IRON MOUNTAIN: THE HISTORY AND COMPLICATIONS IN METAL ORE MINING, REMEDIATION AND RECLAMATION OF A NATIONAL SUPERFUND SITE

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Abstract

Metal ore mining has been a critical part to modern society both in what they produce and what they do for the economy. They do, however, come with several environmental impacts. This report discusses different impacts including geological impacts, air quality impacts, soil and agricultural impacts, and water quality impacts. This report focuses on the Iron Mountain Superfund Site north of Redding, California. Based on information gathered from an in-depth literature review, this thesis provides a general examination of the various environmental impact associated with metal ore mining along with several possible remediation processes and techniques. Also discussed is the background of the Superfund Program, the general mining process and the basic geology and history of operations at Iron Mountain. There is a large focus on the specific issues associated with the Iron Mountain Site as well as the different remediation efforts that have been conducted at the site. This report, with the provided information, is written to provide information as to the mistakes that have been made and the most effective ways to prevent another operation like Iron Mountain to occur.

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1. Introduction

Iron Mountain is a historical mining operation that operated from the 1860's to 1963. The mountain itself is described as a massive iron sulfide deposit where iron, copper, gold, pyrite, silver, and zinc were extracted. The operations that took place at the site were a combination of open pit and underground mining, milling, rail transport of mined ore, cyanide leaching plant, and smelting facilities. Iron Mountain is located nine miles northwest of Redding, California (USACE, 2018). The large deposit found at Iron Mountain makes up the southernmost section of the West Shasta Mining District. Iron Mountain contains approximately 4,400 acres of land where, once mining operations stopped, close to 10 individual mines were located in and on the mountain. These included The Old Mine, No. 8 Mine, Richmond Mine, Hornet Mine, Confidence-Complex Mine, Mattie Mine, and an open pit operation at Brick Flat, which is near the mountain's peak (EPA, 2006). Iron Mountain has some of the most acidic water in the world (Nordstrom & Alpers, 1999) and is designated by the U.S. Environmental Protection Agency as a one of 98 Superfund sites located in California.

The purpose of this thesis is to discuss the history, background, and basic geology of the Iron Mountain Superfund site, briefly elaborate on the superfund program, analyze the various environmental impacts associated with this type of mining as well as the impacts that have and are occurring specifically at this site. Also assessed in this report is what the U.S. and state governments have done to reclaim and remediate the site and how changes in environmental regulations have helped prevent this caliber of damage from taking place again. To accomplish this, a literature review has been conducted utilizing government documents and reports as well as numerous peer reviewed scientific articles. Reports from multiple agencies including the U.S.

Army Corps of Engineers (“USACE”), U.S. EPA, U.S. Geological Survey (“USGS”) as well as both federal and state Department of Fish and Wildlife, have been used as reference in this study.

1.1. History and Basic Geology

The Iron Mountain deposit was formed between 350 and 400 million years ago in a marine environment due to geothermal vents on the seafloor releasing sulfur-rich fluids (Alpers et al., 2003). The mountain deposit was originally discovered in the 1860s and was determined to contain silver and iron in 1879, which is when mining originally began. The internal deposits of sulfide were discovered around the mid-1890s when major copper mining began (EPA, 2006). Multiple sulfide pockets were located throughout the mountain as much as 60 meters thick. The three largest orebodies were Brick Flat, Richmond, and Hornet deposits. The Richmond deposit was located between 2,600 feet and 3,300 feet in the mountain and the hornet deposit was located between 2,100 feet and 2,600 feet. They originally comprised a single massive deposit 1.4 kilometers long, 300 meters wide, and 60 meters thick, but was then divided by normal faults within the mountain (Alpers et al., 2003). A total of 6.8 million tons of material was extracted at Iron Mountain over the course of operations and the mine was the top producer of copper in California, sixth in the country and tenth in the world. There were several different individual mines that made up the Iron Mountain Mine operation. The Old Mine, No. 8 Mine, Confidence-Complex Mine, Mattie Mine, Richmond and Richmond Extension Mines and Hornet Mines were all mined via underground operations while Brick Flat was mined as an open pit operation. (Alpers et al., 2003; EPA, 2006).

