Remediation of Metal Mines: Heavy Metal Water Pollution British Columbia, Canada

LWS 548: Major Project Report

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August 22, 2023

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1. Acknowledgment

I would like to thank my supervisor, Prof. Les Lavkulich, and our academic coordinator, Julie Wilson, for their selfless help and advice, as well as all of my tutors and classmates for their support and kindness this year. In addition, I would like to thank my parents and friends in China for giving me unlimited moral support even though they are miles apart.

2. Executive Summary

Mining-related heavy metal water pollution is a major environmental problem in B.C., Canada, with serious impacts on local ecology (e.g., food chains, biodiversity, nutrient cycling, and ecosystem function) and population health. Therefore, it is prudent to assess the causes of mining-related heavy metal water pollution in British Columbia and to recommend the most suitable methods currently being used to remediate heavy metal water pollution from mines.

This project is based on a systematic literature review of relevant policies and regulations, remediation methodologies and major case studies (Britannia Mine, Teck and Mount Polley Mine), as well as a specific analysis of the Britannia Mine remediation.

According to the study of mine waste and discharge regulations in British Columbia, and despite joint federal and provincial regulations, historical legacy, inadequate monitoring and reporting, and the complexity of metal contamination have led to persistent metal water contamination problems at mines. Therefore, in addition to preventing new contamination, there is a need to effectively address the past and currently occurring contamination.

In this study, the commonly used methods for heavy metal water pollution remediation were compiled and tabulated with a comprehensive comparative analysis of indicators. The common remediation methods currently used include physical (filtration, adsorption), chemical (precipitation, redox), and biological (bioremediation) methods. Bioremediation is preferred theoretically due to its

lower energy cost and environmental friendliness.

Depending on the mine site, a combination of remediation methods may be a more appropriate remediation strategy. The Britannia Mine was selected for detailed investigation and analysis as it is a typical case of mine contamination in British Columbia and one from which many lessons have been learned.

These analyses lead to recommendations for the prevention, remediation, and public awareness of heavy metal water pollution from mines. This project should increase public awareness of the importance of water protection and remediation measures for heavy metal water pollution. It will help companies and countries save unnecessary costs, reduce possible side effects, and help protect the environment and human health.

3. Introduction

Heavy metal water pollution refers to the degradation or deterioration of water quality caused by abnormal concentrations of metal elements with a density ≥5 g/cm^3 and their compounds in water (Beniah Obinna & Ebere, 2019).

Heavy metal water pollution, both in surface water and groundwater, is a global problem. With the development of modern industry, it is becoming more and more serious for a range of reasons (Table 1), including the promotion of natural rock weathering, surface runoff, and agricultural drainage carrying sediment particles containing heavy metals into water bodies, and contaminated discharge of industrial wastewater.

Table 1. Different sources of heavy metals (Lone et al., 2008)

Heavy metals	Sources
As	Semiconductors, petroleum refining, wood preservatives, animal feed additives, coal power plants, herbicides, volcanoes, mining, and smelting

Heavy metals	Sources
Cu	Electroplating industry, smelting, and refining, mining, biosolids
Cd	Geogenic sources, anthropogenic activities, metal smelting and refining, fossil fuel burning, application of phosphate fertilizers, sewage sludge
Cr	Electroplating industry, sludge, solid waste, tanneries
Pb	Mining and smelting of metalliferous ores, burning of leaded gasoline, municipal sewage, industrial wastes enriched in Pb, paints
Hg	Volcano eruptions, forest fires, emissions from industries producing caustic soda, coal, peat, and wood burning
Se	Coal mining, oil refining, combustion of fossil fuels, glass manufacturing industry, chemical synthesis (e.g., varnish, pigment formulation)
Ni	Volcanic eruptions, landfill, forest fires, bubble bursting and gas exchange in ocean, weathering of soils and geological materials
Zn	Electroplating industry, smelting, and refining, mining, biosolids

Canadian mining activities contribute significantly to heavy metal pollution, for example in British Columbia, it is estimated that there are one million tonnes of waste rock and 950,000 tonnes of tailings produced per day, for a total of 650 million tonnes annually (Hancock, 2016). There are many active and inactive mining sites in B.C. (Figure 1), which generate large volumes of wastewater containing heavy metals, such as lead, copper, zinc, and cadmium from mine drainage, mine cooling, water extraction, and other mining processes. This increases the potential for these heavy metals to enter the environment through various pathways, such as surface runoff, groundwater discharge, and accidental spills, which results in water pollution around mining sites (Qiu & Zhu, 2011; Sonone, et al., 2020). According to an analysis by SkeenaWild and the B.C. Mining Law Reform Network (2021), 116 of the 173 sites identified on the map, either have or have the potential to cause pollution of the surrounding environment, while only two do not pose a threat of water pollution (*New Map Shows Dozens of Mine Pollution Threats in B.C.*, 2021).

Figure 1. B.C. contaminated mine sites map (*New Map Shows Dozens of Mine Pollution Threats in B.C.*, 2021) (Online access: https://reformbcmining.ca/wp-content/uploads/2021/01/BC-Contaminated-Mine-Site-Map_Jan-13-2021-low-resolution.pdf)

In heavy metal-contaminated water bodies, the elements will move from abiotic to living species and accumulate in the biota, creating environmental concerns, such as food chain damage (Figure 2), biodiversity loss, and changes in the nutrient cycle and ecosystem function. Furthermore, due to biomagnification, species at higher trophic levels may possess larger quantities of heavy metals, which may damage human health through the food chain (Zaynab et al., 2022). If humans ingest these foods or are exposed to, or directly drink polluted water, the elements can interact with proteins and enzymes in the body, making them inactive or abundant in certain organs (Jin, 2014), with serious consequences for human health (Table 2).

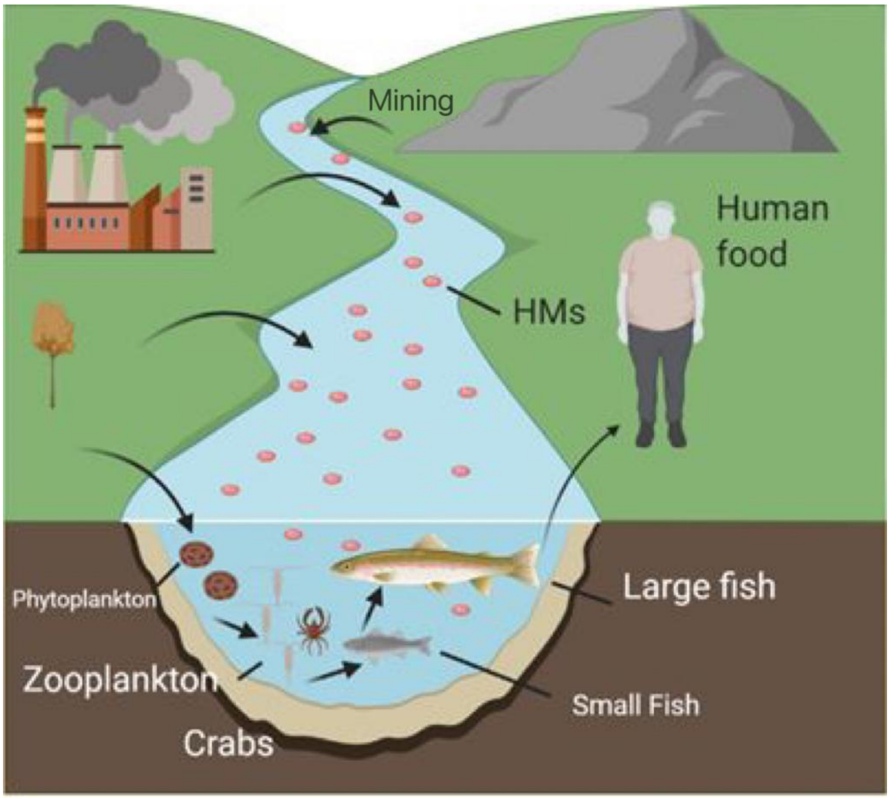

Figure 2. Bioavailability of HMs in food webs. (Zaynab et al., 2022)

Table 2. Human health effects of some heavy metals (Beniah Obinna & Ebere, 2019)

Metal	Effects	Most common Biomarkers of Exposure
Cd	Increased risk of osteoporosis, renal tubular, glomerular, and lung damage, by affecting cardiovascular, developmental, digestive, nervous, urinary, reproductive, and respiratory (From the nose to the lungs) systems.	Blood, urine, feces, liver, kidney, and bone.

Metal	Effects	Most common Biomarkers of Exposure
Cr	Causes allergic dermatitis, low birth weight and also affecting immune, urinary, respiratory, and cardiovascular systems.	Blood or urine
Co	Nausea and vomiting Dermatitis.	Urine and blood.
Cu	Liver and kidney damage, immunotoxic, and death.	Blood, urine, hair, and nails.
Ni	Dermatitis, allergicreaction, and chronic bronchitis.	Blood, bone, and urine.
Pb	Affects the central nervous system, impair neurodevelopment in children, metabolic processes, renal, gastrointestinal, ocular and musculoskeletal systems, thereby causing nausea, anorexia, severe abdominal cramps, colic, weight loss, renal tubular dysfunction, abortion, muscle and joint pains and strong biochemical effect behavioral disorders, low intelligence, strokes	Blood, bone, and urine
Zn	Attacks digestive, haematological, and respiratory system and causing anemia, pancreas damage, and decrease high density lipoprotein (HDL) cholesterol	Serum zinc level. High levels of zinc in feces or urine are indicative of recent exposure

Therefore, it is important to pay attention to the problem of mining-related heavy metal contamination of water bodies in British Columbia and find effective ways to address, or at least mitigate the contamination to protect human health and the environment. The goal of this project is to increase public awareness of the importance of water and environmental protection and to increase understanding of remediation measures for heavy metal water pollution. It will also help companies and countries to save unnecessary costs, reduce possible side effects and help protect the environment and human health.

