may leach into the environment (Pepper et al, 2006).

Containment Cap

A containment cap can be used to physically cover or cap wastes in order to reduce or eliminate mobility of the contaminated medium. According to Tetra Tech (2003) caps can "vary in complexity from a simple earthen cover to a multilayered cap design" (Figure 10). Costs for this strategy will vary depending on the design and the size of the area. Other factors that may increase costs include topography, slope stability, and hydrogeology among others (Tetra Tech, 2003).

Mercury contained under a cap will have reduced exposure to the environment, but the contamination will still be present. This technique is typically considered a temporary solution, but in some cases it can be used long-term (Tetra Tech, 2003). The use of containment caps is a common practice and has been implemented in areas such as the Port of Richmond in San Francisco Bay (Bourne and Chan, 2007; Tetra Tech, 2003)

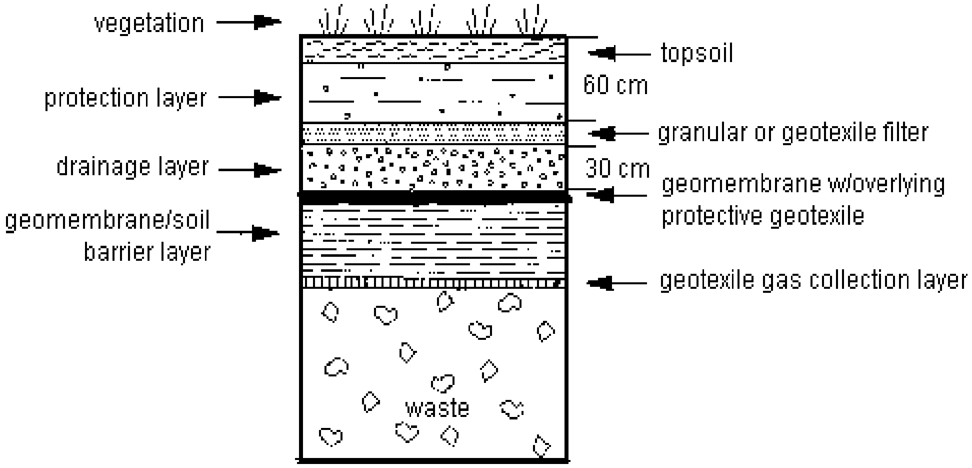


Figure 10: Typical design of a containment cap (FRTR, 2002)

Erosion Controls and Stream Bank Stabilization

Several techniques can be implemented to control erosion and stabilize stream banks. This is important to prevent the downstream transport of sediments containing mercury. It was shown that "erosion of mercury-laden soils from contaminated sites can be reduced by common erosion control practices such as drainage modifications, re-grading, re-vegetation, and slope stabilization" (DTMC & SRWP, 2002). Surface flows and stream flows can be redirected to avoid the erosion of mercury enriched soil. In addition, barriers can be placed between these soils and waterways. Another option to stabilize stream banks is to use materials such as mulch or geotextiles. Additional options include re-vegetation of exposed soil and re-grading to reduce erosion potential.

Re-vegetation

Re-vegetation can decrease erosion potential by reducing the impact from erosive forces like water and wind. Tetra Tech (2003) recommends the following steps when using re-vegetation:

1) select appropriate plant species,
2) prepare seed bed, which may include deep application of soil amendments to provide acid buffering and enhance vegetation,
3) seed and plant,
4) mulch and/or apply chemical fertilizer.

Runoff control

A few strategies can be used to reduce runoff and prevent sediments from being washed into the waterway. Some runoff controls include drains, ditches, and piping (Tetra Tech, 2003).

Geotextiles

Geotextiles are permeable fabrics which are used as separators, filters, and for erosion control (MEOEA, 2003).

Grading

Re-grading hillsides can help to control erosion by reducing slope and increasing infiltration to minimize runoff (Tetra Tech 2003). However, this strategy can be costly since it requires the use earth moving equipment and may be difficult to implement in areas with poor accessibility.

Removal

Removing contaminants is the most fundamental method of remediating contaminated sites. This technique is applied frequently at sites that are highly contaminated with mercury (DTMC & SRWP, 2002). Mercury can be removed through either excavation or by thermal methods like electrokinetic remediation. While these technologies are highly effective they are often expensive and require drastic habitat alterations. Settling basin additions and modifications are also discussed in this section since settling basins require periodic sediment removal.

Excavation (Relocate Material Onsite/Offsite)

Excavation has been used with a high success rate. There are, however, some disadvantages associated with excavation: excavation can expose site workers to concentrated mercury contamination; contaminated media requires potentially costly treatment and/or disposal; excavation is generally feasible only for relatively small, shallow areas with localized and highly contaminated source zones (Pepper et al, 2006). As noted above, after materials are excavated they must be relocated either onsite or offsite. Tetra Tech (2003) proposed the construction of an onsite repository that would have the capacity to store waste from sites that are excavated in the Cache Creek area. If materials are removed offsite they must be taken to an appropriate hazardous waste disposal site, depending on the level of contamination. Soils that are removed can be treated to lower the concentration of or remove mercury contamination. If there is a large volume of waste, this strategy may be cost prohibitive (Tetra Tech 2003).

Settling Basin Additions and Modifications

Settling basins can be designed to catch and retain sediments to prevent them from moving downstream and spreading contamination. Modifying the Cache Creek Settling Basin near Yolo or adding new settling basins may serve as a tool to reduce the downstream transport of mercury adsorbed to suspended sediments in streams. A settling basin slows down the movement of water so that some suspended sediment has an opportunity to settle out. The settling basin must be periodically excavated to remove contaminated materials. According to Cooke and Morris (2005) a settling basin "could be engineered to capture 90-95% of the sediment transported during average storm flows." However, if flows are high the efficiency of a settling basin may be reduced (Cooke and Morris, 2005). This is because the residence time during high flows would be much less, and the suspended sediment would not have enough time to settle out into the basin.

Electrokinetic Remediation (Thermal Treatment and Removal)

Electrokinetic remediation processes remove metals (like mercury) and organic contaminants from low permeability soil, mud, and sludge. FRTR (2002) indicates "the principle of electrokinetic remediation relies upon application of a low-intensity direct current through the soil between ceramic electrodes that are divided into a cathode array and an anode array." This current mobilizes charged particles, causing ions and water to move toward the electrodes (Figure 11). Metal ions including mercury move toward the cathode because they are positively charged. Localized mercury contamination can then be removed through excavation. Effectiveness is sharply reduced for wastes with a moisture content of less than 10 percent (FRTR, 2002). In addition, hydrogen gas is generated during the electrokinetic process through electrolysis of water at the electrode (Virkutyte et.al, 2002). Therefore, gas treatment is an important factor to avoid explosions.

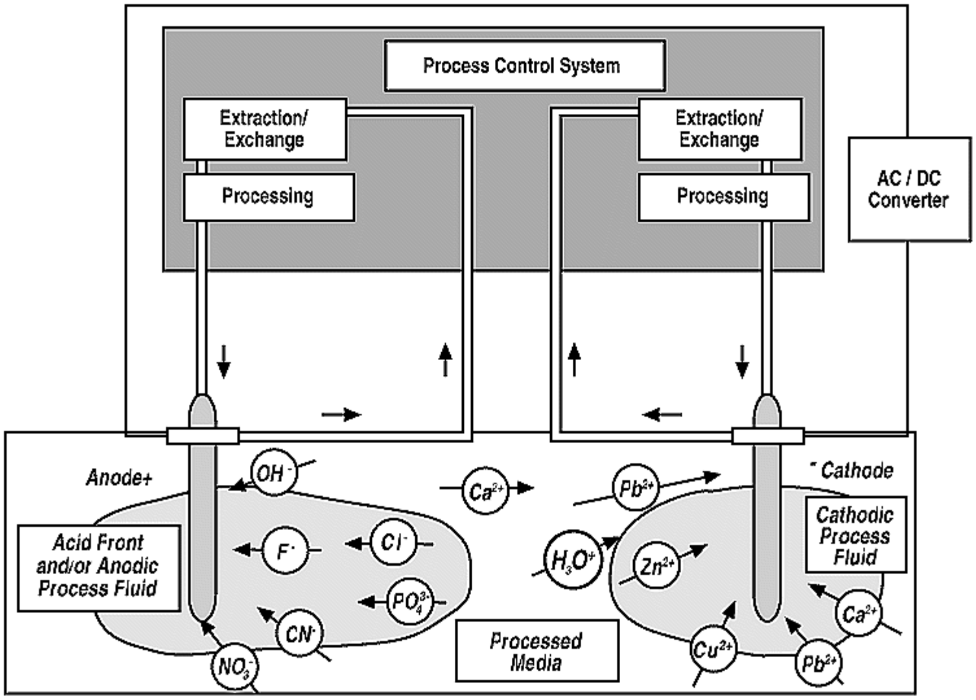


Figure 11: Electrokinetic System (FRTR, 2002)

Phytoremediation

Phytoremediation is one of the major biological treatments for metals, including mercury. There are several types of phytoremediation that can be applied for heavy metal cleanup including: phytoextraction; phytovolatilization; and rhizofiltration. Through these processes, plants either store the mercury in their roots and shoots or volatilize mercury into the atmosphere. While phytoremediation can be used to remove dissolved forms of mercury and methylmercury, it will not be effective at removing insoluble forms of mercury.

Some of the advantages of phytoremediation include: low cost; easy implementation; reduced disturbance of landscape as compared to other technologies; and permanent removal of the contaminant (Cabrejo, 2010; Shukla et al., 2010). However, in order for phytoremediation to be feasible, Henry (2000) notes that plants must:

1) extract large concentrations of heavy metals into their roots,
2) translocate the heavy metals into the surface biomass and
3) produce a large quantity of plant biomass.

In addition, remediative plants must be able to tolerate high mercury concentrations accumulated in their biomass, or have a detoxification mechanism (Henry, 2000). According to Patra and Sharma (2000) plants typically only tolerate mercury concentrations between 5 and 20 mg/kg. Other considerations to take into account with this strategy include the depth of contamination since cleanup is constrained to the root zone and the potential for wildlife to be impacted if they eat the mercury-laden plants (Henry, 2000). Also, plants that store mercury in their tissues must be harvested to fully remove mercury from the system. This will bring up issues for disposal of contaminated plant materials.

It is also important to consider plant species that are non-invasive and plants that are adapted to climatic conditions at the site. The giant bulrush (*Schoenoplectus californicus*) is an aquatic species that has been used in wetland-type environments (Nelson et.al, 2006). Other plant species adapted to wetland-type environments which may be applicable to some sites in the Cache Creek Basin include cordgrasses like *Spartina* spp. as well as poplar trees (*Liriodendron tulipifera*) (Pilon-Smits and Pilon, 2000). Another potential plant species that may be applicable to the Cache Creek Basin is vetiver grass (*Vetiveria zizanioides*). This grass would be suitable to the Cache Creek Basin because of its ability to tolerate high levels of contamination, adapt to Mediterranean climates, and prevent erosion (Truong, 2000).

Phytoextraction

Phytoextraction can be applied to media such as soil, sludge, sediment, and in some cases water (Fuller, 2002). Plants absorb mercury from the soil and accumulate it in their tissues (Figure 12) (Henry, 2000). The most effective plants are those that are hyperaccumulators. Some hyperaccumulators can absorb "100 times more metals than a common non-accumulating plant" (Henry, 2000). Once mercury has been removed from the soil by the plants, the plants must be harvested and disposed of properly as hazardous waste. Some species that have been applied include Indian mustard, sunflowers, poplars, and pennycress (Fuller, 2002).

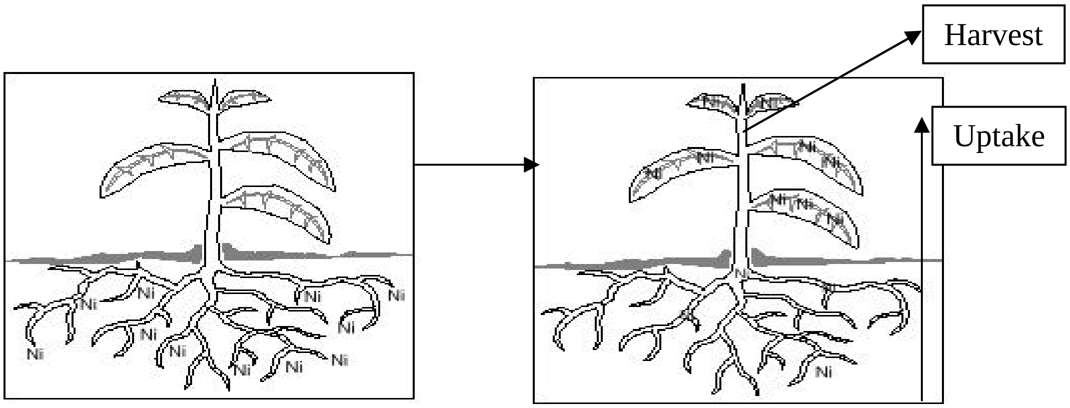


Figure 12: Mechanism of Phytoremediation (Henry, 2000)

Phytovolatilization

According to Jadia et al. (2008) "phytovolatilization involves the use of plants to take up contaminants from the soil, transforming them into volatile forms and transpiring them into the atmosphere." Although mercury is removed from the contaminated soil, this method produces the unwanted side effect of releasing mercury into the atmosphere, which can be deposited elsewhere in the watershed or transported outside the Basin. In laboratory experiments, genetically modified tobacco (*N. abacum*) and a small flowering plant (*Arabidopsis thaliana*) have been used to convert ionic mercury (Hg^{2+}) to the less toxic elemental mercury (Hg^0) through phytovolatilization. The disadvantage to this is mercury can be released into the atmosphere and back into lakes and oceans by precipitation, repeating the production of methylmercury by anaerobic bacteria (Jadia et.al, 2008).

Rhizofiltration

Rhizofiltration is also used to extract mercury but it is mainly used to treat contaminated groundwater and surface water (Fuller, 2002; Henry, 2000) (Figure 13). This technique is similar to phytoextraction (Analya & Ramachandra, 2006). Some species that are capable of rhizofilitration include water hyacinth, Indian mustard, and hybrid poplars (Fuller, 2002).

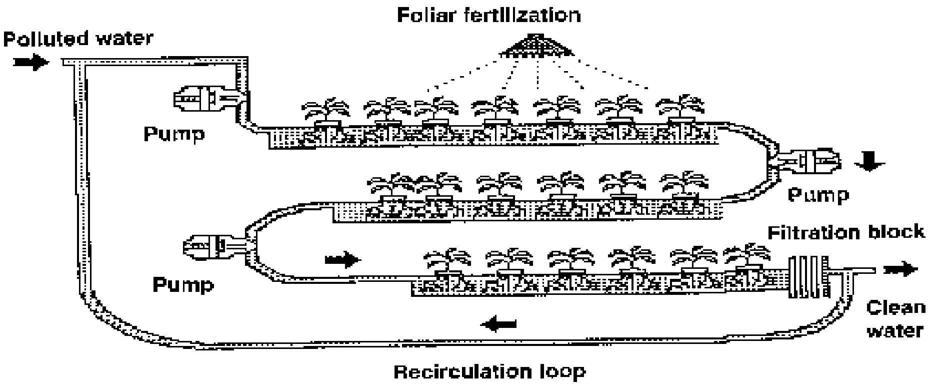


Figure 13: Rhizofiltration Sytem (Henry, 2000)

Physical and Chemical Treatment (Soil)

Soils can be treated by a number of physical and chemical techniques. Some of these techniques include soil washing, acid extraction, alkaline leaching, and soil flushing. These technologies may be applicable in the Cache Creek Basin in order to treat excavated materials prior to disposal or for reuse as fill. However, relatively high costs are associated with the excavation of contaminated materials and subsequent treatment (Tetra Tech, 2003).

Soil Washing/ Acid Extraction

Soil washing and acid extraction are both ex-situ remediation techniques used to remove mercury from contaminated soils. Soil washing removes contaminants from soil by first physically separating particles and then using aqueous based chemicals to remove mercury (USEPA, 2007; Kahn et al., 2004; Wood, 2003). After particles are separated by size classification, oxidative leaching can occur (Figure 14). However, the use of soil washing or acid extraction may require additional treatment of byproducts or sludge (Tetra Tech, 2003).

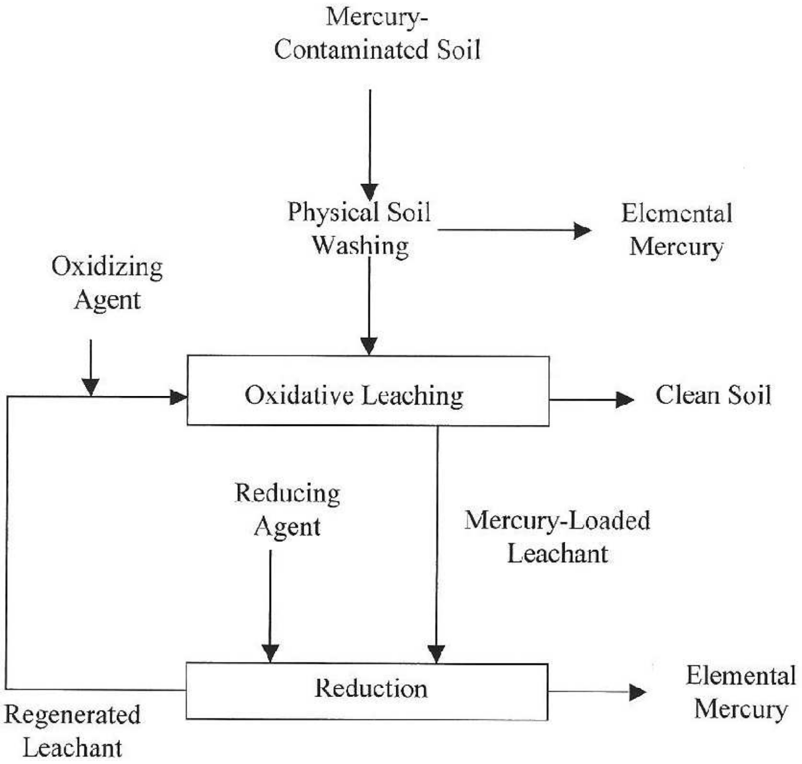


Figure 14: Typical soil washing process (Rüdiger et. al, 2010)

Alkaline Leaching

Alkaline leaching also uses the addition of chemicals to treat contaminated soils. Thiol groups are used as reagents for leaching under alkaline conditions. “Complexes such as thiocarboxylates and dithiocarboxylates are powerful and selective mercury (II) complexants and may be more stable than simple thiols under alkaline conditions” (Rapko et al., 2002). According to Tetra Tech (2003) “ammonia, lime, or caustic soda is applied to the contaminated medium in a heap, vat, or agitated vessel.” Alkaline leaching could be effective in leaching mercury from contaminated media that has been excavated.

Chemical Treatment (Water)

Chemical treatments for mercury in water include adsorption as well as precipitation and co-precipitation. Often it is necessary to use these technologies in combination with others in order to achieve effective results (Tetra Tech 2003). While these techniques have been shown to be effective at mercury removal they will require the construction of a treatment facility near the site being treated. Construction of a treatment facility may be costly and would require an energy source nearby. This may make it difficult to apply these methods to the Cache Creek Basin.

Adsorption and Stabilization

Adsorption is the process of accumulating mercury from contaminated water onto a solid surface so that it can be removed (Tetra Tech, 2003). According to Otto and Bajpai (2007) this technology is "used more often when mercury is the only contaminant to be treated, for relatively smaller systems, and as a polishing effluent from larger systems." This technology is applicable for groundwater, surface water, and wastewater.

The most commonly used adsorbent in this process (often implemented at industrial waste facilities) is granular activated carbon (USEPA, 1997). Huang and Blankenship (1984) studied the removal of Hg^{2+} from synthetic wastes using eleven different brands of commercial activated carbon. Among the eleven different types of activated carbon, Nuchar SA and Nuchar SN showed the most effective (>99.9%) removal of mercury in a wide pH range (2.5 to 11) (USEPA, 1997).

Other materials that can stabilize mercury in water include thiol-modified zeolite and magnesium oxide. Thiol-modified zeolite is a material with self-assembled monolayers on mesoporous supports consisting of zeolite. It can be used as reagent to stabilize mercury in its molecules (Hagemann, 2009). Magnesium oxide can work as a binder reagent. Using this binder, mercury is stabilized and solidified in a magnesium hydroxide matrix (S. Hagemann, 2009). In addition, treatment of adsorbents that contain mercury should be considered to prevent the release of mercury into the atmosphere.

Precipitation and Co-precipitation

Precipitation transforms dissolved contaminants into solid forms, which can then be collected. Chemicals used include: ferric salts, ferric sulfate, ferric hydroxide, alum, pH adjustment, lime softening, limestone, calcium hydroxide, sulfide, and lignin derivatives (USEPA, 2007). The most commonly used precipitation method for removing inorganic mercury from wastewater is sulfide precipitation. In this process, sulfide as sodium sulfide or another sulfide salt is added to the waste stream to convert the soluble mercury to the relatively insoluble mercury sulfide. The USEPA (1997) reports mercury removal efficiencies of 95 to 99.9 percent with this method. The best pH range for this technology is between 7 and 9. The steps involved in the precipitation or co-precipitation process are:

1) water is mixed with treatment chemicals,
2) a solid matrix is formed through precipitation or coprecipitation, and
3) the solid matrix is removed from the water (USEPA, 2007).

Water Treatment – Industrial Applications

There are many other treatment technologies for removing mercury from contaminated water such as coagulation and sedimentation, coagulation and filtration, granular activated carbon, reverse osmosis and air stripping. However, these methods are mainly used for ex-situ treatment at sites such as wastewater and drinking water treatment facilities. Since these technologies are primarily applied in industrial settings and have not been tested in more natural setting they may not be applicable to the Cache Creek Basin at this time.

Emerging Technologies

There are a number of emerging technologies being tested to treat mercury-contaminated sites. However, many of the newer technologies have only been tested in laboratory settings and their applicability for treating natural sites has not been thoroughly investigated.

Soil Flushing

Soil flushing is similar to soil washing described above except that it is an in-situ treatment (Figure 15). An acid-based reagent is injected into solid media to solubilize metals that are then extracted and treated. This technology is still being evaluated for its applicability and has only been tested on a pilot scale (Tetra Tech 2003). This technique has also been used in laboratory tests exploring its effectiveness for mercury remediation (Garcia-Rubio et al., 2007). The effectiveness of this technique is influenced by soil type. In soils that have too much silt or clay, the flushing solution may not be able to come into contact with contaminants (Kahn et al., 2004).

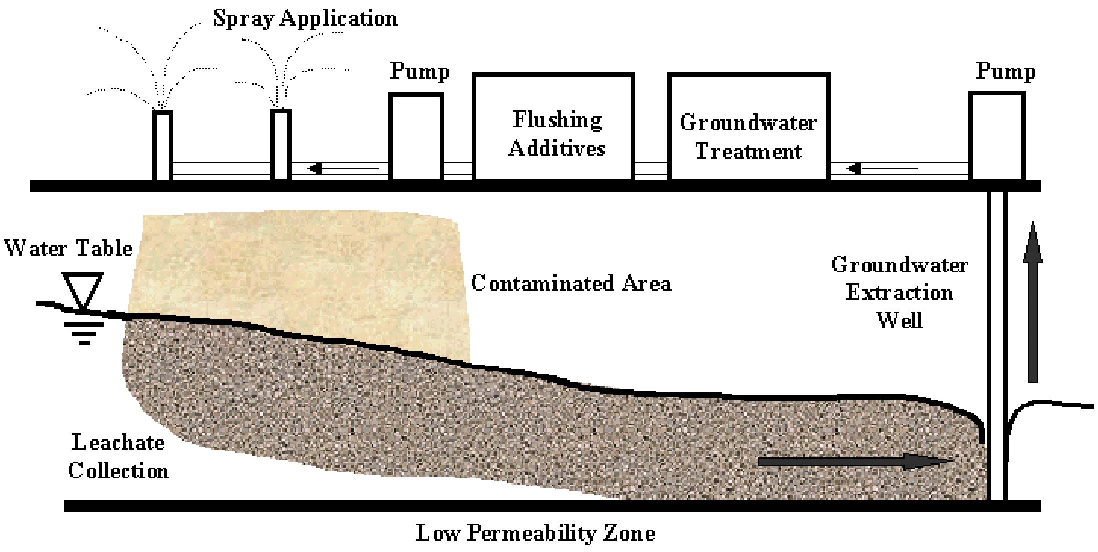


Figure 15: Diagram of soil flushing.（FRTR, 2008）

Nanotechnology

Nanotechnology has mainly been applied in industrial settings to treat mercury-contaminated wastewater. A pilot study was conducted using thiol self-asembled monolayers on mesoporous silica to treat an aqueous waste stream (USEPA, 2007; Otto and Bajpai, 2007). This technology was very effective at mercury remediation, removing over 99 percent of the contaminant. Another application of nanotechnology is the use of iron sulfide nanoparticles to treat mercury in soils. In this process, soils are injected with nanoparticles in order to immbolize the mercury as HgS (Cabrejo, 2010).

It has been suggested that nanotechnology can be used in environmental settings to treat and clean up polluted areas (Karn et al., 2009). This type of technology is still being investigated for its applicability in more natural settings since there are many unknowns about long-term impacts from introducing nanomaterials into the environment. There are also concerns about how nanomaterials may impact the health of humans or wildlife (Karn et al., 2009). Despite these risks, the use of nanoremediation should continue to be explored since it can reduce costs and cleanup time as well as "eliminate the need for treatment and disposal of contaminated dredged soil" (Karn et al., 2009).

Thermal Treatment (In-situ Thermal Desorption)

Thermal treatment works by heating subsurface soil and removing contaminants using a vacuum (Otto and Bajpai, 2007). In laboratory experiments, 99.8 percent of elemental mercury was removed from soils (Kunkle et al., 2006). This technology is still being evaluated for applicability in the field. Some disadvantages to this technology include high cost and challenges with site accessibility due to the need to install a number of wells.

Vitrification

Vitrification can either be used in-situ (Figure 16) or ex-situ. During this process, contaminated soil is heated to an extremely high temperature, anywhere from 1,600 to 2,000 °C (USEPA, 2007; Tetra Tech, 2003). The high heat essentially melts the soil and immobilizes the contaminants, which become incorporated into the vitrified end-product (USEPA, 2007). Vaporized mercury should be captured by an off-gas hood and treated to avoid transfer of the contaminant to the atmosphere (Figure 17). The depth of contamination and the concentration of contaminants present can limit this technology. If contamination is too shallow or too deep (>20 feet) this process may not be applicable in-situ (USEPA, 2007). Also, the process is more effective with lower concentrations of mercury (USEPA, 2007). In addition, vitrification may be relatively expensive compared to other management strategies (Tetra Tech, 2003).

This technology was used on a pilot scale to treat mercury contamination in the Lower Fox River, Wisconsin (USEPA, 2007). A full scale study was conducted at the Parsons Chemical Superfund Site where 3,000 cubic yards of sediment were treated for mercury contamination (FRTR, 1995).

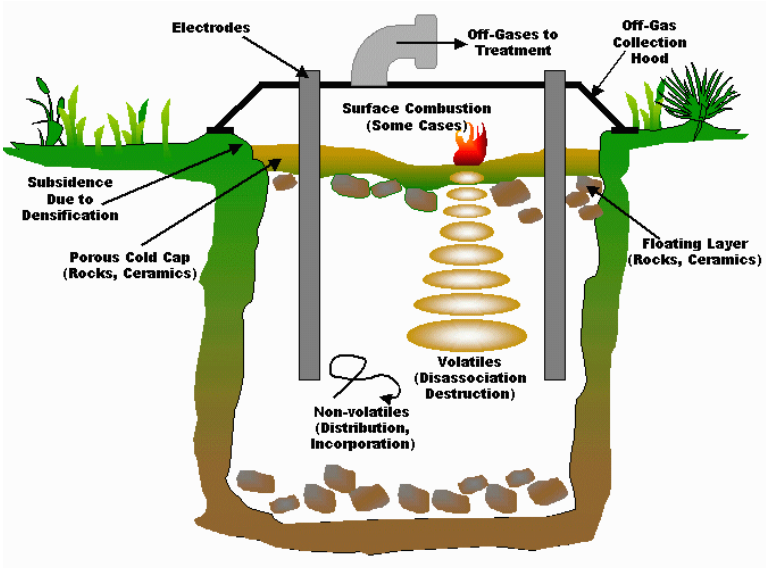


Figure 16: Diagram of in-situ vitrification system (FRTR, 2008)

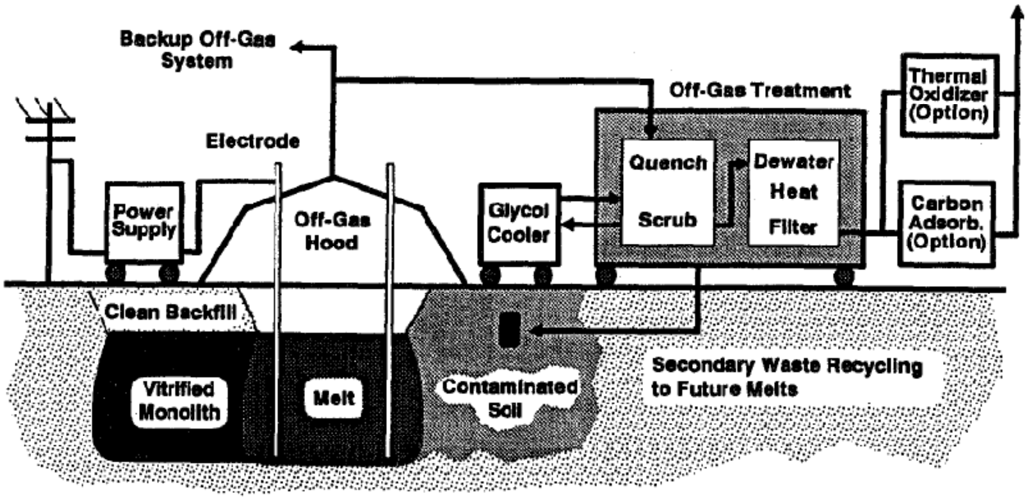


Figure 17: Vitrification processing and equipment scheme (Geosafe Corporation, 1994)

Air stripping

Air stripping is a remediation technology that can be used to treat contaminated water. This technology is still being evaluated for its applicability in the field. A study at the Savannah River in South Carolina showed that this technology has the potential to be effective for removing mercury contamination when combined with chemical reduction (USEPA, 2007; Otto and Bajpai, 2007). In this study, stannous chloride was added to the groundwater and then the water was processed through an air stripping device (USEPA, 2007; Otto and Bajpai, 2007). Off-gas treatment could be incorporated using a Mercury Removal Adsorbent System, which removes mercury by adsorption such as with sulfur-impregnated activated carbon or an alternative low temperature gas phase Hg^0 treatment system (B. Looney et.al, 2001). A typical air stripping device can be seen below (Figure 18).

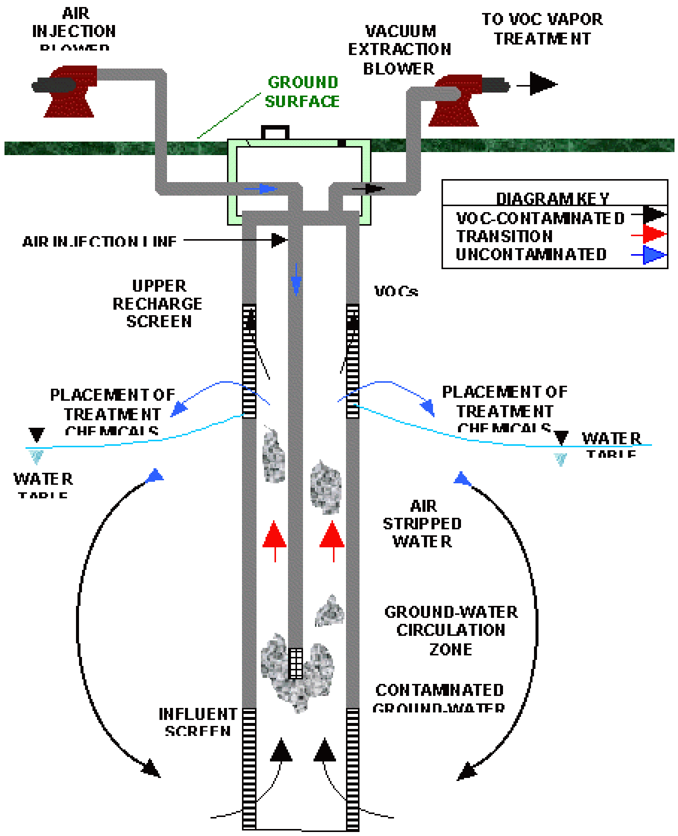


Figure 18: Example of an in-situ air stripping system. (FRTR, 2008)

Bioremediation

Bioremediation is the use of "microorganisms to reduce, eliminate, contain, or transform contaminants present in soils to benign products" (Adeniji, 2004). There are two types of bioremediation: in-situ bioremediation and ex-situ bioremediation, which is used typically in wastewater and drinking water treatment facilities. Although in-situ bioremediation is used primarily for organic contaminants (Pepper et al., 2006), there are emerging bioremediation technologies to reduce mercury contamination using mercury resistant bacteria (MRB). MRB can transform toxic Hg^{2+} and methylmercury to less toxic Hg^0. Mercury can be contained and immobilized in the bodies of MRB, and removed with bio-films from wastewater. However Hg^0 can be released into atmosphere more easily, so treatment of volatilized gas should be considered. There has also been research using genes from MRB to genetically modify plants. Insertion of the genes into the DNA of plants allows the plants to withstand higher mercury concentrations and more effectively remediate contaminated sites (Omichinski, 2007; Meagher et al., 2000). Some species that have been manipulated to enhance mercury tolerance include tobacco and yellow poplars (Omichinski, 2007).

Another new form of bioremediation involves using earthworms to treat contamination in soils. Earthworms have been shown to "effectively bioaccumulate or biodegrade several organic and inorganic chemicals including heavy metals" (Sinha et al., 2010). Parra et al. (2010) conducted a feasibility study to determine whether or not earthworms could be used to clean up mercury contamination. While this research is promising, there are still challenges that need to be addressed, for example how to remove mercury-laden earthworms from the soil.

Additional Management Options

Do Nothing

One option addressed in our analysis is to "do nothing," letting mercury naturally attenuate from contaminated sites. However, it would likely take hundreds of years for mercury in highly contaminated areas to be removed naturally from the system. While this management option would not require direct remediation and restoration actions, monitoring would be necessary. Public outreach programs may also be necessary to ensure awareness about mercury contamination issues, especially regarding the consumption of contaminated fish (Cooke and Morris, 2005).

Institutional Controls

Institutional controls do not reduce mercury loading, but could be used to protect human health and the environment. They are primarily used to reduce the exposure of humans and wildlife to contaminated materials. One example of an institutional control is to build a fence and put up signs that would minimize access to the mine sites and reduce contact by humans and animals with contaminated material. Another example of an institutional control is to provide more education to make the public aware of the safe limits of fish consumption in the area. This management strategy would be low cost, but it would not address the sources of mercury pollution (Tetra Tech, 2003).

Summary of Remediation Technologies

There are many approaches that can be used to reduce mercury concentrations in contaminated soils and water of the Cache Creek Basin. Many options like excavation and capping can be costly, however there are some emerging technologies such as phytoremediation that are being developed to meet the need for low-footprint, low-cost technologies to treat contaminated sites. Since these technologies are still emerging, an option may be to use the Cache Creek Basin as an area to conduct feasibility studies to assess whether or not these types of technologies can be applied in a natural setting. The use of a low-cost, low-footprint technology such as nanoremediation could help to solve many of the contamination issues in the Basin.

The applicability, cost, and effectiveness of these methods depend heavily on site-specific features, as well as the type of media to be treated by the technology (Table 9). To meet the TMDL, these technologies can be implemented individually or combined to achieve better results. In the following sections, some of these technologies will be evaluated based on their applicability, effectiveness, duration and cost for sites within the Cache Creek Basin.