1.2. The Superfund Program

The Superfund Program was established in 1980 as part of the Comprehensive Environmental Response, Compensation, and Liability Act. The main push for this legislation was from the events that took place at Love Canal in New York with the discovery, in the 1970s, of large quantities of hazardous waste buried beneath the town. The mission of the Superfund Program is to provide funding to the U.S. EPA for the cleanup of abandoned hazardous and toxic sites. It also pushes responsible parties, such as land owners and factory owners, to clean up after themselves or even pay back the EPA for their cleanup of the site (Publishers, 2010). There is a specific process in order to have a toxic site be cover under the Superfund Program. In order for the EPA to take action through the Superfund Program, the site must score above 28.5 on the EPA's Hazard Ranking System in order to be placed on the National Priority List (NPL). The NPL is the group of toxic sites that would qualify for federal funding to clean up. From 1980 to 2009, the EPA identified at least 47,000 sites that could potentially require clean up and of that 47,000 sites only 1,269 have been placed on the NPL (Hird, 1993).

The Superfund action process starts with a remedial investigation and feasibility study, which determines the level and scope of contamination, potential risks and possible remedies. A remedy plan is chosen based on the results of the investigation and a Record of Decision is formed (Hird, 1993; Publishers, 2010).

1.3. The Mining Process

The mining process associated with metal ore extraction depends on the type and location of the deposit. The first step in the mining process is made up of two phases. Those phases are drilling and blasting. Drilling is both an exploratory process and pre-mining process, which is used to extract sample cores of the deposit to examine the quality and a rough idea of where the deposit is located. Drilling is also used to create the access tunnels, or adits, to conduct underground mining (Norgate & Haque, 2010). Blasting involves the use of explosives to separate the desired ores from the hard rock. The blasting material is made from a combination of explosives and powder. The most common explosive used is ammonium nitrate/fuel oil. The powder aspect of the blasting is determined by the amount of explosive used per unit of rock blasted as well as the type of rock to be blasted. Blasting has been a crucial part of hard rock mineral mining for many years making it easier and less labor intensive for extraction (Norgate & Haque, 2010).

The second step in the mining process is ventilation. This is the process of moving stale and contaminated air from the underground mine shafts and replacing it with clean fresh air from the surface. This is crucial for the health and safety of miners as the inhalation of dust and metallic particles can lead to severe respiratory and other health issues. The ventilation process can also aid in the cooling of work areas in deep underground mines (Norgate & Haque, 2010).

The third step of the mining process, which is also an ongoing process, is the dewatering of the open pits and mine shafts. This is an important aspect as it helps to prevent the uptake of toxic metal contaminants by water. The dewatering of mining areas also helps to clear the work areas and aids in the health and safety of miners (Norgate & Haque, 2010).

The fourth step is another continuous process in mining operations, the loading and hauling of excavated, or blasted materials. In the world of open pit mining, excavators or loaders will pick up the blasted or extracted material and load it into large haul trucks to be carried to different locations such as train car loading areas, conveyor belt systems or directly to processing facilities (Norgate & Haque, 2010). This leads to the fifth step in the mining process, which is the crushing and grinding of the mined material. This is the process of crushing the extracted material down to a more manageable size of coarse product (larger than 5mm). The grinding process reduced mined material down to a finer grain product (less than 0.1mm). The efficiency of these processes is determined by the extraction process and how the material was initially fractured (Norgate & Haque, 2010).