4. Objectives

The overall aim of this project is to identify current remediation methods for mining-related heavy metal water pollution and to further investigate the effectiveness, efficiency, advantages, and limitations of these methods to determine the methods most suitable for the application for the remediation of heavy metal water pollution from mines in British Columbia.

5. Methods

This project is based on a systematic literature review and analysis of case studies of water contamination from several metal mines to provide an overview of the types of mine contamination events that have occurred in British Columbia. The relevant literature was selected from authoritative or peer-reviewed journal articles, reports, newspapers, and government archives. Starting with the British Columbia mine waste and discharge regulations (Province of British Columbia, n.d.), this report examines why metal pollution from mines continues to reach waterways despite these regulations. And to collate the current methods commonly used to manage heavy metal water pollution to provide a comprehensive comparative analysis of the indicators. The Britannia Mine, which is a typical case of mine pollution in British Columbia, was investigated and analyzed. Finally, recommendations are made for the remediation of heavy metal water pollution from mines are made.

6. Regulatory Frameworks for Mine Waste and Discharges in B.C.

6.1 Regulations

Metal mine wastes and discharges in B.C., Canada, are regulated through a combination of provincial and federal laws and regulations designed to minimize the environmental impact of mining activities. The main provincial regulations include the Environmental Assessment Act (EAA), the Mines Act, and the Environmental Management Act (EMA), and the federal regulations include the Fisheries Act, and the Canadian Environmental Act.

6.1.1 Environmental Assessment Act (EAA)

In British Columbia, the Environmental Assessment Act (EAA) is a significant piece of legislation since it requires mining operations to get permission before releasing effluent. The

Environmental Assessment Office (EAO) reviews major projects, including all mining operations, in accordance with the requirements of the EAA and conducts a comprehensive assessment of their potential environmental, social, economic, and health impacts.

EAA emphasizes the importance of public participation and collaboration throughout the assessment process, providing opportunities for the public, indigenous communities, and stakeholders to provide input, voice concerns, and participate in decision-making (Papillon & Rodon, 2016). The process typically includes reviewing project proposals, engaging with indigenous communities and stakeholders, conducting studies and analyses, assessing potential environmental impacts, and proposing mitigation measures. Finally, whether to approve the proposed project will be approved and, under what stated conditions. The decision may include specific requirements related to mine waste management, water pollution prevention, and monitoring. (Environmental Assessment Act, n.d.)

6.1.2 Mines Act

The Mines Act and its accompanying Health, Safety and Reclamation Code for Mines in British Columbia (the Code, as stated 2022) promote and regulate safe and environmentally responsible exploration and development of mineral resources and protect workers, the public, and the environment through provisions that minimize health, safety and environmental risks associated with mining activities. It establishes requirements and regulations related to all aspects of mining operations, including mining permits, plans of operations, mine safety, environmental protection, mine reclamation, and closure (*Mines Act*, 2022). The Mining Act requires that proposed large mines (e.g., metals and coal), major expansions/upgrades of existing mines, and some large exploration/development projects require approval under Part 10 (Province of British Columbia, n.d.), including specific conditions for waste management, water protection, air quality, and specific environmental protection, reclamation, and closure plans.

The Code is a regulatory document of the Mines Act that provides detailed requirements and guidelines for the health, safety, and reclamation aspects of mining operations. In addition to comprehensive health and safety standards and requirements for mining operations, it also provides for environmental protection and mine reclamation, including provisions for waste management, water management, reclamation planning, soil erosion control, and restoration of disturbed areas (Ministry of Energy, Mines and Low Carbon Innovation, 2022). The Code establishes a framework for inspecting and enforcing mining operations to ensure compliance with health, safety, and reclamation requirements.

As stated, the Mining Act and the Code provide a comprehensive regulatory framework for mining activities in British Columbia. They are designed to safeguard the health and safety of workers and to protect and reclaim land and waterways affected by mining. Ensuring that mining is conducted to the maximum extent possible with minimal environmental disturbance, considering good engineering practices and prevailing economic conditions (Ministry of Energy, Mines and Low Carbon Innovation, n.d.).

6.1.3 Environmental Management Act (EMA)

The Environmental Management Act (EMA) provides the framework for environmental protection, pollution prevention, and management of various activities that may affect the environment. It covers a wide range of activities, such as industrial operations, waste management, and environmental monitoring and gives the B.C. Ministry of Environment and Climate Change Strategy is the authority to develop regulations, standards, permits (including activities such as waste emissions, air emissions, hazardous waste management, water extraction, and landfills), and guidelines (Province of British Columbia, n.d.). Activities that may have an impact on the environment are managed and regulated by conducting environmental assessments for large projects including air quality, water quality, land use, biodiversity, and cumulative effects considered, which also ensures that potential environmental impacts are assessed and mitigated before project approval.

The EMA emphasizes pollution prevention and requires individuals, businesses, and industries to take measures to implement pollution prevention best practices and plans and the use of clean technologies to minimize, or eliminate, the release of pollutants into the environment. At the same time, it provides the authority and procedures to respond to and manage environmental emergencies and establishes mechanisms to ensure compliance with environmental regulations. It gives authorities the power to inspect facilities, issue compliance orders, conduct investigations, and impose penalties for violations, helping to promote accountability and deter violations. (*Table of Contents - Environmental Management Act*, n.d.)

6.1.4 Federal Statutes

Several federal statutes play a crucial role in regulating environmental aspects related to mining projects in British Columbia, Canada. Fisheries and Oceans Canada and Environment Canada have jurisdiction over the Fisheries Act, which includes the Metal Mining Effluent

Regulations that apply to most major mining projects in B.C. Additionally, under the Canadian Environmental Assessment Act, of 2012, the Canadian Environmental Assessment Agency conducts reviews of major projects, including significant mine projects in B.C. Other federal statutes that contribute to environmental protection include the Canadian Environmental Protection Act addressing various aspects of pollution prevention and control, the Migratory Birds Convention Act protecting migratory birds and their habitats, the Navigation Protection Act regulating navigable waters and related construction activities, and the Species at Risk Act that aims to protect endangered and threatened species. (Province of British Columbia, n.d.)

These federal statutes work in conjunction to ensure the conservation of natural resources, the protection of wildlife and habitats, and the assessment of potential environmental impacts in mining projects.

6.2 Possible Pollution Reasons Despite Regulations

Despite the provincial and federal regulations stated above, heavy metal pollution from mines can still reach waterways due to various factors, including legacy issues, technical challenges, compliance and enforcement issues, human error and accidents, and natural disasters.

6.2.1 Legacy Issues

Many of British Columbia's mines were established before modern environmental regulations were implemented. Whereas environmental regulations at that time may have been less stringent, mining operations may not have employed proper waste management practices and containment systems, resulting in pollution from abandoned or idled mines that can continue to impact nearby waterways.

For example, the Britannia Mine near Howe Sound, 50 km north of Vancouver, operated from the early 1900s until 1974. For more than 70 years, mining activities at the site released about 600 kg of metals per day into Howe Sound, generating large amounts of acid mine drainage and heavy metal pollution, making the mine one of the largest sources of metal pollution in North America (Auditor General of British Columbia, 2016). Until its closure in 1974, it remained one of the most polluted areas and continued to impact the surrounding waterways and aquatic ecosystems. Up to 2021, the cleanup has cost $40 million, with an additional $3 million per year to operate a water treatment plant to reduce acid mine drainage and heavy metals entering Howe Sound (Leotaud, 2021).

6.2.2 Compliance and Enforcement Issues

Inadequate monitoring, reporting, and penalties for mining activities and violations may impede the detection and prevention of pollution, resulting in undetected or improperly addressed pollution incidents.

Located in Trail, B.C., Canada, Teck is one of the world's largest lead and zinc smelters. On September 4, 1990, they accidentally spilled 31 gallons of mercury, an unknown amount of zinc, and 300-400 gallons of sulfuric acid in the river. As the B.C. Environmental Incident Report stated, the concentrated sulfuric acid was not reported until 14 hours after the spill occurred because the plant's alarm did not sound. (*Teck Smelter – Timeline of Pollution*, 2011)

Despite regulations and oversight, non-compliance or poor enforcement can occur. For example, Teck agreed to pay $40,000 for a river study in Canada after they admitted to violating their waste management permit in 1991, resulting in zinc and cadmium spills (*Teck*

Smelter – Timeline of Pollution, 2011).

6.2.3 Human Error and Accidents

Human error, negligence, or inadequate training can lead to errors or accidents in mining operations, such as spills, leaks, or equipment failures, which can result in the direct release of heavy metals into waterways.

For example, in 1995 Teck's smelter reported an accidental spill of 1,000 gallons of sulfuric acid. According to their records, the accident was caused by a lack of worker attention. They accidentally released 12.5 million mg/L of arsenic, 186 million mg/L of cadmium, 8.19 million mg/L of mercury, 63.8 million mg/L of lead, and 2.5 tons of zinc in the river. (*Teck Smelter – Timeline of Pollution*, 2011)

On August 4, 2014, a catastrophic failure occurred at the tailings dam at the Mount Polley copper and gold mine in the Cariboo region. The investigation revealed that the accident occurred because the mine engineers failed to consider the glacial silt beneath the tailings containment pond, resulting in a structural defect (*News and Information on the Mount Polley Mine Disaster*, n.d.). This breach released 17 million cubic meters of water and 8 million cubic meters of tailings or materials into nearby water bodies, resulting in significant heavy metal pollution, including elevated levels of copper and selenium, in Polley Lake, Hazeltine Creek, Quesnel Lake, and surrounding watersheds (Ministry of Environment and Climate Change Strategy, n.d.).