Table 9: Summary of media treated and applicability of remediation technologies

Remediation Option		Media Treated	In-situ/Ex-situ	Applicable Site Type
Do Nothing (Natural Attenuation)		N/A	N/A	Any
Institutional Controls		N/A	In-situ	Any
Excavate and contain waste on site		Soil	In-situ	Stream bank sediment, wetlands, waste rock, tailings pile
Excavate and transport waste to an offsite treatment facility		Soil	In-situ	Stream bank sediment, wetlands, waste rock, tailings pile
Erosion Controls/Bank Stabilization (Place barriers between material and waterway, recontour/regrade, revegetate, redirect storm runoff or geotextiles)		Soil	In-situ	Stream bank sediment, waste rock, tailings pile
Containment	A) Cap	Soil	In-situ	Stream bank sediment, wetlands, waste rock, tailings pile
	B) Solidification and Stabilization	Soil	In-situ or Ex-situ	Stream bank sediment, waste rock, tailings pile
	C) Physical barriers: to prevent leaching of contaminated water from waste	Soil and Groundwater	In-situ	Tailings pile
Chemical Treatment (Soil)	A) Soil washing	Soil	Ex-situ	Stream bank sediment, waste rock, tailings pile
	B) Acid extraction	Soil	Ex-situ	Stream bank sediment, waste rock, tailings pile
	C) Alkaline leaching	Soil	Ex-situ	Stream bank sediment, waste rock, tailings pile
	D) Soil Flushing	Soil	In-situ	Stream bank sediment, waste rock, tailings pile

Table 9 *continued*: Summary of media treated and applicability of remediation technologies

Remediation Option		**Media Treated**	**In-situ/Ex-situ**	**Applicable Site Type**
Chemical Treatment (Water)	A) Adsorption	Water	Ex-situ	Thermal springs, areas with contaminated water
	B) Precipitation/Coprecipitation	Water	Ex-situ	Thermal springs, areas with contaminated water
In-situ Thermal Desorption		Soil	In-situ	Waste rock, tailings pile
Vitrification		Soil	In-situ or Ex-situ	Waste rock, tailings pile
Phytoremediation		Soil	In-situ	Stream bank sediment, wetlands, waste rock, tailings pile
Settling Basin Modifications	A)Expand existing settling basin	Removal of sediments suspended in water	In-situ	When sediments are suspended in water
	B) Create new settling basins	Removal of sediments suspended in water	In-situ	When sediments are suspended in water
	C) Redirect thermal springs to settling basins	Removal of sediments suspended in water	In-situ	Thermal springs, when sediments are suspended in water
Air stripping		Water	In-situ or Ex-situ	Thermal springs, areas with contaminated water
Nanotechnology – Developing Technology		Soil or Water	In-situ or Ex-situ	Stream bank sediment thermal springs, stream bank sediment, waste rock
Bioremediation – Developing Technology		Soil or Water	In-situ or Ex-situ	Stream bank sediment thermal springs, stream bank sediment, waste rock

Current Remediation in the Cache Creek Basin

Some remediation projects have already taken place in the Cache Creek Basin, including the Sulphur Bank Mercury Mine, Abbott and Turkey Run Mines, and the Reed Mine. Additionally, the BLM is currently beginning remediation efforts at the Rathburn and Petray Mines.

Sulphur Bank Mercury Mine

Cleanup efforts at the Sulphur Bank Mercury Mine (SBMM) started in 1992, however the majority of the work was conducted in early 2008. The USEPA has removed soil, cut back the slope of mine waste to control erosion, created a surface water diversion, and removed mine waste from roadways (USEPA, 2010c). The USEPA will continue with cleanup at Sulphur Bank by “conducting a remedial investigation to fully characterize the SBMM site to propose final remedies” (USEPA, 2010c). Further action will be need for several years in order “to address the ongoing surface and ground water releases from SBMM” (USEPA, 2010c).

In 2006-2007 the USEPA excavated, removed and disposed of all contaminated soils and mine waste located in the residential area at the Elem Indian Colony. These wastes were disposed of in a landfill near SBMM and the USEPA is currently evaluating long-term strategies for effective cleanup of the main mine property. Complete mine waste excavation and disposal was planned by September 2010 (USEPA, 2010d).

Abbott and Turkey Run Mines

Remediation efforts at Abbott and Turkey Run mines started in fall 2006 and were completed in early September 2007. El Paso Merchant Energy-Petroleum Company, which purchased COG Minerals Corp. (the original operator of the mines), was identified as the party responsible for the cleanup of the site. El Paso contracted CDM, a Cambridge, MA-based engineering consultant, to design and implement the remediation of the mines (Larson, 2007). During the implementation phase, they not only cleaned up the mines but also disposed of 23 abandoned vehicles and several tons of illegally dumped garbage (Larson, 2007).The mining material that was considered to be non-leachable was consolidated at the Abbott Mine, re-graded to minimize erosion, capped with 2 feet of clean soil, and re-vegetated (Larson, 2007). Erosion of the pile is further reduced by placing straw wattles parallel to the surface every 15-20 feet to slow down surface runoff. Runoff no longer traverses the entire length of the slope, but is directed by a number of small channels to the main channel that runs along side of the pile. This channel is armored in riprap to slow the velocity of water. Runoff from this channel flows into the West Fork of Harley Gulch, which has also been riprapped below the pile. The mining material that was considered to be leachable, as well as other material that may have had high concentrations of mercury were excavated and trucked to a hazardous waste site in Nevada. Mine entries were also filled and capped. Capping materials were intended to withstand a 100-year flood event. As of 2007, a monitoring plan had not been determined since there was no requirement for post cleanup monitoring (Larson, 2007).

Knoxville Mining District

Homestake Mining Company purchased a large portion of the Knoxville Mining District near Davis Creek in 1984. Since that time, the Davis Creek reservoir was built and Homestake has made efforts to clean up the mining areas. The remediation of the Reed Mine included capping tailings with clean soil, extensive re-vegetation, and plugging the adit (Holloway, et al., 2009; Foe and Croyle, 1998). The Davis Creek reservoir traps as much as 300 kg/year of mercury during wet years, despite remediation efforts at the Reed Mine (Reuter et al., 1996).

METHODOLOGY

Decision Trees & Matrices

We created a series of decision trees to assist the BLM in determining whether to begin restoration or remediation of a contaminated site and, if so, which cleanup technologies would be appropriate. The decision tree has been broken down into three parts (APPENDIX I: Decision Trees). The first decision tree asks general questions about the site meant to identify whether or not the site is a good candidate for restoration. The information gathered from this decision tree is entered into a site characterization matrix, which will aid the user in proceeding with the second tree. The second decision tree outlines the different remediation and restoration technology options that we have determined to be the most appropriate for the Cache Creek Basin.

In the second decision tree, the user navigates through a series of questions about each remediation or restoration option; a “no” answer disqualifies the option from further consideration for that specific site. If each question is answered “yes” then that option is retained for the final decision tree. The third and final decision tree evaluates details of the remediation and restoration technologies taken from the previous tree. The goal of this final decision tree is to determine which options are most cost-effective and most efficient at reducing mercury contamination at a specific site. Information gathered from the second and third decision trees is entered into a management options matrix. Upon completion of the matrix, we recommend the most applicable options be analyzed in further detail using the assessment criteria and ranking system described below.

Assessment Criteria

In order to assess different management options, remediation technologies were classified as high, medium, or low for three categories: cost, effectiveness, and timeframe (c.f. Table 8). Cost categories were determined qualitatively based on a literature review in order to avoid difficulties with comparing across media (e.g., units for soil versus units for water volumes or flow rates). Some technology estimates of cost were not stated quantitatively in studies reviewed, but just referred to as “low cost” or “high cost.” For example, we defined a technology as “high cost” when the option was referred to as "high cost" or "cost prohibitive." Also, options that would require the construction of a treatment facility were often defined as “high cost,” even if operational costs would be low. Technology cost classifications can be found in Table 8. Rough estimates of cost for some technologies are listed, however the actual costs to implement the technologies described will vary greatly depending on site-specific conditions.

For effectiveness, a technology was classified as high if mercury concentrations are expected to be reduced by greater than 90 percent, based on published studies. Technologies in the medium range are expected to reduce concentrations 50-90 percent and technologies with low effectiveness are expected to remove less than 50 percent of mercury in the contaminated media. Wood (2003) proposed a similar system for assessing remediation technologies, however thresholds were set much lower (high = >50 percent, medium = 25-50 percent, and low = <25 percent). In our study, thresholds were set higher because of the strict requirements for mercury removal set forth in the TMDL reports for the Cache Creek Basin. Timeframe was considered as the amount of time it would take to implement a remediation strategy and how long the process of removal would take. A long timeframe was considered greater than 20 years; a medium timeframe 10 to 20 years; and a short time frame less than 10 years.

Ranking System & Case Studies

Selected remediation technologies were ranked for each case study based on the three assessment criteria (cost, effectiveness, and timeframe). A low score indicates a preferred technology or remediation strategy. Scores were based on classifications (high, medium, and low) of each management option (Table 10).

Table 10: Scores given for cost, effectiveness, and timeframe used to rank management options

Category	High or Short	Medium	Low or Long
Cost	3	2	1
Effectiveness	1	2	3
Timeframe	1	2	3

To combine the scores for cost, effectiveness and timeframe, the individual scores were adjusted by adding coefficients to emphasize varying levels of importance a decision maker may put on the assessment criteria. The final score was calculated using the following equation:

$$\text{Score} = \left(\left(\frac{a}{a+b+c}\right) * X\right) + \left(\left(\frac{b}{a+b+c}\right) * Y\right) + \left(\left(\frac{c}{a+b+c}\right) * Z\right)$$

X = Effectiveness Score

Y = Cost Score

Z = Time Score

a, b, and c = weighting coefficients determined by the decision maker depending on the amount of emphasis they put on the various parameters. Weighting coefficients range between one and five (Figure 19).

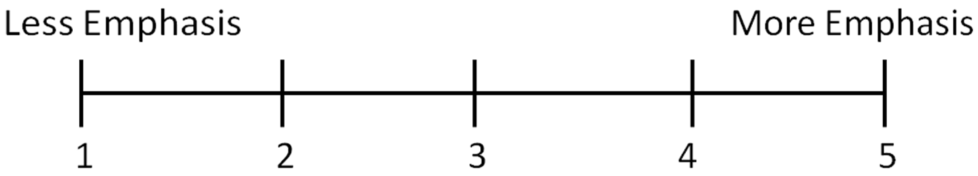


Figure 19: Ranges for ranking coefficients. When parameters are emphasized less, the coefficient is lower and when parameters are emphasized more, the coefficient is higher

For each case study, management options were evaluated from the perspective of two types of decision makers (Table 11). This was done to illustrate how adjusting the assessment criteria can produce different results, and how decision makers can rank technologies based on case-specific constraints. The first type of decision maker is constrained by a low budget and may put more emphasis on technologies that are lower cost, even if they are less effective or take longer. The second type of decision maker puts more emphasis on preventing adverse health effects on humans and wildlife. This type of decision maker may prefer higher-cost technologies that are more effective and take less time.

Table 11: Ranking coefficients for the two types of decision makers selected

	Cost	Effectiveness	Timeframe
Decision Maker 1 (Low Budget)	5	2	3
Decision Maker 2 (Health Effects)	2	4	4

We have prepared six case studies to illustrate our decision tree process for determining the restoration and remediation techniques most applicable to a specific contaminated site. After the applicable management actions were chosen, they were ranked taking into account the different priorities of various decision makers. The specific steps outlined by the decision trees are simulated in our first case study of the Harley Gulch wetlands; the remaining case studies assume these steps have already been completed.

Harley Gulch Wetlands

The wetlands in Harley Gulch are located along the West Branch, downstream from the inactive Abbott and Turkey Run mines and parallel to Highway 20 (Figure 20 and Figure 21). It is believed that the majority of the methylmercury in Harley Gulch is produced in the wetland (Cooke, et al., 2004; Rytuba, 2000). The Abbott and Turkey Run Mines have been a large source of inorganic mercury in Harley Gulch and Cache Creek and are responsible for the high concentrations of mercury in the sediment of the wetlands (Cooke and Morris, 2005). A thermal spring at the Turkey Run Mine also contributes a large amount of sulfate to the wetland, which has been shown to promote methylation (Rytuba, 2000). It is estimated that the methylmercury load exported from Harley Gulch is about 1 g/yr on average, and that loads may be higher during wet years (Cooke, et al., 2004).

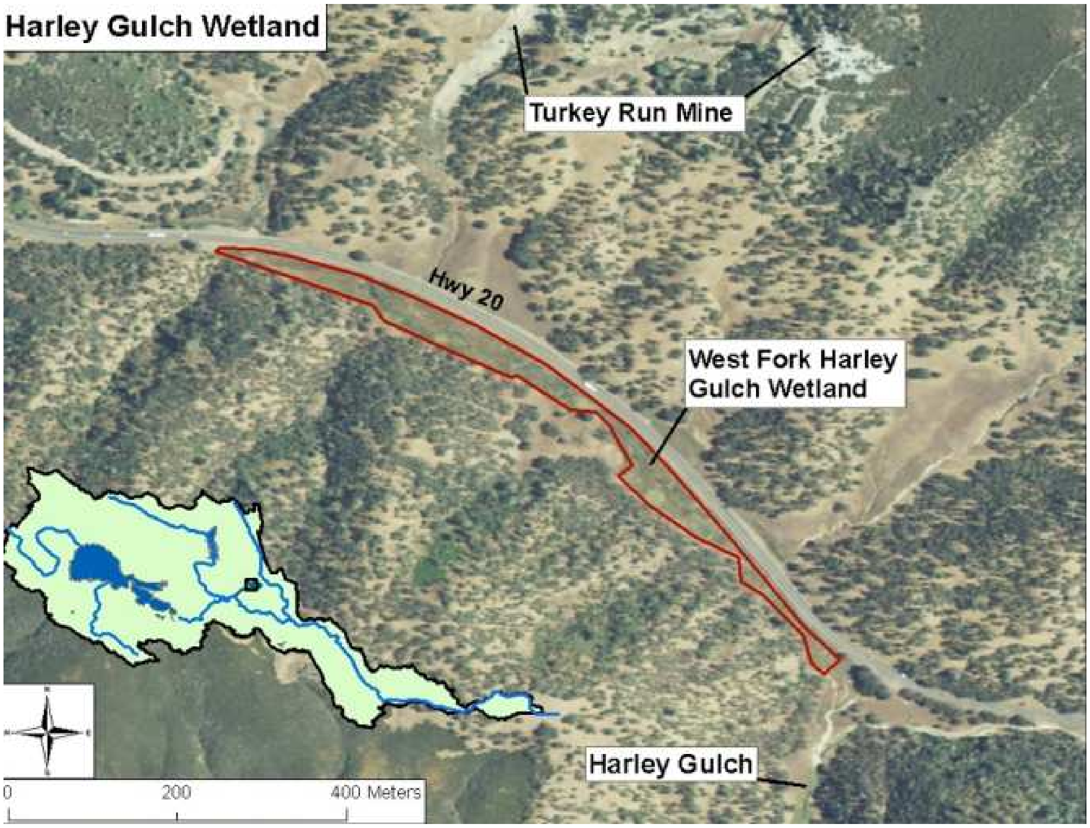


Figure 20: Site location of Harley Gulch Wetland

Figure 21: Photograph of Harley Gulch Wetland (Summer 2010)

It was recommended by the CVRWQCB (Cooke and Morris, 2005) that the Abbott and Turkey Run mines as well as the wetland be remediated in order to reduce methylmercury concentrations in Harley Gulch; specific remediation suggestions included "removing sediments containing mercury, rerouting water flow, reducing residence time of the water," (Cooke and Morris, 2005) among other options. As discussed above, the Abbott and Turkey Run mines have undergone remediation efforts, but to date no remediation has occurred in the wetland.

The first step in determining applicable remediation technologies is to characterize the site as outlined in Decision Tree I (Figure 22). The first question is used to determine if the site should be targeted for restoration based on the level of contamination. Given the concentration of mercury (Table 12) at the site and its location in the Basin it would be a good site to conduct restoration actions in order to meet water quality objectives downstream.

Since the wetlands are not owned by the BLM cooperation with the landowner would be necessary. The BLM could encourage restoration activities and make a plan with the landowner on how to proceed. The next question that needs to be addressed is if the site is within the wilderness area. Since this site is not within the wilderness area one can proceed to the next question in the tree. If the site had been in the wilderness, it is recommended that an alternative site is selected since there are a number of legal and policy constraints associated with restoration activities in the wilderness area.

The next issue that must be considered when characterizing a site is accessibility. The Harley Gulch wetlands are located adjacent to a highway so accessibility is not an issue in this case. If a site is not easily accessible it may be necessary to choose an alternative site to avoid the need to build roads or other actions in order to transport equipment and materials needed for remediation or restoration activities. Transporting materials or creating roads to inaccessible sites may be costly and cause harm to the environment.

After it has been determined that a site is accessible enough to conduct remediation or restoration actions the next step is to determine if there are historical or cultural resources in the area. If there are then a new site may need to be determined since it may be difficult to obtain permits to work in areas with historical and cultural significance. In the case of the wetlands there are no issues with cultural and historical resources so the next question in the decision tree can be addressed; funding is another important consideration in the remediation and restoration process. At some sites, like the wetland, NRDAR funding may be available and should be pursued to help complete remediation and restoration actions.

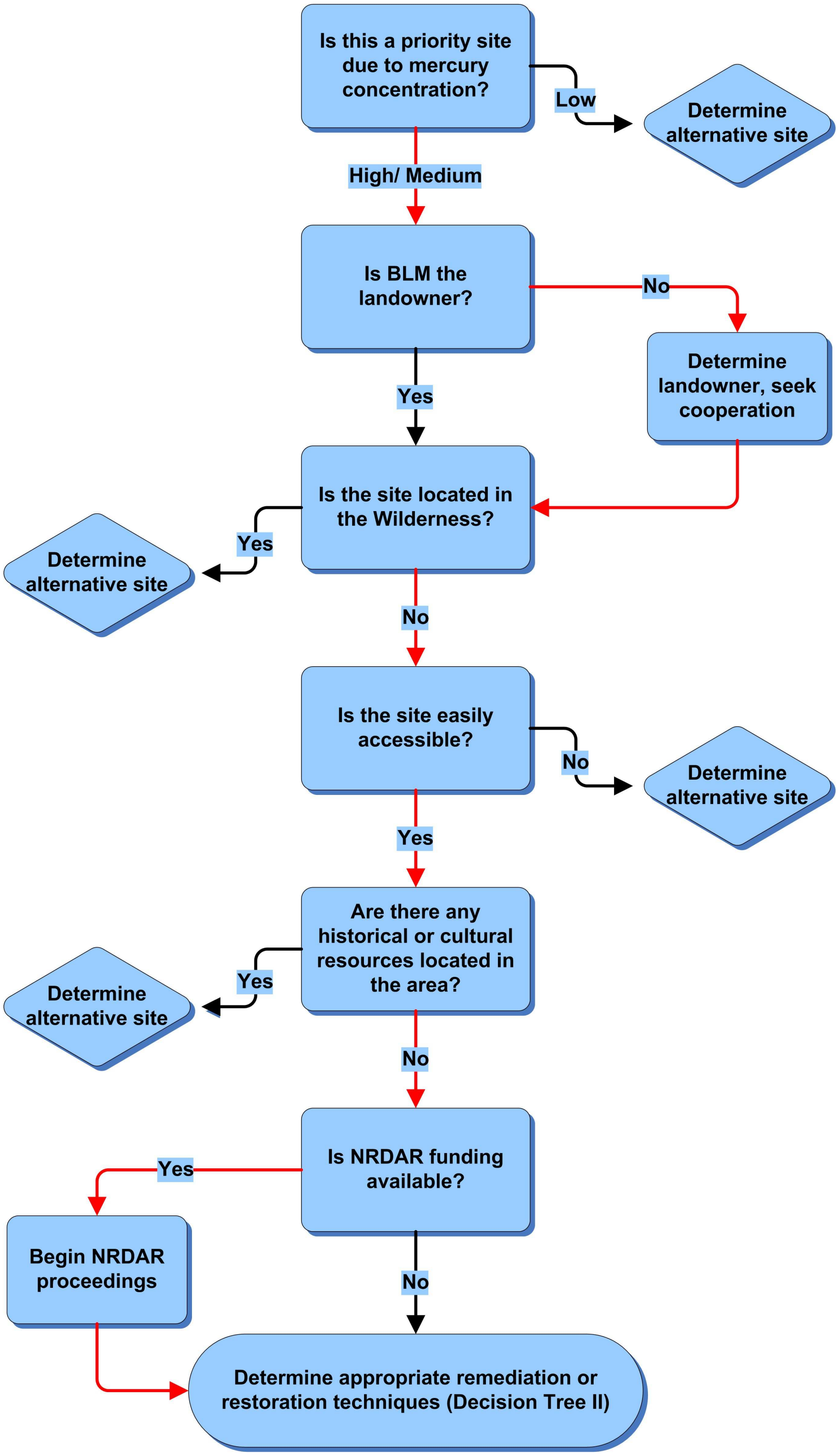


Figure 22: Decision Tree I for Harley Gulch Wetland

Table 12: Site Characteristics for Harley Gulch Wetland

Location	Harley Gulch Wetland
Land Owner	Private trust
Wilderness Area?	No
Site Type	Upstream wetlands
Amount of total mercury	135 - 540 kg (estimation)[(a)]
Annual mercury delivery in dry/wet year	Unknown, but not much, the thick vegetation prohibits much erosion
Annual methylmercury delivery in dry/wet year	0.8 g/yr[(b)]
Source of methylmercury?	Yes, moderate source
Mercury Concentration	5 - 20 mg/kg (estimation)[(c)]
Area of site	18,000 m^2[(d)]
Volume of contaminated soil	18,000 m^3 (assume 1 meter deep)[(e)]
Slope	Flat
Vegetation Cover	Grasses
Accessibility	High - accessible from Highway 20
Issues	Wetland provides valuable habitat

(a) Amount of total mercury calculated from our estimation of mercury concentration
(b) Cooke and Morris, 2005
(c) Mercury concentration estimated by assuming that wetland soil has a higher concentration of mercury than Harley Gulch, which our study measured to be 4.0 mg/kg, but lower than the 20 – 220 mg/kg that Churchill and Clinkenbeard estimated to be eroding from the Abbott Mine tailings pile. The concentration of mercury in the wetland soil may be higher than 20 mg/kg, and should be measured.
(d) Measured from NAIP aerials in ArcMap.
(e) The depth of contaminated soil should be measured.

After the first decision tree is complete, the second decision tree (Figure 23) can be followed to determine the best management actions available. Since the mercury at this site is primarily associated with sediments, phytoremediation, containment cap, removal and excavation, erosion control, solidification and stabilization, thermal treatments, and vitrification are all considered after asking if the mercury is present in the sediments. Settling basin construction and redirection of flows are considered because mercury may be present in the water adsorbed to suspended sediment. Chemical treatments of water and air stripping are eliminated since the mercury is not primarily in the water. Physical barriers are eliminated since the main concern for mercury contamination at this site is not associated with groundwater. Chemical treatments of soil can also be considered, but would primarily be used as an ex-situ step after contaminated materials have been excavated. The next technologies that can be eliminated are vitrification and thermal treatments of soil since they require energy sources that are not present at the site. Also, stabilization and solidification may be eliminated based on the moisture content at the site. Further analysis of the site characteristics like the pH and particle size would also be needed before further consideration of this option.

Phytoremediation continues to be considered since it would be applicable to the species of mercury present (although it cannot remove insoluble forms of mercury it can help manage methylmercury and soluble forms of mercury). Mercury concentrations are low enough to allow for vegetation growth, and based on the site description (that there is vegetation cover currently at the site) plants would likely grow under the climatic conditions and soil type present. This also remains an option since the slope is flat and would allow for vegetation to grow successfully.

A containment cap is also an option that can be considered further. It is not likely that flows will be high enough to wash away a cap and the slope of the site would accommodate the construction of a cap in the area.

Removal and excavation remains a feasible option; given the accessibility of the site this option would be relatively easy to implement. One extra consideration for this option is if there is an appropriate site for disposal of materials. An offsite treatment and disposal facility will need to be selected or an onsite option will need to be determined. Also, in this case erosion controls are combined with excavation. After excavating the site it will be necessary to stabilize the area by adding fill and re-vegetating.

The last options that remain to be considered are the construction of a settling basin or redirection of flows around the wetland. The settling basin option is possible since some of the mercury at this site will be adsorbed to suspended sediment. Because the site is not an existing settling basin the beneficial uses of the water body should be considered before proceeding. There is adequate space for a settling basin at this site and it should be able to contain the amount of mercury suspended in the sediment. Further testing will be necessary to determine the feasibility of these options from an engineering perspective. Redirection of flows around the wetland could reduce the amount of methylmercury that is transported from the wetland. Habitat alteration must be considered for both options.

In addition to determining the most applicable remediation options, it is necessary to evaluate them based on effectiveness, cost, and timeframe to meet the TMDL as in the third decision tree (Figure 24). After these characteristics are defined for each remediation or restoration option, the options can be ranked to determine the best course of action. If an option is not likely to meet the TMDL then it may be necessary to combine the action with other remediation strategies. However, in some cases even if an option does not fully meet the TMDL it continues to be considered if it is the best available technology.

In summary, for the Harley Gulch Wetlands the most applicable restoration options determined from the second and third decision trees include: removal of sediments followed by filling and re-vegetating the site, phytoremediation, constructing a containment cap, constructing a settling basin, and redirecting flows (Table 13). While these options have been determined to be applicable in the wetlands there are a number of additional factors to consider for these restoration strategies. These options also need to be compared against the option to do nothing and let the mercury attenuate naturally.

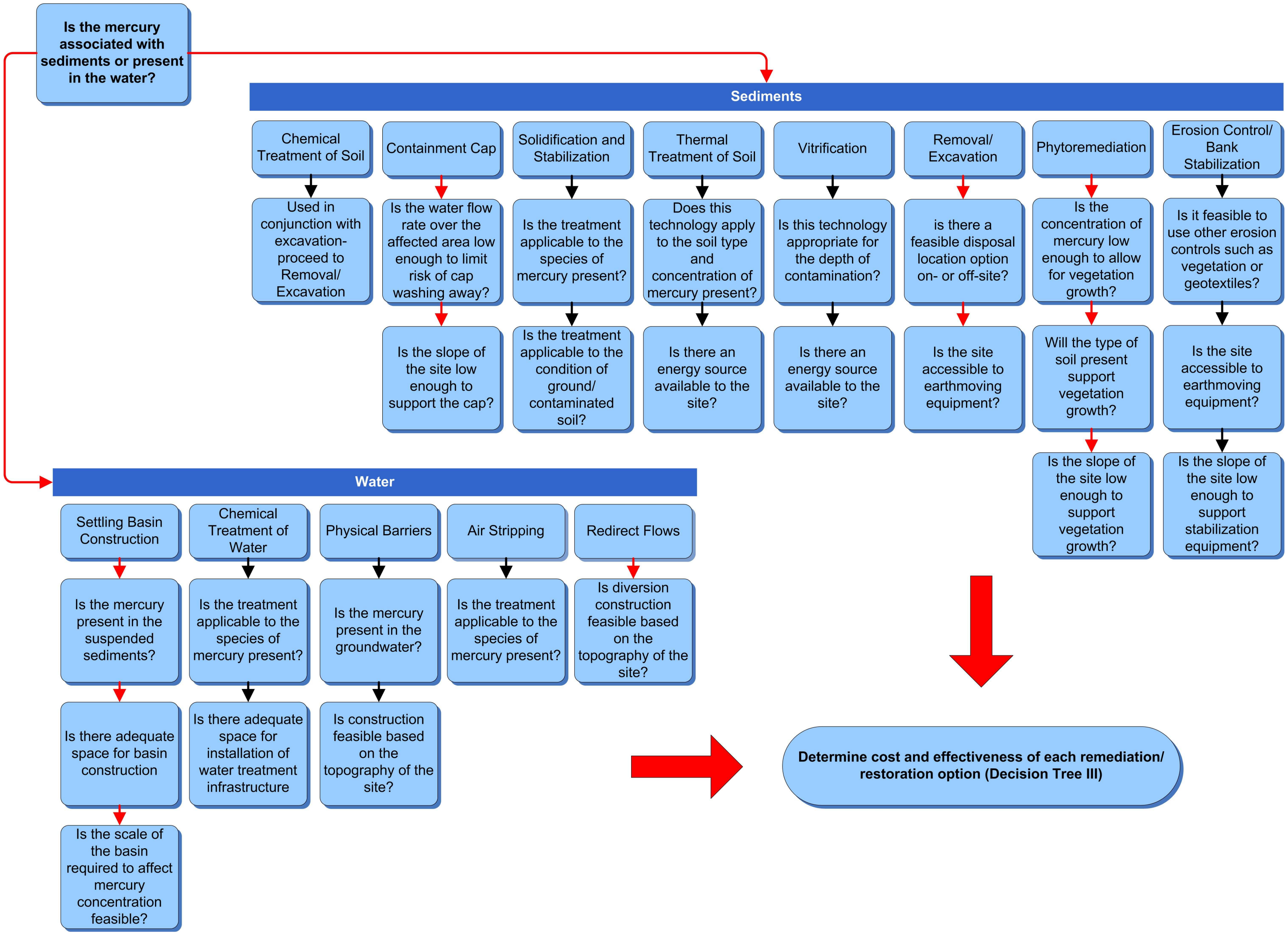


Figure 23: Decision Tree II for Harley Gulch wetlands

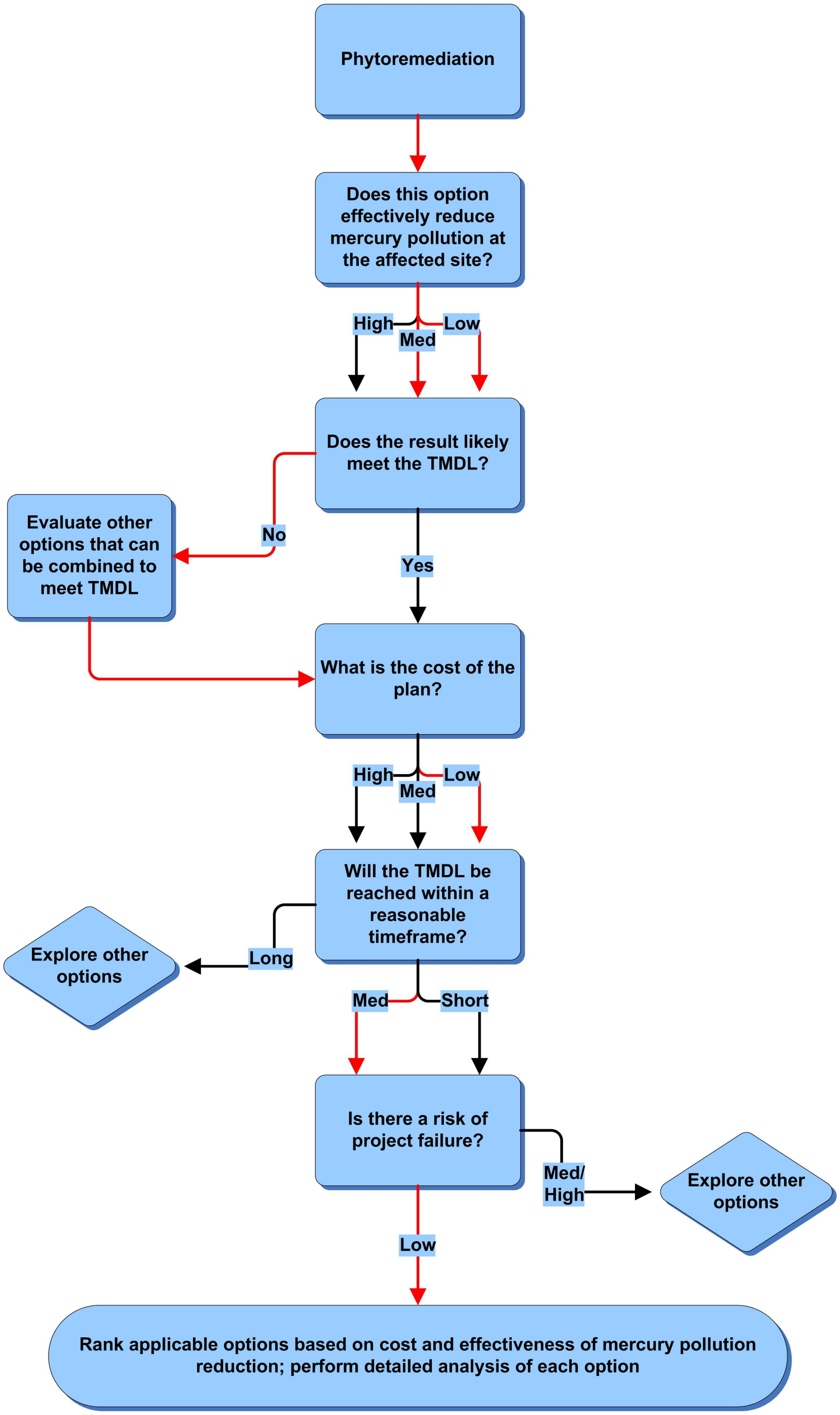


Figure 24: Decision Tree III for phytoremediation in Harley Gulch wetlands

Table 13: Management options for the Harley Gulch Wetlands

Option	Time Frame	Cost	Effectiveness	Other Issues
Do nothing	N/A	Low	None	Monitoring costs are necessary
Remove sediments, add fill, re-vegetate	Short	High	High	Waste disposal; access; habitat alteration
Phytoremediation	Medium	Low	Low-Medium	Can wash away; long time frame; depth of contamination may not be met, harvesting, disposal
Containment Cap	Short	High	Medium-High	Contamination still there; Can wash away; importing clay
Settling Basin	Short	Medium - High	High	High flows may cause efficiency to be reduced; maintenance required; Methylmercury may form
Redirect Flows	Short	Medium - High	Low - High	Habitat alteration

The first option listed for the wetlands, "Do nothing," would not usually be considered since it would take a long time to meet water quality objectives and agencies often must take some sort action to meet mandated objectives. However, this option was used as a baseline against which to compare other proposed actions. The next option is to remove sediments, add fill, and re-vegetate the area. This strategy would be very effective in a short amount of time, but could potentially be very costly, considering the size of the site. However, since the site is very accessible, the use of earth-moving equipment in the area would not pose a significant challenge. Another cost that may be associated with this option is the treatment of contaminated materials that have been excavated. Sediments can be treated after removal with chemical or physical technologies described in the remediation technologies section above as well as Table 8, Remediation Options Descriptions. After treatment, the sediments could be returned to the area but this would be costly and postpone refilling of the site. Another option would be to excavate, dispose of the hazardous sediments, and refill the area with fresh materials to avoid the costs of soil treatments.

The next option is to use phytoremediation. However, plants in this case may be constrained by the high mercury concentrations. According to Patra and Sharma (2000) most plants are only able to withstand mercury concentrations between 5 and 20 mg/kg. In addition, the depth of contamination should be considered since the plant roots may not be able to reach far enough to remove all of the mercury at the site. Since this site is a wetland, more water tolerant species may be applicable. Some potential plant species that can be used include cordgrass, cat-tails, and bulrush (Pilon-Smits and Pilon, 2000). It will be important to choose plant species that are native to the area and tolerant of climatic conditions. In addition to concerns about the limitations of the plant species used there are other concerns with phytoremediation like the possibility that the vegetation could be washed away during a large storm event. Also, if the plants used accumulate mercury in their tissues they would need to be harvested and disposed of properly. Another drawback to phytoremediation is the long timeframe required to meet cleanup objectives. Other options that have a shorter time frame and are more effective may be more applicable.

The third remediation option is to place a containment cap of clay over the site to prevent sediments from flowing further downstream. The cap would then be re-vegetated to restore the wetland plant community. This option would be more effective and take less time than phytoremediation; however, there are other concerns that must be considered with this option. One of the major concerns with this option is that a portion of the cap may be washed away in the event of a large storm, exposing the mercury-contaminated soil below. Containment caps with water flowing over them must follow the natural gradient that the water would take, or else the natural hydrologic forces will attempt to erode the cap and restore the natural gradient. A risk assessment should be conducted to determine if the benefits of the cap outweigh the risk that it may need to be rebuilt after a large storm event.