The final step of the mining process is separation, which involves the separation of the valuable and desired ores and minerals from the host rock. Flotation and screening are the two most common separation methods in metal ore mining (Norgate & Haque, 2010). Flotation involves the chemical treatment of mined material forcing the desired ore to separate, attach to air bubbles, and float to the water surface where they are then collected. Screening is the more popular of the two methods in iron ore mining. Screening involves the pouring of mined material through a series of screens allowing the desired material to fall through the whole series to be collected at the bottom (Norgate & Haque, 2010)

These processes, while generally tied to modern mining practices, can be related to historical operations at Iron Mountain. The same general practices have been used for many generations with the only changes coming in the technology used. The only other difference is the regulations and safety practices that are in place to protect the operators from injury and fatalities.

1.4. Environmental Impacts of Mining

There are several environmental impacts associated with the mining and processing of metal ore mining and processing, that are tied to different methods of mining. These methods include open pit and underground mining, both of which were utilized at Iron Mountain. The environmental impacts generally associated with metal ore mining and processing include geologic impacts, water impacts, air and greenhouse gas impacts, and economic impacts. These impacts, while general to modern metal mining operations, still apply to the historical mining operations that took place at Iron Mountain.

1.4.1. Geological Impacts

The first, and obvious, impact to the environment is the effect mining has on the geologic structure of the area. While mines can range in size from a few acres, others, such as the Bingham Mine in Salt Lake County, Utah, whose open pit alone is four kilometers across and one kilometer deep (Hibert et al., 2014). Open pit mining impacts the geology of the mining area differently than underground mining in that it requires the removal of large quantities of over burden, which is the topsoil and general dirt that has little to no value. The removal of overburden can result in the excavation of thousands of cubic yards of material that are usually stored in stockpiles somewhere on the property. Any form of open pit surface mining will leave a noticeable indent and scar on the surface, especially on mountains (Altun et al., 2010). Underground mining has a different kind of geologic effect in that it deteriorates the geologic structural integrity of the mountain as the interior of the mountain is excavated and extracted. The major issue regarding underground mining and the effect on the mountain's structural integrity is subsidence, which is the vertical aspect of ground movement. This is due to the creation of the creation of a large cut out or cavity beneath the surface (Altun et al., 2010). Subsidence and slope deformation can have serious impacts on surrounding communities by the wiping out of structures, neighborhoods, water sources and infrastructure. The main causes of subsidence and slope deformation by underground mining are cracking, changes in the geologic stress distribution throughout the rock, and a change in the water aspects of the upper soil (Altun et al., 2010).

1.4.2. Air Quality Impacts

Impacts to air quality are of great concern in the mining and metal processing industry. Air quality is impacts by several different processes. These processes can range from the greenhouse gas emissions from the mining equipment and processing facilities to the dust particulates that are emitted from the physical mining and transport of material. It can also encompass the indirect impacts from the energy production required to power the facilities. The two main contributors to air pollution are particulate matter and gas emissions. Particulate matter emissions come from multiple different sources, including the blasting of drill holes and rock for excavation, the diesel emissions from mobile equipment, the dust that is kicked up from mobile equipment, as well as the dust that is emitted from the transfer or dumping of material into transport containers. Particulate matter can have a serious detrimental effect on human health. Different types of material particulate matter can lead to different impacts. In the mining industry, multiple kinds of metals and minerals are removed from the earth and can be released into the air, each with its own impacts to humans. Smelting also leads to a large amount of air pollution via the release of vaporized metals. Smelting is the process where the desired metal is removed from the ore by way of heating beyond the metal’s melting point. This results in the release of metals into the atmosphere.

The metals produced from mining and smelting can lead to severe impacts on air quality and human health. A large portion of these contaminants undergo atmospheric deposition and contaminate the soil in areas surround the mines and smelters. The release of lead from mining and smelting operations is one of the many problems in terms of air quality. Lead is a known neurotoxin and can lead to developmental issues in children at a young age. Atmospheric deposition is an aspect of larger concern regarding lead, especially if found in and on crops and other food stuffs that are to be consumed by the public (Dudka & Adriano, 1997; Thornton, 1996).