6.2.4 Natural Disasters

Natural disasters, such as earthquakes, and extreme weather events, such as heavy rainfall or snowmelt, can damage mining infrastructure, including tailings dams or containment ponds (Government of Canada, 2022). When dams fail and infrastructure is damaged, cracks or spills could be created, which allows associated contaminants to be released into nearby bodies of water. Flooding may carry mine waste, tailings, or contaminated sediments downstream, spreading heavy metal contamination to new areas and affecting aquatic ecosystems along the way.

In addition, natural disasters can disrupt the functioning of water treatment systems used in mining operations. Their resulting power outages, infrastructure damage, or inability to use treatment facilities can prevent the effective removal or containment of heavy metals from mine wastewater. As a result, untreated or improperly treated water may be discharged into waterways during or after a natural disaster, leading to contamination.

For example, on August 29, 1991, heavy rains caused flooding through Britannia Beach. The government removed part of the acid rock drainage (ARD) pipes from the sewerage system for river restoration but this also resulted in untreated sewage and ARD from Britannia Mine flowing through the bottom of the Britannia River, exacerbating the problem of heavy metal water pollution in the area (Britannia Mine Museum, n.d.-b).

Therefore, while B.C. has many provincial and federal regulations in place to regulate or prevent mining-related heavy metal water pollution, they are still not completely effective. Appropriate remediation approaches are needed to address the heavy metal water contamination that has occurred or cannot be avoided in the future.

7. Remediation Approaches

According to Yuehua Jin (2014), the remediation and treatment of heavy metal pollution in water bodies adopt the following two basic approaches:

1. Reduce the bioavailability and migration capacity of heavy metals in water bodies.

2. Completely remove heavy metals from the polluted water.

Various conventional and emerging technologies can be used for the remediation of heavy metal water pollution. These methods can may be simply classified into physical, chemical, and biological treatment processes based on their mechanisms of action. In this section, some of the methods commonly used are listed and their mechanisms of action, conditions of application, influencing factors, and advantages and disadvantages are briefly described.

7.1 Physical Methods

7.1.1 Filtration

Filtration is a traditional physical remediation technique that is widely used to remove heavy metal contaminants from water. The mechanism of this method consists in passing contaminated water through various filtration media or membranes, where suspended particles, including heavy metal contaminants, are trapped in the filter media due to physical mechanisms such as filtration, adsorption, and sedimentation. Its effectiveness in removing particulates and dissolved heavy metals from water is dependent on the type of filtration media used, such as granular media (sand, gravel, or activated carbon filters).

Membrane filtration technology has received a lot of attention in recent years (Xiang et al., 2022). Membrane filtration involves the use of semi-permeable membranes with microscopic pores that selectively allow the passage of water molecules while retaining heavy metal ions and suspended particles. There are various types of membrane filtration for heavy metal removal depending on the size of the particles that can be retained. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) (Figure 2) are the different types that can be used for heavy metal filtration of industrial wastewater (Sharma et al., 2022). According to previous research, nanofiltration and reverse osmosis have higher retention values for the removal of metal ions (Castro-Muñoz et al., 2017). The different types of filtrations can be accomplished by different membrane species made of different materials, such as polymeric and ceramic membranes.

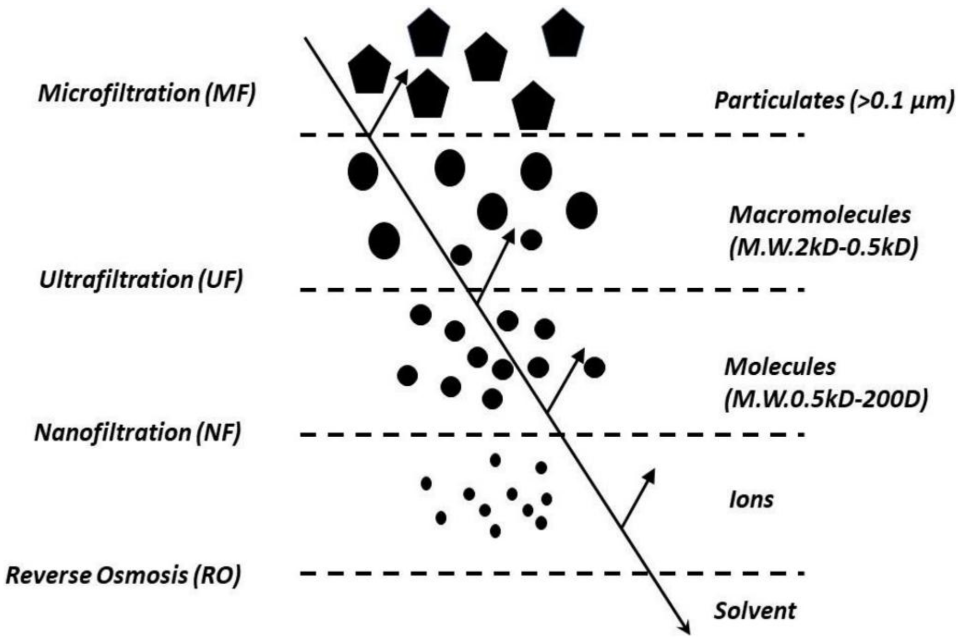

Figure 3. Schematic representation of microfiltration (MF), ultrafiltration (UF), nano filtration (NF) and reverse osmosis (RO) separation principles (Sharma et al., 2022).

In the water treatment process for the mining industry, the feed pump triggers the filtration process by generating pressure that allows the feed water to pass through the membrane. The permeate will begin to pass through the membrane structure as the filtered liquid. First, the permeate will pass through a silicon carbide membrane layer. Next, the permeate will pass through the membrane substrate structure made of a silicon carbide gain that is larger than the membrane coating. After heavy metal filtration is complete, the permeate ends up in a permeate tank that is free of heavy metals. As the effluent is filtered, objects such as heavy metals, particles, oils, and other substances from the feed water will eventually begin to contaminate the membrane. (*Membrane Filtration for Heavy Metal Removal*, n.d.)

Filtration reduces energy consumption and waste generation with high efficiency. It is also easy to integrate with traditional processes and does not require chemicals to be added for treatment. The advantages of polymeric membranes are their ease of manufacture and high efficiency. However, they also face many problems such as fouling deposits on the pores and membrane surface, low thermal and chemical strength, short lifetime, and difficulty in handling corrosive fluids in harsh environments. Ceramic membranes made of silicon carbide are the best and most effective for membrane filtration for heavy metal removal because they are made of inorganic materials that provide mechanical, thermal, and chemical strength and are ideal for membrane filtration for heavy metal removal in harsh environments (Algieri et al., 2021). In addition, it means longer membrane life and higher hydrophilic levels, which provide higher fluxes and fewer membrane contamination problems. However, ceramic membranes are typically more expensive compared to other membrane materials, posing a significant barrier to their large-scale application.

7.1.2 Adsorption

The adsorption method is a common method to treat wastewater by using porous solid substances to attract and bind heavy metal ions for removal. According to the classification of adsorbents, they may be divided into activated carbon adsorption, mineral adsorbent adsorption, and natural adsorbent adsorption (Mureseanu, et al., 2008).

Various substances can be used as adsorbents for the adsorption of heavy metal ions in water. Not only common chemicals (e.g., activated carbon, zeolite, alumina, manganese oxide, and iron oxide), but also agricultural wastes (e.g., walnut shells, coffee grounds, rice husk ash, and sawdust) and industrial wastes (e.g., red sludge, power plant fly ash, and steel slag) can be used as adsorbents. However, the use of natural soils and deposits to remove heavy metals from wastewater appears to be the least effective method because they have limited adsorption capacity and often require large amounts of material to be effectively removed. Recently, the use of graphene-based porous composite hydrogels for the removal of heavy metal ions from wastewater has also been found to be effective (Zhang et al., 2023).

The use of biochar, especially biomass-derived activated carbon compounds and biochar from agricultural wastes, has shown great potential as an adsorbent for water purification and treatment of heavy metal contaminants. Biochar is a solid material rich in carbon, obtained by the thermochemical transformation of biomass at 250-800°C under oxygen-limited or anaerobic conditions (Qiu et al., 2021). According to Zhang et al. (2020), the adsorption of heavy metals by biochar is not a single mechanism but mainly includes physical adsorption, ion exchange, electrostatic adsorption, etc. (Figure 4).