A settling basin could be constructed to prevent sediments from moving further downstream into Harley Gulch. This strategy would require periodic maintenance that would involve removing the sediments from within the basin; however the accessibility of the site would make this process more feasible. This strategy is higher-cost but results would be seen more quickly than with a strategy like phytoremediation. The settling basin option is unique among the options, because it can also help with removal of mercury originating from the areas upstream of the wetlands. Care must be taken that the settling basin is not a source of methylation, because it may create conditions with anoxic wetland soils that are ideal for methylmercury production.

The last management option is to redirect flows away from the wetland to prevent methylmercury from flowing further downstream into Harley Gulch. This would involve creating a structure such as the concrete lined channel that already exists from upstream of the wetland to the Abbott Mine. While redirecting the flows may be effective, it would prevent the wetland from receiving water, and potential habitat alterations should be considered before implementing this strategy.

The remediation options chosen above were ranked under two different scenarios to determine the best technologies under varying management constraints as described in the methods section. When calculating the scores in some cases, where a range of values were presented, an average value was used. For example, when the effectiveness of a remediation option was scored as medium to low or high to medium an average number was used. In the case of phytoremediation, which is ranked low to medium for effectiveness, a score of 2.5 was assigned instead of calculating the score based on the range of 2-3.

The first scenario was scored with an emphasis on remediation options that are low-cost, to simulate a situation where remediation actions must be taken under budget constraints. In this scenario, phytoremediation would be the best option since it received the lowest score (Table 14). The second scenario was scored to emphasize the effectiveness in meeting the TMDL and the concern about adverse health effects of contamination. In this case, remediation options that are more effective at quickly reducing mercury contamination would be preferred. Ranking the options shows that excavation should be used in this situation (Table 15).

Table 14: Results of ranking options in the Harley Gulch Wetland for a decision maker that puts a larger emphasis on low cost technologies. Weighted coefficients for effectivness, cost, and timeframe are in bold and in parentheses.

Option	Effectiveness (2)	Cost (5)	Timeframe (3)	Calculation	Total Score
Do nothing	3	1	3	3(0.2)+1(0.5)+3(0.3)	2
Remove sediments, add fill, re-vegetate	1	3	1	1(0.2)+3(0.5)+1(0.3)	2
Phytoremediation	2.5	1	2	(2.5)(0.2)+1(0.5)+2(0.2)	***1.6***
Containment Cap	1.5	3	1	(1.5)(0.2)+3(0.5)+1(0.3)	2.1
Settling Basin	2	2.5	2	(2)(0.2)+(2.5)(0.5)+2(0.3)	2.25
Redirect Flows	2	2.5	2	(2)(0.2)+(2.5)(0.5)+2(0.3)	2.25

Table 15: Results of ranking options in the Harley Gulch Wetland for a decision maker that puts a larger emphasis on prevention of adverse health effects from contamination. Weighted coefficients are in bold and parentheses.

Option	Effectiveness (4)	Cost (2)	Timeframe (4)	Calculation	Total Score
Do nothing	3	1	3	3(0.4)+1(0.2)+3(0.4)	2.6
Remove sediments, add fill, re-vegetate	1	3	1	1(0.4)+3(0.2)+1(0.4)	***1.4***
Phytoremediation	2.5	1	2	(2.5)(0.4)+1(0.2)+2(0.4)	2
Containment Cap	1.5	3	1	(1.5)(0.4)+3(0.2)+1(0.4)	1.6
Settling Basin	2	2.5	2	(2)(0.4)+(2.5)(0.2)+2(0.4)	2.1
Redirect Flows	2	2.5	2	(2)(0.4)+(2.5)(0.2)+2(0.4)	2.1

Harley Gulch Delta

The Harley Gulch Delta is located at the confluence of Harley Gulch and Cache Creek within the Cache Creek Wilderness Area. The Delta is in the floodplain of both Harley Gulch and Cache Creek (Figure 25 and Figure 26). This area contains a large quantity of mercury-enriched sediment from erosion of the Abbott and Turkey Run Mines. Due to the level of contamination at this site and its location, it would be an important area to clean up to reduce contamination further downstream. However, there are a number of issues regarding gaining access to the site since it is located in the wilderness. There are also concerns about disturbance at the site since it is located adjacent to an area of archaeological and cultural significance (see Table 16 for site characteristics). According to Cooke and Morris (2005):

> Accessibility to the delta is limited as no roads or significant trails exist. Potentially, small earth moving equipment could be lifted by air into the delta area so that trail construction would not be necessary. Feasibility would depend, in part, on whether remediation could be designed to avoid disturbance to archaeological and traditional cultural sites in the watershed.

These considerations will constrain the feasibility of using some remediation technologies that are more invasive.

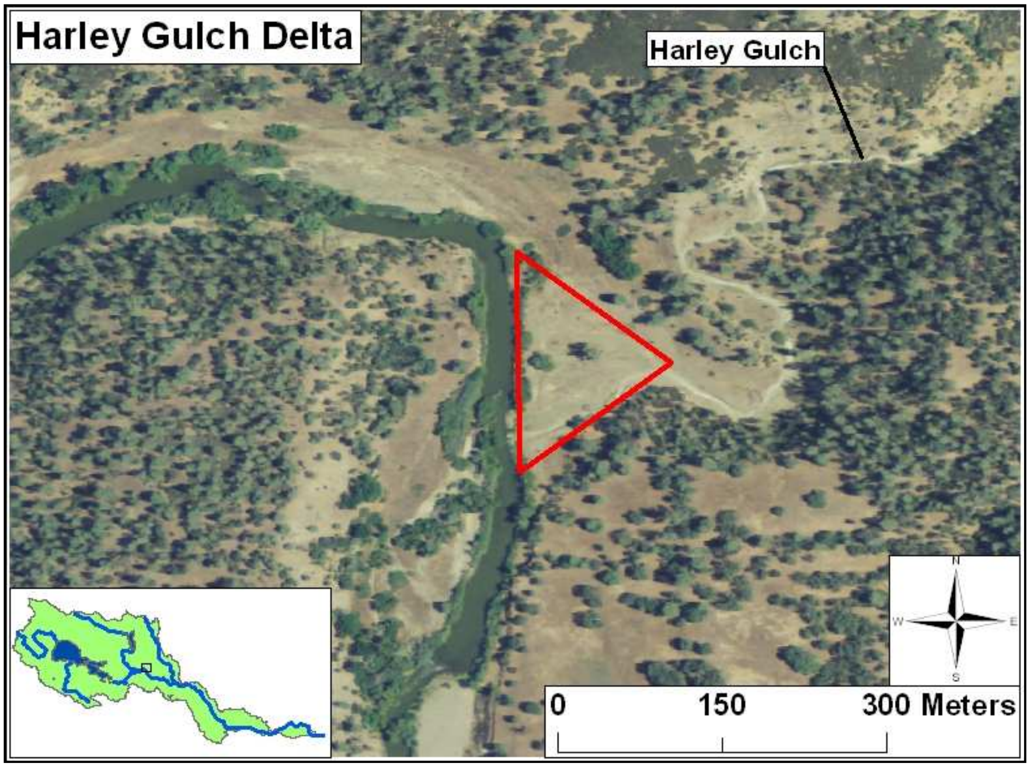


Figure 25: Map of Harley Gulch Delta

Figure 26: Harley Gulch Delta looking east

Table 16: Site description matrix for Harley Gulch Delta

Location	**Harley Gulch Delta**
Land Owner	BLM
Wilderness Area?	Yes
Site Type	Small intermittent stream, Stream bank sediment
Amount of total mercury	15(a) – 75(b) kg
Source of methylmercury?	Small
Mercury Concentration(c)	4.83 mg/kg silt, 4.20 mg/kg sand
Area of site(a)	6000 m^2
Volume of contaminated soil(a)	12,000 m^3
Slope	Flat
Vegetation Cover	Low – Grass
Accessibility	Inaccessible

(a) Cooke and Morris (2005) estimated the total mass of mercury in the delta to be 15-20 kg
(b) Estimation based on assuming that the 12,000 m^3, the density of soil is 1,400 kg/m^3, and that the average mercury concentration is 4.5 mg/kg.
(c) Foe and Bosworth, 2008

From the decision trees, a number of remediation options for the Harley Gulch Delta were selected (Table 17). Management strategies that were determined to be most applicable for this site include: excavation and disposal onsite, phytoremediation, and a containment cap. Do nothing was also considered again as a baseline for the comparison of cost, effectiveness, and timeframe of other technologies. Other technologies such as chemical treatments of water were not considered since the mercury in this area is primarily associated with sediments. Thermal treatments were not considered since these would require additional infrastructure that would be difficult to construct considering that the site is relatively inaccessible and has many policy constraints associated with being classified as wilderness area. In addition, constructing a settling basin to catch sediments may not be feasible due to accessibility issues that may present barriers to conducting required maintenance.

Table 17: Management options for the Harley Gulch Delta

Option	Time Frame	Cost	Effectiveness	Other Issues
Do Nothing	N/A	Low	None	Monitoring costs are necessary
Excavation and Erosion Control	Short	High	High	Waste disposal; access; cultural sensitivities; habitat alteration
Phytoremediation	Medium	Low	Low-Medium	Can wash away; long time frame; depth of contamination may not be met
Containment Cap	Short	High	Medium-High	Contamination still there; Can wash away; importing clay
Solidification and Stabilization	Short	Medium - High	High	Leaching

The first option is to do nothing and let the mercury naturally attenuate. This option is not realistic since it may take hundreds of years for the mercury contamination to be minimized. This would not meet the TMDL and there would be substantial costs associated with continued monitoring. This option will be considered a baseline for each of our case studies.

The next option is to excavate contaminated materials. This option would remove mercury from the system quickly and effectively. However, it would not fully address the mercury issues in the Harley Gulch Delta since sources upstream would still be contributing to contamination. If mercury continues to flow from upstream, additional excavation may be necessary in the future. Excavation would also be expensive because of the inaccessibility of the site. According to Cooke and Morris (2005) equipment would need to be airlifted into the area in order to conduct an excavation of the site. Another option would be to construct new access roads, but this would also be expensive and invasive. Some other considerations that need to be taken into account for this site include determining where the waste will be taken and how disturbance to the site may affect the habitat and cultural significance of the grassland just south of the Delta.

Phytoremediation is another potential remediation option for this area that would be lower cost and be less invasive compared to other management options. Plants could be used to extract mercury from the soils over a longer period of time. However, there is a possibility that the vegetation planted could be washed away during a big storm event. Also the plant roots may not reach the depth of contamination. Another concern is the harvesting and disposal of contaminated plants that would be needed for those that hyperaccumulate mercury rather than volatilize it.

Another lower cost option that would be quicker and more effective than phytoremediation is a containment cap of clay. This would contain the mercury and prevent it from washing downstream and entering the aquatic ecosystem. The area is flat so steep slopes would not impact the construction of a containment cap. However, this may not be the best option because the mercury is still present under the cap and there is a relatively high probability that portions of the containment cap would be washed away during a large storm event.

The final management option considered for this site was solidification and stabilization. This strategy would immobilize mercury and prevent it from eroding into Cache Creek. The types of binders used would influence cost of this strategy.

After the above management options were selected, they were ranked based on two types of decision makers. From the perspective of a budget-constrained decision maker, phytoremediation would be the recommended strategy (Table 18). This strategy may take longer, but the benefits of its low cost would mitigate this concern. For the second type of decision maker, who emphasizes health effects, the best options would be solidification and stabilization (Table 19).

Table 18: Results of ranking options in the Harley Gulch Delta for a decision maker that puts more of an emphasis on low-cost technologies

Option	Effectiveness (2)	Cost (5)	Timeframe (3)	Calculation	Total Score
Do nothing	3	1	3	3(0.2)+1(0.5)+3(0.3)	2
Excavation and Erosion Control	1	3	1	1(0.2)+3(0.5)+1(0.3)	2
Phytoremediation	2.5	1	2	(2.5)(0.2)+1(0.5)+2(0.2)	***1.6***
Containment Cap	1.5	3	1	(1.5)(0.2)+3(0.5)+1(0.3)	2.1
Solidification and Stabilization	1	2.5	1	(1)(0.2)+(2.5)(0.5)+2(0.3)	1.75

Table 19: Results of ranking options in the Harley Gulch Delta for a decision maker that puts more emphasis of preventing adverse health effects from contamination

Option	Effectiveness (4)	Cost (2)	Timeframe (4)	Calculation	Total Score
Do nothing	3	1	3	3(0.4)+1(0.2)+3(0.4)	2.6
Excavation and Erosion Control	1	3	1	1(0.4)+3(0.2)+1(0.4)	1.4
Phytoremediation	2.5	1	2	(2.5)(0.4)+1(0.2)+2(0.4)	2
Containment Cap	1.5	3	1	(1.5)(0.4)+3(0.2)+1(0.4)	1.6
Solidification and Stabilization	1	2.5	1	(1)(0.4)+(2.5)(0.2)+1(0.4)	***1.3***

Sulphur Creek Stream Banks, Cherry Hill to Manzanita

The stream bank sediment within Sulphur Creek Valley contains high concentrations of mercury from both natural background levels and historical mining activities. The stream banks from the Cherry Hill Mine to the downstream side of the Manzanita Mine, approximately 400 meters, may erode during high flows and be a large source of mercury for the watershed (Figure 27, also see Table 20 for site characterization matrix). Aerial images reviewed in Google Earth show that a bend adjacent to the Manzanita Mine has moved approximately 10 meters from 1993 to 2009, although it is difficult to measure with accuracy. The Manzanita mine (Figure 28 and Figure 29), located north of Sulphur Creek, was both a gold and mercury mine from mid-1800s to mid-1900s (Churchill & Clinkenbeard, 2003). The Cherry Hill mine, located south of Sulphur Creek, southwest of the Manzanita mine, was a gold mine that operated in a similar timeframe. The stream banks may also have mercury contamination originating from upstream mines including the Elgin and Wide Awake mines. Mercury was most likely used during the gold amalgamation process, and soil in the area may also have naturally high concentrations of elemental mercury. Elemental mercury is more easily dissolved in water and may contribute to higher levels of methylation than cinnabar.

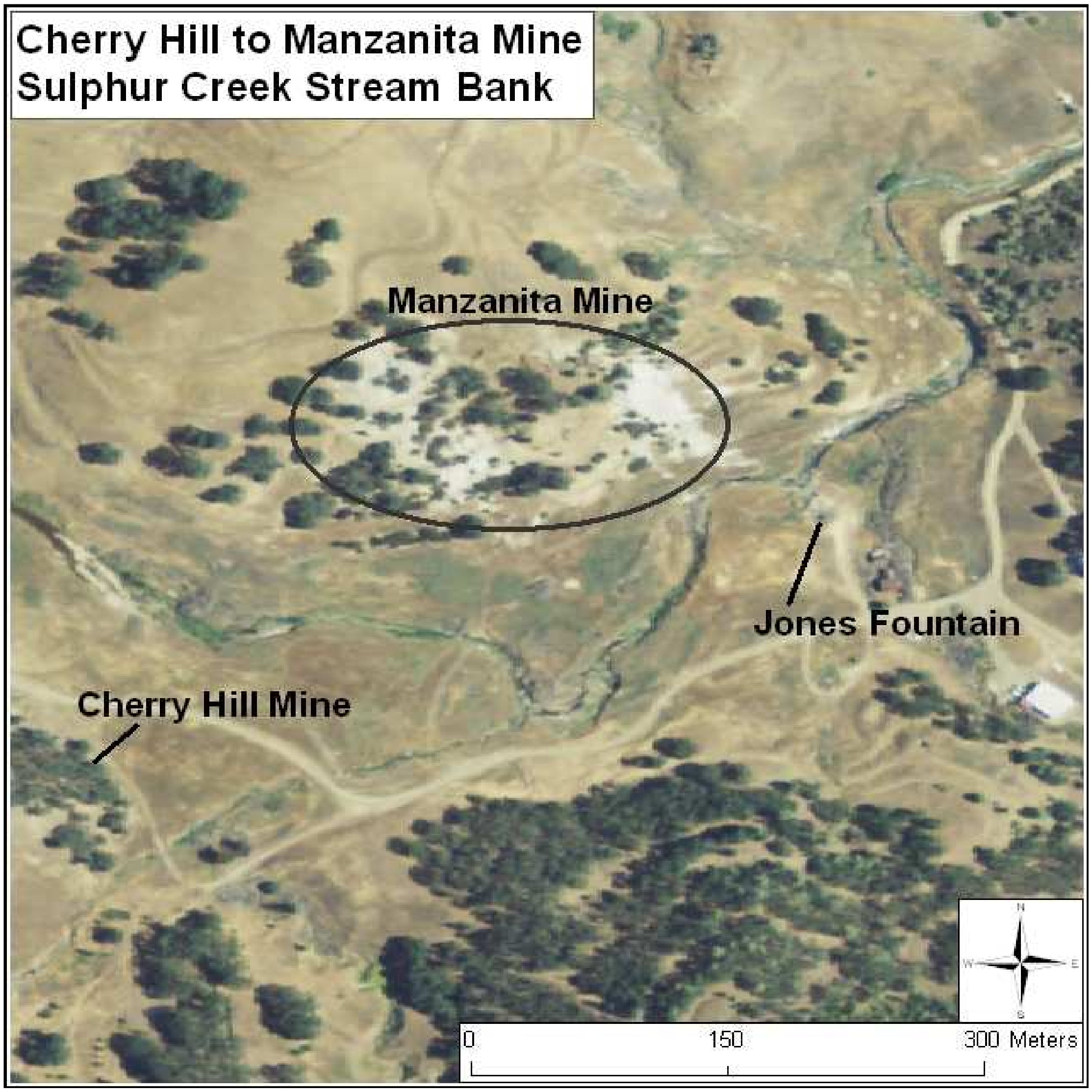
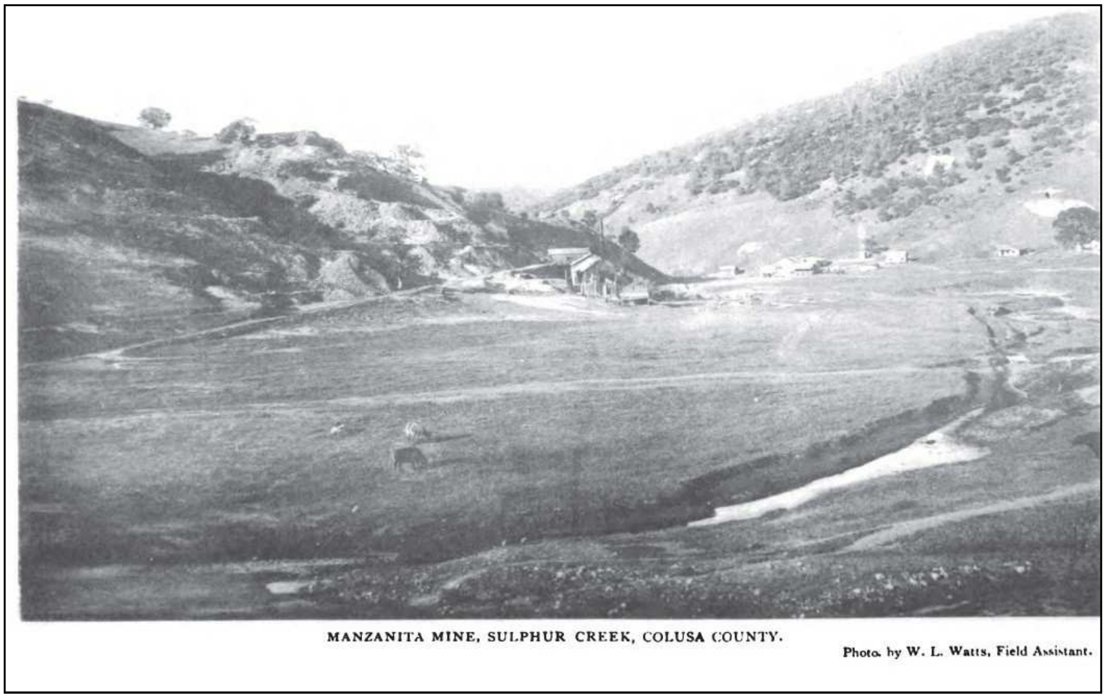


Figure 27: Site location of stream bank between Cherry Hill and Manzanita mines



MANZANITA MINE, SULPHUR CREEK, COLUSA COUNTY.

Photo. by W. L. Watts, Field Assistant.

Figure 28: Photograph of Manzanita Mine (Watts, 1893)

Figure 29: Photograph of Manzanita Mine Summer 2010

Waste material from the Cherry Hill and Manzanita mines is incorporated into stream bank sediments, and some areas may contain mercury concentrations with several hundred mg/kg. Churchill and Clinkenbeard (2003) reported on several samples of bank alluvium taken along Sulphur Creek in the area of the mines, and confirmed that at least some of the bank is highly enriched with mercury. There was a range of concentrations found between 25 and 78 mg/kg at the Manzanita mine and as high as 280 mg/kg near Cherry Hill (Churchill & Clinkenbeard, 2003). In addition to those two mines, West End Mine, Empire Mine, and Central Mine are near this location. The CVRWQCB has estimated that an average annual load of 0.3-8.7 kg of mercury originates from these mine sites, including Manzanita and Cherry Hill (Cooke and Morris, 2005). They have also determined that a 95 percent reduction at these sites is a necessary part of meeting the TMDL for Sulphur Creek. The estimates were based on data collected during or after six storms, but did not include erosion from bank sediments between Cherry Hill and Manzanita mines (Cooke and Morris, 2005). This additional erosion could add several kilograms in storm events (Churchill & Clinkenbeard, 2003). It is also estimated that annually a load of 4.8 kg of mercury comes from the Manzanita Mine sub-watershed, which contributes 40 percent of the load found at the USGS gauge downstream (Figure 30) (Cooke & Stanish, 2007). It is also recognized by the CVRWQCB that too few samples were taken to be able to statistically develop a relationship between mercury concentrations and flow from each site (Cooke and Morris, 2005).

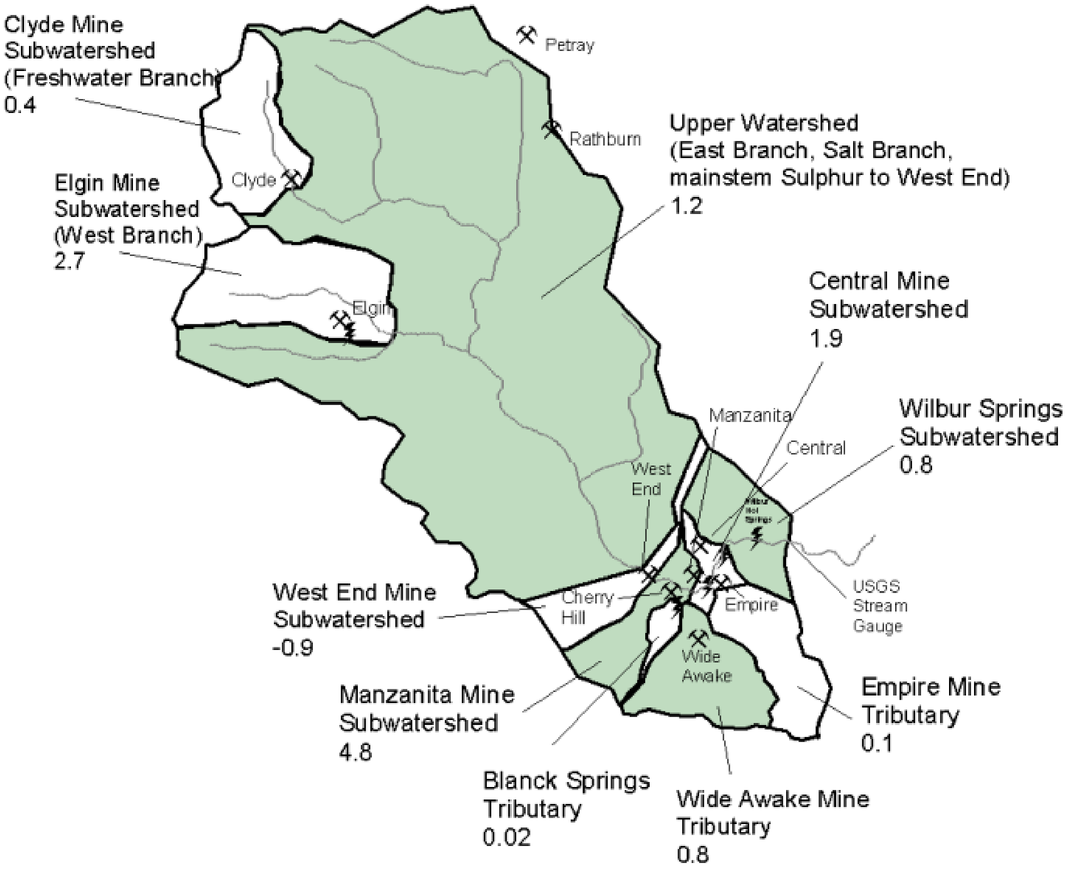


Figure 30: Sulphur Creek sub-watershed and tributary load (kg/yr) (Cook & Stanish, 2007)

Table 20: Site Characteristics for Cherry Hill to Manzanita Mine Sulphur Creek Stream Bank

Location	Cherry Hill to Manzanita
Land Owner	Richard Miller or American Land Conservancy[(a)]
Wilderness Area?	No
Site Type	Small perennial stream (Drainage area: 22.8 km^2)[(b)], Stream bank sediments
Amount of total mercury	Hundreds of kg[(c)]
Annual mercury delivery in dry/wet year	Unknown
Annual methylmercury delivery in dry/wet year	Unknown
Source of methylmercury?	No
Mercury Concentration	10 - 280 mg/kg[(c)]
Length of Stream Bank	400 m[(d)]
Slope	Very Low
Vegetation Cover	Low - grasses
Accessibility	Moderate - Past a private gate and at least partially on private property
Issues	• Private Property • Area floods during very high flows

(a) Richard Miller and the American Land Conservancy own large portions of the Sulphur Creek Valley, although property lines are not known.
(b) Measured in ArcHydro 9
(c) Churchill and Clinkenbeard, 2003
(d) Measured in ArcMap from NAIP aerials. This length will change depending on how much stream bank is determined to restoration actions taken.

The Cherry Hill to Manzanita site is not owned by the BLM, and it is unclear whether it is owned by Richard Miller or the American Land Conservancy (both own large portions of the valley). Although the BLM does not own the property, it will be important for remediation and restoration actions to be taken so that the BLM can meet the TMDL and protect water quality downstream of this site. The technologies considered for the Cherry Hill to Mazanita site are similar to those discussed for the Harley Gulch Delta, which is expected since most of the mercury at these sites is associated with stream bank sediments (Table 21). However there are some differences in the sites. For example, Cherry Hill to Manzanita is not located in the wilderness area and would be more accessible. This would make excavation and removal of sediments easier and less costly. However the site is on private lands and would require landowner cooperation for remediation actions to be taken.

Table 21: Management options for Cherry Hill to Manzanita

Option	Time Frame	Cost	Effectiveness	Other Issues
Do nothing	N/A	Low	None	Monitoring costs are necessary
Excavation and Disposal	Short	High	High	Waste disposal; access; cultural sensitivities; habitat alteration
Phytoremediation	Medium	Low	Low-Medium	Can wash away; long time frame; depth of contamination may not be met
Containment Cap	Short	High	Medium-High	Contamination still present; Can wash away; importing clay
Solidification and Stabilization	Short	Medium - High	High	Leaching

While phytoremediation is a proposed action for this site, it may not be feasible due to the high concentrations of mercury in the soils (10-280 mg/kg) as well as the climatic conditions at the site. The effectiveness of this option would depend on the ability for plants to grow in the area and to withstand high levels of mercury and flooding in the event of high flows. Containment strategies as well as excavation pose the same risks as described in the Harley Gulch Delta section.

As a result of the remediation option's ranking analysis, again phytoremediation would be the recommended strategy for decision maker one (Table 22). However as mentioned above, choosing plants which can withstand high mercury concentrations and survive in the climatic conditions is necessary. Genetically engineered plants using the bacterial *merA* (mercuric ion reductase) and *mer*B (organomercurial lyase) genes may be applied (Ruiz andDaniell, 2009). If appropriate plants cannot be identified then the next option that should be considered would be in-situ solidification and stabilization. Solidification and stabilization would be the recommended strategy for decision maker two (Table 23).

Table 22: Results of ranking options for the Cherry Hill to Manzanita Mine stream bank sediments for a decision maker that puts more of an emphasis on low cost technologies

Option	Effectiveness (2)	Cost (5)	Timeframe (3)	Calculation	Total Score
Do nothing	3	1	3	3(0.2)+1(0.5)+3(0.3)	2
Excavation and Erosion Control	1	3	1	1(0.2)+3(0.5)+1(0.3)	2
Phytoremediation	2.5	1	2	(2.5)(0.2)+1(0.5)+2(0.2)	***1.6***
Containment Cap	1.5	3	1	(1.5)(0.2)+3(0.5)+1(0.3)	2.1
Solidification and Stabilization	1	2.5	1	(1)(0.2)+(2.5)(0.5)+2(0.3)	1.75

Table 23: Results of ranking options for the Cherry Hill to Manzanita Mine stream bank sediments for a decision maker that puts more of an emphasis on effectiveness

Option	Effectiveness (4)	Cost (2)	Timeframe (4)	Calculation	Total Score
Do nothing	3	1	3	3(0.4)+1(0.2)+3(0.4)	2.6
Excavation and Erosion Control	1	3	1	1(0.4)+3(0.2)+1(0.4)	1.4
Phytoremediation	2.5	1	2	(2.5)(0.4)+1(0.2)+2(0.4)	2
Containment Cap	1.5	3	1	(1.5)(0.4)+3(0.2)+1(0.4)	1.6
Solidification and Stabilization	1	2.5	1	(1)(0.4)+(2.5)(0.2)+1(0.4)	***1.3***

West End Mine Waste Rock Pile

The West End Mine is part of the Manzanita Mine Group, and was mined exclusively for gold. Currently, the West End Mine consists of an adit and a large waste rock pile north of Sulphur Creek and west of where the processing facilities at the Manzanita Mine were formerly located (Figure 31, Figure 32). The pile of waste rock contains and estimated 1,400 kg of mercury, and may contribute significant amounts of mercury to Sulphur Creek, especially during large storms (see Table 24 for site characterization matrix). The average annual erosion rate, as reported by Churchill and Clinkenbeard (2003) is 0.02-5.9 tons/acre. This waste pile contains a large percentage of rock fragments, with the eastern side eroding directly into Sulphur Creek (Churchill & Clinkenbeard, 2003). The western side of the pile erodes into a lowland area with dense grass, which seems to limit erosion to the lower threshold of 0.02 tons/acre (Churchill & Clinkenbeard, 2003). Churchill and Clinkenbeard (2003) also estimated an annual load 0.002-1.1 kg of mercury entering Sulphur Creek from the West End rock pile. Conversely, the CVRWQCB (Cooke & Stanish, 2007) found a slight decrease in loads downstream of the West End Mine compared to upstream. This would indicate that this is actually a depositional area and not a source of mercury. However, it is noteworthy that samples were taken upstream and downstream of the West End Mine and not taken directly from the site. Additionally, there were just four sampling events and only half the samples indicated this decrease in mercury (Cooke & Stanish, 2007).

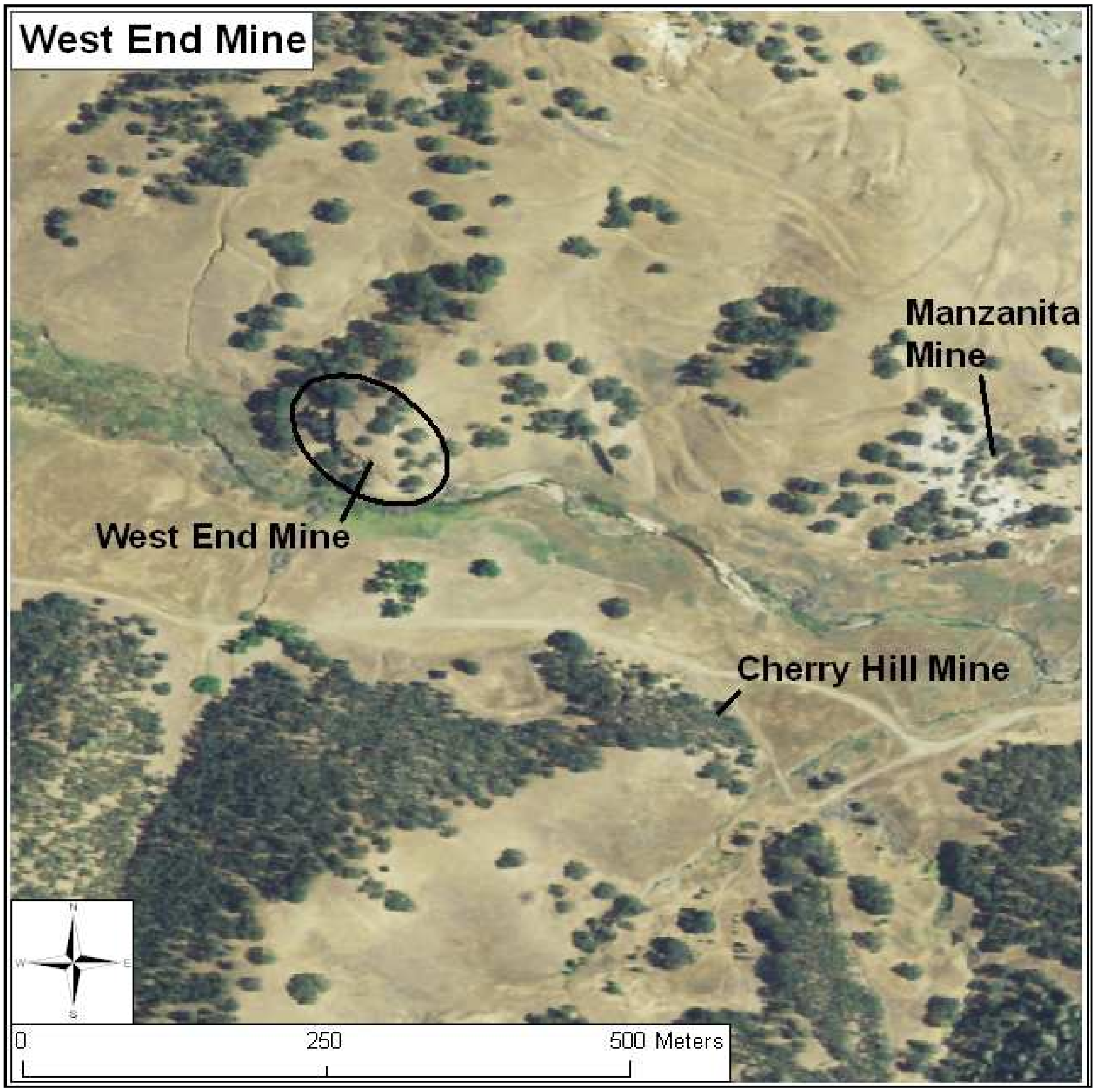


Figure 31: Site location of the West End Mine

Figure 32: Photograph of West End Mine rock pile (summer 2010)

Table 24: Site Characteristics for West End Mine rock pile

Location	West End Mine Rock Pile
Land Owner	Richard Miller or the American Land Conservancy(a)
Wilderness Area?	No
Site Type	Waste Rock
Amount of total mercury	1,400 kg(b)
Annual mercury delivery in dry/wet year	0.002-1.1 kg/yr average(b)
Annual methylmercury delivery in dry/wet year	< 0.1 g(\c)
Source of methylmercury?	No
Mercury Concentration	300 mg/kg(b)
Area of site	647 m2(b)
Volume of contaminated soil	2,750 m^3(b)
Slope	See photo
Vegetation Cover	Low
Accessibility	Moderate - Past a private gate, may be on private property, across Sulphur Creek

(a) Richard Miller and the American Land Conservancy own large portions of the Sulphur Creek Valley, although property lines are not known.
(b) Churchill and Clinkenbeard, 2003
(c) Estimation base on the fact that the waste rock pile is very dry in the dry season, which is necessary for methylation

The possible options for the West End Mine as determined by our decision trees are: do nothing, excavation and disposal onsite, phytoremediation, containment cap, and erosion control (Table 25).