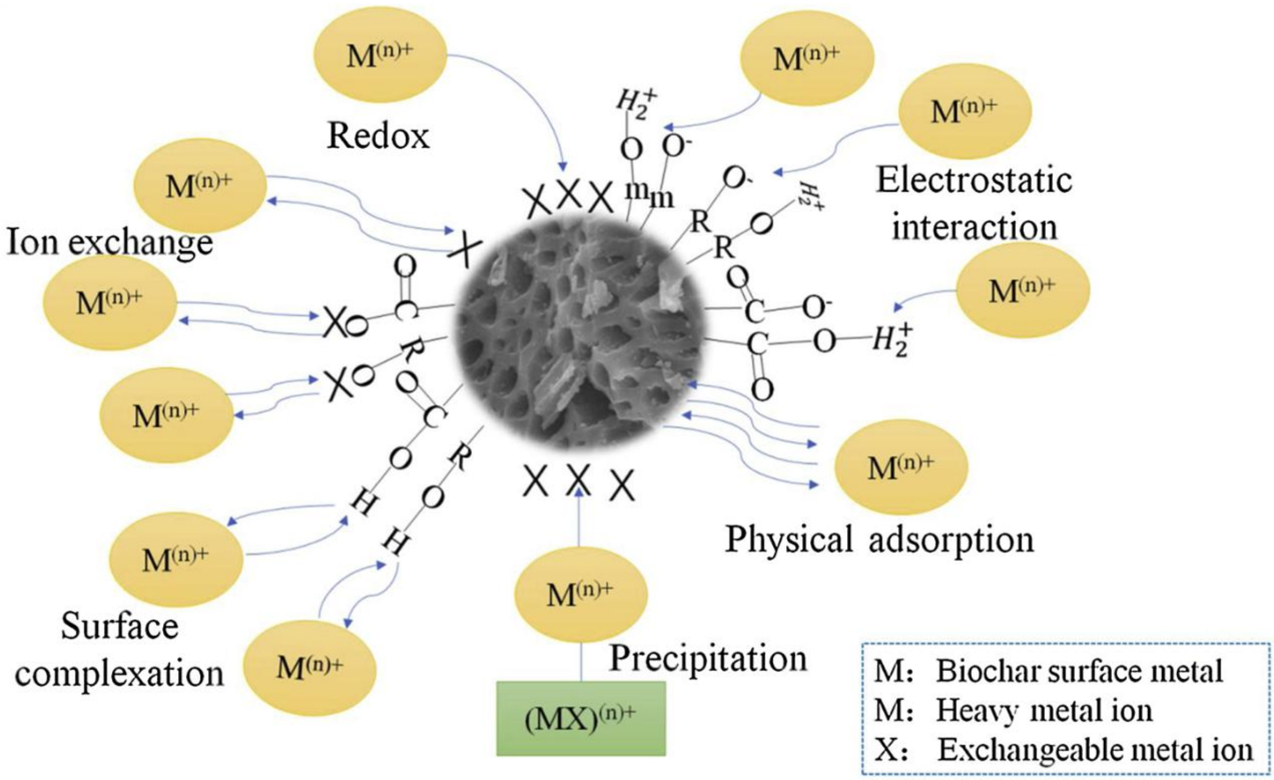

Figure 4. Schematic diagram of adsorption mechanism of biochar on heavy metal ions in water. (Qiu et al., 2021)

The adsorption of heavy metals by biochar is also influenced by various parameters, such as the dose of biochar, water temperature, water pH, type of heavy metals, initial concentration, and the presence of other cations in water (Aziz et al., 2023). According to the research conducted by Roy and Bharadvaja (2021), *Plumbago zeylanica* shoot-derived biochar could be used for the removal of cadmium and chromium from wastewater, and the highest removal efficiency was achieved when incubated for 6 hours under neutral conditions at a biochar concentration of 2 mg/ml and 100 ppm.

Adsorption has proven its effectiveness and economic viability for the removal of heavy metal ions from contaminated water. Due to its efficiency, ease of implementation, operation, design, and adaptability to environmental considerations, it has become one of the main methods for heavy metal removal from water. The main advantages of adsorption-based treatment technologies are the generation of minimal residual waste and the ability to recover and reuse the adsorbent. Biochar is also a widely accepted adsorbent due to several advantages such as its low cost, pore filling effect, π - π stacking interaction, hydrogen bonding, high specific surface area and pore volume, a wide range of functional groups, ability to synthesize from various raw materials and eco-friendliness (Aziz et al., 2023).

However, although adsorption, including biochar adsorption, is an effective method for removing heavy metal contaminants from water, these processes still have some drawbacks. For example, adsorption processes have a limited ability to adsorb heavy metal ions. Once the adsorption material is saturated with contaminants, its effectiveness decreases and it needs to be replaced or regenerated. Regeneration processes can be time-consuming, require additional resources, and may generate waste that requires proper management. In addition, the adsorption capacity of adsorbent materials can be affected by numerous factors that may limit their suitability for certain types of heavy metal contaminants or specific environmental conditions. In some cases, conditions may need to be adjusted to optimize the adsorption process, thereby increasing the complexity of the treatment system. Proper management and disposal of spent sorbent materials to prevent the potential release of heavy metals back into the environment is also critical.

7.2 Chemical Methods

7.2.1 Precipitation

Chemical precipitation is an effective method for removing heavy metals from acid mine drainage. In this process, chemical precipitants (e.g., alum, lime, iron salts, and some polymers) can react with heavy metals in wastewater to produce insoluble precipitation, which results in the removal of heavy metals (Ahmed et al., 2022). The removal capacity and efficiency depend mainly on parameters such as pH, temperature, initial concentration, and ionic charge (Gunatilake, 2015).

Most of the heavy metals in the water are cations. Generally, alkaline substances and anionic substances are added to increase the pH value of the water and promote the formation of precipitation of most of the heavy metals, which can be separated from the water and removed (Jin, 2014). Alkaline conditions (pH 9-11) have the greatest influence on hydroxide precipitation. The mechanism can be expressed by the chemical equation:

$$M^{2+} + 2(OH)^{-} \leftrightarrow M(OH)_2$$

where M^{2+} is metal ions, OH^- is precipitant, and M(OH)2 is the metal hydroxide (Zamora-Ledezma et al., 2021). Sulfide precipitation can be used to remove arsenic(As) from water. Sulfide ions from pyrite react with As (III) ions to form the stable compound As_2S_3. During the reaction, F (II) and As (III) is oxidized to Fe (III) and As (V) and form crystalline iron feldspar eventually, resulting in the removal of about 99.4% of arsenic from the wastewater (Ahmed et al., 2022).

The advantages of the chemical precipitation method are low capital investment, simple operation, and easy automation of the treatment method (Zamora-Ledezma et al., 2021). Hydroxide precipitation is highly efficient and can effectively remove many heavy metals from water, including lead, copper, zinc, and cadmium. Also, the chemicals used for hydroxide precipitation, such as lime (calcium hydroxide) or caustic soda (sodium hydroxide), are relatively inexpensive and the operating process is relatively simple, making the method more cost-effective. Sulfide precipitation has a high affinity for specific heavy metals, such as mercury, copper, and lead, allowing selective removal and high efficiency in the removal of the target heavy metals. The precipitated heavy metal sulfides can also be further processed for metal recovery.

This method also has some disadvantages. For example, the treatment process requires the use of large amounts of chemicals to reduce metals to acceptable discharge levels, thus producing large amounts of sludge containing toxic compounds that require further treatment and may have long-term environmental impacts (Zamora-Ledezma et al., 2021). Hydroxide precipitation requires careful monitoring and adjustment to maintain the proper pH range, and sulfide precipitation methods may result in some heavy metal residues, especially those with low solubility products. In addition, the production of toxic and strong-smelling hydrogen sulfide gas and sulfide requires pre and post-treatment as well as precise control of reagent addition (Ahmed et al., 2022).

7.2.2 Redox (Oxidation-Reduction) Process

Redox reactions can control the oxidation state of elements to convert heavy metal contaminants to inactive states, thus reducing their toxicity or mobility and heavy metal pollution of water bodies (Tandon & Singh, 2015). It can also be used to convert heavy metals into a form that can be more easily removed, such as more easily precipitated, for final removal.

In reduction reactions, zero-valent iron and divalent iron are often used as common reducing agents. For example, zero-valent iron nanoparticles can convert mobile oxide anions (e.g., CrO_4^{2-} and TcO_4^-) and cations (e.g., UO_2^{2+}) into immobile forms. Fe(II)-containing green rusts can reduce Cu(II), Ag(II), and Hg (II) to their elemental forms (Borch et al. 2010). Oxidation processes can oxidize the more mobile, toxic, and easily transported in water selenite [Se(IV)] to selenate [Se(VI)]. Since As(III) is highly mobile and more toxic below pH 9.2, it needs to be oxidized to As(V) and then eventually removed by other removal processes such as coagulation, adsorption, or ion exchange (Lescano et al. 2011). HClO, K_3-$Fe(CN)_6$, Na_2FeO_4, air, pure oxygen, and ozone can all be used as oxidizing agents (Tandon & Singh, 2015).

Chemical redox can effectively target a wide range of heavy metal contaminants to achieve rapid treatment and removal of heavy metals from water, minimizing contact time and reducing overall treatment time. However, care needs to be taken in the selection of chemical oxidizing or reducing agents and the monitoring of reaction conditions to ensure effectiveness and reduce potential secondary effects. In addition, oxidation/reduction processes can be costly due to the need for specific chemical reagents and periodic replenishment and can generate chemical wastes or by-products that can cause environmental problems. These substances need to be properly handled, stored, and disposed of. When considering this method for remediation of mining-related heavy metal water contamination, it is critical to assess the specific characteristics of the heavy metal contaminants, site conditions, and treatment objectives. Regulatory compliance and adherence to safety protocols are also important considerations in implementing chemical redox technologies.

7.3 Biological Methods

7.3.1 Bioremediation

Bioremediation refers to organism-mediated contaminant removal mechanisms that have long-term effects on contaminated sites. The process utilizes the metabolic mechanisms of organisms that develop adaptively in a heavy metal environment for heavy metal detoxification. Commonly used organisms include bacteria, fungi, and plants.

Bacteria are classified as Gram-positive and Gram-negative based on the structure of their cell walls (Sharma et al., 2016). Gram-positive bacteria have peptidoglycan, teichoic acid, and teichuronic acid in their cell walls that contain anionic functional groups and therefore bind metals (Sharma et al., 2016). Gram-negative bacteria, on the other hand, possess an anionic characterization because of phospholipids and lipopolysaccharides. Bacteria commonly used include *Pseudomonas putida*, *Bacillus thuringiensis*, *Bacillus circulans*, *Chryseomonas luteola*, etc. (Karn et al., 2021)

The cell walls of fungi contain large amounts of chitin, dextran, mannan, and chitosan, which are rich sources of metal binding sites such as carboxyl, amine, phosphate, and hydroxyl groups (Sharma et al., 2016). When using fungi as biosorbents, factors to be considered are the initial solute concentration, the nature and concentration of the biomass, and physicochemical factors such as pH, temperature, and ionic strength. The fungi currently used for bioremediation include Aspergillus awamori, Penicillin ochrochloron, Termitomyces clypeatus, etc. (Karn et al., 2021)

Phytoremediation is to use plants to transfer, accommodate or transform pollutants to make them harmless to the environment (Qiu & Zhu, 2011). It mainly removes heavy metals from water through rhizofiltration, phytoextraction, phytostabilization, phytodegradation, and phytovolatilization (Figure 5).

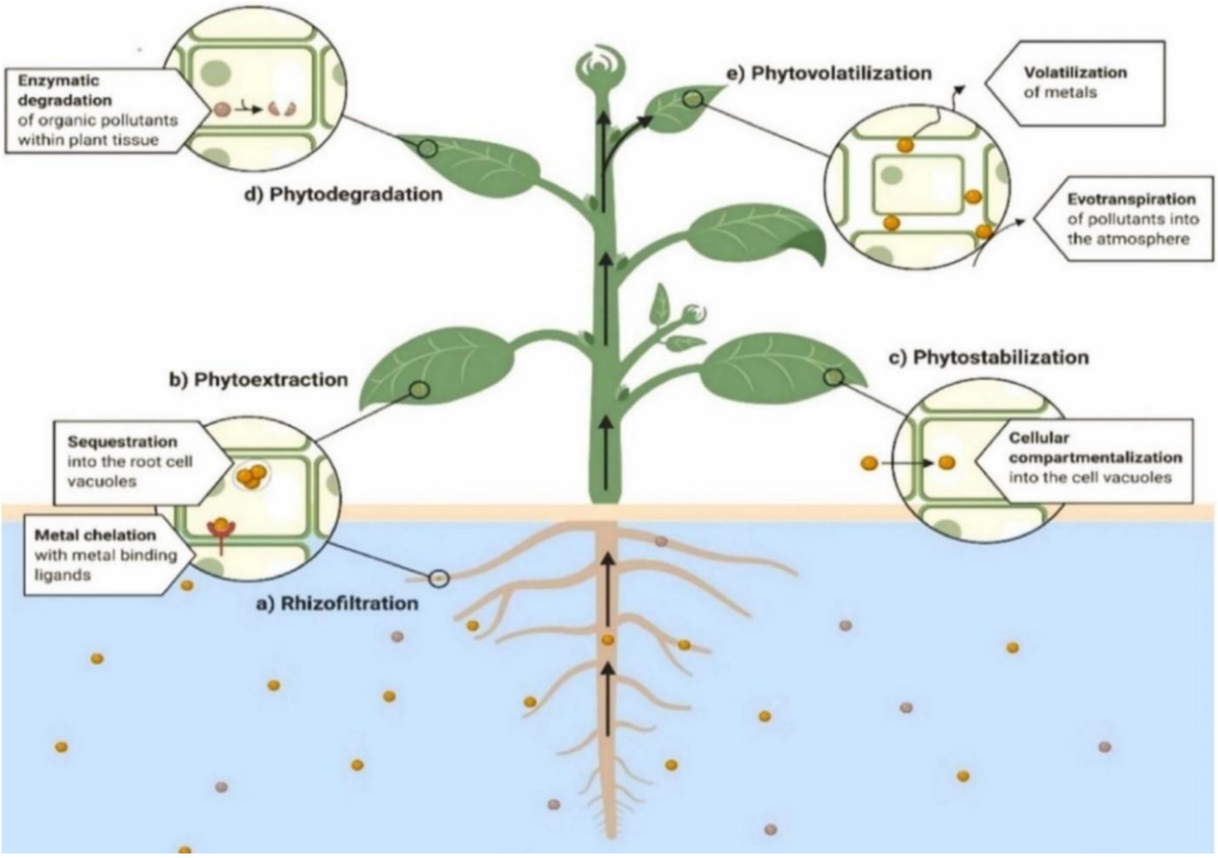

Figure 5. Various processes of phytoremediation (Delgado-González et al., 2021)

Plants with fast growth rates, high biomass, complex root systems, and tolerance to high concentrations of heavy metals are commonly used for phytoextraction and are harvested and destroyed after the accumulation of absorbed heavy metals in roots and shoots (Jyoti et al., 2022). Phytostabilization can be carried out where phytoextraction is not possible, limiting the mobility and bioavailability of heavy metals and preventing their migration to water bodies and food chains (Karn et al., 2021). During phytovolatilization, with the help of specific substances secreted by the roots, metal contaminants are taken up by the plant and converted into a volatile or gaseous state and released into the environment (Jyoti et al., 2022). Indian mustard (Brassica juncea), Indian grass (Sorghastrum nutans), poplar (Populus deltoides), willow (Salix), and sunflower (Helianthus annus) are some of the plants used for phytoremediation (Karn et al., 2021).

When heavy metal concentrations are very low, physicochemical methods may be ineffective or costly, making biological methods an attractive alternative. In addition, it includes sustainable remediation techniques that can correct and re-establish the natural conditions of the water body. Microorganisms can reproduce under harsh environmental conditions and can be applied on-site to minimize disturbance to the ecosystem. Phytoremediation has low infrastructure and maintenance requirements, while it can be applied on a large scale and landscaped to provide habitat for wildlife and contribute to ecological restoration. The approach can be further extended by creating artificial wetland systems with specially selected plants and microorganisms to help remove heavy metals through biological and physical processes. However, compared to some physical or chemical methods, bioremediation can be a slower process and may take time to achieve the desired results.

7.4 Discussion

The reviewed literature indicates that there are many remediation methods for heavy metal contamination of water bodies, suggesting that the problem is being actively addressed with critical attention. However, different remediation methods differ in terms of effectiveness, cost, and target pollutants, each with its advantages and disadvantages, and further comparative analysis is needed to determine which method is most suitable for the application.

Based on the study of the above heavy metal water pollution remediation methods, the following table (Table 3) can be listed, including the advantages and disadvantages of each method.

Table 3. Comparison of different heavy metal water pollution remediation methods.

Type	Method	Advantages	Disadvantages
Physical	Filtration	High efficiency, low energy consumption, less waste generation, easy to combine with traditional processes	Deposition on membrane surfaces, low thermal and chemical strength, short life, and difficult to handle corrosive fluids in harsh environments. Ceramic membranes avoid these problems but are expensive and difficult to apply on a large scale.
	Adsorption	Highly efficient, able to recover and reuse adsorbents.	The adsorption material regeneration process requires additional time and resources and may produce waste. In some cases, conditions need to be adjusted, increasing the complexity of the processing system.
Chemical	Precipitation	Simple operation and the processing method is easy to automate. Efficient, relatively cheap, and more cost-effective.	The use of large amounts of chemicals produces sludge and toxic gases that require further treatment and can have long-term environmental impacts.
	Redox	Effectively target various heavy metal pollutants and maximize the rapid treatment and removal of heavy metals in water.	Chemicals that need to be replenished regularly can be costly. Produce chemical waste or by-products, which can cause environmental problems.
Biological	Bioremediation	Still applicable with low metal concentrations. Sustainable remediation techniques with minimal disturbance to the ecosystem. Phytoremediation can be applied on a large scale while providing habitat for wildlife.	May be a slower process and take time to achieve the desired results.

Overall, the removal rate of physical methods is high, but the actual operation is complicated. Chemical process is simple, but it is easy to cause secondary pollution. As can be seen from the table, as a promising treatment method, the biological method has the advantages of low energy consumption, high efficiency, no secondary pollution, and low treatment cost. However, bioremediation takes a long time compared to physicochemical methods. Also, there is little literature on the restoration of large flowing water bodies, such as polluted rivers and streams (Karn et al., 2021).

The most appropriate remediation method for mining-related heavy metal water contamination in British Columbia depends on a variety of factors, including specific contaminants, site characteristics, environmental regulations, and desired treatment goals. This requires a site-specific assessment to determine the hydrogeological and environmental conditions at each mining site, the type, concentration, and distribution of heavy metals present in the water, and the potential environmental impacts of remediation methods. Cost-effectiveness, ease of implementation, and long-term sustainability should also be considered. Before full implementation, small-scale pilot studies of selected remediation methods can be conducted to assess their effectiveness and efficiency at specific mining sites.

Depending on the severity and complexity of the contamination, it may be necessary to use a combination of remediation methods. For example, using filtration to remove suspended heavy metal particles followed by further treatment of heavy metal ions through other physicochemical processes or bioremediation can provide synergistic effects and better overall results. Environmental experts and engineers can be consulted to design a site-specific and comprehensive remediation strategy for heavy metal contaminants in mining-impacted areas.

8. Case Study – Britannia Mine

Britannia Mine is often selected as a typical example of BC mine remediation because of its extensive contamination footprint and lessons learned for similar cases. Over the years, a variety of remediation and remediation efforts have been undertaken to address heavy metal contamination at the Britannia Mine. These efforts have involved physical, chemical, and biological methods and innovative technologies to minimize the release of heavy metals into the environment and to control or treat acid mine drainage. This section will specifically address the contamination and the remediation process at Britannia Mine.