Table 25: Management options for the West End Mine waste rock pile

Option	**Time Frame**	**Cost**	**Effectiveness**	**Other Issues**
Do Nothing	N/A	Low	None	Monitoring costs are necessary
Excavation and Disposal	Short	High	High	Waste disposal; access; cultural sensitivities; habitat alteration
Containment Cap	Short	High	Medium-High	Contamination present; Can wash away; importing clay
Erosion Control	Short	Medium	Medium	Contamination still present

The second option is to excavate the contaminated materials and remove the waste rock. Excavation would be expensive, but it would be effective in removing mercury from the system. By disposing of waste onsite, costs can be reduced since the wastes are not taken to a treatment facility.

If excavation cannot be conducted, a containment cap or erosion controls can be used to stabilize the contaminated materials at this site. Erosion control is another lower-cost option that can be considered in this situation. There are a number of erosion control methods ranging from the application of geotextiles to re-grading of slopes. This option can prevent contaminated soil from being transported downstream; however, the mercury is still present in the area.

From the perspective of the first decision maker, erosion controls like geotextiles or re-grading would be the best option (Table 26). The second type of decision maker has more options. Ranking the options shows that excavation, containment cap or erosion control would be effective (Table 27).

Table 26: Results of ranking options in the West End Mine waste rock pile for a decision maker that puts more of an emphasis on low cost technologies

Option	Effectiveness (2)	Cost (5)	Timeframe (3)	Calculation	Total Score
Do nothing	3	1	3	3(0.2)+1(0.5)+3(0.3)	2
Excavation and Disposal	1	3	1	1(0.2)+3(0.5)+1(0.3)	2
Containment Cap	1.5	3	1	(1.5)(0.2)+3(0.5)+1(0.3)	2.1
Erosion Controls	2	2	1	2(0.2)+2(0.5)+1(0.3)	***1.7***

Table 27: Results of ranking options in the West End Mine waste rock pile for a decision maker that puts more emphasis on preventing adverse health effects from contamination

Option	Effectiveness (4)	Cost (2)	Timeframe (4)	Calculation	Total Score
Do nothing	3	1	3	3(0.4)+1(0.2)+3(0.4)	2.6
Excavation and Disposal	1	3	1	1(0.4)+3(0.2)+1(0.4)	1.4
Containment Cap	1.5	3	1	(1.5)(0.4)+3(0.2)+1(0.4)	1.6
Erosion Controls	2	2	1	2(0.4)+2(0.2)+1(0.4)	1.6

Clyde Mine

The Clyde Mine is a historical gold mine located on both sides of the Freshwater Branch of Sulphur Creek (Figure 33). It was operational in the late 1890s and was used again in the 1970s for gold recovery (Churchill & Clinkenbeard, 2003). The most recent activity may have included the reprocessing of older mined materials, which likely created the current tailings pile and three small ponds found on the site (Churchill & Clinkenbeard, 2003) (see Table 28 for site characterization matrix). In 2009 a cleanup and abatement order was issued by the CVRWQCB to the BLM, the current owner of the site. Presumably, the BLM is working on a remediation plan similar to the remediation plan that was released for the Rathburn and Petray mines. According to the cleanup order, the Clyde Mine remediation is supposed to be completed by the end of 2011 (CVRWQB, 2009b). However, it is unknown whether remediation plans have been finalized, and most likely this deadline will not be met.

It has been estimated that an annual load of 0.4kg of mercury enters Sulphur Creek from this mine site and a 95 percent reduction goal is to be met in order to comply with the TMDL (Cooke and Morris, 2005). Mercury concentrations at this site are in the range of 0.79-330 mg/kg (Cooke & Stanish, 2007). However, Churchill and Clinkenbeard (2003) concluded that remediation efforts would likely have a limited impact on lowering mercury levels in Sulphur Creek due to the relatively low mercury content of the tailings pile.

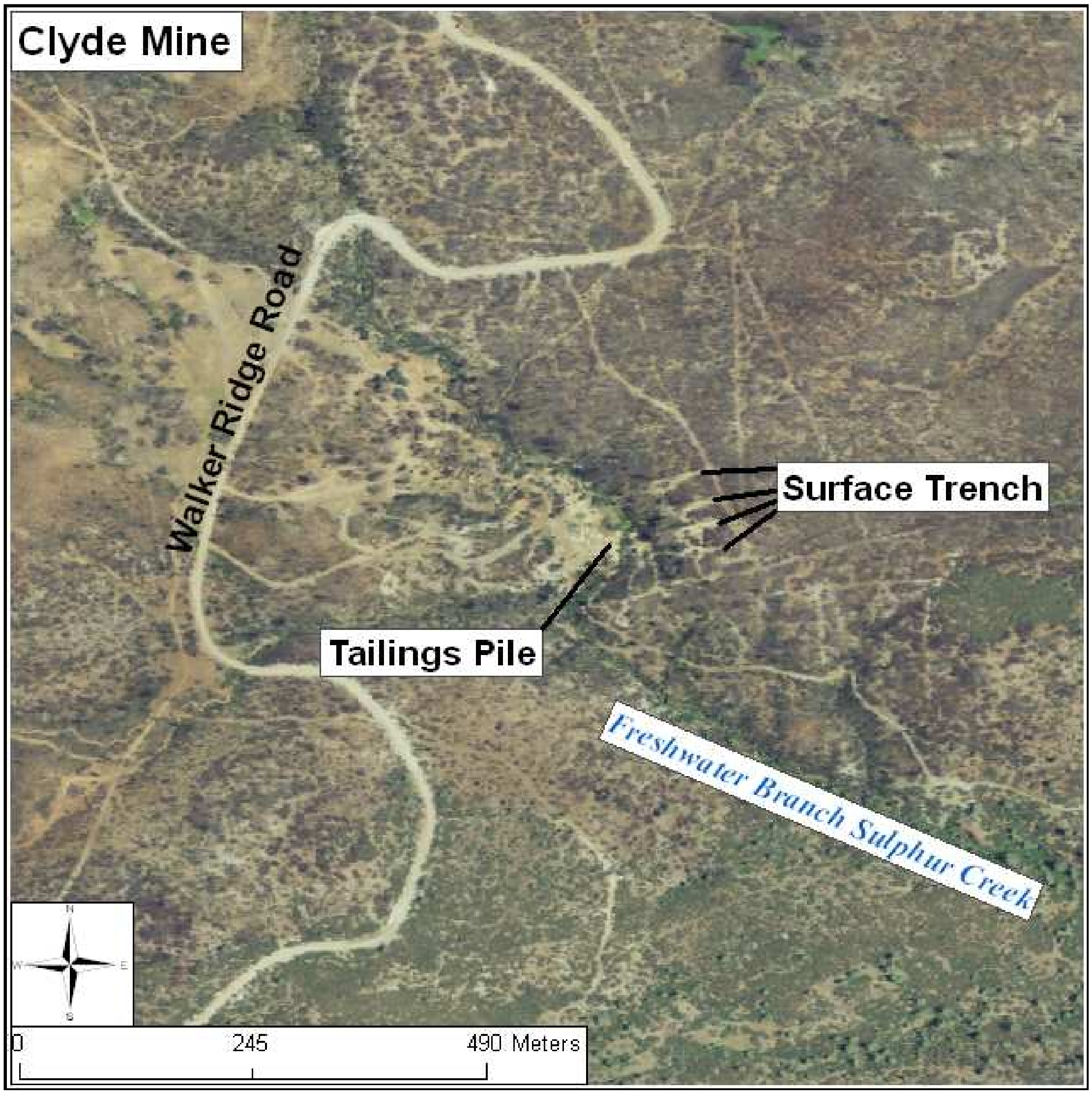


Figure 33: Site location of Clyde Mine

Table 28: Site Characteristics for Clyde Mine

Location	**Clyde Mine**
Land Owner	BLM
Wilderness Area?	No
Site Type	Waste Rock, Mined Area, Tailings Pile
Amount of total mercury	140 kg(a)
Annual mercury delivery in dry/wet year	0.033 – 0.11 kg average(a)
Annual methylmercury delivery in dry/wet year	Unknown
Source of methylmercury?	No
Mercury Concentration	5 - 6.7 mg/kg(a)
Area of site	Tailings Pile: 1,540 m^2; Other Piles and trenches: 1,540 m^2(a)
Volume of contaminated soil	Tailings Pile: 15,500 m^3; Pile 1: 600 m^3; Pile 2: 450 m^3; Pile 3: 400 m3(a)
Slope	Moderate – High; Tailings Pile: 78%; Other piles: 30 – 78%(a)
Vegetation Cover	Moderate - grasses, chamise, oak
Accessibility	Easily accessible from Walker Ridge Road
Issues	

(a) Churchill and Clinkenbeard, 2003

Possible management options for Clyde Mine are to do nothing, excavation and erosion control, phytoremediation and a containment cap (Table 29).

Table 29: Management options for the Clyde Mine

Option	**Time Frame**	**Cost**	**Effectiveness**	**Other Issues**
Do Nothing	N/A	Low	None	Monitoring costs are necessary
Excavation and Erosion Control	Short	High	High	Waste disposal; access; habitat alteration
Phytoremediation	Medium	Low	Low-Medium	Can wash away; long time frame; depth of contamination may not be met
Containment Cap	Short	High	Medium-High	Contamination still there; Can wash away; importing clay

Excavation followed by erosion control (like geotextiles or re-vegetation) is the first option besides do nothing that can be applied for this site. This option will remove mercury quickly but can be relatively expensive. Both onsite disposal and offsite disposal are possible. After the site is excavated, erosion control will be needed to prevent sediment from washing downstream. Phytoremediation is the next possible option for this site. In addition, a containment cap of clay on both the mine and tailings pile could contain the mercury and prevent it from entering the aquatic ecosystem. This may not be the best option because the mercury is still present and there is a possibility that the containment cap could be washed away during a storm event.

Again, for decision maker one the best option based on the assessment criteria is phytoremediation. From the perspective of decision maker two the recommended action would be excavation and removal of contaminated materials (Table 30 and Table 31).

Table 30: Results of ranking options in the Clyde Mine for a decision maker that puts more of an emphasis on low cost technologies

Option	**Effectiveness (2)**	**Cost (5)**	**Timeframe (3)**	**Calculation**	**Total Score**
Do nothing	3	1	3	3(0.2)+1(0.5)+3(0.3)	2
Excavation and Erosion Control	1	3	1	1(0.2)+3(0.5)+1(0.3)	2
Phytoremediation	2.5	1	2	(2.5)(0.2)+1(0.5)+2(0.2)	***1.6***
Containment Cap	1.5	3	1	(1.5)(0.2)+3(0.5)+1(0.3)	2.1

Table 31: Results of ranking options in the Clyde Mine for a decision maker that puts more emphasis on preventing adverse health effects from contamination

Option	**Effectiveness (4)**	**Cost (2)**	**Timeframe (4)**	**Calculation**	**Total Score**
Do nothing	3	1	3	3(0.4)+1(0.2)+3(0.4)	2.6
Excavation and Erosion Control	1	3	1	1(0.4)+3(0.2)+1(0.4)	1.4
Phytoremediation	2.5	1	2	(2.5)(0.4)+1(0.2)+2(0.4)	2
Containment Cap	1.5	3	1	(1.5)(0.4)+3(0.2)+1(0.4)	1.6

Turkey Run Spring

The Turkey Run Spring flows into a small tributary of the West Fork of Harley Gulch, at the north end of the wetland, from the southern part of the Turkey Run mine (Figure 34). The estimated flow of the spring isapproximately 15 gpm (Tetra Tech, 2003); it is a relatively small source of mercury but a large source of sulfate (see Table 32 for site characterization matrix). It is estimated that the spring contributes about 0.005-0.006 kg/yr of mercury to Harley Gulch (Churchill & Clinkenbeard, 2003). According to a report issued by Tetra Tech (2003), the concentration of total mercury in the Turkey Run Spring is 10-200 ng/l and the concentration of methylmercury is 0.005-0.009 ng/l. It is also estimated that the spring contributes 50,720-159,083 kg of sulfate to Harley Gulch each year, which is approximately 90 percent of the known sulfate discharge from the Sulfur Creek Mining District (Tetra Tech, 2003). Sulfate reducing bacteria have been found to increase the rate of methylation. Therefore, reducing the sulfate load, as well as the mercury load in Harley Gulch could be very important in reducing methylmercury loads entering Cache Creek. This would also serve to decrease the methylation that occurs downstream in Cache Creek.

Figure 34: Site location of Turkey Run Spring

Table 32: Site Characteristics for Turkey Run Spring

Location	**Turkey Run Spring**
Land Owner	El Paso Merchant Energy-Petroleum Co.
Wilderness Area?	No
Site Type	Thermal Spring
Amount of total mercury	0 kg
Annual mercury delivery in dry/wet year	0.005-0.006 kg/yr(a)
Annual methylmercury delivery in dry/wet year	< 0.1 g/yr(a)
Source of methylmercury?	very small
Mercury Concentration	200 ng/l(a)
Flow Rate	50 - 57 l/min(a)
Annual Flow	26,280,000 - 29,959,200(a)
Slope	Moderate
Accessibility	Moderate - only 150 meters from Highway 20
Issues	Annual maintenance required

(a) Churchill and Clinkenbeard, 2003

Feasible management options for the Turkey Run Spring are: redirect the spring to a settling basin and chemical treatments of water including adsorption/ ion exchange and precipitation/coagulation (

Table 33). Again “do nothing” was considered as a baseline.

Table 33: Management options for the Turkey Run Spring

Option	Time Frame	Cost	Effectiveness	Other Issues
Do Nothing	N/A	Low	None	Monitoring costs are necessary
Redirect Spring to Settling Basin	Short	High	Med	Habitat alteration, high flows may reduce effectiveness
Chemical Treatment (Adsorption/ Ion Exchange or Precipitation/ Coagulation)	Short	High	Medium - High	Disposal of sludge

The first option besides “do nothing” is to redirect the spring to a sediment retention basin. This option would prevent mercury from running into the West Fork of Harley Gulch; however, it may not meet the TMDL since further remediation actions would be necessary to fully address the mercury issues in Harley Gulch. This option would also be expensive because of the construction costs associated with building a settling basin and would cause habitat alterations.

Since sulfate is the major concern at this site it will be necessary to treat the water for not only mercury but also sulfate. There are two types of chemical treatment that can be used to reduce sulfate as well as mercury: adsorption and ion exchange; or precipitation and coagulation. This option would also be very costly because it would require the construction of an onsite treatment facility, associated flow diversion structure and access road. Another consideration would be how the waste would be disposed of since, especially in the case of mercury treatment, “the spent adsorption material and coagulants may contain high concentrations of metals, which may require expensive disposal” (Tetra Tech 2003).

In this case, the best option for decision maker one would be to do nothing. This option receives the lowest score since all other possible options are so expensive (Table 34). However, this option may be considered unacceptable since it is a natural source of mercury and sulfate and would not likely attenuate if left unchecked. If some action must be taken, the best option would be to chemically treat the water. The second type of decision maker would likely opt to chemically treat the water coming from the spring since it may be more effective than redirecting the flows into a settling basin (Table 35).

Table 34: Results of ranking options in the Turkey Run Spring for a decision maker that puts more of an emphasis on low cost technologies

Option	Effectiveness	Cost	Timeframe	Calculation	Total Score
Do nothing	3	1	3	3(0.2)+1(0.5)+3(0.3)	2
Redirect Spring to Settling Basin	2	3	1	2(0.2)+3(0.5)+1(0.3)	2.2
Chemical Treatment (Adsorption/ Ion Exchange or Precipitation/ Coagulation)	1.5	3	1	(1.5)(0.2)+3(0.5)+1(0.3)	2.1

Table 35: Results of ranking options in the Turkey Run Spring for a decision maker that puts more emphasis of preventing adverse health effects from contamination

Option	Effectiveness	Cost	Timeframe	Calculation	Total Score
Do nothing	3	1	3	3(0.4)+1(0.2)+3(0.4)	2.6
Redirect Spring to Settling Basin	2	3	1	2(0.4)+3(0.2)+1(0.4)	1.8
Chemical Treatment (Adsorption/ Ion Exchange or Precipitation/ Coagulation)	1.5	3	1	(1.5)(0.4)+3(0.2)+1(0.4)	1.6

Summary of Case Studies

While remediation and restoration options vary based on site specific factors, some trends emerged when evaluating the six case studies presented in this report. The same remediation/ restoration options were chosen from the decision tree analysis for a number of different sites. Additionally, these choices were often ranked similarly. For example, in most cases phytoremediation was recommended as the best option for the decision maker who put more emphasis on remediation options that are low cost. It was selected for four of the six sites when ranking options for this type of decision maker (Table 36 and

Table 37). In addition, for this type of decision maker, the best option for Turkey Run Spring was determined to be "do nothing" because all other possible options for treating water at the spring would be cost prohibitive. If some action must be taken then the best option would be to chemically treat the water.

For the decision maker who puts more emphasis on mitigating health effects, the best remediation/ restoration strategies would be highly effective options such as excavation and erosion control or solidification and stabilization (Table 36 and

Table 37). Despite the cost and disadvantages of these options, they would be highly effective and take less time to implement than phytoremediation or other less invasive actions.

Table 36: Results from ranking of remediation options for three case studies including Harley Gulch Delta, Harley Gulch Wetlands, and Cherry Hill to Manzanita.

	Harley Gulch Delta	Harley Gulch Wetlands	Cherry Hill to Manzanita
Decision Maker 1 (Low Budget)	Phytoremediation	Phytoremediation	Phytoremediation
Decision Maker 2 (Health Effects)	Excavation and Erosion Control	Remove sediments, add fill, re-vegetate	Solidification and Stabilization

Table 37: Results from ranking of remediation options for three case studies including West End Mine Waste Rock Pile, Clyde Mine, Turkey Run Spring.

	West End Mine Waste Rock Pile	Clyde Mine	Turkey Run Spring
Decision Maker 1 (Low Budget)	Erosion Control	Phytoremediation	Do Nothing
Decision Maker 2 (Health Effects)	Excavation and Removal	Excavation and Removal	Chemical Treatment

The options presented for these case studies show how the decision-making framework developed in this report can be used for potential cleanup sites. Depending on the priorities of decision makers and their specific constraints, the recommended remediation options may change. In addition, when it is determined that one remediation option may not be effective on its own it may be necessary to combine remediation and restoration options. For example when excavation is used as an option it should be combined with erosion control practices in order to stabilize the excavated area. Also, when re-vegetating as a form of erosion control it may be useful to use plants with pytoremediative properties to reduce mercury concentrations in the sediment while preventing contaminated sediments from eroding.

These decision trees and resulting information matrices are meant to serve as a starting point for BLM staff to gather the basic information necessary to prioritize sites for cleanup and begin restoration or remediation activities. The assessment and ranking system can aid decision makers in determining the best course of action. We attempted to generalize the decision process in a way that would facilitate a wider applicability not only across the entire Cache Creek Basin, but in other locations where legacy mercury pollution exists.

Watershed Modeling

To model the Cache Creek Basin we choose to use WARMF (Watershed Analysis Risk Management Framework), a software program developed by Systech Water Resources Inc. This program was chosen because it is one of the only watershed modeling programs available that adequately models mercury as well as other pollutants. WARMF has the ability to fully model all aspects of hydrology and biogeochemistry within a watershed, and its use is gaining in popularity for modeling watersheds with water quality impairments. In order to model mercury properly, Systech scientists reviewed 118 papers on the current state of knowledge on the fate and transport of mercury within a watershed, and assembled that information to most accurately model each of the biogeochemical processes that mercury undergoes given the environmental conditions specific to that watershed (Chen et al., 2003). WARMF also has the ability to model remediation and restoration scenarios in which point and non-point pollution sources are diminished over time to evaluate how to best meet TMDL requirements.

The information needed to set up a WARMF model includes the following:

- A Digital Elevation Model (DEM)
- Land Use
- Soil Characteristics
- Point Source Data
- Stream Flow Data
- Meteorological Data
- Air and Rain Chemistry
- Wet and Dry Deposition Data

Much of this data is publically available from the USGS, USEPA, or other government agencies, and the rest was gathered from a literature review of studies conducted in the Cache Creek Basin.

WARMF divides a watershed into subcatchments and their corresponding stream reaches. For our model, we choose not to include Clear Lake and Indian Valley

Reservoir and their watersheds explicitly, but instead to focus on the region downstream of the two dams. The outflows of the reservoirs were modeled as point sources so the water flow and chemistry could be specified. By representing Clear Lake and Indian Valley Reservoir as point sources, it allowed us to concentrate our modeling efforts on the downstream subcatchments that include the Sulphur Creek and Knoxville Mining Districts. We also increased the resolution of Harley Gulch and Sulphur Creek by subdividing each into four subcatchments. The Davis Creek subcatchment was also divided into catchments above and below the reservoir.

Watershed Model Setup and Calibration Process

The most important aspects of the model setup and calibration are outlined here; a more detailed discussion of the model is found in Appendix II. Many parameters in WARMF have a significant impact on sediment and mercury loads in addition to methylation and demethylation rates. After all of the available data is inputted to the model, it is necessary to first calibrate the hydrology, then erosion rates, and then mercury concentrations. Mercury concentrations in streams are dependent on soil erosion, which is also dependent on hydrology, so all three must be calibrated in order to model mercury correctly.

The hydrology auto-calibration function in WARMF performed well: the modeled flows matched the observed flows with an R^2 value of 0.82 at Rumsey (Figure 35). To model the mines and thermal springs, a point source was created for each one, with the average yearly contribution of each source gathered from data in the Churchill and Clinkenbeard (2003) task 5C1 report as part of the CALFED Bay-Delta Mercury Project. Churchill and Clinkenbeard (2003) calculated a range of annual average mercury loads for each mine based on the uncertainty that exists for both the mercury concentration at mines and erosion rates. The point source value for each mine used in the WARMF model is the mean of the range for the given mine, unless additional information is available which indicates that this is not the true annual loading to the stream, such as is the case in the Rathburn and Petray mines (Table 38). The WARMF model runs on a daily time step, and it was necessary to calculate daily mercury loads from each mine point source estimated based on daily rainfall and stream flow data, as explained further in Appendix II. It should be kept in mind that there is uncertainty in determining point sources, and therefore uncertainty in the WARMF model.

The daily mercury loads from each thermal spring also use the average value of the range given in Churchill and Clinkenbeard (2003) and were assumed to remain constant throughout the year. Thermal springs are not a large source of mercury, and in the Sulphur Creek watershed, where most of the thermal springs are located, they only account for 0.382 g/d or only 0.7 percent of the total mercury load in the watershed. However, they are very important in the dry season when even small amounts of mercury lead to high concentrations. Also, most of the mercury from thermal springs is dissolved, which creates high rates of methylation in Sulphur Creek.

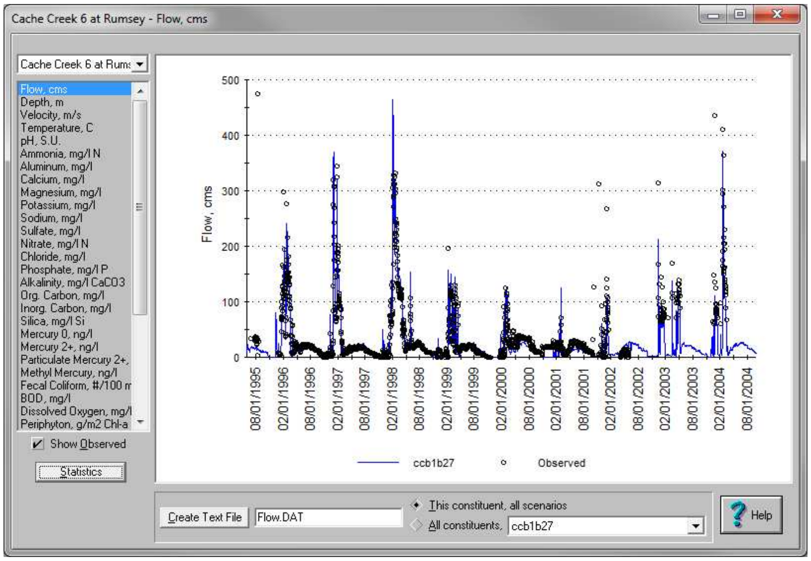


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Figure 35: WARMF screenshot of modeled (blue line) vs. observed flow (black dots) at Rumsey for water years 1996-2004. Some observed flows during 2002-2004 are missing

Table 38: Annual average mercury loads from mines in the Cache Creek Basin

Mine	Churchill and Clinkenbeard (2003) Calculation	WARMF Value	WARMF Subcatchment
Reed(a)		6.65	Upper Davis Creek
Abbott(b,c)	0.7 - 3.6	2.15	West Fork Harley Gulch
Turkey Run(b,c)	0.4 - 6.7	4	West Fork Harley Gulch
Wide Awake	0.02 - 0.44	0.23	Lower Sulphur Creek
West End	0.002 - 1.1	0.55	Lower Sulphur Creek
Cherry Hill	0 - 1	0.5	Lower Sulphur Creek
Empire	0.04 - 0.06	0.05	Lower Sulphur Creek
Manzanita	0.3 - 6.5	3.4	Lower Sulphur Creek
Central	0.0028 - 0.034	0.015	Lower Sulphur Creek
Totals for Wilbur Springs Area Sites	0.4 - 8.1		Lower Sulphur Creek
Elgin	3.9 - 9.4	6.65	West Fork Sulphur Creek
Clyde	0.033 - 0.11	0.06	East Fork Sulphur Creek
Rathburn Central Pit(d)	0.67 - 19.7	0.5	Bear Creek
Petray(d)	0.44 - 4.6	0.2	Bear Creek

(a) There is very little data to accurately estimate runoff from the Reed Mine. It is also unknown how much mercury is sequestered in Davis Creek Reservoir.
(b) Not included in the WARMF. Although the Abbott and Turkey Run was not cleaned up until 2007, we wanted to compare the current conditions of the mines to the future conditions after the cleanup of every mine.
(c) Does not include the upper area of the mine, although the WARMF value is increased to reflect an additional contribution from the upper area
(d) Most erosion does not reach Bear Creek

Erosivity

In addition to point sources from mines and thermal springs, erosion rates and mercury concentrations of soil are the two components that WARMF uses to determine the mercury loads from the watershed. WARMF uses the Universal Soil Loss Equation (USLE) to determine erosion rates, a method developed by the U.S. Department of Agriculture (USDA), primarily to calculate erosion from agricultural land. Values given by the USLE should be checked against measured values for accuracy so the different factors in the USLE can then be better calibrated. There are five components of the USLE: a rainfall intensity factor,; a soil erosivity factor (K); a slope length-gradient factor (the longer and steeper the slope the more erosion); a crop/vegetation factor; and a support practice factor, which accounts for any erosion prevention practices that are employed (Stone and Hilborn, 2000). The rainfall intensity factor was calculated by WARMF as part of the hydrology calibration. The slope length-gradient factor was calculated from the digital elevation model (DEM) during the model setup. The crop/vegetation factor was calculated when land use types were inputted to the model. The support practice value is assumed to be 1.0, or not an important factor, when no erosion prevention practices have been employed. In places such as the old tailing pile at the Abbott Mine, where drains, wattles, and riprap have been installed, erosion is considered being controlled, and this factor would be less than 1.0.

The erosivity factor, K is the only factor that must be specified by the user during the setup of a WARMF model. K is related to the ability of a soil to be eroded, and will be high when the soil contains particles that are easily detached during rainfall. In general, soils that contain more organic matter have a lower K, whereas loamy soils have a higher K. In order to determine K values, we used the USDA STATSGO soil database which is a more generalized form of SSURGO, but of a higher resolution necessary for our purposes. In order to match sediment concentrations that were measured in the field by Foe and Croyle (1998), it was necessary to increase the K values of Benmore Creek, Grizzly Creek, and the Cache Creek Canyon subcatchments to 0.40 (Figure 36). We also decreased the K values for the subcatchments of Bear Creek above Sulphur Creek to 0.09 to match the low sediment concentrations measured by Slotton et al (2004).

It can be seen from Figure 36 that portions of the Sulphur Creek Mining District have highly erosive soil. The high erosivity combined with high mercury soil concentrations and high slopes produce large mercury loads. Each of the subcatchments from the Cache Creek Canyon down to Yolo also have high erosion rates. These highly erosive soils explain the large increase in sediment that occurs between Rumsey and Yolo, as seen in Table 2 (Cooke et al 2004).

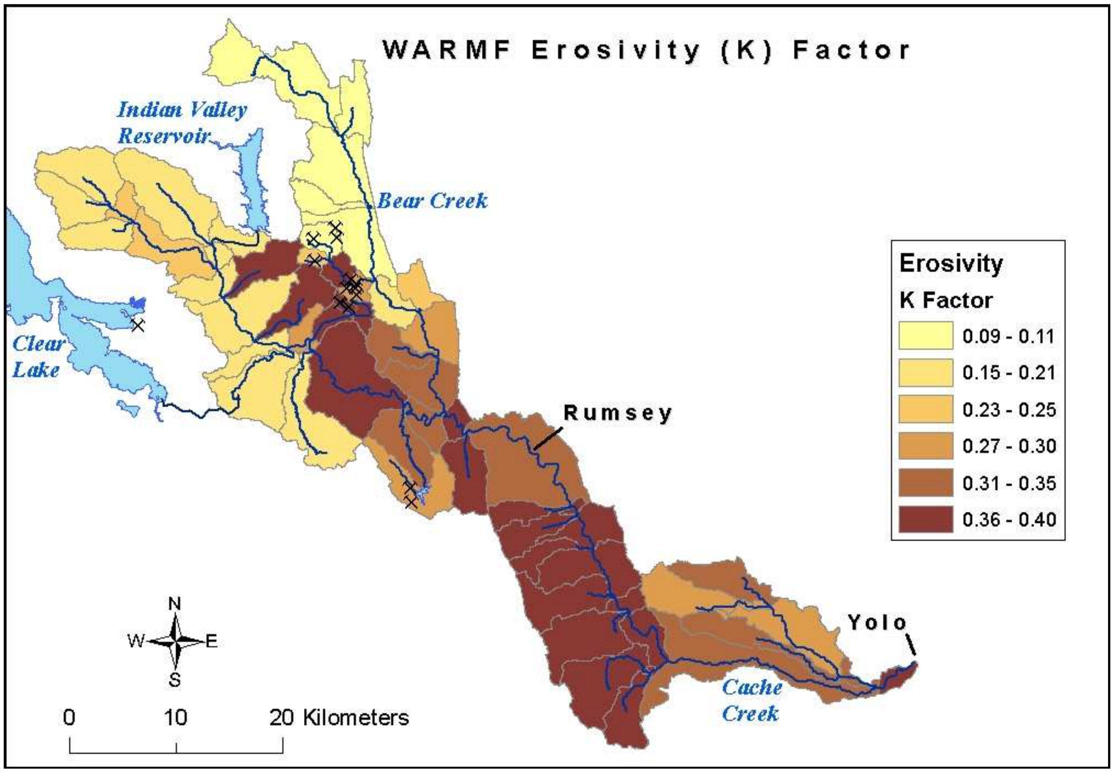


Figure 36: Erosivity factors in the watershed model

Soil Mercury Concentrations

WARMF calculates the mercury loads from soil erosion in each subcatchment by multiplying the total erosion in that subcatchment by the mercury concentration in the top layer of soil. Mercury concentrations in the soil were estimated using soil sample data from Churchill and Clinkenbeard (2003), Slowey and Rytuba (2008), Holloway (2009), Foe and Bosworth (2008), Bosworth and Morris (2009), as well as our own sediment samples taken in Harley Gulch. In addition to these soil samples, mercury concentration was calibrated using the mercury/sediment ratio of water samples. This mercury/sediment ratio, especially during large storms, is representative of the average mercury concentration of soils within a watershed. There have been very few samples taken of background mercury concentrations, and the ones that have been taken were from mining areas or along creeks. Therefore, background mercury concentrations in many of the subcatchments are largely unknown. Furthermore, although WARMF averages erosivity and mercury concentration throughout a subcatchment, it is conceivable that soils containing high concentrations of mercury have less vegetation and therefore higher erosion rates. To account for this in the model, it is better to attempt to match the mercury/sediment ratio in the water samples than the soil samples. Unfortunately, there have not been enough samples taken during high flows to make a determination of the true mercury concentration in soil for each subcatchment.

Many of the background soil mercury concentrations in our model (Figure 37) away from mining sites are far higher the background mercury concentrations that are stated in Churchill and Clinkenbeard (2003) and Cooke et al. (2004). Churchill and Clinkenbeard (2003) calculate that mercury concentrations average 0.19 mg/kg in non-mineralized soil and average 93 mg/kg in mineralized soils. However, when they calculate the natural background levels of mercury from the Cache Creek Basin, they assume that mineralized soils are only near mining area. Foe and Croyle (1998) found that the largest source of mercury in the Basin is from unknown sources within the Cache Creek Canyon. Due to the difficulty of accessing this area, very few samples have been taken, but it is possible that this region contains extensive mineralized soils which explain the high concentrations seen in Figure 37 needed to match the model to the high mercury/sediment ratios measured in water samples from this region.

Soils far away from mining areas were assigned a mercury concentration of 0.15 mg/kg, which is within the range stated by Churchill and Clinkenbeard (2003) and Foe and Croyle (1998). Subcatchments closer to mining areas, or areas where sampling has shown elevated levels of mercury, were assigned concentrations ranging from 0.2-1.25 mg/kg. The subcatchments that contain mines including Lower Sulphur

Creek, the West Fork of Sulphur Creek, the West Fork of Harley Gulch, and the Upper Davis Creek were assigned a concentration of 2.0 mg/kg. The Cache Creek Canyon subcatchment was assigned a concentration of 1.25 mg/kg and the Lower Davis Creek subcatchment was assigned a concentration of 1.0 mg/kg because of the large unknown source of mercury that originates from within this region (Foe and Croyle, 1998; Cooke et al., 2004), as well as the high mercury concentrations that were found in sediment samples (Foe and Bosworth, 2008). These unknown sources are assumed to be either erosion of legacy mercury in the Cache Creek bed sediments or unidentified regions with high background levels of mercury (Cooke et al., 2004).

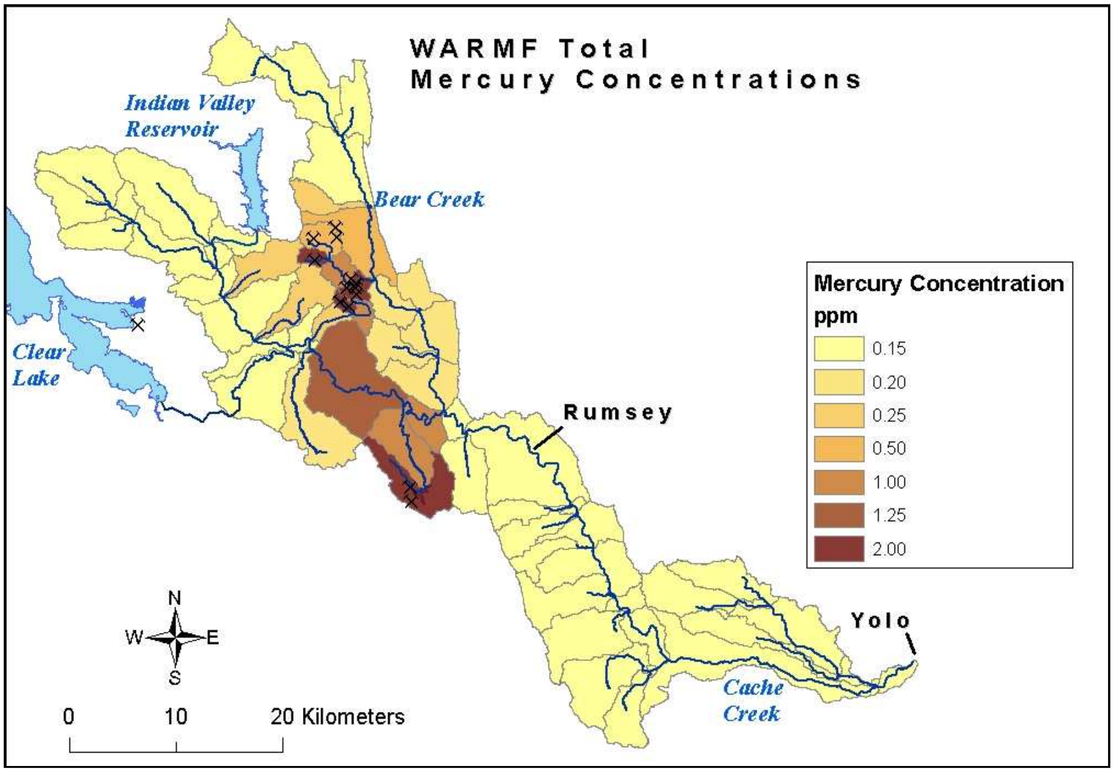


Figure 37: Total soil mercury concentrations in the watershed model

Watershed Modeling Results

After completing the calibration process, the model was run for the water years 1996 to 2004, and provides the daily concentrations and loading for nearly 30 water quality parameters. This nine year time frame was used because it contains the most data on the watershed including: flow information for Harley Gulch, Sulphur Creek, and Davis Creek from 1990-2004; flow information from Indian Valley Reservoir, which did not begin until 1995; as well as most of the mercury soil and water samples that have been taken in the area. In addition, 1996, 1997, and especially 1998 were relatively wet years, and it is critical to include these years in order to calibrate the model correctly during high flows.