8.1 Site Information

The Britannia Mine, once one of the largest copper producers in the British Commonwealth, is located about 48 kilometers north of Vancouver on Britannia Beach, on the eastern shore of Howe Sound. It was operated by Britannia Mining and Smelting Ltd. from 1904 to 1963, and by Anaconda Mining Co. after 1963 until it closed permanently in 1974. About 80 kilometers of underground workings and 5 open pits were excavated (British Columbia Ministry of Sustainable Resource Management, 2005). During the operation, the core mined was enough to produce about 800,000 tons of metal, mostly copper, but also lead, zinc, gold, silver, and cadmium (Britannia Mine Museum, n.d.-a).

Exposure of excavation works to air and rainwater leads to chemical reactions (main reaction formula: $2FeS_2(s) + 7O_2(g) + 2H_2O(l) \rightarrow 2Fe^{2+}(aq) + 4SO_4^{2-}(aq) + 4H^+(aq)$) in pyrite (iron sulfide), chalcopyrite (copper ore), galena (lead) and sphalerite (zinc), producing sulfuric acid and dissolves the metal. At the same time, rainfall and snowfall cause large volumes of water (3,600 cubic meters per hour) to flow out of the mine shaft, through the old tunnels, and into the fractured rock created by the mining operation, creating acid rock drainage (ARD). (Britannia Mine Museum, n.d.-a) As the ARD flows out of the mine, it sinks into local creeks and Howe

Sound. According to the Auditor General of British Columbia (2016), 600 kg per day of dissolved metals (e.g., copper, zinc, and cadmium), on average, are washed into Howe Sound, adversely affecting the local ecology.

Between 1995 and 2003, the British Columbia Ministry of Environment's Environmental Monitoring System (EMS) examined concentrations of metal contaminants aluminum, copper, iron, and zinc at freshwater sampling sites near the mine site (Figure 6). The data showed that before the official start of mine remediation in 2001, concentrations of aluminum, copper, iron, and zinc at Site A exceeded the British Columbia Water quality guidelines (WQGs) to varying degrees, with copper levels exceeding the limit the most (Figure 7). Metal contamination from the mine-affected 15 species of mussels, salmon fry, and algae. Invertebrates were influenced and primary production was reduced at Howe Sound. Important food items, such as midge larvae and amphipods were poisoned, and salmonid reproduction and blue mussel growth have been impaired at Britannia Creek. (Alava & Bodtker, 2017)

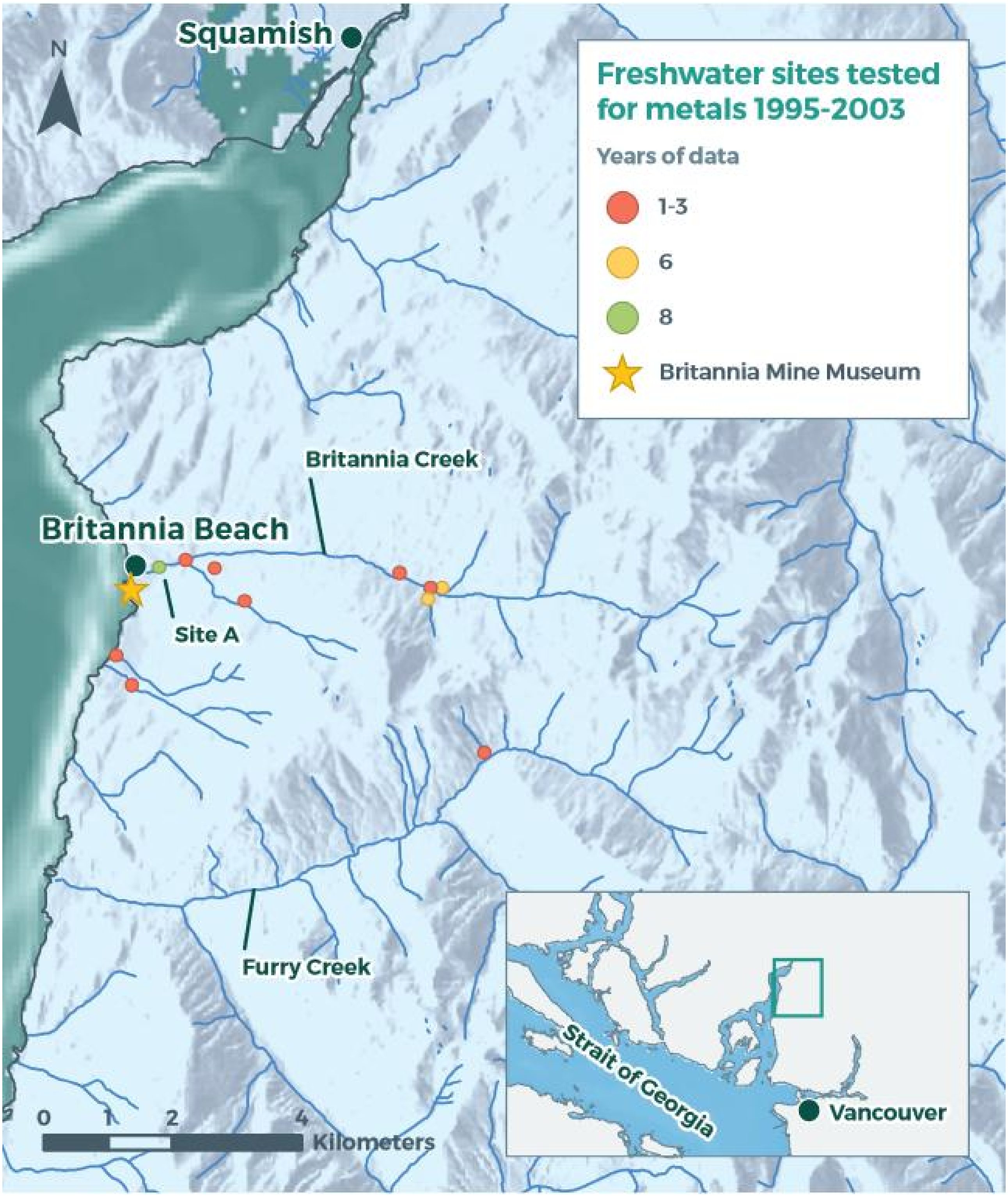

Figure 6. Britannia Beach community, Britannia Mine Museum, and freshwater sampling sites were tested for metal contaminants between 1995 and 2003. (Alava & Bodtker, 2017)

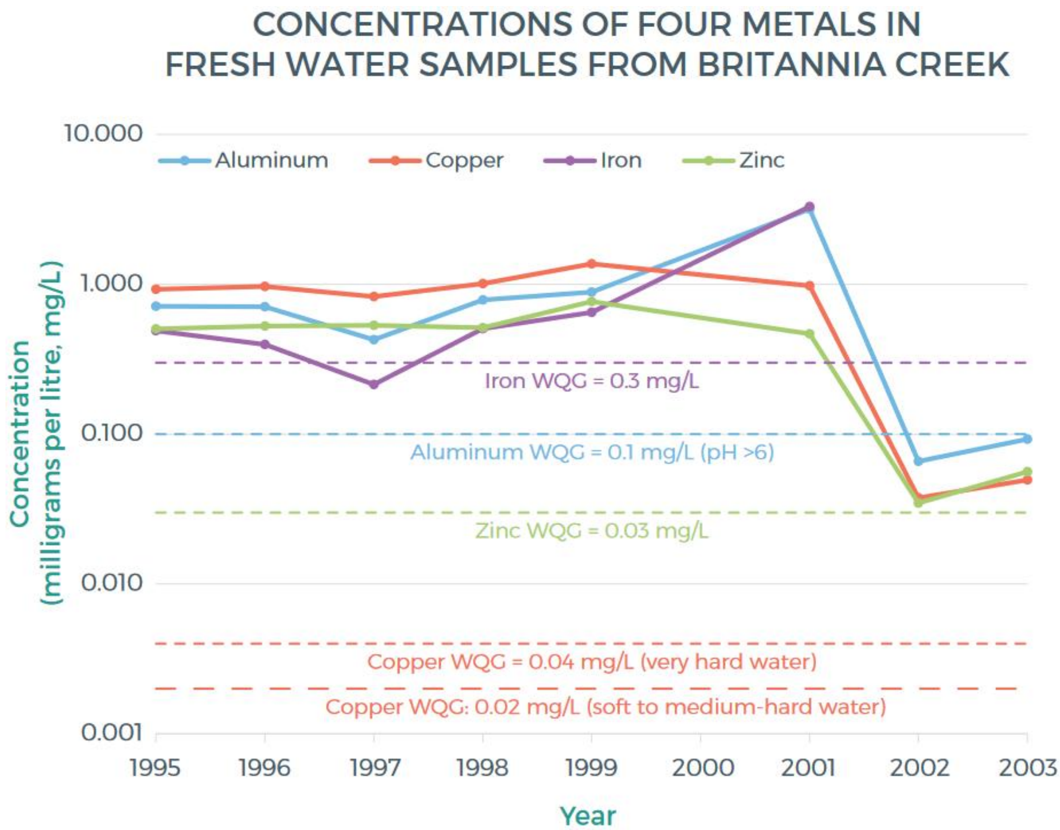

Figure 7. Concentrations of aluminum, copper, iron, and zinc in freshwater samples collected from 1995 to 2003 around Britannia Mine in Britannia Creek (Site A, Figure 6). The y-axis is on a logarithmic scale. (Alava & Bodtker, 2017)

8.2 Remediation

According to Britannia Mine Museum records, the Pollution Control Act, which was enacted in 1967 and enforced in 1970, required a permit for any form of waste dumping and brought the issue of remediation of heavy metal water contamination at the Britannia Mine to the forefront. In 1974, the Pollution Control Department and Anaconda engaged in several discussions that resulted in an agreement for a submarine discharge system in which water from the 2200 level would be redirected to the 4100 level and discharged to a depth of 100 feet. However, the system failed in 1984 due to landslides or debris blockages, resulting in the AMD overflow at Outlet 2200 becoming the most serious problem in the area (Figure 8). In 1995, the BC Environment began a weekly surface water monitoring program. (Britannia Mine Museum, n.d.-b)

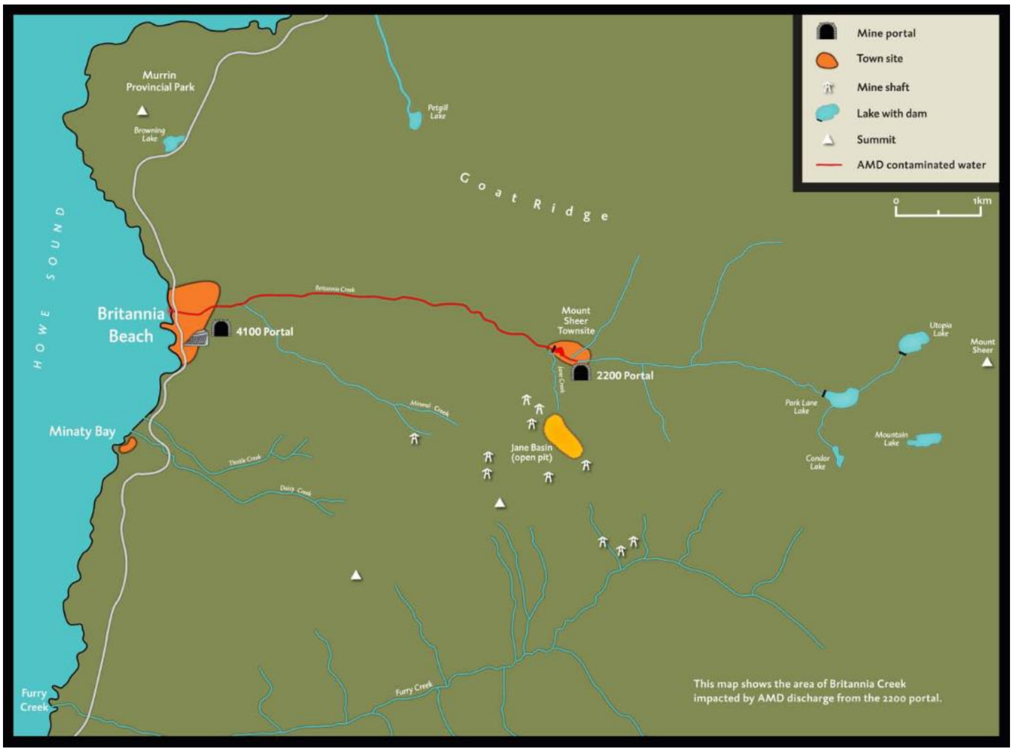

Figure 8. Map showing the area of Britannia Creek impacted by AMD discharge from the 2200 portal. (Britannia Mine Museum, n.d.-b)

At the same time, a report by H.A. Simons (1998) indicated that the Britannia Mine tried a variety of AMD treatment options (Table 4) and ultimately chose a lime-based high-density sludge type process that was best suited to the Britannia site based on capital cost, operating cost, and operational complexity considerations (Tremblay & Hogan, 2000).

Table 4. Summary of AMD treatment options considered for the Britannia Mine (Simons, 1998).

Process	Description	Assessment and Comment
Lime Neutralization Low and High	Lime is added to neutralize acid and precipitate metals. The process is carried out in agitated tanks. Solids removed in clarifier can be recycled to improve performance and increase sludge density.	Density Conventional proven technology for medium to high flows. Can produce high-quality effluent and high-density sludges.
Iron/Alum Coagulation	Iron or alum can be added in some situations to improve performance by coprecipitating metals and generating sludge to enhance the high-density sludge process.	Britannia drainage contains sufficient iron to remove metals via coprecipitation and generate sludge. Testwork did not demonstrate a significant advantage to warrant further consideration.

Process	Description	Assessment and Comment
Neutralization –Alternative Reagents	Alternative reagents such as soda ash, caustic soda and limestone can be considered to achieve neutralization.	None of the alternative reagents demonstrated an advantage over lime. Some may have some applications in combination with lime
Sulphide Precipitation using either Chemical Reagent or Biologically Produced Hydrogen Sulphide	Metals can be removed by precipitation with sulphide using NaHS. Process requires excess of sulphide to be effective for zinc and iron. Sulphide precipitates difficult to settle. Sulphide commonly used to remove Cd and Pb as part of lime treatment.	Reagent costs high relative to lime, since separate neutralization step still required, use of NaHS has no process advantage over lime. Cost of biologically-generated sulphide can be as high as chemical reagents. The need for an organic reductant adds additional cost to the biological system. Not applicable at Britannia due to insufficient cost recovery from metals.
Sea Water Dilution	ARD would be diluted and neutralized by seawater and then settled in a large clarifier to remove precipitates.	Capital costs for clarifier would be very high. Unproven concept. Precipitate could be difficult to settle and thicken. Space requirements would be high. Not applicable to Britannia.
Ion Exchange	Resins exchange H^+, OH^-, or other ions for contaminant ions. Resin regeneration removes the contaminant ions into a concentrated waste stream.	Resins subject to fouling by suspended solids or organic compounds. Concentrated waste regenerant stream still requires extensive additional treatment to generate dry product for disposal. Complex system with high capital and operating costs. Potential for high purity products but no significant process advantage over lime treatment.
Activated Carbon Adsorption	Carbon used to adsorb heavy metals, acts as catalyst to oxidize reduced species such as ferrous iron.	Carbon does not have affinity for some metals. Could require extensive pre-treatment. Costs for replacement of carbon would be high. Not widely practised for primary removal of metals.
Reverse Osmosis	Water flows across semipermeable membrane under pressure in excess of osmotic pressure; contaminants remain behind. Currently used for small flows and desalination.	Subject to gypsum and suspended solids fouling, may require pre-treatment. Complex system with high pressures required. Membrane replacement costs could be high. Concentrated waste solution requires additional treatment, does not produce a dry product.
SX/EW Solvent Extraction in Combination with Electrowinning and Direct Electrowinning	Certain contaminants transferred from aqueous solution to immiscible organic solvent. Solvent regeneration gives concentrated contaminant stream that can be treated via electrowinning.	Potential for selective recovery of valuable contaminants (e.g., copper by electrowinning). Highly complex with high capital and operating costs. Solvent losses costly for low-strength feed. May not be effective for zinc and iron, not practical at Britannia at low copper

Process	Description	Assessment and Comment
		concentrations insufficient cost recovery from metals to cover additional costs.

In 2001, UBC initiated a research project to address this problem. The plan was to build an 8-meter-thick concrete plug on the 2200 portal with a system of outflow pipes and valves carefully controlling the flow of water from the mine to the treatment facility, allowing all water to be redirected to the 4100 portal next to the water treatment plant (Figure 9). At the same time, the mine can act as a reservoir to balance seasonal flows, capable of storing up to 430,000 cubic meters of water (Britannia Mine Museum, n.d.-a). The project immediately reduced acid mine drainage from Britannia Creek and nearshore areas and allowed the beach ecosystem to begin to recover. Within six months of its installation, blue mussels were re-colonizing the estuary (Britannia Mine Museum, n.d.-b).

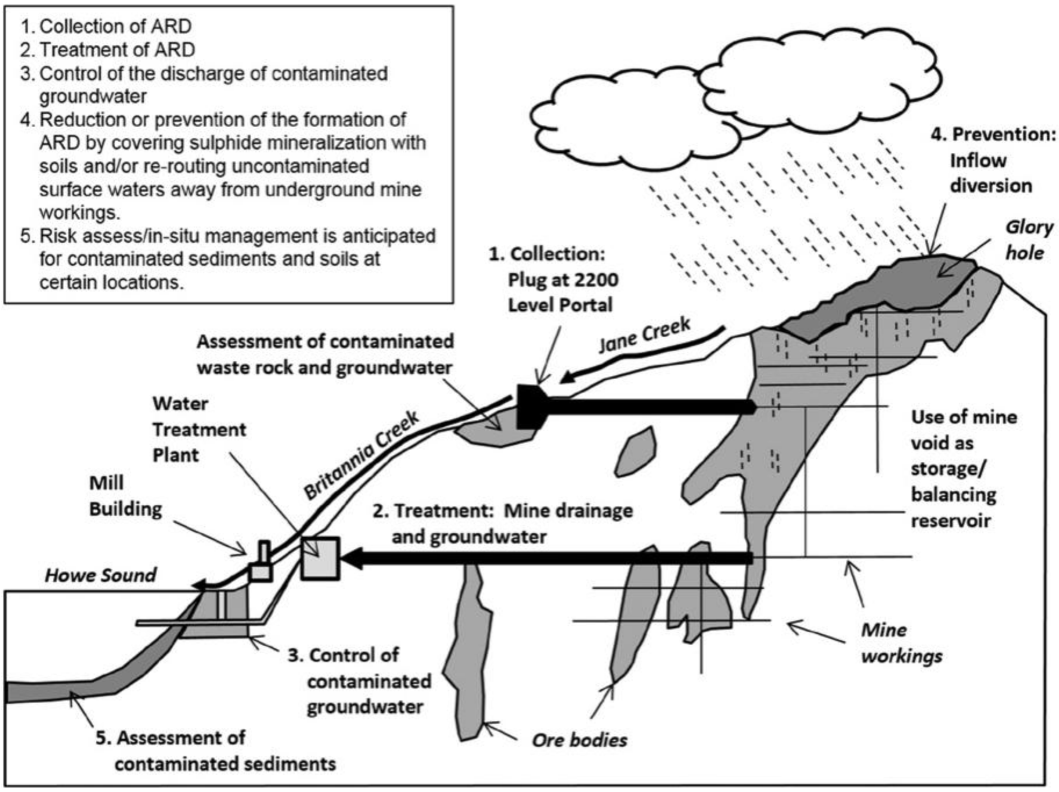

Figure 9. Some of the pollution prevention measures and remediation systems required to address and mitigate metal contamination in the coastal marine environment from Britannia Mine. (Alava & Bodtker, 2017)

Another key component of the Britannia Mine remediation project is the water treatment plant, which began operations in 2005. The treatment plant is a public-private partnership between the Ministry of Sustainable Resource Management and EPCOR Water Services Inc. at a capital cost of $15.5 million (EPCOR, n.d.).