The following WARMF results for flow, sediment, mercury, and methylmercury are presented in a similar way to the TMDL Report (Cooke et al., 2004), so that comparisons can be made. Table 2 in this report shows mercury and sediment budgets copied from the TMDL Report (Cooke et al., 2004), and can be compared directly to Table 42 and Table 43 of this report from the WARMF model. Our modeling results indicate that there is a very large range of values between a dry year such as 2001 and a wet year such as 1998. During wet years there can be up to twenty times more sediment and mercury loads than during a dry year. Additionally, sediment and mercury loads in the model are not necessarily proportional to runoff. For instance, 1999 was an average year for runoff, but it was very low in terms of sediment and mercury loads. This may be because there is less loose soil to erode following a large storm or a wet year, and 1998 was a very wet year. Further research is needed to explain this result, and verify if this also occurs in the field.

Water Budget

The USGS stream gauge at Yolo has flow data dating back to 1903, allowing for a good estimation of the average runoff as well as the range of runoff for Cache Creek. From water years 1904 to 2010 the measured average runoff was 384,000 acre-feet/yr. During the nine year period for which our model was run, the measured average runoff was 504,000 acre-feet/yr, and the modeled runoff was 497,000 acre-feet/yr (Table 39, Table 40). This increase in runoff was observed despite the increase in irrigation diversions that resulted both after the Clear Lake Dam was built in 1914, and the Indian Valley Reservoir Dam was built in 1975. For the 107-year record, the measured runoff ranges from 0 acre-feet in 1977 to 1,773,267 acre-feet in 1983. Agricultural diversions at the Capay Dam averaged 208,000 acre-feet/yr over the nine year period. In dry years, such as 2001, the Capay Dam can divert a large proportion of total runoff. In dry years, winter or spring releases from Clear Lake and Indian Valley Reservoir are not required, and all the water that is released from the reservoirs during irrigation season is diverted at Capay Dam and does not reach Yolo. It can be seen from Table 40 that the modeled runoff ranges from 88.1 - 129.5 percent of measured runoff with an average difference of only 1.4 percent across the nine year period, indicating a good hydrologic calibration outcome.

Table 39: Modeled water flow (acre-feet/yr) in the Cache Creek Basin for water years 1996-2004

Water Year [a]	South Fork Cache Creek [b]	North Fork Cache Creek [c]	Harley Gulch [d]	Sulphur Creek [e]	Bear Creek above Sulphur Creek	Bear Creek [d]	Davis Creek [d]	Cache Creek below Rumsey [f]	Ag Diver-sions [g]	Cache Creek at Yolo
1996	482,000	240,000	1,920	3,980	32,200	43,900	8,160	806,200	-186,100	687,900
1997	485,800	272,300	1,530	3,190	26,600	35,500	6,420	823,200	-227,200	662,300
1998	832,000	302,500	4,640	9,330	64,100	96,400	19,770	1,321,300	-179,900	1,229,900
1999	360,700	191,200	1,130	2,550	21,300	27,300	5,020	597,800	-217,300	417,400
2000	232,600	144,600	1,210	2,620	22,800	29,300	5,040	428,500	-223,900	265,900
2001	59,300	143,400	810	1,920	17,700	21,400	3,290	237,700	-203,000	94,300
2002	158,900	171,600	830	1,920	18,000	21,700	3,160	365,800	-214,400	201,800
2003	349,400	126,300	1,900	3,940	33,100	44,600	8,540	555,900	-185,600	424,900
2004	392,700	178,600	2,390	4,790	37,100	52,200	10,130	665,800	-234,500	488,600
Avg	372,600	196,700	1,820	3,800	30,300	41,400	7,730	644,700	-208,000	497,000

(a) Water years are from October 1st to September 30th.
(b) At the confluence with the North Fork.
(c) At the confluence with the South Fork.
(d) At the confluence with Cache Creek.
(e) At the confluence with Bear Creek.
(f) Seven kilometers below Rumsey at the confluence with Johnson Creek.
(g) At Capay Dam, diversions are to Adams Canal and Winters Canal.

Table 40: Measured vs. modeled runoff for the Cache Creek at Yolo

Water Year	Measured	Modeled	Difference
1996	646,300	687,900	106.4%
1997	677,100	662,300	97.8%
1998	1,395,500	1,229,900	88.1%
1999	463,300	417,400	90.1%
2000	217,600	265,900	122.2%
2001	72,800	94,300	129.5%
2002	186,500	201,800	108.2%
2003	410,700	424,900	103.5%
2004	465,900	488,600	104.9%
avg	504,000	497,000	98.6%

Sediment Budget

Although our water budget matches with the measured values as well as the water budget in Cooke et al. (2004), the modeled budgets for sediment, mercury, and methylmercury vary significantly from the equivalent budgets reported in Cooke et al. (2004). Table 41 and Table 42 show the suspended sediment and total sediment budgets at different locations in the Cache Creek Basin. These tables can be compared to Table 2 in this report, which is the sediment budget from Cooke et al. (2004). The model divides sediment into clay, silt, and sand, although it considers only clay and silt to be a part of the suspended sediment, and all three to be a part of the total sediment. It is difficult to accurately compare modeled sediment values with the measured samples of suspended sediment because sand is considered bed load in the model, but in creeks in the real world, some sand is suspended and also travels as suspended load, especially if the flow is turbulent. During high flows, it is possible that large portions of sand will be suspended in water, although sand concentrations in suspended sediment will always be higher near the bottom. Therefore, measured suspended sediment concentrations are highly dependent on where in the water column the sample was taken. In addition, the model does not convert sand to silt, re-creating the process by which particles traveling down a stream are broken up and made smaller during transport. Suspended sediment measurements in the field are therefore somewhere in between what WARMF labels suspended sediment and what it labels sediment.

When comparing the sediment loads in the TMDL with our model, we see that our model compares better if sand is included (Table 42). Our model compares well to the TMDL Report (Cooke et al., 2004) for total sediment at Rumsey and Yolo with average loads of 436 and 768 kilo-tonnes per year (kt/yr), respectively, while the TMDL Report has average loads of 396 and 786 kt/yr (Table 2). However, these numbers should be compared with care because of the unknown quantity of sand that is suspended load.

In our model, there is much more sediment coming from each of the tributaries compared to the TMDL Report (Cooke et al., 2004), which may help to explain the large unknown sources of sediment that the TMDL Report identifies. For instance, the annual sediment load from Harley Gulch is 3.4 kt/yr in our model, compared to 0.02 kt/yr in the TMDL Report. The 0.02 kt/yr is measured below the confluence of the two Forks of Harley Gulch, but this does not account for the large discrepancy. For Bear Creek, our model predicts that the average total sediment load to Cache Creek is 82 kt/yr, whereas the TMDL Report estimates 6 kt/yr. The model may be over-predicting sediment concentrations within Bear Creek during high flows compared to measurements in Foe and Croyle (1998), although not by a factor of nearly 14. Bear Creek most likely contains a depositional stretch in the large grassland in the upper Bear Creek watershed that accounts for the low measured sediment concentrations. There are very few samples taken during high flows to better calibrate sediment concentrations in Bear Creek.

Table 41: Modeled suspended sediment flux (kg/yr x 10^6) in the Cache Creek Basin for water years 1996-2004.

Water Year	South Fork Cache Creek	North Fork Cache Creek	Harley Gulch	Sulphur Creek	Bear Creek above Sulphur Creek	Bear Creek	Davis Creek	Cache Creek below Rumsey	Ag Diversions	Cache Creek at Yolo
1996	44	124	2.4	1.9	33	58	23.9	478	--	857
1997	25	71	1.7	1.1	13	16	2.7	212	--	393
1998	59	148	6.7	6.4	53	139	37.3	727	--	1,379
1999	16	15	0.1	0.1	4	4	0.5	41	--	65
2000	10	13	0.7	0.6	8	8	0.9	71	--	310
2001	2	5	0.2	0.1	1	2	0.2	24	--	117
2002	9	45	0.5	0.8	17	14	4.3	90	--	249
2003	19	142	1.4	1.8	35	38	13.4	240	--	461
2004	19	41	0.1	0.7	14	17	2.0	125	--	351
Avg	**23**	**67**	**1.5**	**1.5**	**20**	**33**	**9.5**	**223**	**-8.9**	**465**

Table 42: Modeled total sediment flux including bedload (kg/yr x 106) in the Cache Creek Basin for water years 1996-2004

Water Year	South Fork Cache Creek	North Fork Cache Creek	Harley Gulch	Sulphur Creek	Bear Creek above Sulphur Creek	Bear Creek	Davis Creek	Cache Creek below Rumsey	Ag Diversions [a]	Cache Creek at Yolo
1996	68	282	5.4	7.7	89	151	33.3	960	--	1,374
1997	33	131	3.7	4.0	32	42	3.6	383	--	676
1998	84	326	14.4	19.7	132	317	60.1	1406	--	2,190
1999	16	32	0.2	0.4	11	12	0.7	73	--	113
2000	10	29	1.6	2.4	19	23	1.2	125	--	542
2001	2	9	0.4	0.2	3	4	0.3	39	--	217
2002	13	104	1.3	3.6	45	45	5.6	206	--	413
2003	24	283	3.3	7.0	83	102	16.3	502	--	773
2004	20	92	0.3	2.7	37	45	2.8	232	--	616
Avg	**30**	**143**	**3.4**	**5.3**	**50**	**82**	**13.8**	**436**	**-15.4**	**768**

(a) The model does not give daily or yearly values for diversions.

Mercury Budget

For the mercury budget, both the North Fork and the South Fork of Cache Creek contribute a comparable amount of mercury in the WARMF model and the TMDL Report (Cooke et al., 2004) (Table 43). The model was run with the assumption that the Abbott and Turkey Run Mines have been cleaned up, although the cleanup was not completed until 2007 (Larson, 2007). This was done so that the model could best represent the sources of mercury as they currently are, and the conditions of mines can be compared to the results of the remediation actions that this plan recommends. The removal of the Abbott and Turkey Run mines result in a reduction of an average of 6.15 kg/yr of total mercury to Harley Gulch, which then flows into Cache Creek. If the model was run with the mines still contributing mercury to Harley Gulch, there would be a similar amount of mercury in the model and the TMDL Report, with the exception of 1998 where our model predicts 24 kg of total mercury and the TMDL Report indicates 13 kg. It is possible that either the model is overestimating the erosion that occurs during the extremely heavy rains of 1998, or the regression that was used to calculate mercury loads in the TMDL Report may have underestimated erosion.

There is also a large difference between our model and the TMDL Report (Cooke et al., 2004) in annual average mercury loads in Bear Creek. Our model predicts the average mercury load from Bear Creek to be 35.1 kg/yr, with 12.9 kg/yr originating from upstream of Sulphur Creek, 19.0 kg/yr from Sulphur Creek, and only 3.2 kg/yr from below Sulphur Creek. This is different from the TMDL which calculated that the annual mercury load from Bear Creek is 15 kg/yr, of which only 10 percent originates from above Sulphur Creek, 50 percent from Sulphur Creek, and 40 percent from downstream of Sulphur Creek. This difference is due to the much larger amount of sediment in our model that originates in the Upper Bear Creek Watershed. As noted above, the model may be over-predicting sediment from the Upper Bear Creek Watershed, and therefore also over-predicting mercury loads.

Table 43: Modeled total mercury flux (kg) in the Cache Creek Basin for water years 1996-2004

Water Year	South Fork Cache Creek	North Fork Cache Creek	Harley Gulch	Sulphur Creek	Bear Creek above Sulphur Creek	Bear Creek	Davis Creek	Cache Creek below Rumsey	Ag Diver-sions	Cache Creek at Yolo
1996	16.3	53.9	4.7	24.6	21.9	56.1	55.7	422	--	406
1997	11.2	23.7	3.0	18.4	8.4	26.3	12.3	154	--	192
1998	23.4	62.7	11.7	50.6	33.6	111.7	86.8	568	--	584
1999	7.1	7.0	0.3	8.9	3.5	10.7	5.5	44	--	46
2000	4.5	6.1	1.7	11.1	5.6	15.1	6.0	51	--	99
2001	1.1	2.4	0.7	5.3	1.3	5.6	3.1	19	--	38
2002	4.0	20.1	1.4	12.2	11.0	21.1	12.6	94	--	92
2003	8.1	51.5	3.6	23.1	20.6	43.2	34.0	212	--	200
2004	8.0	17.7	0.7	17.1	9.8	25.8	11.5	89	--	132
Avg	**9.3**	**27.2**	**3.1**	**19.0**	**12.9**	**35.1**	**25.3**	**184**	**-10.1**	**199**

It is unknown how much mercury is being contributed to Bear Creek by the Rathburn and Petray Mines, although evidence exists for erosion from the mines into Bear Creek (Churchill and Clinkenbeard 2002; Slowey and Rytuba 2008). Naturally occurring saline groundwater may be a large source of mercury in this region, as well as a significant source of mercury for both Harley Gulch and Sulphur Creek (Slowey and Rytuba 2008, Personal Communication 2011). These springs are especially problematic because most of the mercury from these sources is dissolved and therefore more readily methylated.

In the TMDL Report (Cooke et al., 2004), 349 out of 400 kg/yr of total mercury at Rumsey are from unknown sources during the years 1996-2000 (Table 1). In our model, 248 kg/yr is the mercury flux at Rumsey from 1996 to 2000, which is only 62 percent of the assumed flux in the TMDL. A number of factors could be contributing to this incongruity:

- The mines are contributing more mercury than assumed
- Legacy mercury in creek sediments are a large source
- Background mercury concentrations are higher than assumed in our model
- Erosion rates are higher than assumed in our model
- Other sediment sources may exist, such as landslides
- The actual mercury load is less than 400 kg/yr

The mining areas may be contributing more than is assumed; however, Harley Gulch and Sulphur Creek are well-studied, and could not possibly account for the large discrepancy. The Knoxville Mining District and Davis Creek may be contributing to the large source of mercury in the canyon, but there are not enough samples during high flows to confirm loads from this tributary. This may be a large source especially during large storms when the residence time for water in Davis Creek

Reservoir is reduced. Legacy mercury in Cache Creek may be mobilized along with sediment during high flows, but as discussed later in this report, the results of Foe and Bosworth (2008) indicate that there is not enough mercury in depositional areas of the Cache Creek Canyon to be a large source of mercury. Background concentrations of mercury and erosion rates in the canyon may be higher, but modeled concentrations of mercury and sediment at Rumsey match reasonable well with samples taken by Foe and Croyle (1998). Other sediment sources such as landslides are an unknown but possibly significant source of sediment during extremely wet years California (Mount, 1995). This could be a large source of mercury if landslides contain mineralized soils with high mercury concentrations. The results of the model indicate that the large discrepancy in the amount of mercury originating from the canyon is most likely due to an over-prediction of mercury loads at Rumsey and Yolo in the TMDL Report (Cooke et al., 2004).

Without a model such as WARMF, it is difficult to predict the relationships between flow, sediment, and total mercury because there are a number of intricacies which make clear that linear regressions between sediment load and flow are not adequate for this system. The model can provide insight into these relationships in a complex watershed such as the Cache Creek Basin; the Basin contains two major reservoirs that may alter hydrology and water chemistry in unpredictable ways. In order to better understand this complexity, Figure 38 shows the relationship between total mercury concentration and flow from January 24, 1998 to March 20th, 1998. The relationship between sediment concentration and flow looks very similar to Figure 38, because the mercury concentration of sediment remains fairly constant. Therefore, it is satisfactory just to illustrate the relationship between mercury and flow, although the same principle applies for the relationship between sediment and flow.

The winter of 1998 was a period of very high flow, sedimention, and mercury runoff, and included a seven-day stretch beginning February 2nd in which thirteen inches of rain fell at Clear Lake. In Figure 38 it can be seen that there is a fairly linear relationship between total mercury concentration and flow until February 5th. After this point, there is a non-linear trend in which the mercury concentration is reduced. As the rain intensity lessened, mercury concentrations fell, although they did increase again with additional rainfall from February 11th to the 14th. Both Clear Lake and Indian Valley Reservoir began releasing water at extremely high rates around February 2nd, and Clear Lake continued heavy releases into April. Clear Lake reached its highest recorded level ever on February 24th, as widespread flooding occurred around the fringe of the lake. In our model, mercury concentrations continued to drop to only 100 ng/l by February 25th, which was just after the rain stopped. The ephemeral tributaries of Cache Creek stopped contributing flow and mercury around this time, and the flow became dominated by releases from Clear Lake, which contains low concentrations of sediment and mercury.

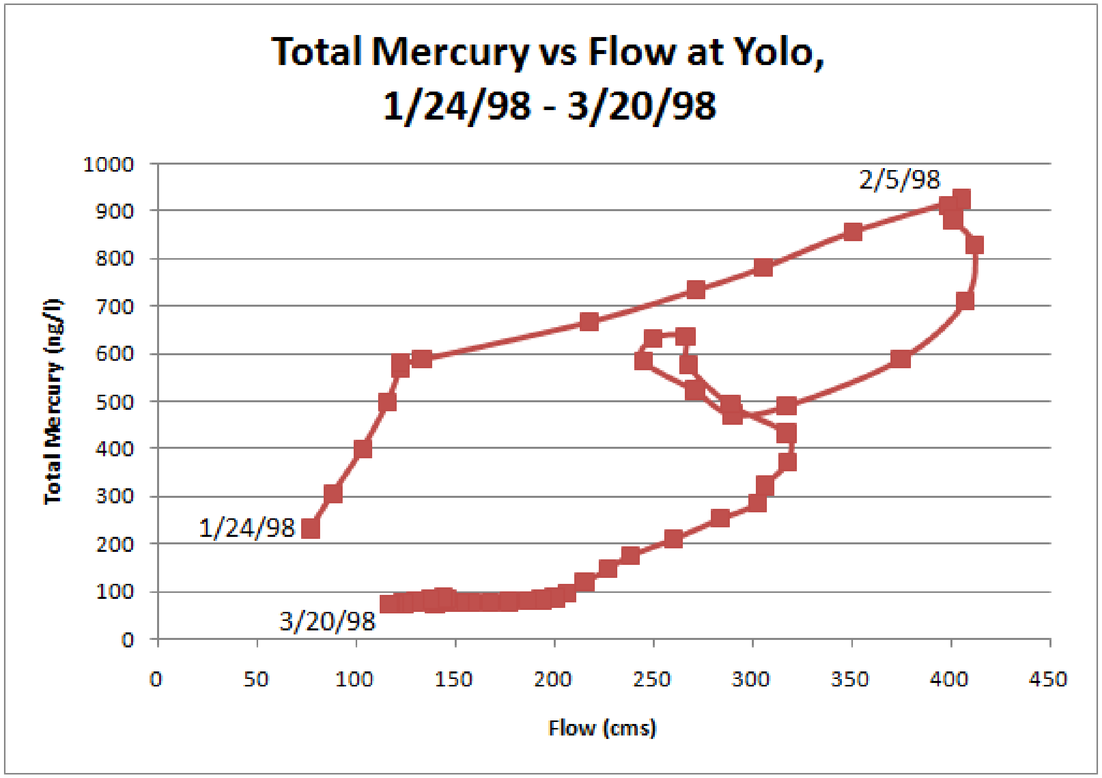


Figure 38: Modeled 5-day averaged total mercury vs. flow at Yolo, 1/24/98 – 3/20/98, a very wet time period

Prior Mercury Load Calculations for the Cache Creek Basin

There have been two prior attempts to evaluate mercury loads from the Cache Creek Basin. The first was Foe and Croyle (1998), and the second was Cooke et al. (2004), although both estimates use largely the same data set and report nearly identical results. Foe and Croyle (1998) originally took a number of mercury samples in 1994 and 1995 and, realizing that the

Cache Creek Basin was a large source of mercury to the Sacramento/ San Joaquin Delta, gathered additional information in 1996, 1997, and 1998. They were fortunate that these years were wet, because it gave them a relatively good number of mercury and sediment samples during high flows, which are critical because such a large proportion of erosion occurs during large storms. Large storms did not occur in 2000 and 2001, when other samples were taken, leading to many of the results of the CALFED Bay-Delta Mercury Program possibly underestimating mercury loads from different sources. Interestingly, Foe and Croyle (1998) discovered that the total mercury concentrations of multiple samples taken at the same time and location may vary by up to a factor of three. Difference in observed values may be due to turbulent flow causing uneven mixing of the water. This highlights the considerable uncertainty in all mercury measurements, and the care that must be taken in comparing measured values to modeled values.

Foe and Croyle (1998) used a polynomial regression line to determine mercury concentrations based on flows at Yolo (Figure 39). They were able to take measurements in three different years in which the flow was over 15,000 cfs, a level which is considered very high. As seen in Figure 39, there is a large range of mercury concentrations given a similar flow, presumably because of the complications highlighted by Figure 38 and the possibility that the stream is not well mixed.

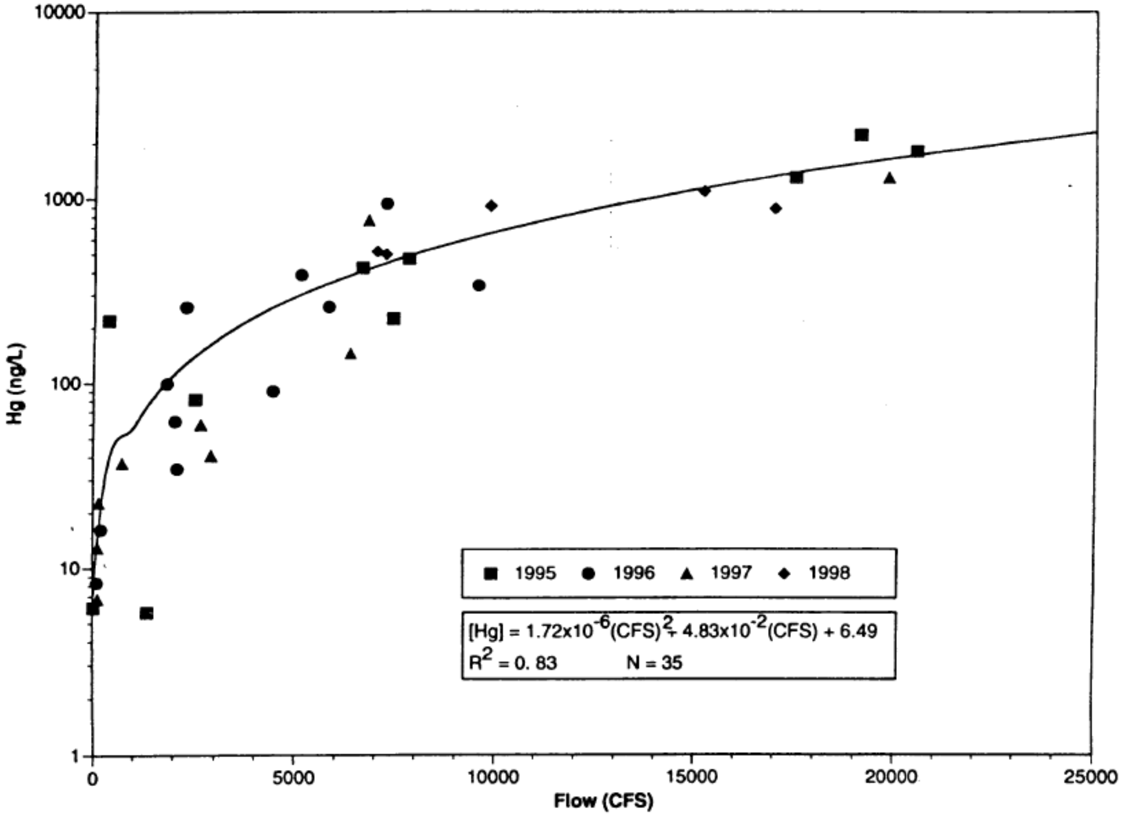


Figure 39: Mercury concentrations based on flows at Yolo (Foe and Croyle, 1998)

With the regression line calculated in Figure 39 and the stream flow data at Yolo, the mercury loads can be estimated for any year in which stream flow information is available. Figure 40 shows total mercury loads at Yolo from water year 1975 to 2010. From Figure 40, it can be seen how wet 1995 to 1998 is relative to the 36 year period. For the 36 year period, the average mercury load at Yolo is 199 kg/yr, with many of the years having relatively small mercury loads. In fact, in 1976, the highest flow was 2 cfs, and in 1977 no water at all flowed past Yolo resulting in a mercury load of zero for both years. Around half of the mercury flowing past Yolo will end up settling out in the Cache Creek Settling Basin, and the other half will flow to the Sacramento/ San Joaquin Delta (Foe and Croyle, 1998).

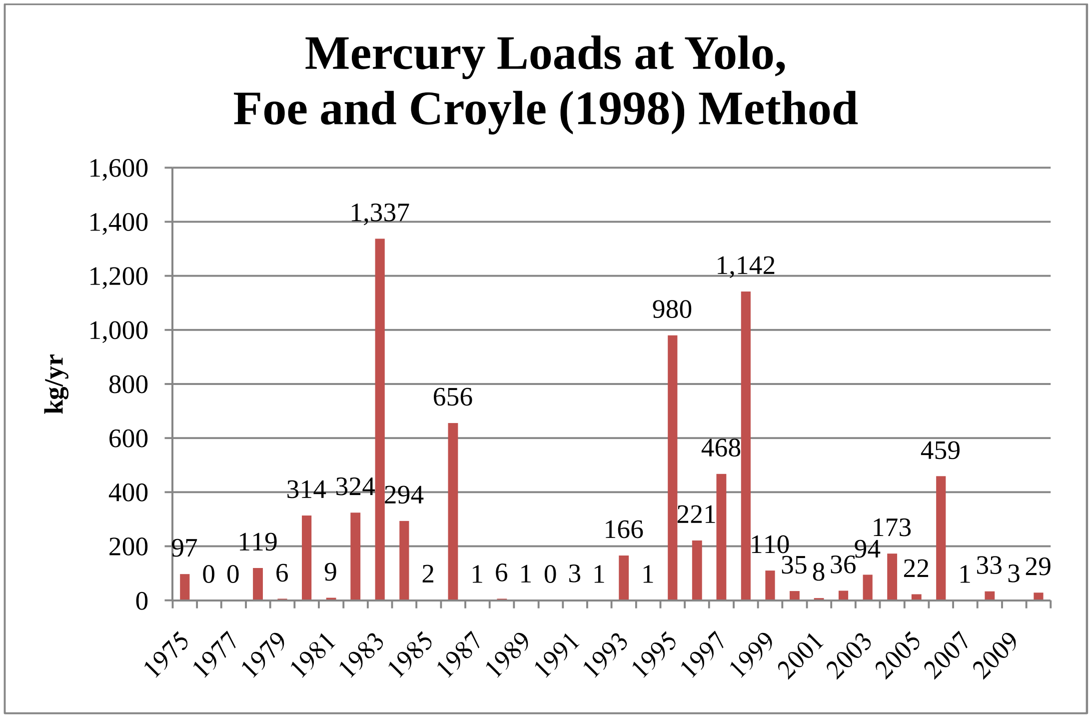
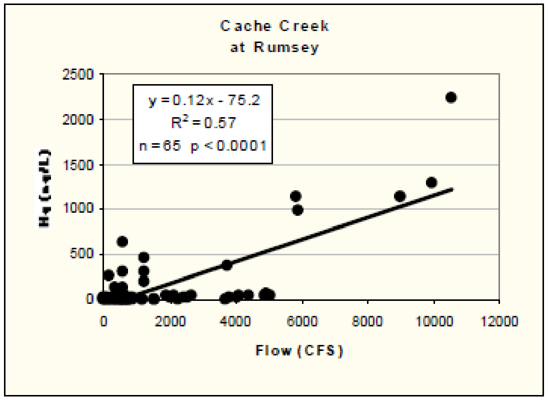


Figure 40: Annual mercury loads at Yolo, using the regression equation from Figure 39 (Foe and Croyle, 1998)

The USGS began monitoring the outflow from the Cache Creek Settling Basin in January of 2008. Over time, a more accurate relationship between inflow and outflow will be established, as well as the suspended sediment concentrations of the inflow and outflow. This will allow for a better estimate of mercury loads that enter the Yolo Bypass from Cache Creek. During the current water year— from October 1, 2010 to March 19, 2011— 111,800 acre-feet of water had entered the 3,600 acre-foot basin, while only 86,800 had exited the basin, which amounts to a 22% loss, or an average of 245 acre-feet/day of loss. The water that has entered the setting basin that has not left is either still in the basin, has been lost to evapotranspiration, or has infiltrated into the ground. Additional research should be performed to determine this rate, as it may hold implications as to the amount of sediment and mercury that is sequestered within the settling basin. Foe and Croyle (1998) used the assumption that the flow entering the basin was equal to the flow leaving the basin, but these results indicate that this is not the case. This may have caused them to overestimate sediment and mercury contributions from Cache Creek to the Delta during low flow and average flow years, when a larger percentage of water, sediment, and mercury do not leave the settling basin. There are plans to raise the outflow weir of the from 35 feet to 41 feet, which would greatly expand the capacity of the settling basin and increase the settling efficiency.

High flows can transport a significant amount of mercury during just one day; obtaining water quality samples from these high flows is crucial to understanding mercury transport in the Cache Creek Basin. Using the Foe and Croyle (1998) method in Figure 39, on January 9th, 1995, 182 kg of mercury flowed past Yolo. In the three week period beginning February 3rd, 1998, 833 kg passed Yolo. However, as shown in Figure 38, their regression method may be significantly over-predicting mercury concentrations when flows in Cache Creek are dominated by releases from Clear Lake and Indian Valley Reservoir. There were no water samples taken from late February to late March, the period after it stopped raining when sediment concentrations may have been much lower than the regression method would estimate.

The second report that calculated mercury loads within the Basin was the 2004 TMDL Report for Cache Creek, Bear Creek, and Harley Gulch (Cooke et al., 2004). This report used the samples from Foe and Croyle (1998), as well as other samples from Slotton (2004) and Domalgalski et al. (2004). Figure 41 shows the linear regressions for mercury concentration versus flow at Rumsey and Yolo. In addition, mercury loads were calculated at a number of other locations using similar regressions and estimations were made based on measured and estimated stream flow. The report admits that there is often not a linear relationship between total mercury concentration and flow, especially for smaller tributaries. The simplicity of the linear regression may also be a reason for the large discrepancy in sediment loads between the model and the TMDL Report (Cooke et al., 2004) for Harley Gulch.



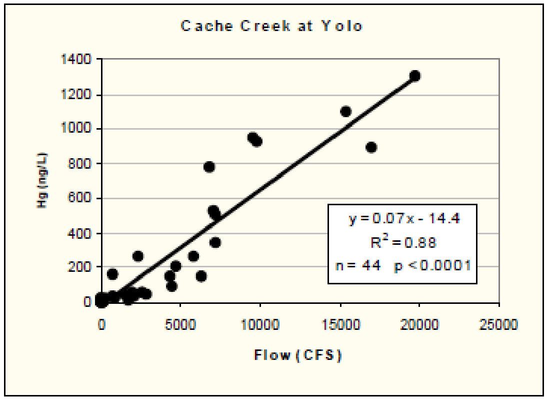


Figure 41: Linear regressions of mercury vs. flow at Rumsey and Yolo (Cooke, et al., 2004)

Another way to determine the mercury concentration of sediment leaving the Basin is to take sediment samples from within the settling basin itself. Surprisingly, there have only been a small number of samples taken from the basin that we are aware of, four by Foe and Bosworth (2008) which averaged 0.295 mg/kg, and, and four by Marvin-DiPasquale et al., (2009) which averaged 0.263 mg/kg. These values are well below the TMDL Report (Cooke et al. 2004) estimation that the sediment entering the setting basin has an average concentration of 0.50 mg/kg. The measured concentration also agrees well with our model's mercury/sediment ratio of 0.27 mg/kg at Yolo. Additional sediment samples should be taken throughout the settling basin to determine a more accurate mercury concentration of the trapped sediment. The mercury concentration of the sediments also have implications on any future plans the Army Corp may have to dredge the settling basin, because the sediments may not be considered to be as toxic as once thought if the mercury concentration is found to be in the 0.26 – 0.30 mg/kg range. In addition to further sediment sampling, more mercury samples should be taken of the water discharged from the settling basin to better understand the mercury loads that Cache Creek is contributing to the Delta.

Methylmercury Budget

There are four sources of methylmercury in our model: point sources from Clear Lake and Indian Valley Reservoir, point sources from the thermal springs, soil pore water, and in-stream methylation. Methylmercury concentrations from Clear Lake and Indian Valley Reservoir were estimated from samples in Slotton et al. (2004) and Domagalski et al. (2004). Methylmercury concentrations of thermal springs were assumed to be 0.1 percent of total mercury output, as this is the average for the few samples which have been taken (Suchanek et al. 2002). Methylmercury concentrations in soil pore water were assigned a concentration of 0.1 – 1.0 ng/l, depending on the mercury concentration in that subcatchment. These values are estimates based on calibrating the sampled methylmercury concentrations with the modeled methylmercury concentrations during the wet season when in-stream methylation is minimized. The modeled results for methylmercury in the Basin are shown in Table 44.

Table 44: Modeled methylmercury flux (g) in the Cache Creek Basin for water years 1996-2004Table 44: Modeled methylmercury flux (g) in the Cache Creek Basin for water years 1996-2004

Water Year	South Fork Cache Creek	North Fork Cache Creek	Harley Gulch	Sulphur Creek	Bear Creek above Sulphur Creek	Bear Creek	Davis Creek	Cache Creek below Rumsey	Ag Diver-sions	Cache Creek at Yolo
1996	66.9	56.9	3.3	7.1	13.5	30.8	23.3	269.7	--	316.5
1997	68.6	44.4	2.3	4.7	7.0	14.2	6.0	167.8	--	176.3
1998	126.4	79.4	7.5	16.7	22.3	67.1	36.5	437.0	--	507.7
1999	46.7	20.9	0.9	2.5	4.1	7.6	3.7	88.5	--	68.8
2000	29.1	17.4	1.5	3.3	5.2	9.8	3.8	73.8	--	87.0
2001	7.3	13.3	0.8	1.8	2.8	5.1	2.3	34.7	--	33.9
2002	20.3	26.2	1.2	3.3	6.8	10.6	5.7	78.7	--	83.9
2003	45.8	59.8	2.6	6.3	12.8	23.4	16.6	182.3	--	193.0
2004	53.4	32.2	1.7	5.1	8.6	17.2	7.4	131.5	--	136.5
Avg	51.6	38.9	2.4	5.7	9.2	20.7	11.7	162.7	27.0	178.1

The sources of methylmercury, and the processes that affect methylation and demethylation, are not completely understood (Rytuba, 2000; Slowey and Rytuba, 2008). WARMF simulates this process using the current state of knowledge, although it may not accurately reflect the biogeochemical complexity that exists within a given stream reach (Chen et al., 2003). Conditions that promote methylation are fairly well known, and primarily occur in the dry season within the top few centimeters of sediment in streams and wetlands. Anoxic sediments in streams and wetlands promote methylation, while oxic sediments promote demethylation. In order for the sediment to become anoxic, the water must be stagnant or moving very slowly.

WARMF models a stream reach as being composed of a water column and a sediment column, each with its own chemical concentrations and reaction rates. During the dry season, the water slows down, becomes less well-mixed, and decomposition of organic matter within the water column and the sediment column causes dissolved oxygen levels within the sediment to drop below a specified threshold. Attainment of this threshold in WARMF will trigger the methylation reaction to begin converting dissolved mercury into methylmercury at a certain rate. The methylation rate is dependent on a number of factors including the concentration of dissolved mercury within the stream sediments, the sulfate reduction rate, and the thickness of the sediment column. As the stream sediments then increase in methylmercury concentration, the bed diffusion rate will diffuse the methylmercury into the water column and increase the methylmercury concentration in the water. When it rains and the stream becomes well-mixed, the dissolved oxygen concentration in the sediment will increase, and the methylation reaction in the model will turn off. Once in the water, the methylmercury will be demethylated back to dissolved mercury at a certain rate.

More research must be done to understand how to better calibrate the methylation and demethylation process in WARMF. WARMF appears to be underestimating in-stream methylation during the dry season, creating lower than measured methylmercury concentrations in Harley Gulch, Sulphur Creek, Bear Creek, and Cache Creek. It is possible that WARMF does not account for the complexity of real streams, and underestimates the extent of conditions that promote methylation.

Evaluation of Remediation Actions in the Cache Creek Basin

The WARMF model was run with all mine point sources removed to simulate the benefits of mine remediation. As seen in Table 45, mine cleanup reduces mercury loads from Sulphur Creek and Bear Creek much more than Cache Creek. However, these numbers do not include the reductions that would occur if legacy mercury in stream sediments in those tributaries were also not contributing to mercury loading. The benefits of remediation and restoration actions in the Upper Davis Creek watershed are unknown, because it is unknown how much mercury exits the Davis Creek Reservoir, and how much of this mercury originates from the Knoxville mines. It should also be noted that the model was calibrated for the time period of 1996 to 2004, which had more precipitation than the long-term average from 1904 to 2010. The total mercury loads in Table 45 are higher than the long-term average, and the mercury loads from the mines are also higher than long-term averages, although the percent reduction would be similar.

Table 45: Total mercury loads before and after mine cleanup

Location	With Mines	Without Mines	Percent Reduction
Sulphur Creek	19.0	5.8	69.5%
Bear Creek	35.1	21.9	37.6%
Cache Creek at Rumsey	184	162.3	11.8%
Cache Creek at Yolo	199	177.3	10.9%

The TMDL goal for Cache Creek is to keep average methylmercury concentrations below 0.14 ng/l a majority of the time. The largest source of methylmercury to Cache Creek is Clear Lake; this source dominates during irrigation season, when Clear Lake contributes approximately two thirds of the total flow of Cache Creek. High rates of methylation are suspected to occur in Anderson Marsh, adjacent to the outlet of the lake; this source must be addressed if methylmercury loads in Cache Creek are to be reduced (Cooke and Morris, 2005). Currently, methylmercury concentrations are approximately 0.05 – 0.4 ng/l at Rumsey and 0.09 – 0.58 ng/l at Yolo (Slotton et al., 2004; Domalgalski et al., 2004). Mine remediation should lower the concentration of mercury in the sediments of Cache Creek, and also reduce methylation. This reduction of mercury concentrations may take many years, and will require high flow events to flush out the mercury enriched sediments after the sources from the mines have been reduced. As seen in Figure 42, mine remediation alone is not expected to meet the TMDL goals, and it will be necessary to address the loads originating from Clear Lake.

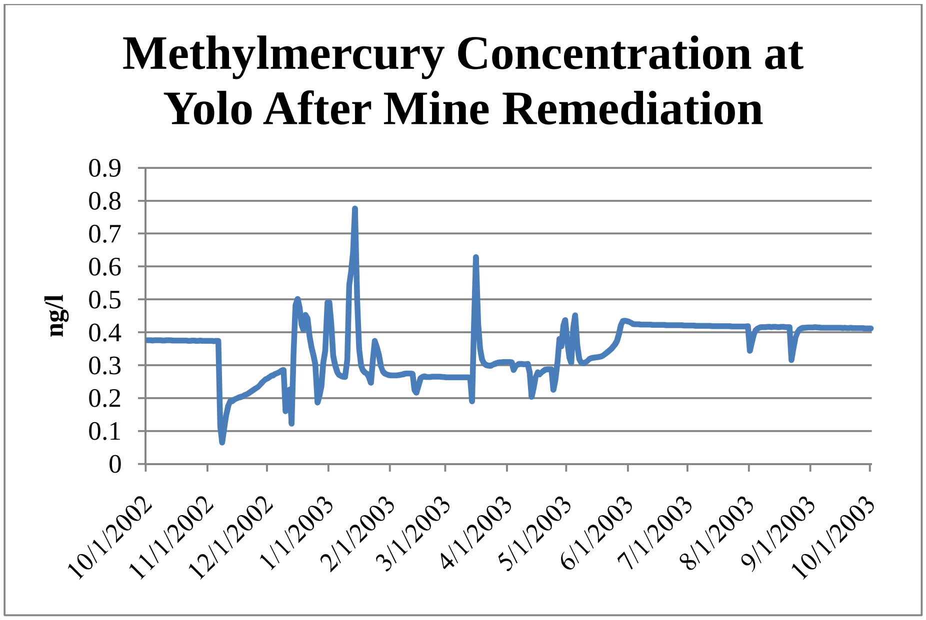


Figure 42: Methylmercury concentration at Yolo after mine cleanup, using precipitation data from 2003. Other methylmercury sources, such as Clear Lake, have not been reduced.

Evaluation of Remediation Actions in the Harley Gulch Watershed

The TMDL Report (Cooke et al., 2004) established that methylmercury in Harley Gulch should be below 0.09 ng/l a majority of the time to be protective of the beneficial uses of the stream, including habitat for trophic level 2 and 3 fish, as well as to protect the wildlife that consume fish and invertebrates within Harley Gulch. The Abbott and Turkey Run Mines are upstream of Harley Gulch, and the majority of this mining area was cleaned up in 2007 (Larson, 2007); very little erosion is expected to originate from the former tailings pile at the Abbott Mine. It is expected that by cutting off this sediment source, mercury will slowly make its way out of the sediments between the mining area and Cache Creek. Unfortunately, there is a sizeable wetland that exists on the West Fork of Harley Gulch, in addition to a number of wetland areas within Harley Gulch, which contain sediments that have elevated mercury concentrations. This increased mercury concentration and the stagnant conditions of Harley Gulch during the dry season promote high rates of methylation. The wetland on the West Fork is well-vegetated and shows no evidence that it will erode in the future; it will continue to be a source of methylmercury until restoration actions are taken. Previously in this report, the Harley Gulch Wetlands case study analyzed technologies applicable for the potential cleanup of the wetland area. Sediment concentrations may eventually lower to background levels as future high flows move the legacy mercury out of Harley Gulch, although this process may take many years. Sediment samples taken by our study and the BLM over the summer of 2010 indicated that current sediment concentrations in Harley Gulch average 4.0 mg/kg of total mercury, which is assumed to be much higher than the natural background concentration.

In personal communication between James Weigand of the BLM and James Rytuba of the USGS, Mr. Rytuba indicated that methylmercury concentrations in upper Harley Gulch are naturally elevated in the dry season from the addition of saline connate groundwater that emerges in Harley Gulch below the confluence of the East and West Branches. Cold carbonate springs with high levels of mercury and other minerals are also observed in the Bear Creek Valley above the confluence with Sulphur Creek, leading to naturally high methylmercury concentrations (Slowey and Rytuba, 2008). The water from this natural source may be the primary reason why Harley Gulch has such high concentrations of methylmercury, which range from 0.06 - 1.2 ng/l during the wet season and 0.64 - 18 ng/l during the dry season (Domagalski et al., 2004; Slotton et al., 2004; Janis Cooke, personal communication). There has not been a comprehensive sampling program in effect since the mine cleanup; therefore, current concentrations during different times of the year are yet unknown.

Although it is assumed that the reduction of mercury concentrations within Harley Gulch will have a beneficial impact on methylmercury concentrations, it is possible that the TMDL will not be met here because of naturally high background levels of mercury. The WARMF model predicts that methylmercury production in the stream sediments will be directly proportional to mercury concentrations in those sediments. This implies that methylmercury concentrations in water may also be proportional to mercury concentration in stream sediments, although some methylmercury is demethylated once it enters the water column. If these relationships hold, then they could be used to estimate the expected methylmercury concentration in streams using only the mercury concentrations in the sediments.

Slotton et al. (2004) took a number of water quality samples in Bear Creek far above the confluence of Sulphur Creek and also above the region where Bear Creek is receiving sediment from the Rathburn-Petray Mine. The data from these eleven samples is shown in Table 46Table 46: Water quality samples taken in Upper Bear Creek, an area with low background mercury concentrations (Slotton et al., 2004). Methylmercury concentrations are higher during the summer and fall than in the winter. This is to be expected, because the summer and fall are low flow periods in which the stream sediments become anoxic, and methylmercury is produced. In the six samples taken from May to October, the average concentration of methylmercury was 0.16 ng/l, and in the five samples taken from November to March the average concentration was 0.08 ng/l.

If the relationship between mercury concentration in sediments and methylmercury concentration in water holds, then the natural methylmercury concentration can be estimated if the mercury concentration of the stream sediments is known. Water samples indicate that the background mercury concentration in the East Fork of Harley Gulch watershed range from 0.25 – 0.60 ppm (Foe and Croyle, 1998; Cooke, personal communication). The West Fork of Harley Gulch watershed, which contains the mines, most likely has a higher background mercury concentration. If mercury concentrations in the sediments of Upper Bear Creek are assumed to be 0.16 mg/kg, and mercury concentrations in sediment in Harley Gulch are currently 4.0 mg/kg, then Harley Gulch would have a dry season methylmercury concentration of approximately 4.0 ng/l, and a wet season concentration of approximately 2.0 ng/l. As the mercury concentration of these sediments decreases over time, the methylmercury concentrations will decrease proportionally. If this relationship does hold, then it is most likely that the TMDL will be exceeded by several factors.

Table 46: Water quality samples taken in Upper Bear Creek, an area with low background mercury concentrations (Slotton et al., 2004)

Date	Time	Temp, C	Flow, cfs	Total Hg Raw	Total Hg Filtered	TotHg / TSS (PPM)	MeHg Raw	MeHg Filt	TSS, mg/l
6/14/2000	1110	22.8	2.5	0.6	1.2		0.21	0.085	3.44
10/11/2000	1320	14.5	2.5	0.6	0.4	0.21	0.09	0.024	1.07
11/7/2000	1210	13	2	0.8	0.7		0.05	0.051	
12/11/2000	1300	8.5	2.5	0.7	0.5	0.18	0.07	0.028	1.2
1/11/2001	1320	6	10	3.8	0.9	0.14	0.18	0.063	20.99
2/13/2001	1445	8	4	1.7	1	0.15	0.05	0.034	4.04
3/22/2001	1245	21.6		1.4	0.8	0.28	0.07	0.034	2.18
5/3/2001	1310	18	3	1	0.6	0.26	0.06	0.036	1.56
6/7/2001	1345	27	3.5	1.3	1	0.15	0.23	0.084	2.06
7/12/2001	1200	24	3	1	1	0.02	0.3	0.17	1.57
8/23/2001	1130	22	3	0.8	0.7	0.04	0.09	0.094	1.41

Evaluation of Remediation Actions in the Sulphur Creek Watershed

The TMDL goals for Sulphur Creek are to have total mercury concentrations during low flow conditions (below three cubic feet per second) less than 1,800 ng/l, and to have high flow total mercury to suspended sediment ratios less than 35 mg/kg (Cooke and Stanish, 2007). These targets are 25 percent of the highest values ever sampled, and represent a reduction in mercury loads in Sulphur Creek of 75 percent. As seen in Table 45, our WARMF model has a similar level of reduction in mercury if all of the mines are fully remediated. Erosion from mines and the input from thermal springs cause Sulphur Creek to exceed these targets; after the mines are remediated, it is expected that the TMDL goals will be met. Both the low and high flow TMDL targets for Sulphur Creek are relatively high, compared to the TMDL goals for Harley Gulch, Bear Creek, and Cache Creek (Cooke and Morris, 2005). Sulphur Creek is already meeting its TMDL targets in nearly all samples (Foe and Croyle, 1998; Slotton et al. 2004; Domagalski et al. 2004; Suchanek et al., 2002).

In order to model a reduction of mining contributions, the model was run with all mine point sources removed, and stream sediments at reduced mercury concentrations (Figure 43). Winter storms cause the mercury/sediment ratio to decrease as meteoric water becomes more influential than the thermal spring water. As the dry season begins and water flow decreases, the thermal spring water inputs and in-stream methylation raise the methylmercury concentration in the creek to around 18 ppm. This analysis shows that if the mines can be completely removed as sources, it is possible to meet the TMDL goal of staying below 35 mg/kg during high flows.

For the low flow goals to be met, it may be necessary to prevent the water from the Jones Fountain of Life from reaching Sulphur Creek. This geysering thermal spring was measured to have a mercury concentration of 24,262 – 39,700 ng/l, and significantly raises the mercury concentrations of Sulphur Creek (Suchanek et al., 2002). Wilbur Springs, the largest thermal spring in the watershed, also has elevated mercury levels, and has been measured at 3,460 – 7,250 ng/l. Preventing this water from reaching Sulphur Creek should also be considered.

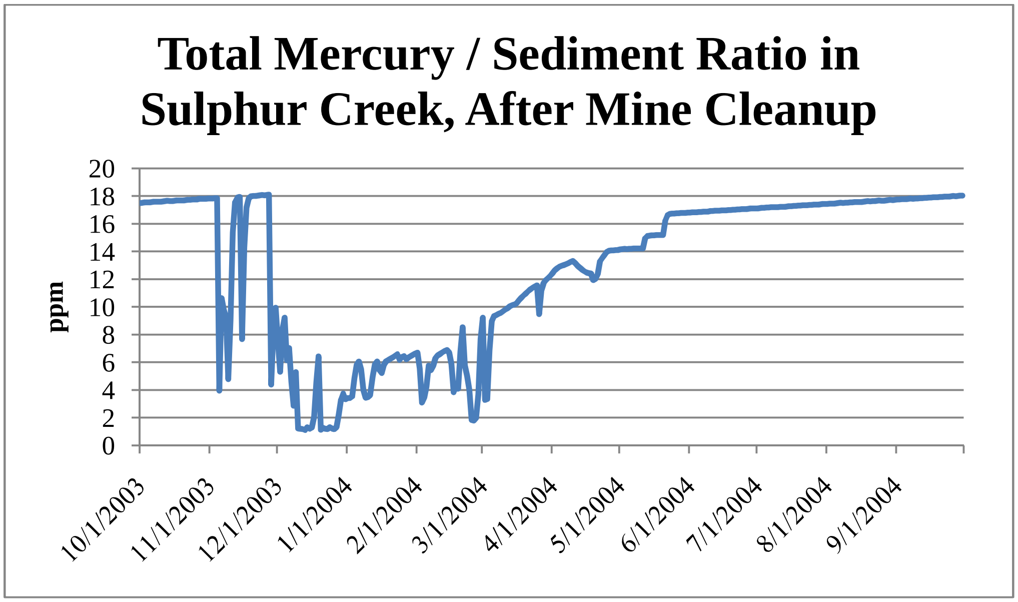


Figure 43: Modeled Sulphur Creek total mercury to sediment ratios after mine cleanup, using the precipitation data from the 2004 water year.

Evaluation of Remediation Actions in the Bear Creek Watershed

According to the model, Sulphur Creek supplies over half of the total mercury to Bear Creek. Mercury concentrations in Bear Creek sediments also rise dramatically after the confluence with Sulphur Creek. Sulphur Creek provides 41 percent of the methylmercury load to Bear Creek (Cooke and Stanish 2007). It is therefore necessary to reduce the mercury output from Sulphur Creek in order to meet the Bear Creek TMDL. The TMDL goal of Bear Creek is to maintain average methylmercury concentrations below 0.06 ng/l (Cooke and Morris, 2005). As shown in Table 46, background methylmercury concentrations in Upper Bear Creek are 0.08 ng/l during the wet season and 0.16 ng/l during the dry season. It is therefore unlikely that the TMDL will be met. As seen in Figure 44, methylmercury concentrations are naturally high in Bear Creek because of the high natural mercury loads coming from Sulphur Creek and the cold carbonate springs just above the confluence with Sulphur Creek

(Slowey and Rytuba, 2008). These sources of mercury create naturally elevated concentrations of methylmercury in Bear Creek, and the TMDL goals are not met, even in the wet season (Figure 44). Mine remediation and other restoration efforts in the Sulphur Creek watershed should significantly reduce the total mercury loads from Bear Creek.

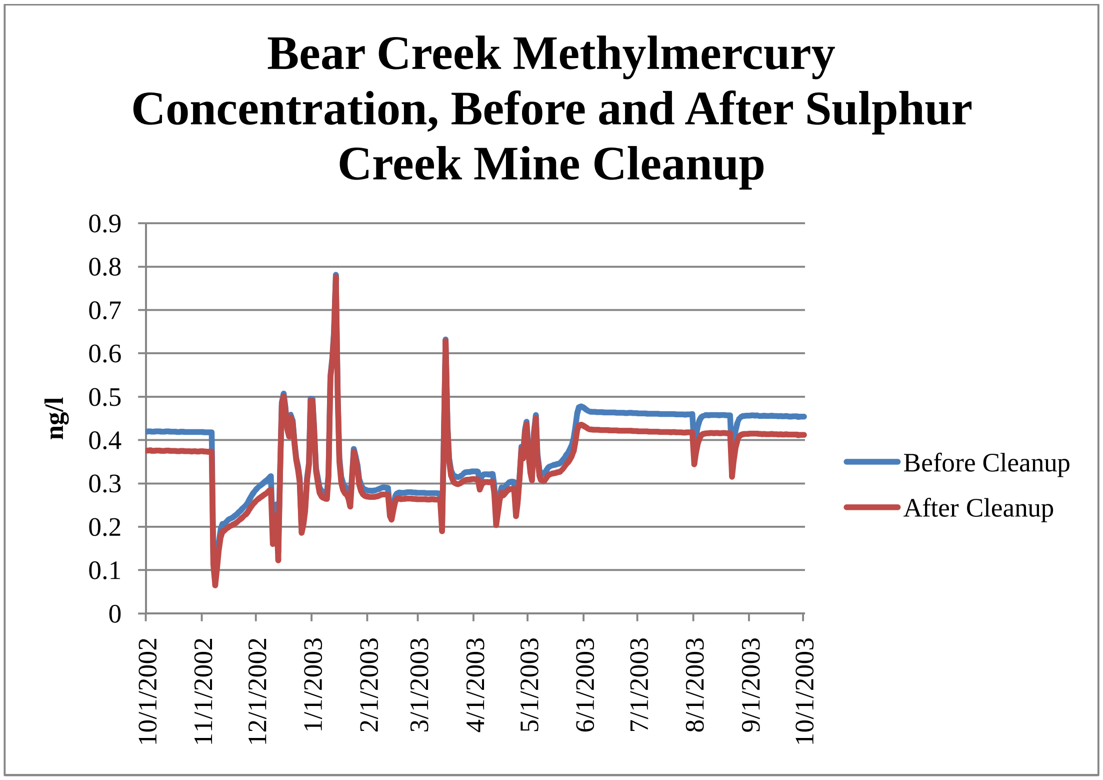


Figure 44: Modeled Bear Creek methylmercury concentration, before and after Sulphur Creek Mine Cleanups, using the precipitation data from the 2003 water-year

Discussion of Cache Creek Canyon

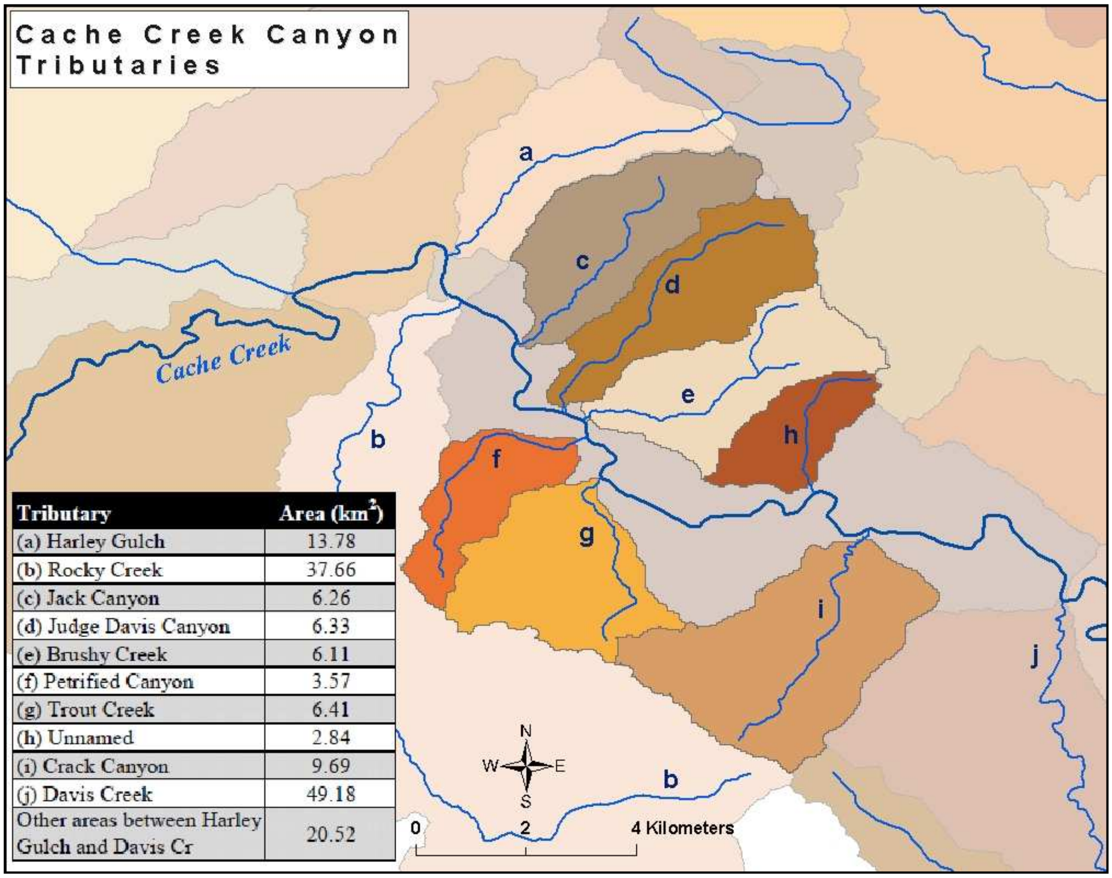
The Cache Creek Canyon from the confluence of Harley Gulch to the confluence of Bear Creek is a large source of both sediment and mercury to Cache Creek (Foe and Croyle, 1998; Cooke et al. 2004). Cooke et al. (2004) found that for the years from 1996 to 2000, the canyon was the source of 260,000 tonnes/yr of sediment and 349 kg/yr of mercury, making the canyon the largest source of sediment and mercury in the Cache Creek Basin by a large margin. The WARMF model finds that this number may be too high, but even so, 112 kg out of 209 kg of mercury from the entire Cache Creek Basin originates from within the canyon in the model. By understanding where exactly this source is located we may obtain a better understanding of how mercury loads from the Cache Creek Basin will be reduced in the future, after mine remediation.

There is only one road that accesses this 24 km stretch of creek, so taking water and sediment samples during high flows is extremely difficult. Most of the sediment and mercury transport happens during just a few large storms per year, and it is necessary to capture data from these precipitation events in order to accurately measure sediment and mercury runoff. It has been hypothesized by Cooke et al. (2004) that the unknown source of mercury is either from existing legacy mining sediment stored within the canyon, from tributaries in the canyon, or a combination of both.

In order to determine the extent of sediment and mercury deposits within the Canyon, a mercury inventory was performed for the 24 reach km from Harley Gulch to Bear Creek (Foe and Bosworth, 2008). This study collected many sediment samples along Cache Creek, as well samples of the sediment in each of the tributaries entering the canyon. Using aerial photographs to delineate depositional areas, the quantity of sediment and mercury was calculated within the canyon, as well as the average sediment mercury concentrations originating from each tributary. The report calculated that there are approximately 1,600,000 m^3 of sediment with 2,200 kg of mercury within this stretch of Cache Creek. This is far lower than the 9,000-500,000 kg previously estimated to reside within the canyon (Cooke and Morris, 2005).

Since the Cache Creek Canyon sediments only contain 2,200 kg of mercury it is unlikely that it can be the major unknown source of mercury from within the canyon. The depositional areas of the canyon are not very extensive because of the steep nature of the terrain, and there is not enough mercury in the canyon to contribute the high quantities of mercury that originate from the region during wet years Cooke et al. (2004) calculated that 809 kg of mercury was from unknown sources within the canyon in 1998 (Table 1). Foe and Bosworth (2008) assumed that depositional areas were four meters deep, and therefore, if this were a large source of mercury, considerable scouring of these depositional areas would be required. In a trip to Rocky Creek and Harley Gulch during the summer of 2010, the stream banks appeared to be stable, and there was no evidence of significant scouring. Additionally, aerial photographs in Google Earth show that many of the depositional areas contain large riparian trees that would have their roots undermined if significant scouring was occurring.

Foe and Bosworth (2008) found that mercury concentrations increase sharply after Harley Gulch, but also increase after Trout Creek and Davis Creek (Figure 45). For the tributary measurements, Harley Gulch had extremely high concentrations of mercury. Judge Davis Canyon, Crack Canyon, and Davis Creek also had elevated levels of mercury. Mercury concentrations in the sediment of Cache Creek are particularly high after Davis Creek, with some measurements as high as 11 mg/kg for both silt and gravel (Foe and Bosworth, 2008). This increase in mercury concentration is surprising because it was assumed that Davis Creek Reservoir has been trapping much of the sediment coming from the mining areas for the last 30 years. The silt particles may originate from the Knoxville Mining District because they can remain suspended as the water travels through the reservoir, but the gravel is either from local sources or is legacy mercury. Cooke et al. (2004) identified elevated mercury to total suspended solids ratios in Judge Davis Creek, Bushy Creek, Petrified Canyon, Trout Creek, and Crack Canyon. The only creek within Cache Creek Canyon that did not have elevated levels of mercury was Rocky Creek. Although there are only two samples taken from each creek, these findings may suggest that elevated mercury levels are widespread in the region.



Tributary	Area (km^2)
(a) Harley Gulch	13.78
(b) Rocky Creek	37.66
(c) Jack Canyon	6.26
(d) Judge Davis Canyon	6.33
(e) Brushy Creek	6.11
(f) Petrified Canyon	3.57
(g) Trout Creek	6.41
(h) Unnamed	2.84
(i) Crack Canyon	9.69
(j) Davis Creek	49.18
Other areas between Harley Gulch and Davis Cr	20.52

Figure 45: Cache Creek Canyon and tributaries. The gray regions within the canyon are smaller tributaries or areas that drain directly into Cache Creek.

A study released in 2009 quantified the amount of mercury within the sediments of Bear Creek from Sulphur Creek to Cache Creek (Bosworth and Morris 2009). Researchers determined that Bear Creek sediments contained 91 kg of mercury, which is also too low for legacy mining sediments within the channel to be a significant source of mercury. Both Foe and Bosworth (2008) and Bosworth and Morris (2009) admit that they may be missing mercury in smaller piles, but not enough to account for the unknown mercury sources. The evidence outlined here indicates that scour of legacy mercury is most likely not the major source of mercury from within the Cache Creek Canyon or Bear Creek Canyon.

In addition to the mercury that may originate from legacy sediment within the canyon, high erosion rates of soils naturally enriched in mercury, landsliding of soils naturally enriched in mercury, and contributions from the Knoxville Mining District may also be large sources. Further measurements of suspended sediment from Cache Creek and its tributaries are necessary to determine the source of this mercury. It is possible that landsliding within the Cache Creek Canyon or its tributaries are a major source, if the soils are enriched in mercury. As seen in aerial photographs in Google Earth, there is evidence of many areas where the canyon walls are actively eroding into the channel, which may contribute an unappreciated amount of sediment during high flow events (Mount, 1995). Holloway et al (2009) found that mineralized ultramafic soils in the Upper Davis Creek watershed contain 34 – 290 mg/kg of mercury. If these soils are more widespread in the Canyon this may contribute to the large unknown source of mercury.

Summary of Watershed Model

By creating a watershed model of the Cache Creek Basin, we were better able to analyze the sources of mercury within the Basin. It allowed for insights into how sediment and mercury concentration change during the rising and falling limb of a hydrograph that otherwise would not have been possible. It also allowed us to analyze how mine remediation will affect mercury concentrations, both immediately downstream of the mining lands, and in further reaches of Cache Creek. It is our hope that additional water quality samples will be incorporated into this model, or a similar model, to increase the accuracy of its predictions.

RECOMMENDATIONS

To decrease mercury loads in the Cache Creek Basin and to meet TMDL requirements, remediation and restoration actions must be taken, as well as additional measures to reduce erosion in the Basin and the transport of mercury. As stated in the Basin Plan, it is the liability of the BLM and other responsible parties to reduce mercury concentrations in Cache Creek and its tributaries to background levels, even if restoration actions may not meet water quality objectives. The BLM goals also include reducing human impact on the environment and restoring the land to its natural condition. Working together with the CVRWQCB and other responsible parties, the BLM can achieve these goals and fulfill their responsibility within the Basin in regards to management water quality.

As the largest land manager in the mining region, the BLM is in a position to influence the overall administration of the area. They can reduce mercury loads, while improving the state of knowledge about mercury sources and conditions that contribute to high methylmercury concentrations. Our recommendations for the BLM can be grouped into four categories:

1) Actions to take: Remediation and restoration actions as well as best management practices in the region;
2) Additional data collection: More water quality samples to understand mercury sources, as well as continued water quality monitoring before and after remediation and restoration actions;
3) Further research: More research into methylation processes, better understanding of mercury sources and concentrations, and better understanding of remediation and restoration options, including emerging technologies;
4) Partnerships: Collaborations that the BLM can encourage with other agencies and entities to help reduce mercury pollution within the Basin and downstream;

Actions to take

The BLM should continue the process of cleaning up the mines on their own land, and encourage the cleanup of mines on adjacent lands. This would address the primary anthropogenic sources of mercury in the Basin, and allow researchers to better assess natural mercury loads and background soil mercury concentrations within each subwatershed. The goal of these remediation and restoration action should be 95 percent reduction in mercury discharge from each site, as recommended in the TMDL Report (Cooke et al., 2004). Concentrations of mercury in stream sediments will remain high, but should reduce over time as the legacy mercury moves downstream. After the mine sources have been removed, the BLM should perform a cost benefit analysis for the removal of stream sediments with high concentrations of mercury. By lowering the concentrations of mercury within the stream sediments, the rate of methylation within the sediments will also be reduced, possibly leading to lower methylmercury concentrations overall.

The BLM can implement best management practices (BMPs) on their land to reduce erosion, and therefore reduce mercury loads. It is especially important to identify regions of high mercury concentrations, and efforts should be made to reduce erosion as much as possible from these regions. The TMDL Report (Cooke and Morris, 2005) defines mercury-enriched soils as having a concentration greater than 0.4 mg/kg. Our watershed model, which uses values given in Churchill and Clinkenbeard (2003) for the mercury loads from each mine, estimates that the total loads from all mines averages 18.8 kg/yr. Our model calculated annual average mercury loads from the mines to be 21.66 kg/yr for the 1996 to 2004, representing only 11 percent of the total mercury loads for the Basin, although there are additional anthropogenic sources of mercury from the legacy mercury within the stream sediments. This shows that erosion of soils with naturally high concentrations of mercury may be a large source of mercury from within the basin, and must be addressed.

Erosion in the Basin is increased by anthropogenic activities including: creation of roads; construction projects; grazing; historical logging; firewood collection; recreational off-highway vehicle (OHV) use; and gravel mining. Managing these activities will reduce the amount of erosion and therefore reduce mercury loads from within the Basin. OHV use is already prohibited in much of the Basin; however, there are some highly-erodible areas where off-highway vehicle use is still permitted, such as in and around the Rathburn and Petray mines. Further limitations on OHV use and enforcement of these rules are necessary to reduce erosion impacts of this activity. Restrictions on uses of the Cache Creek Wilderness limit anthropogenic influences on erosion in this area. Unfortunately, the Cache Creek Canyon, the largest source of mercury in the Basin (Foe and Croyle, 1998; Cooke et al., 2004), is located mostly within the Wilderness; there may be little that can be done to reduce mercury loads associated with natural erosion in the Canyon.

Historically, there was significant logging throughout the Cache Creek Basin, which may still be causing elevated rates of erosion (Suchanek et al., 2002b). Large amounts of timber were needed to support mining tunnels, as well as to heat the furnaces used to extract the mercury from the cinnabar ore (Watts, 1893). There was also significant logging in the Basin in the 20th century. According to Suchanek et al., (2002b):

> By 1870 no fewer than five commercial sawmills were operating on the lake; by 1905, there were eleven mills that processed over 1.5×10^6 board feet of lumber annually, and in 1946 more than 11×10^6 board feet was processed (Simoons 1952).

In addition to historical logging, a high occurrence of fires in the Basin also contributes to erosion (Suchanek et al., 2002). The hot, dry conditions experienced during the summer, combined with the widespread dominance of chamise (*Adenostoma fasciculatum*) in much of the watershed, make the region vulnerable to large and destructive fires. There should be more research conducted on how much current erosion rates are affected by prior logging activities and what can be done to establish forests or other vegetation that will reduce erosion. If vegetation types that grow well in the region are found to have lower erosion rates than chamise or other vegetation currently occupying the region, a plan should be implemented to re-vegetate regions with naturally high mercury concentrations to vegetation with lower associated erosion rates. Another option that should be considered is using vegetation that is appropriate for phytoremediation which could increase the benefits of erosion control through re-vegetation. Vetiver grass (*Vetiveria zizanioides*) is one type of plant that may be effective in the Cache Creek Basin due to its ability to withstand extreme climatic variation, tolerate high concentrations of mercury, and provide erosion control (Truong, 2000). Use of this or a similar plant could stabilize insoluble forms of mercury, preventing further erosion of mercury-enriched soils while removing the soluble forms of mercury in the plant tissue (Truong, 2000).

Additional Data Collection and Monitoring Plan

It is important that a comprehensive monitoring and sampling plan be implemented so mercury loads can be analyzed before and after remediation and restoration actions are taken. Increased sampling will also help to ensure that all natural mercury sources are identified. The BLM should work with other agencies, such as the CVRWQCB, to coordinate a plan among all groups that are collecting mercury data in the region so sampling efforts are not duplicated and information is shared openly. The management of this data should reside with the CVRWQCB, as they produce the TMDL reports and are responsible for ensuring the beneficial uses of the Cache Creek Basin are maintained. An organized sampling plan will bridge knowledge gaps and ensure better understanding about the effectiveness of remediation and restoration actions that take place in the Basin. This monitoring effort will also benefit future remediation and restoration actions, by informing realistic expectations of mercury load reductions. Also, if the BLM mining areas are used as a testing ground for new remediation and restorations options, a monitoring plan will provide feedback about the effectiveness of these options.

The monitoring plan must be strategic, collecting the most valuable information in the most critical areas. All water quality samples must collect stream flow and suspended sediment data, as these are crucial factors in understanding mercury transport. It is difficult to accurately estimate stream flow at many locations; therefore, rating curves must be made at all sampling locations, and calibrated at least once per year. Samples must be collected during high flows, preferably from both the rising and falling limbs of the hydrograph. It is these high flows that transport the most mercury, and are critical to the understanding of mercury sources. Samples should also be taken during the dry season, especially in the late summer and early fall when methylation rates are at their peak, and before and after a remediation or restoration project to evaluate the effectiveness of the project.

Because sampling for mercury is very expensive, and budgets are often constrained, the sampling and monitoring plan must maximize the value of information obtained while minimizing the number of samples taken. The following map (Figure 46) and corresponding list are the minimum sampling locations that should be a part of the monitoring plan.