The purpose of the water treatment plant is to treat ARD before the water enters Howe Sound. According to EPCOR's website, the treatment facility uses slaked lime to precipitate dissolved heavy metals out of the mine water. The alkaline lime neutralizes the acidic water, causing the pH of the ARD to rapidly increase from 3.8 to 9.3, at which point the dissolved metals (including copper, iron, zinc, aluminum, manganese, and cadmium) precipitate out of solution to the greatest extent possible (Britannia Mine Museum, n.d.-a). The lime/sludge mixture that settles to the bottom of the settling tank is dewatered (dried to 45%) and stored off-site. After final testing for pH and turbidity, the treated wastewater flows down a 1,700-meter drainage into Howe Sound.

Golder monitored dissolved metal levels and their ecology on the Britannia coast after the remediation project began. It was proved to be effective, winning the Government of British Columbia Premier's Award for Innovation and Excellence 2007 and the Fraser Basin Council Caring for Ecosystems Award 2006. (EPCOR, n.d.) By the following summer, there were positive changes in the Britannia intertidal zone. There are still some hot spots, but the quality of the shoreline and water has improved dramatically and life has returned. Pink and silver salmon were also found in the lower reaches of the Britannia River in 2011. (Britannia Mine Museum, n.d.-a)

9. Conclusion

Despite combined federal and provincial regulations, mining-related heavy metal water pollution remains a significant environmental problem in B.C., Canada, with serious impacts on local ecology and population health. Historical legacies, inadequate monitoring and reporting, and the complexity of metal contamination contribute to the persistence of contaminants in aquatic ecosystems. In addition to preventing new contamination, there is a need to effectively address the contamination that has already occurred.

Remediation methods commonly used today include physical (filtration, adsorption), chemical (precipitation, redox), and bioremediation. Theoretically, bioremediation is preferred due to its low energy consumption, no secondary pollution, and low treatment cost. In practical application, it is necessary to design a comprehensive remediation strategy for the affected area that is appropriate for the mine site, based on the water quality analysis, contaminant distribution, hydrogeological and ecological conditions of the mine site, as well as cost-effectiveness, implementation and long-term sustainability. A combination of remediation approaches may be necessary for this purpose. Collaboration between government agencies, the mining industry, researchers, and local communities is essential to promote sustainable mining practices and implement robust remediation strategies.

10. Recommendations

In response to the challenges and complexities of mining-related heavy metal water pollution in British Columbia, Canada, the following recommendations are made to improve remediation efforts and protect water resources.

First, to prevent new contamination, regulations need to be constantly reviewed and updated to match technological advances and emerging best management practices in heavy metal remediation. At the same time, supervision over mining sites' work needs to be strengthened, with strict compliance with existing regulations to hold mining companies accountable for their environmental impacts. Strengthen monitoring and reporting by implementing a comprehensive and robust monitoring program that regularly assesses water quality in and around mining sites and encourages mining companies to transparently report on their pollution prevention measures. Promote sustainable mining practices that prioritize pollution prevention and mitigation. Encourage mining companies to implement cleaner production technologies and waste reduction strategies.

For contamination that has already occurred, a site-specific assessment should be conducted to determine the type and concentration of heavy metals in the water, as well as the hydrogeological and environmental conditions at each mining site. Consider the effectiveness, efficiency, cost, practicality, and sustainability of implementing each method at a given mining site and assess their potential environmental impacts to ensure that the method selected minimizes further damage to ecosystems and natural habitats. In addition, there is a need to ensure that the selected remediation methods comply with local, provincial, and federal regulations in British Columbia regarding water pollution and remediation activities. Based on the findings of this project, bioremediation techniques can be explored. Species suitable for specific metal contaminants in different regions of British Columbia can be identified and promoted for the natural absorption or degradation of heavy metal contaminants. A comprehensive monitoring program can also be implemented to track the progress of remediation efforts, to keep abreast of the latest research and technological developments in the remediation of heavy metal water pollution, and to adjust the chosen approach according to monitoring results and new scientific advances. These require collaboration between government agencies, the mining industry, researchers, and local communities to achieve the goals of eliminating or mitigating heavy metal contamination and restoring and protecting affected ecosystems and water resources.

In addition, education needs to be encouraged to raise public awareness of the importance of maintaining water quality and the impact of heavy metal pollution on ecosystems and human health. Specific measures could include presentations in communities or schools, popularizing science in mining sites, etc. The Britannia Mine Museum, for example, provides an educational resource for visitors, students, and researchers, showing the mine's history and restoration efforts and raising awareness of the historical impacts of mining activities on water contamination. By learning about past practices and consequences, visitors can become more informed advocates for responsible mining practices and pollution prevention.

By implementing these recommendations, it is believed that B.C. can make significant progress in addressing mining-related heavy metal water pollution, protecting water resources, and promoting sustainable mining practices that benefit the environment and local communities.

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Communication Feature

REMEDIATION OF MINING-RELATED HEAVY METAL WATER POLLUTION IN BRITISH COLUMBIA, CANADA

By: Tingxuan Zhou
Master of Land and Water Systems
https://mlws.landfood.ubc.ca/student-projects/

Despite statutes, mining-related heavy metal water pollution is still serious in BC

⟶ **Prevent** new contamination
& **Remediate** current contamination

1 INTRODUCTION

Heavy Metals

- Metallic elements (density ⩾5 g/cm3)
- Move from abiotic to living species

Mining activities in BC can produce

- Daily: **1 million** tonnes of waste rock & **950,000** tonnes of tailings
- Annually: **650 million** tonnes

(Hancock, 2016)

2 STATUTES

(Province of British Columbia, n.d.)

Provincial

- **Environmental Assessment Act**
  - require permission before discharging
- **Mines Act** & **Health, Safety & Reclamation Code for Mines**
  - require approval for existing mines' upgrades
- **Environmental Management Act**
  - use permits, regulations & enforcement options

Federal

- **Fisheries Act**
  - Metal Mining Effluent Regulations
- **Canadian Environmental Assessment Act,2012**
  - review major mine projects in BC
- **Canadian Environmental Protection Act**

POSSIBLE POLLUTION REASONS DESPITE REGULATIONS

- Legacy Issues (Britannia Mine)
- Compliance & Enforcement Issues (Teck)
- Human Error & Accidents (Teck, Mount Polley Mine)
- Natural Disasters (Britannia Mine)

3 REMEDIATION METHODS & COMPARISON

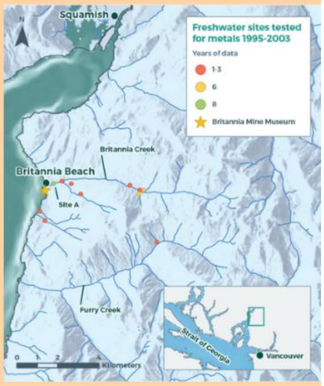
Type	Method	Advantages	Disadvantages
Physical	Filtration	High efficiency, low energy consumption	Deposition on membrane surfaces, low thermal and chemical strength, short life, difficulty in handling corrosive fluids in harsh environments
	Adsorption	Highly efficient, can recover and reuse adsorbents.	The adsorption material regeneration process requires time and resources
Chemical	Precipitation	Simple operation and the processing method, easy to automate.	Use large amounts of chemicals, produces sludge and toxic gases, requires further treatment
	Redox	Effectively target heavy metal pollutants, rapid treatment, and removal	Chemicals need to be replenished. Produce chemical waste or by-products, cause environmental problems.
Biological	Bioremediation	Sustainable remediation techniques, and minimal disturbance to the ecosystem.	Maybe a slower process, take time to achieve the desired results.

Theoretically preferred - Environmentally friendly → Biological

4 CASE STUDY - BRITANNIA MINE

- **600 kg/day** of dissolved metals were washed into Howe Sound, adversely affecting local ecology

(Auditor General of BC, 2016)



- Concentrations of Al, Cu, Fe, and Zn exceeded BC Water Quality Guidelines

Remediation

- **1967** (enacted) - **1970** (enforced): The Pollution Control Act
- **1974**: Submarine discharge system (redirected and discharged to a depth of 30m)
- **1995**: Weekly surface water monitoring program
- **2001**: 8-meter-thick concrete plug & water treatment plant (lime-based sludge process, began operations in 2005)

(Alava & Bodtker, 2017)

5 CONCLUSION & RECOMMENDATIONS

Prevention

- Review & update regulations
- Implement monitoring program
- Promote sustainable mining practices

Remediation

- Practically, **site-specific assessment**
  - contaminant distribution
  - hydrogeological & ecological conditions
  - cost-effectiveness
  - implementation
  - long-term sustainability

Government, Mining Industry & Local Communities Collaboration