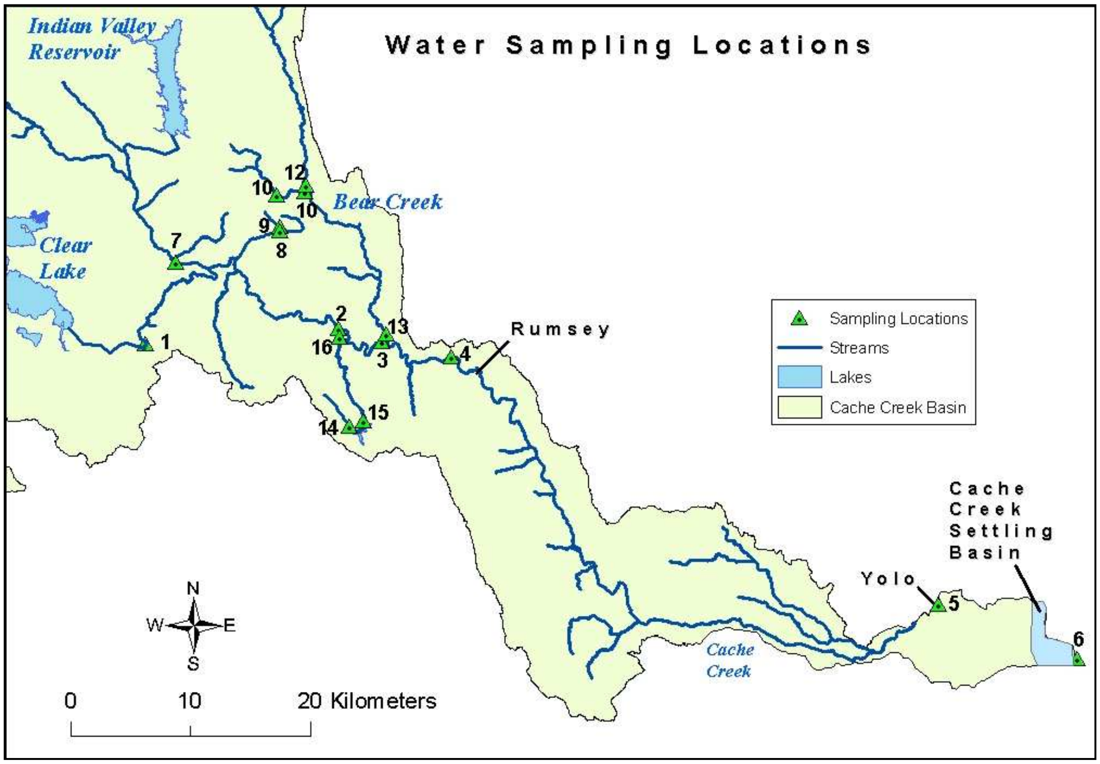


Figure 46: Minimum sampling locations in Cache Creek Basin for a monitoring plan.

1) Cache Creek at the outflow of Cache Creek Dam
2) Cache Creek before the confluence of Davis Creek
3) Cache Creek before the confluence of Bear Creek
4) Cache Creek at Rumsey
5) Cache Creek at Yolo
6) Cache Creek at the outflow of the settling basin
7) The North Fork of Cache Creek at the confluence of Cache Creek
8) West Fork of Harley Gulch above the confluence of the two forks
9) Harley Gulch below the confluence of the two forks
10) Sulphur Creek above West End Mine
11) Sulphur Creek at the confluence of Bear Creek
12) Bear Creek above the confluence of Sulphur Creek
13) Bear Creek at the confluence of Cache Creek
14) Davis Creek at the inflow of Davis Creek Reservoir
15) Davis Creek at the outflow of Davis Creek Reservoir
16) Davis Creek at the confluence of Cache Creek

In addition to these locations that will help researchers better understand mercury loads throughout the Basin, there is a need to understand the large mercury source originating from within the Cache Creek Canyon. This region has proven to be a large contributor of mercury to Cache Creek during storms, and it is necessary to sample this region when all of the tributary creeks to the canyon are experiencing high flows. Water flows, suspended sediment concentrations, and mercury concentrations should also be measured in Cache Creek upstream of and at the confluence with each of the ten major tributaries (Figure 45). Because samples taken at the same time and place may vary in mercury concentration (Foe and Croyle, 1998), two samples should be taken at each site in order to obtain a more accurate measurement, if the sampling budget allows.

The lack of accessibility in the canyon will require that many of these tributaries be reached by raft. Since access to the Canyon is at the Redbud trailhead, just off Highway 20 on the North Fork of Cache Creek, it would allow for both the North Fork and the South Fork to be sampled, in addition to Grizzly Creek on the North Fork, which may also be a large source of mercury (Foe and Croyle, 1998). Once the data has been analyzed, if certain tributaries or portions of Cache Creek are discovered to be large sources of mercury, additional samples should be taken in these areas to gain a more accurate understanding of exactly from where the mercury is originating. Identifying the sources of mercury in the Basin and classifying them as anthropogenic or natural will determine how far mercury loads can be reduced.

The large data set that will come from this monitoring and sampling program will greatly improve the state of knowledge about the fate and transport of mercury in the Basin, and can also be used to better calibrate a watershed model. A more accurate watershed model will be able predict the result of remediation and restoration actions, as well as BMPs to reduce erosion from within the Basin with a higher level of precision.

Additional methods can be developed to identify the location of mercury sources from within the Cache Creek Canyon. To determine if sediment is being scoured from depositional areas of the Canyon, cross-sections can be surveyed to provide precise data about the elevation of these cross sections over time. These cross-sections would have to be re-surveyed in years after high flows, which may require this to be part of an on-going monitoring process. The surveys would have to be performed during low flows in order to easily stand in and cross Cache Creek. Cross-sections can also be taken in Bear Creek, as it is an area of concern regarding sediment scouring.

Another technology that can be used to determine sediment scour and erosion from a more widespread region is LIDAR (Light Detection And Ranging). LIDAR is a technology in which an airplane flies over the area to be surveyed, and collects accurate information about the elevation of the surface of the Earth. A three-dimensional surface can be created of the canyon or any areas of interest. After wet years in which high erosion may have occurred, the same area can be assessed with LIDAR again, and the difference between the two surfaces can be calculated to see if scouring and landsliding is occurring. This, combined with a comprehensive mass balance approach of water sampling, should provide enough data to determine from where both the sediment and the mercury are originating.

Further Research

The BLM should continue to study the feasibility of different remediation and restoration actions. There are a number of emerging technologies that have the potential to be effective in the Basin and help meet challenges of restoration and remediation in the area; however, some of these are still developing and cannot be applied at this time since they have not been tested extensively in the field. It will be important to find a technology that is highly effective, low in cost, and easily implementable to make further progress, given the budget and policy constraints in the Cache Creek Basin.

While the BLM may not conduct studies regarding these technologies themselves, they could facilitate testing in order to find new technologies that can be applied to BLM lands. The BLM can create partnerships with scientists that are researching remediation and restoration solutions. The Cache Creek Basin can offer a natural environment in which to test new technologies like nanotechnology and phytoremediation. The Cache Creek Basin would be an ideal testing ground for emerging technologies with its variety of different environments that are enriched in mercury. While this is an opportunity to further the body of knowledge about remediation technologies for mercury, care should be taken when considering this option since there is the potential for adverse impacts to occur, such as accidental introduction of an invasive species into the Basin.

In addition to further research about remediation technologies, the BLM should perform a cost-benefit analysis of dredging mercury enriched sediments in Bear Creek, Harley Gulch, Sulphur Creek, Cache Creek, behind Capay Dam, and in the settling basin. After mine remediation is performed, it is unknown how long legacy mercury will remain in creek sediments. It is possible that mercury enriched sediments will persist for many years and continue to contribute to increased methylation rates. The data that this group collected indicates that sediment within Harley Gulch averages 4.0 mg/kg, and should be considered for removal and replacement with clean sediment. Sediments within Sulphur Creek and Bear Creek contain elevated mercury concentrations and should be considered for dredging. Mercury concentrations are also elevated in Cache Creek sediments (Foe and Bosworth, 2008; Bosworth and Morris, 2009). However, due to the inaccessibility of a large portion of Cache Creek, it may not be feasible to remove these sediments. Capay Dam is an inflatable dam that is installed annually during irrigation season to divert Cache Creek into the Winters and Adams canals; the sediment trapped behind the dam may contain large concentrations of mercury and should be considered for annual removal.

Partnerships

It is important that the BLM work will all other agencies, land managers and owners in the Basin to coordinate remediation and restoration efforts. A partnership should be made with the California Department of Parks and Recreation to reduce methylation at the Anderson Marsh State Historic Park (Figure 47), which is an important historical site, and also a large source of methylmercury to Cache Creek (Cooke and Morris, 2005). Methylation in this area not only negatively affects the historic value of the marsh, but also impacts methylmercury concentrations downstream on BLM land. The BLM should also create a partnership with the Army Corp of Engineers to increase the settling efficiency of the Cache Creek Settling Basin. Currently, approximately half of the mercury that reaches the settling basin is sequestered within the basin (Foe and Croyle, 1998). If the efficiency of the setting basin could be increased, presumably by dredging accumulated sediments, enlarging the basin, or by raising the weir, there would be less mercury transported to the Sacramento/ San Joaquin Delta. By increasing the capacity of the settling basin, the water will have a longer residence time in the basin and more sediment will settle out. In addition, a larger settling basin will be able to hold more water so less will spill into the Yolo Bypass. The settling basin has very high rates of methylation, and there should be an effort to reduce the conditions in the settling basin that lead to methylation (Marvin-DiPasquale, 2009). It may be possible to re-grade portions of the settling basin to reduce standing water and therefore reduce methylation. Other agencies that manage lands within the Cache Creek Basin include the USDA Forest Service, the California Department of Fish and Game, and the State Lands Commission (Figure 47).

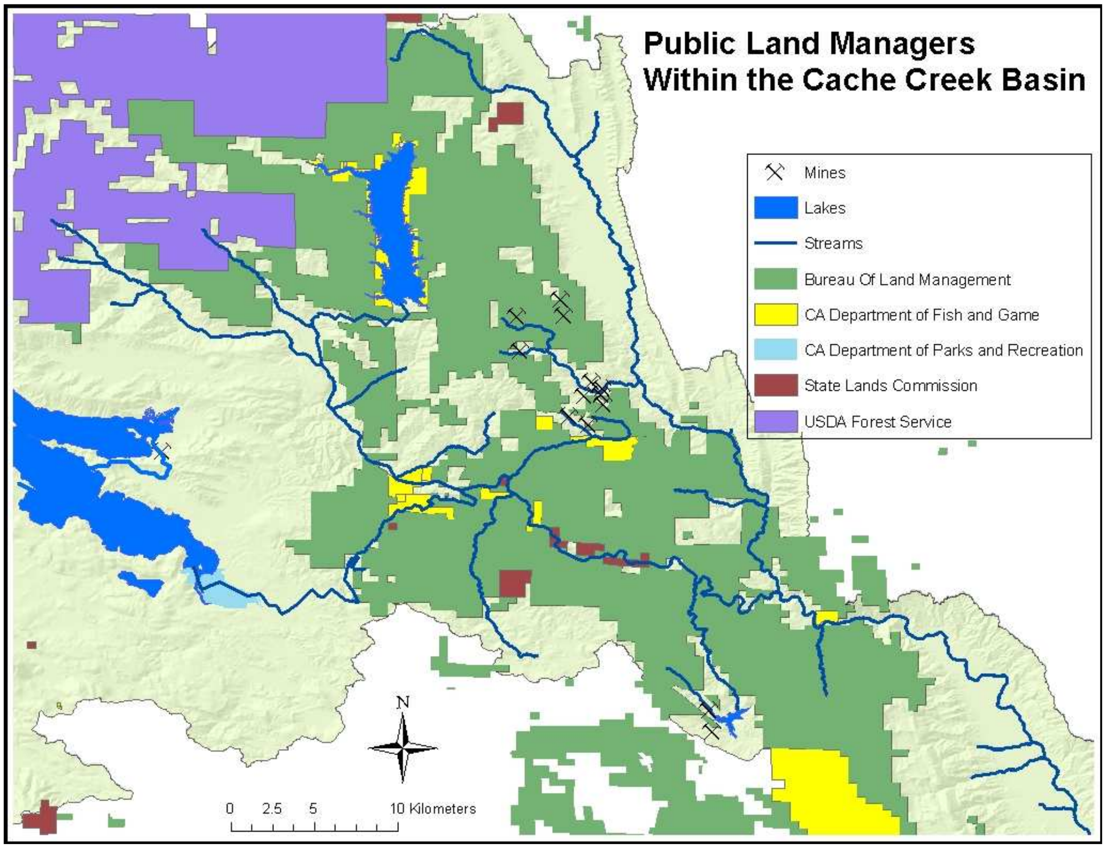


Figure 47: Public land within the Cache Creek Basin

CONCLUSION

Historical mercury mining has significantly impaired the beneficial uses of many of the water bodies within the Cache Creek Basin. The CVRWQCB has issued TMDLs for the impaired water bodies as well as cleanup orders for several abandoned mines. These orders require the BLM and other groups to reduce the downstream impact of mercury originating from the mining areas to near background levels so that the TMDLs are met and the beneficial uses maintained. The purpose of this report is to better understand the challenges associated with managing mercury pollution by: identifying applicable policies and regulations which further complicate the issue; recommending cleanup options; and modeling the fate and transport of both total mercury and methylmercury within the Basin.

This report presents a systematic approach to mercury mine remediation that the BLM will be able to follow for the Cache Creek Basin, as well as other areas affected by legacy mercury pollution. Through the use of our decision trees, remediation options can be selected based on site-specific characteristics and the applicability of individual technologies. The decision trees also take into consideration cost and the effectiveness of remediation options, as well as the laws and policies that govern the implementation of remediation and restoration projects. After the most applicable options were chosen they were ranked based on assessment criteria of cost, effectiveness, and timeframe. Our decision trees provide a framework for quickly determining remediation options; however, further feasibility studies would be required before implementing a particular strategy. In order to show this process, we presented six case studies with a variety of site types to illustrate the use of the decision trees.

From a policy perspective, the decision trees take into consideration the Wilderness area and historical and archaeological sites. These are treated as the last areas to be considered for cleanup, because the laws which protect these sites stipulate that they are not to be disturbed without significant justification. In addition, data gathering and monitoring in these areas have constrained by limited access, both geographically and politically, to the sites. However, the cleanup orders require mercury contamination to be reduced to background levels or, if this is not achievable, to the most stringent level that is technologically and economically feasible. As a responsible party, the BLM may only be required to meet the latter standard if it cannot meet the former standard because of legal constraints. Nevertheless, until acceptable strategies to mitigate sources of mercury in these areas are determined, all other accessible areas should take priority when developing a comprehensive Basin-wide cleanup plan.

The challenge of remediation and restoration in the wilderness area raises the need to find low-footprint, low-cost technologies that are less invasive. However there is still a need for further study of remediation technologies. Currently, there are a limited number of technologies that are effective for mercury cleanup and removal. Many of the most effective technologies like excavation, containment caps, and chemical treatments are very costly and invasive.

Phytoremediation is one emerging technology that has the potential to fit the need for low-footprint, low-cost technologies that are applicable to more natural settings. In our case studies which focused on contaminated stream banks and sediments, phytoremediation was the technology that was most frequently selected from the perspective of a decision maker with a constrained budget. This is because of the relatively low cost of the technology. While this technology may take a longer period of time to reduce mercury contamination, it would not be as invasive as other management actions like excavation. Using plants that hyperaccumulate mercury to re-vegetate areas within the Basin may also be a good way to prevent erosion and the transport of sediment.

In addition to phytoremediation, nanotechnology may be able to fit the need for low-footprint, low-cost technologies. However, further testing of the long-term impacts of nanomaterials is necessary, especially in natural settings like the Cache Creek Basin. Nanotechnologies to address mercury contaminated sites are largely still in developmental phases; this prevented us from recommending their use at this time. However, this is a promising field that holds a great deal of potential for future applications despite the uncertainties regarding the environmental impacts of nanomaterials.

One way technologies can be developed further is by using the Cache Creek Basin as a testing ground for emerging remediation strategies. Even if this is not possible, with the strategies provided in this report, BLM can still make progress toward improving water quality in the Cache Creek Basin.

Excavation of contaminated sites may be best strategy to quickly and effectively remove mercury. In our case studies, it was shown that this would be the recommended strategy at a majority of the sites from the perspective of a decision maker that is more concerned with health effects of mercury. While this strategy is highly effective, it may not be feasible due to the widespread nature of contamination in the Basin.

Another interesting strategy is the use of settling basins in the Cache Creek Basin. This option may be able to assist in restoration of areas downstream from mercury mines that have not been cleaned up. By placing settling basins in strategic locations, upstream sediments containing mercury can be captured and removed from the ecosystem. This would prevent contaminated sediments from impacting ecological functioning downstream.

While these management strategies may more effective and take less time than low-footprint strategies like phytoremediation, habitat alterations would be necessary. Excavation and construction of settling basins would be costly if implemented throughout the entire Cache Creek Basin. In addition, these strategies would not be easily implemented in like the Wilderness area.

Another contribution of this project was to model the Cache Creek Basin using WARMF. Our model allowed us to analyze the daily flow, sediment, and mercury for each stream reach in the Basin from 1996 to 2004. The model allowed us to analyze the mercury contributions from the mines as well as inputs from soils that contain naturally elevated background levels of mercury. By removing the mines from the model to simulate that cleanup had occurred, it was possible to analyze the effects of the remedial actions. It was found that mercury loads from the Basin are reduced by 11% with the removal of all mines, indicating there is a significant amount of mercury originating from natural sources, most likely within the Cache Creek Canyon area, and also from legacy mercury in stream sediments along Cache Creek and its tributaries.

The TMDL for Harley Gulch (Cooke et al., 2004; Cooke and Morris, 2005) is not likely to be met, due to the naturally-elevated mercury concentrations in the region. The TMDL for Sulphur Creek (Cooke and Stanish, 2007) has much lower standards than the Harley Gulch TMDL, an acknowledgement of the high mercury contribution from thermal springs during the dry season, and will most likely be met. The TMDL for Bear Creek (Cooke et al., 2004; Cooke and Morris, 2005) is unlikely to be met, due to high mercury concentrations in the region just upstream of Sulphur Creek as well as the high mercury concentrations from Sulphur Creek. It is unknown whether the TMDL for Cache Creek (Cooke et al., 2004; Cooke and Morris, 2005) will be met, and depends to a large extent on whether methylation in Clear Lake can be reduced.

Mercury loads within the basin, particularly the sources from within the Cache Creek Canyon, may have been overestimated by a factor of two. This has implications for the Sacramento/ San Joaquin Delta Estuary TMDL (Wood et al., 2008) because the Cache Creek may not be as large of a mercury source as previously assumed. This may make it more difficult to reduce mercury in the Delta because remediation and restoration actions completed in the Cache Creek Basin will not have as much of an impact on mercury loads reaching the Delta from the Sacramento River and Yolo Bypass.

The BLM should work with other agencies, especially the CVRWQCB, to establish a comprehensive data collection and monitoring plan within the Basin to further the understanding of mercury transport in the region. There are large gaps in knowledge, particularly regarding the origins of the greatest source of mercury from within the Basin. Improved knowledge and monitoring will also allow for a better understanding of the effectiveness of remediation and restoration actions.

Given these limitations, our project focused on assisting with decision making surrounding remediation and restoration efforts. We developed decision trees and matrices in order to provide a starting point to BLM staff and others faced with similar mercury management decisions. These tools provide a structured approach to addressing a daunting pollution issue, and allow the user to determine a remediation or restoration method that best suits the environmental and political parameters as well as other key considerations, such as cost. Mercury pollution is not unique to the Cache Creek Basin, and our methods are meant to be generalized to allow for application in other geographic locations with legacy mercury contamination.

APPENDIX I: DECISION TREES

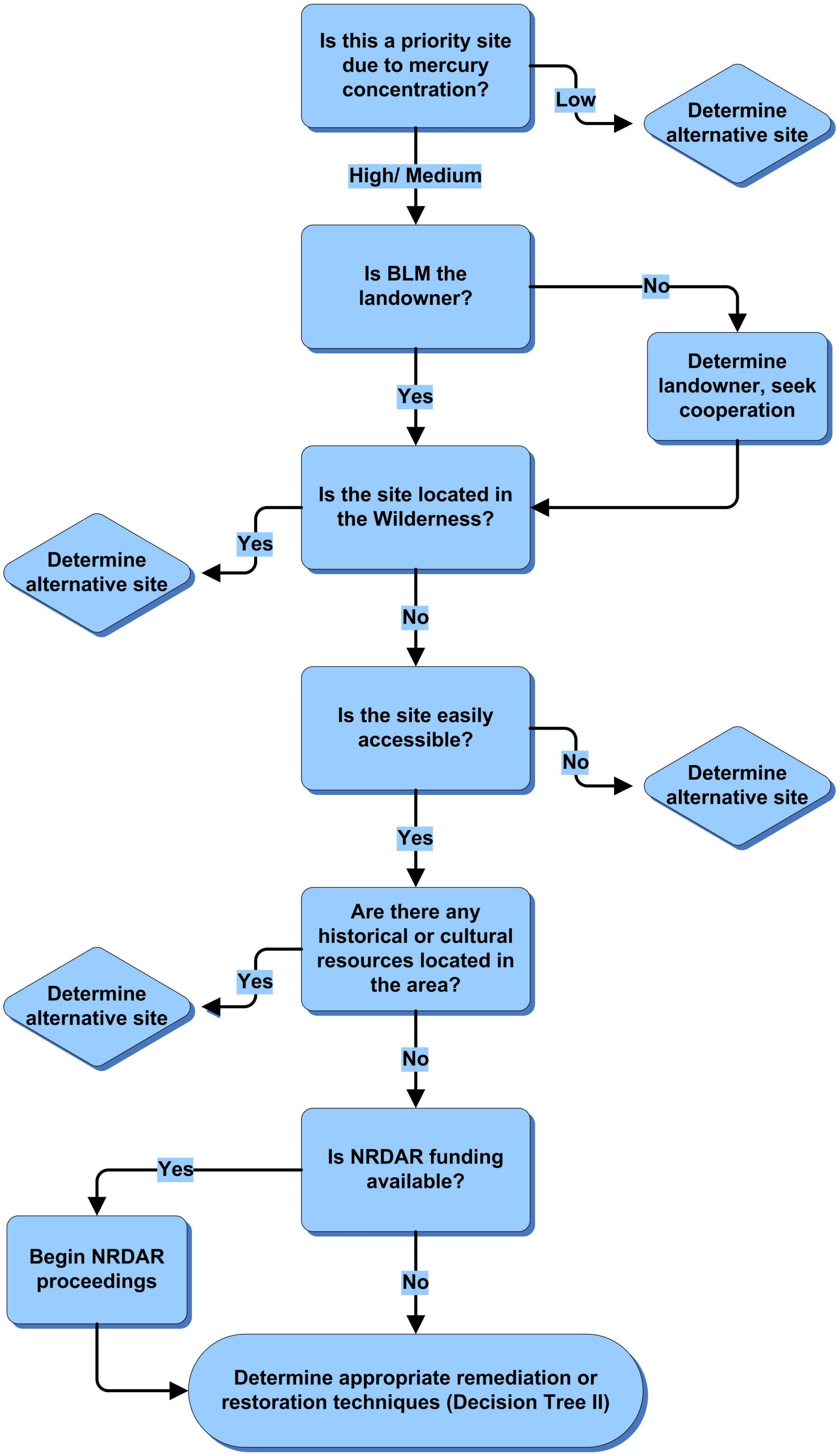


Figure 48: Decision Tree I

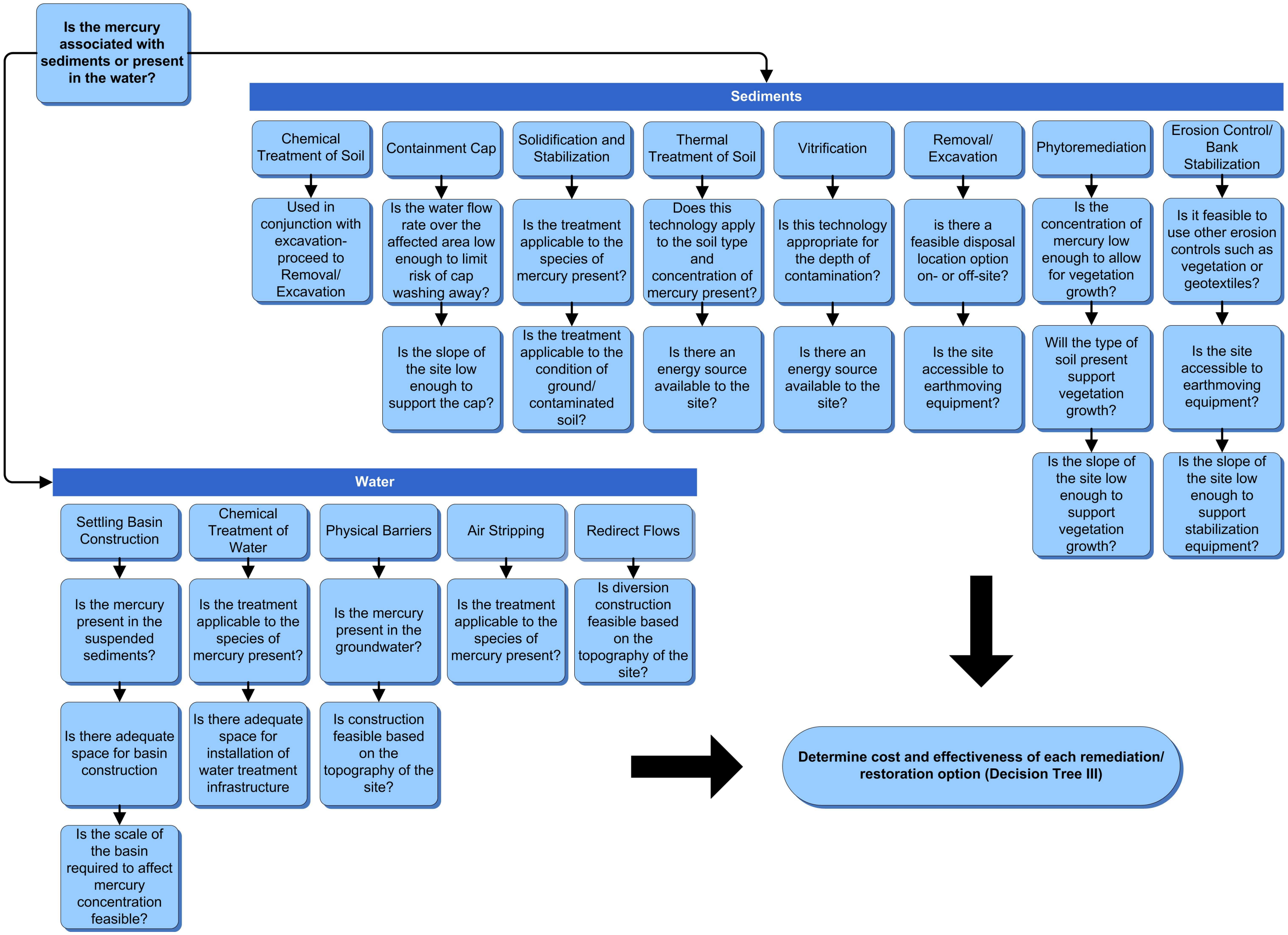


Figure 49: Decision Tree II

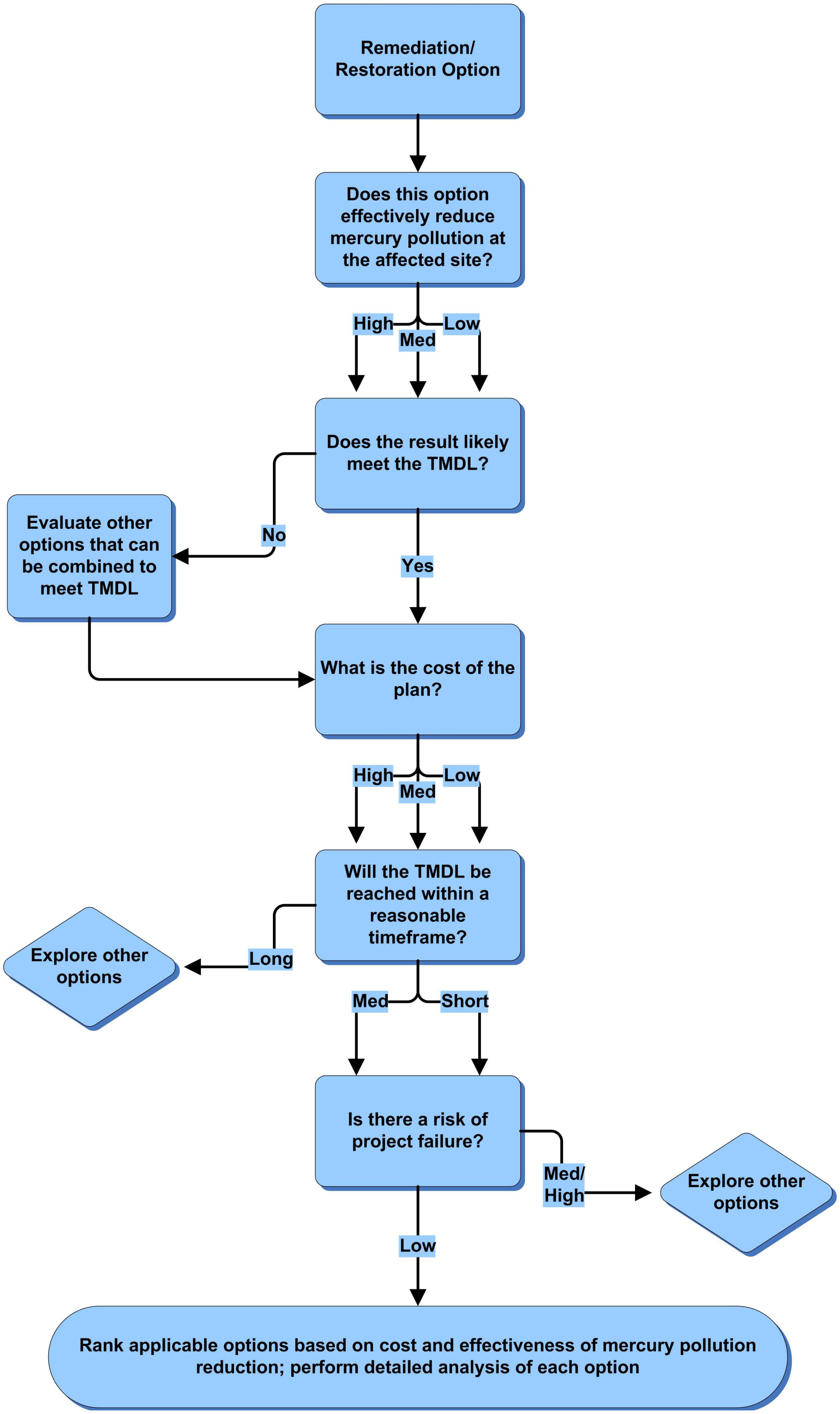


Figure 50: Decision Tree III

APPENDIX II: WARMF MODEL SETUP

There are many steps to setup and calibrate a WARMF model. This appendix describes these steps in greater detail than that presented in the body of the paper. As mentioned in the Methods section, we chose to focus our efforts on reaches of Cache Creek downstream from Clear Lake and Indian Valley Reservoir, and modeled the outputs from these water bodies as point sources. By modeling the basin this way, it greatly reduces the complexity of the model, and also increases its accuracy by allowing us to specify the water quantity and quality exiting these reservoirs. Indian Valley Reservoir was completed in 1975, but water information was only available from 1995 onwards, and even then, there are periods when the gauge was not functioning.

The other lake in the basin is Davis Creek Reservoir, and this was not modeled because WARMF would not run when the lake was included in the model. Instead, the Upper Davis Creek stream reach is modeled as containing an impoundment that serves the same hydrologic purpose as the reservoir. This impoundment will reduce sediment concentration in the stream and increase methylation. Also, Davis Creek Reservoir does not significantly affect the hydrology of Davis Creek since it is always full, there are no summer releases, and there are no diversions.

We choose to model the Cache Creek all the way to Yolo, since this is the boundary of the USGS 8-digit hydrologic unit (HUC-8) for Cache Creek. We set up the model using BASINS (Better Assessment Science Integrating point & Non-point Sources), a free program from the USEPA that includes many tools for downloading watershed data. To set up the model, the first step was to use BASINS to select the two HUC-8 watersheds that comprise the Cache Creek Basin, the Upper Cache Creek, and the Lower Cache Creek. BASINS begins by downloading some basic information to use as a base map for the rest of the project. This information is in shapefile format, and includes an outline of the basin, major streams, county boundaries, and STATSGO (soil information from the USDA) information. BASINS also accessed several other datasets that were needed to set up a WARMF project, including data from the National Elevation Dataset (NED), the National Hydrography Dataset (NHD), and the National Land Cover Dataset 2001 (NLCD 2001). In BASINS, it is also possible to download meteorological data, water quality data, and stream gage data, although we already had this data from another source.

After all the necessary data was brought into BASINS, we needed to merge the two HUC-8 units together in order for BASINS to correctly divide up the Cache Creek Basin into streams and subcatchments. The data for both HUC-8 units were merged within ArcGIS, and a mask was applied to delineate the watershed that is below the two reservoirs. This mask was created by merging together the HUC-12 subwatersheds that comprise the region from below the reservoirs to Yolo. After the NED and NHD data were merged in ArcGIS, they were imported back into BASINS along with the mask. We then performed an automatic delineation from this data, using a 10 km^2 threshold area, which gave us 55 subcatchments. For each of the 55 subcatchments and their corresponding stream reaches, BASINS calculates the parameters that are needed to create a WARMF model. For the subcatchment, this includes the catchment area and slope. For the stream reach, this includes the downstream reach, length, slope, depth, width, minimum elevation, and maximum elevation.

In order to model Harley Gulch, Sulphur Creek, and Davis Creek in more detail, we brought both the subcatchment and stream reach shapefiles into ArcGIS so they could be subdivided further. The automatic BASINS delineation created exactly one subcatchment for each of these creeks. Using ArcHydro 9, a package of hydrology tools for ArcGIS, we were able to divide up Harley Gulch and Sulphur Creek each into four catchments and Davis Creek into two catchments. In order to do this with ArcHydro 9, first it was necessary to calculate a flow direction raster and a stream grid, along with a shapefile of catchments points. With these three files, ArcHydro 9 calculates the exact area that drains into each catchment point. With these smaller catchments delineated, we were able to edit the two original shapefiles to add our additional subcatchments. The attribute tables of the two shapefiles had to be carefully edited in order to properly update the catchment and stream reach information that WARMF requires.

The next steps involved setting up the WARMF model, which requires a significant amount of time to format all the necessary input files and set the necessary parameter values. WARMF has several categories of time series inputs, including: meteorology, air quality, observed hydrology, observed water quality, managed flow, and point sources (Figure 51). Fortunately, much of this data was acquired in a formatted state from another WARMF model from the Sacramento River. This imported data included two meteorological files from Clearlake and Woodland. It also included air quality data, both wet and dry deposition, from Hopland and Davis. It also included a number of observed hydrology files and observed water quality files from most of the gages in the basin. The only files that it did not include were the ones from Sulphur Creek, Harley Gulch, and Davis Creek Reservoir that the USGS set up from 1999-2004 in cooperation with the CVRWQCB's research on the mercury problem. It contained a number of managed flow files in the lower reaches of the watershed, including the large diversion at Capay during irrigation season. It also included a number of point source files, such as the flow from Clear Lake. Originally, Indian Valley Reservoir was not a point source file, but the managed flow information from the reservoir was converted into a point source file. Modeling the outflow from the two reservoirs as a point source allowed us to specify the chemical fluxes from the lake, including mercury.

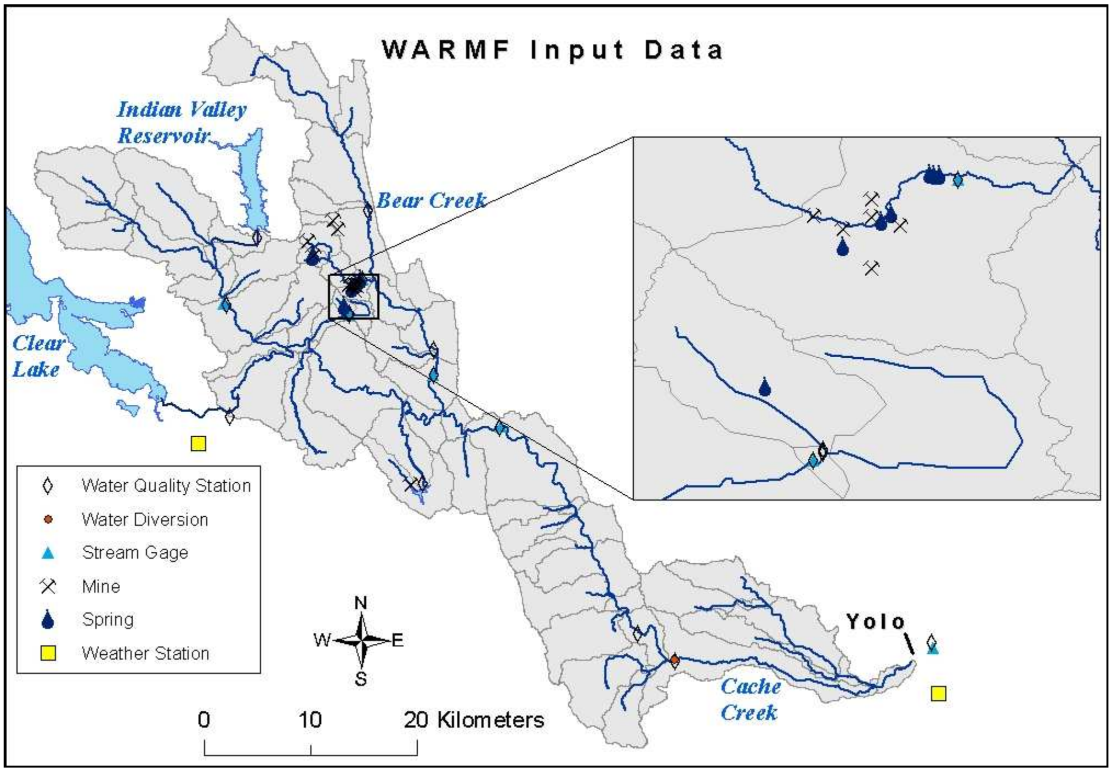


Figure 51: WARMF input data

The input data that required the most processing was the soil data. We decided to download the much more accurate USDA SSURGO data instead of using the more generalized STATSGO data. The USDA provides an application that converts this data into a Microsoft Access database. In ArcGIS, we extracted the percentage of each soil class that is in each subcatchment. Then a MATLAB script calculated the soil properties of each subcatchment based on the soil properties of each soil class and the area of each soil in that subcatchment. The soil properties that were imported into WARMF include: the number of soil layers, the thickness of each layer, the initial moisture, the field capacity, the saturation moisture, the horizontal hydraulic conductivity, the vertical hydraulic conductivity, and the soil density.

Precipitation for each subcatchment was calculated using PRISM information from Oregon State University. Precipitation in WARMF is modeled by assuming that a particular meteorological station has a factor of 1.00, and the precipitation in a subcatchment that is using that meteorological station is a factor of this value. An initial run indicated that modeled flow was much greater than measured flow, and that precipitation and soil parameter values needed to be adjusted. After trying some manual adjustments, the auto-calibration algorithm in WARMF for hydrology was used to adjust parameter values to best match modeled with observed hydrology. This algorithm requires hundreds of runs to adjust all the relevant parameters and usually runs for several hours. We started by calibrating the smaller watersheds such as Harley Gulch and Sulphur Creek, and eventually calibrated the entire watershed. The period of calibration was 1999 to 2004 when the Harley Gulch, Sulphur Creek, and Davis Creek stream gages were operational. For Yolo and Rumsey we calibrated the model back to 1997 because 1997 and 1998 included large storms that our model needed to get correct in order to accurately model periods of high flow. The precipitation factors before and after calibration are shown in Figure 52 and Figure 53. The large difference between the PRISM and calibrated precipitation factors could be due to a number of reasons, including the possibility that we are underestimating evapotranspiration, water is entering the groundwater, the soils are able to hold more water than the model estimates, or the soils are thicker than what is listed in the SSURGO database.

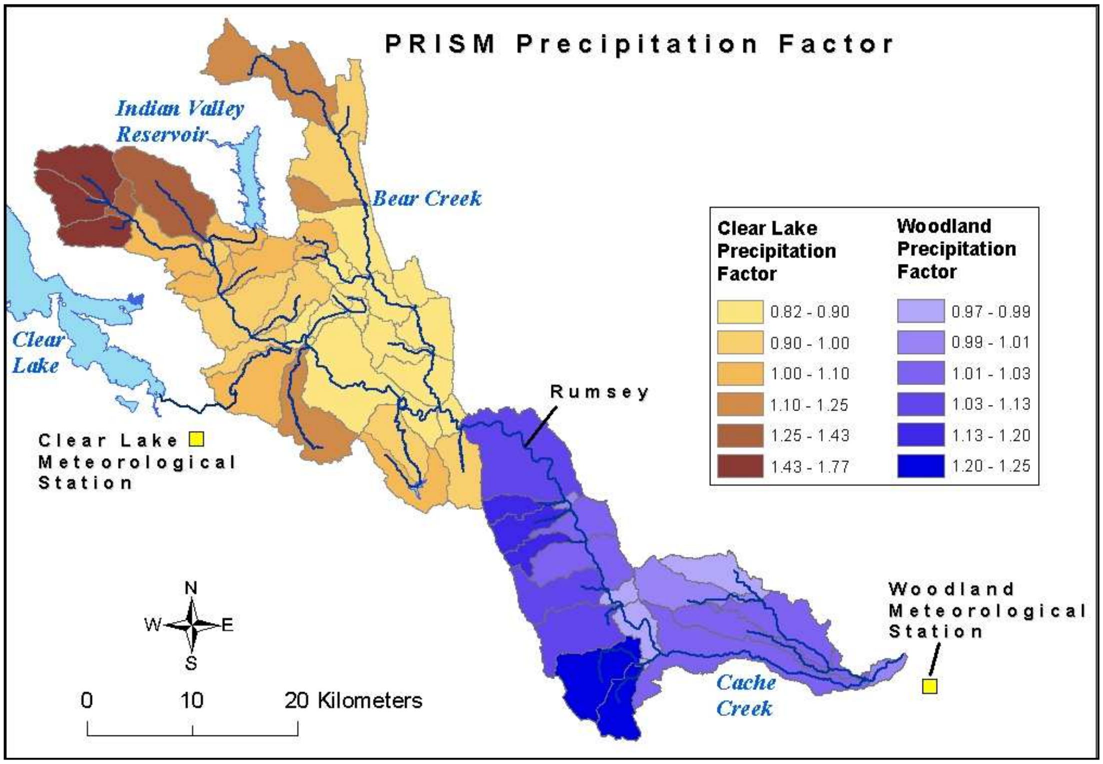


Figure 52: PRISM precipitation factors

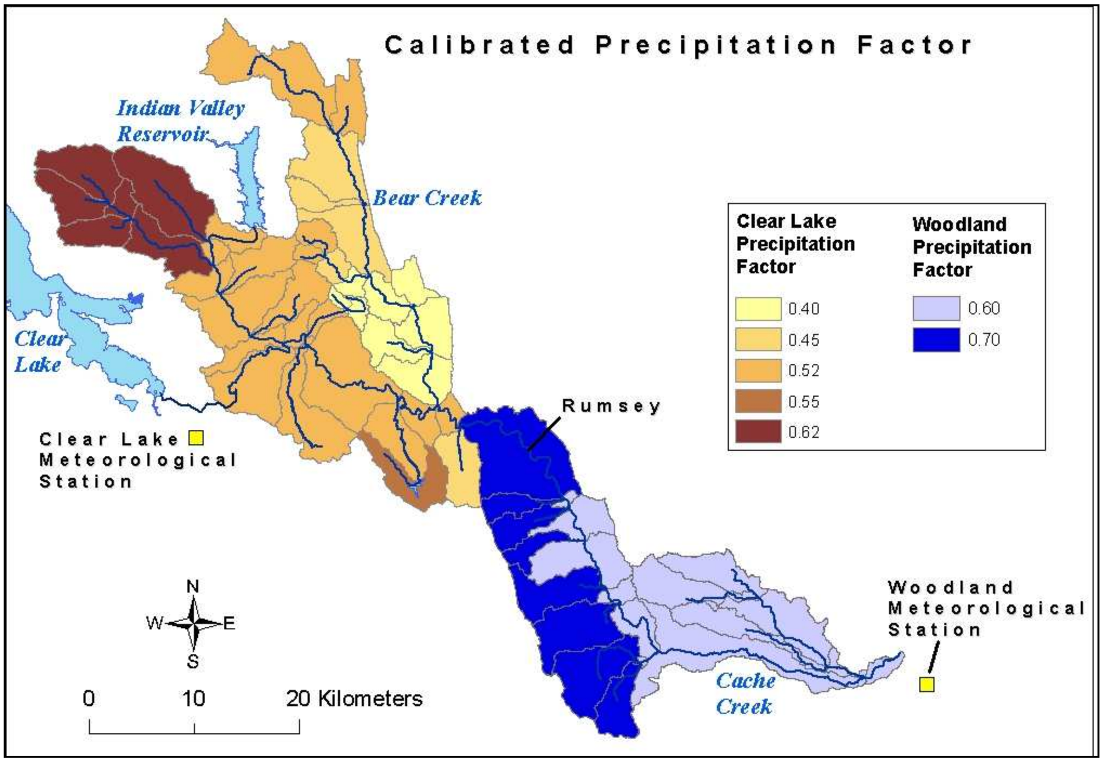


Figure 53: Calibrated precipitation factors

APPENDIX III: ADDITIONAL WARMF RESULTS

Below are selected screen shots from the WARMF model before mine remediation (Figure 54 - Figure 64). The calibration was performed by trying to match the observed with the modeled values at each location where water quality information was available. As seen in the figures, the modeled values match the observed values better in areas such as Yolo and Rumsey where the drainage area is larger, and not as well in the smaller drainages such as Harley Gulch or Sulphur Creek. The blue lines are the modeled results, and the black dots are observed flows.

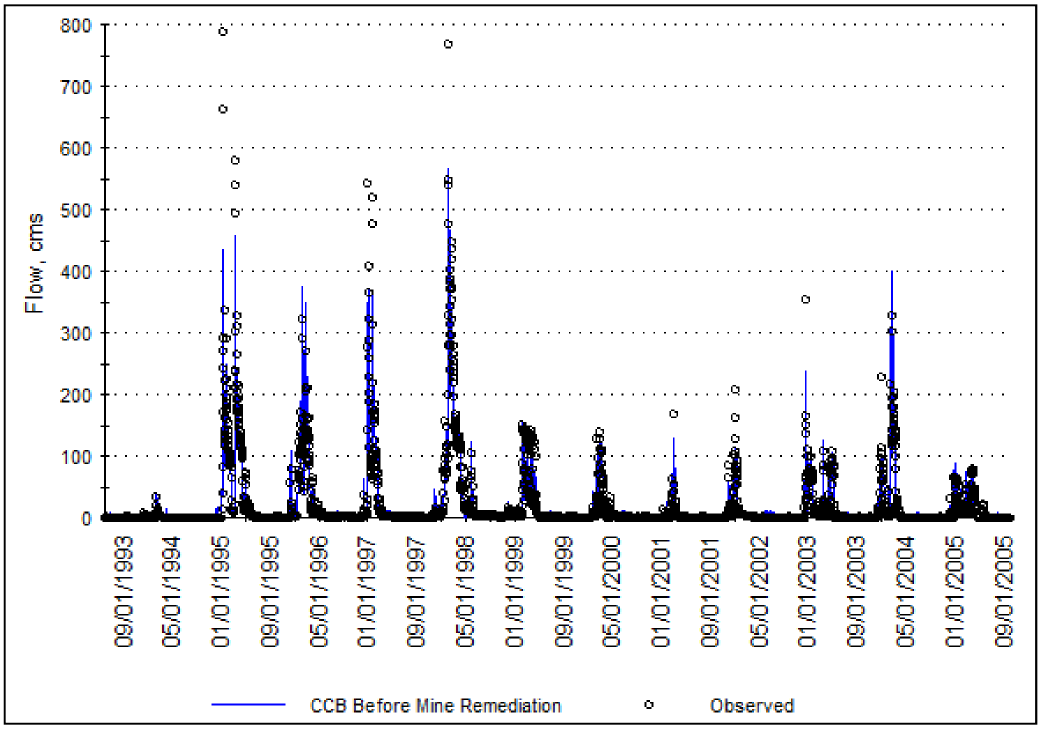


Figure 54: Modeled vs. observed flow at Yolo

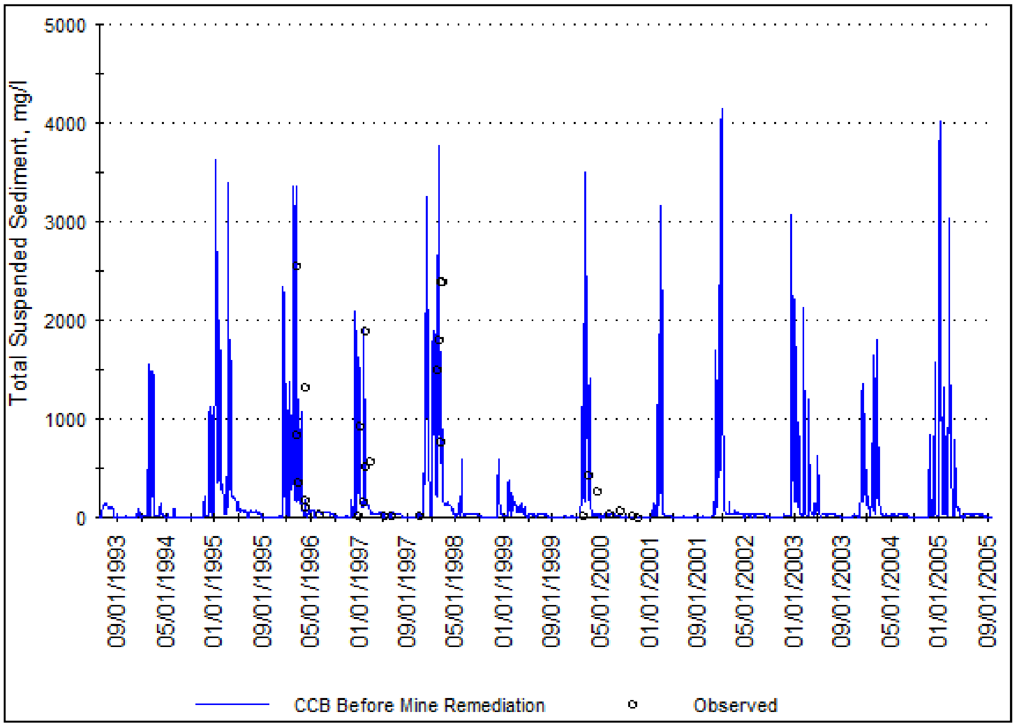


Figure 55: Modeled vs. observed suspended sediment at Yolo

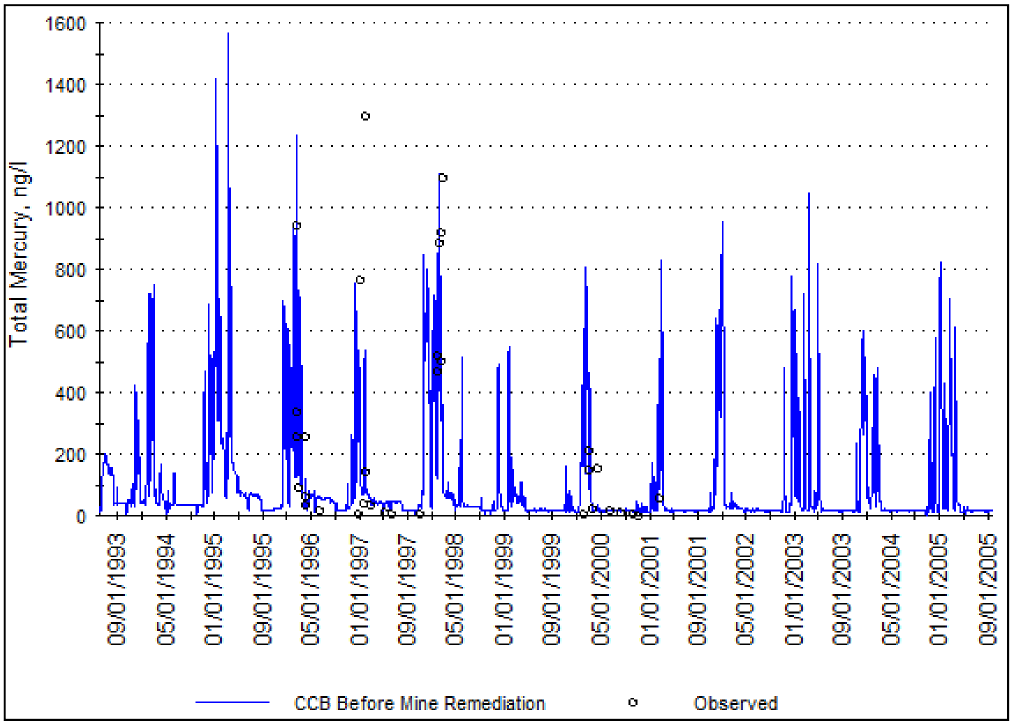


Figure 56: Modeled vs. observed total mercury at Yolo

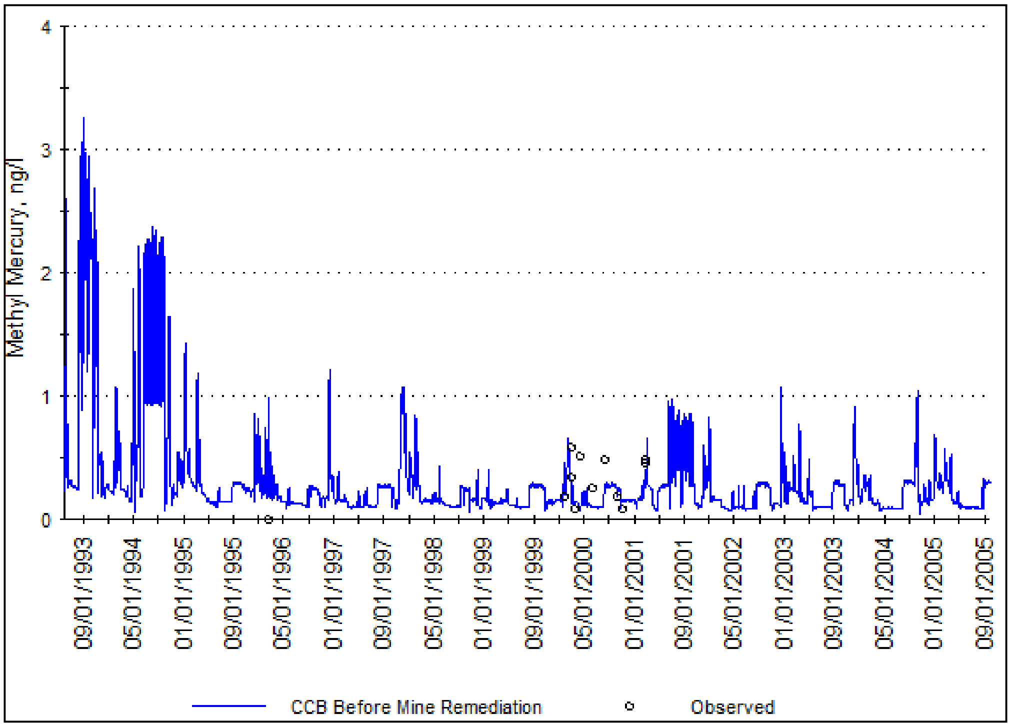


Figure 57: Modeled vs. observed methylmercury at Yolo

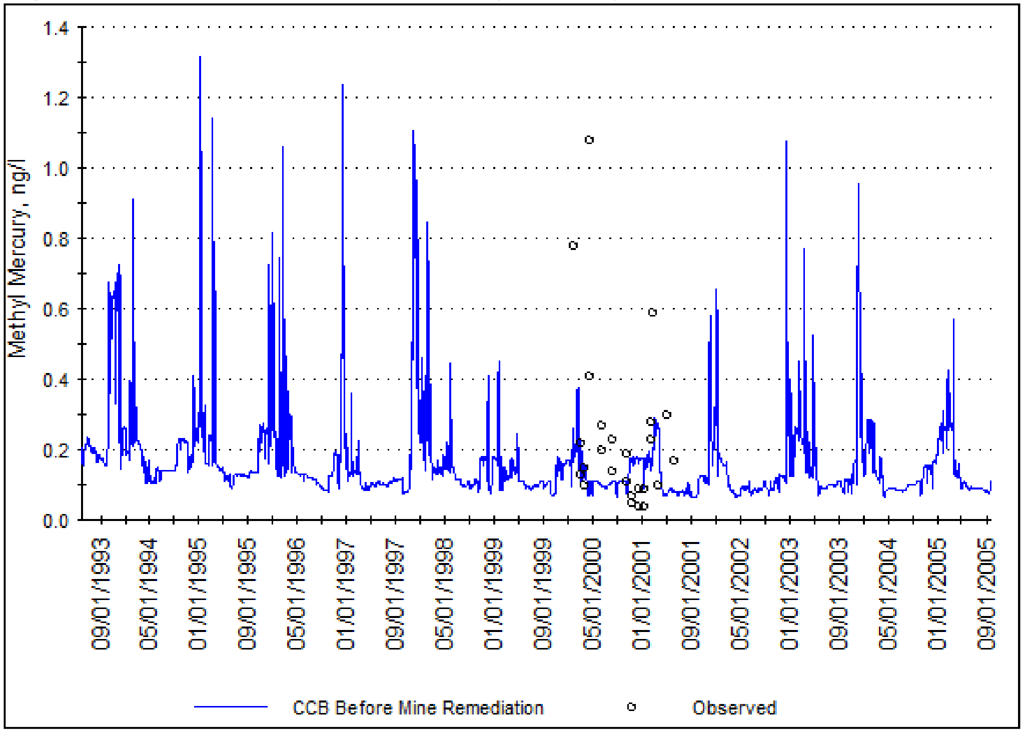


Figure 58: Modeled vs. observed methylmercury at Rumsey

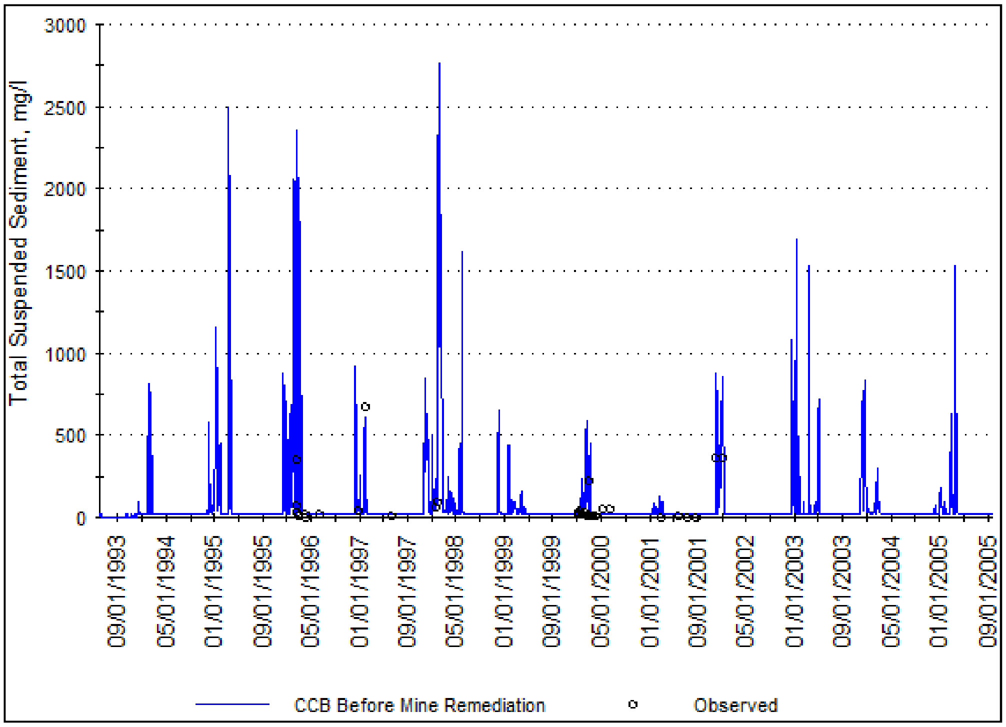


Figure 59: Modeled vs. observed suspended sediment, Bear Creek

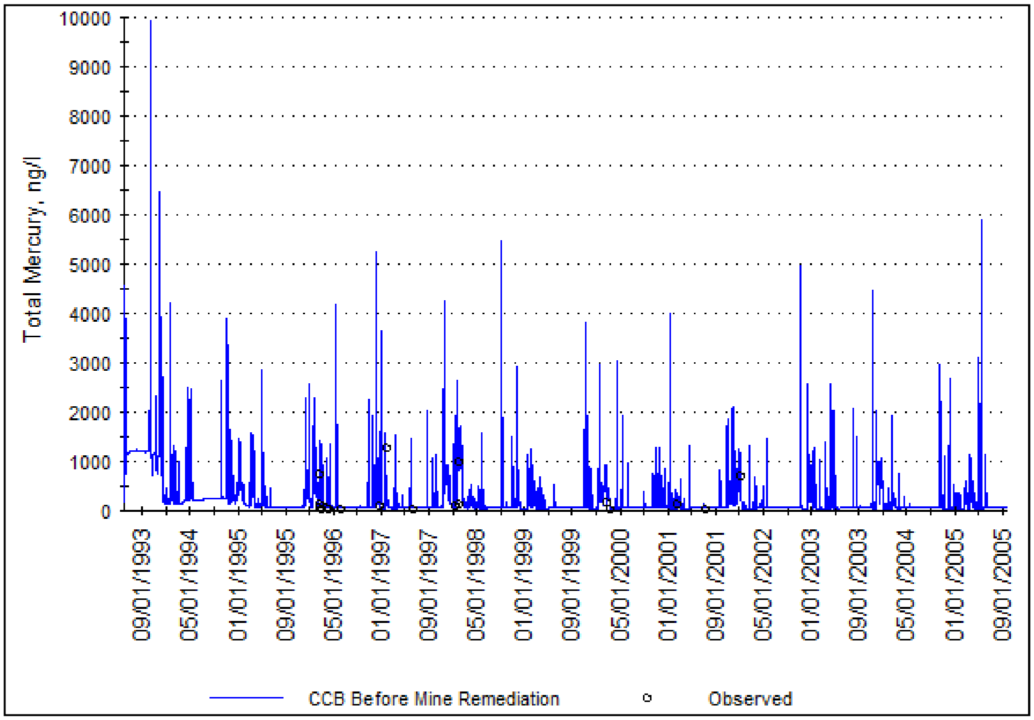


Figure 60: Modeled vs. observed total mercury, Bear Creek

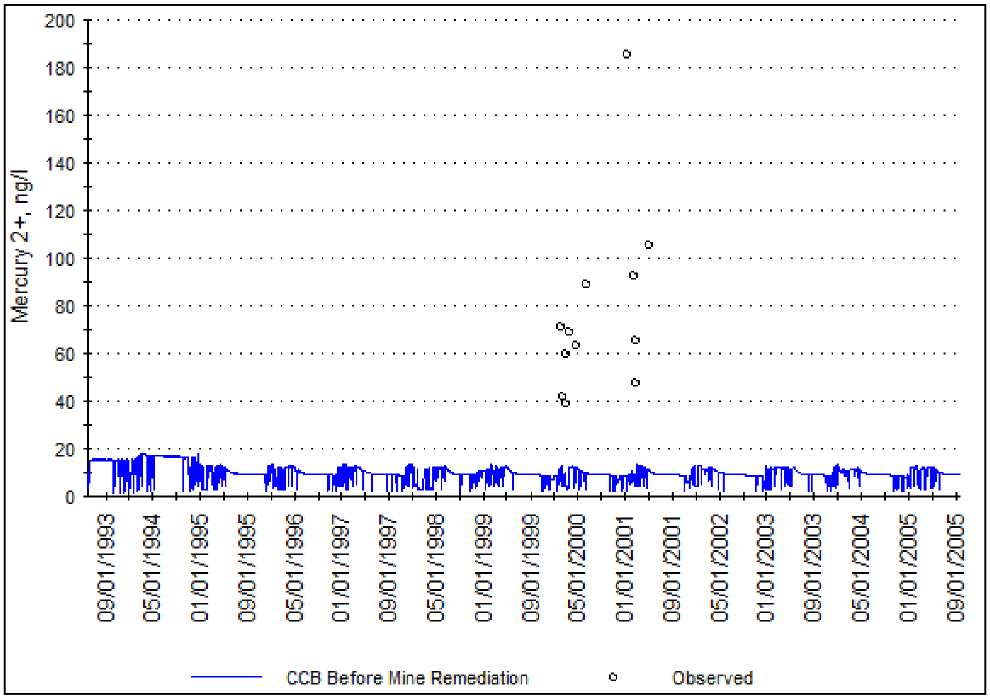


Figure 61: Modeled vs. observed dissolved mercury at the Harley Gulch stream gage. Model does not include the Abbott and Turkey Run mines.

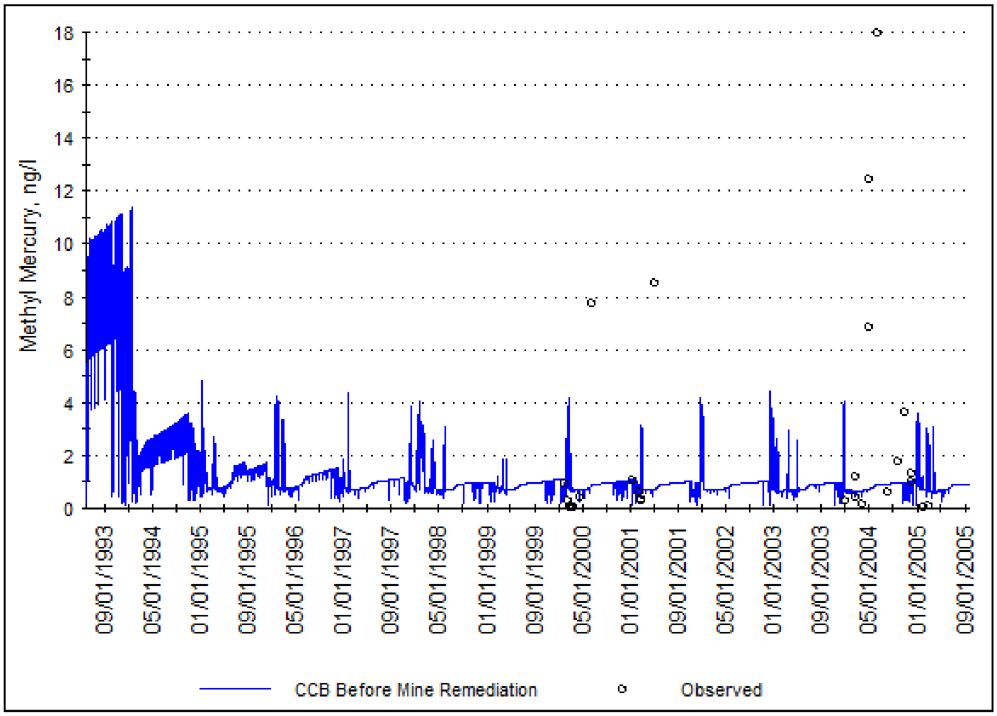


Figure 62: Modeled vs. observed methylmercury at the Harley Gulch stream gage. Model does not include the Abbott and Turkey Run mines.

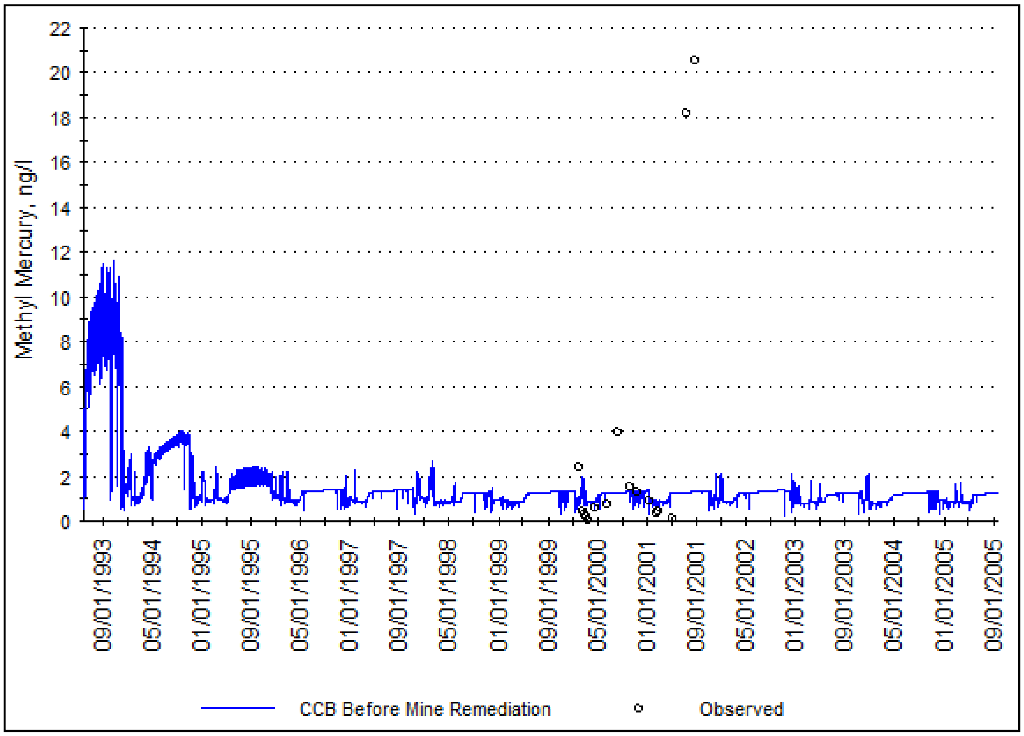


Figure 63: Modeled vs. observed methylmercury in Sulphur Creek.

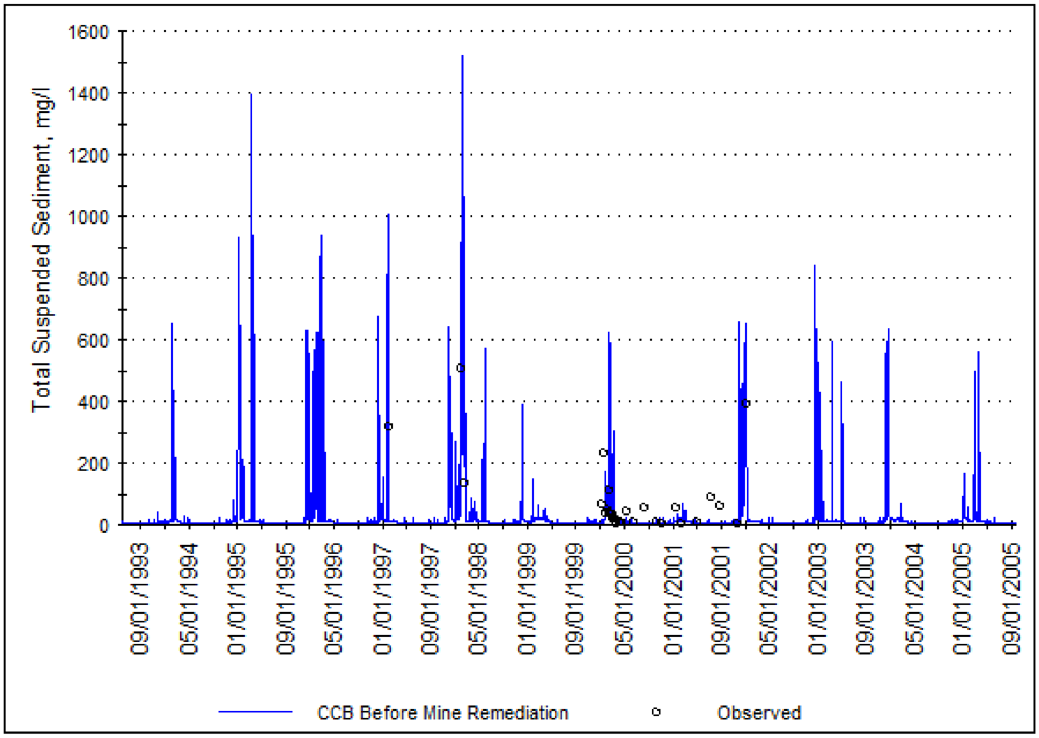


Figure 64: Modeled vs. observed suspended sediment in Sulphur Creek.

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