Cadmium is also another metal contaminant of concern. Cadmium is known to be found where Zinc is produced; for every 1mg of Zinc produced, 3kg of Cadmium are produced. Cadmium is of environmental concern due to plants readily uptaking it, its ability to accumulate in food chain crops, and its persistence once released into the environment. It is also a known human carcinogen and accumulates in the body due to its extensive half-life (IARC, 2012). Copper, another metal released into the atmosphere from mining and smelting, is an essential nutrient in the human body at low levels. At high concentrations, however, it can lead to gastrointestinal ulcerations and hepatic necrosis along with several other adverse effects (Dudka & Adriano, 1997; Thornton, 1996).

Zinc and Arsenic are also released during mining and smelting operations. Zinc, while also a necessary nutrient in the human body, can also be toxic in high volumes. Arsenic is also a contaminant that can be released in the mining process. Arsenic is a known human carcinogen and is naturally occurring in rock and sulfide deposits (IARC, 2012). It is vaporized at 615 degrees Celsius and is released into the atmosphere with the smelting of metal ores. These can be inhaled by humans, but a large portion of these contaminants are deposited on surrounding soils which lead to even greater risk of human exposure and uptake (Dudka & Adriano, 1997; Tabelin et al., 2018; Thornton, 1996).

1.4.3. Soil and Agriculture Impacts

Soil and agricultural impacts from mining are caused primarily through atmospheric deposition of contaminants. Soil can undergo acidification from acid mine drainage, which will be discussed in a future section, as well as the emission of acidic compounds from smoke stacks. The metals and compounds of significance to air quality play a role in agriculture and soil contamination.

Lead deposited on soil can affect the agricultural industry located near mining operations. Lead in soil has been known to be accidentally ingested by grazing cattle, though it does not have a detrimental effect on the quality of meat. Lead has also been known to be deposited on garden vegetable such as lettuce, which can lead to ingestion and uptake by humans. The main route of lead ingestion is through accidental direct consumption of soil and dust with special concern regarding infants and toddlers as lead is a known neurotoxin and can lead to developmental complications. In areas of mining and smelting operations, lead is more readily bioavailable in the soil (Dudka & Adriano, 1997; Tabelin et al., 2018; Thornton, 1996).

Arsenic is another contaminant of concern in soil and agriculture as it is commonly found in areas where Cadmium and Lead are found and mined. These are considered trace metals found in soils that contaminate surrounding areas leading to negative effects on agricultural production (Dudka & Adriano, 1997; Tabelin et al., 2018; Thornton, 1996).

1.4.4. Water Quality Impacts

Mining can have an adverse effect on water quality. This is the issue of primary concern regarding the Iron Mountain Superfund Site. Two sources of poor water quality are runoff and acid mine drainage, with the latter being the source of primary concern. The main source of acid mine drainage is the waste rock piles and mine tailing on the Earth’s surface. The acidity of the mine drainage comes from trace metals in the surface piles being taken up by surface water. The other source of acid drainage comes from unmined ores being exposed to rain and other weathering processes, which is also referred to as acid rock drainage (Alpers et al., 2003; Fields, 2003).

The mineral that is most common in creating acid mine drainage is pyrite with other metal sulfides adding to the process. The trace metals responsible for the acidity in mine drainage include aluminum, cadmium, copper, iron, zinc and copper. The main components necessary for the formation of acid mine drainage are sulfide minerals, water or humid atmospheric conditions, and an oxidant, typically oygen, from the atmosphere or chemical source (Salomons, 1995).

The effects of acid mine drainage are detrimental to surrounding water sources and biological species. Acid mine drainage can have chemical, physical, biological and ecological effects on the environment (Gray, 1997). Chemically, acid mine drainage leads to increased acidity and lowered pH. It can also lead to the elimination of the bicarbonate bufferinig system, which is a mechanism in the blood stream of humans to balance carbonic acid, bicarbonate ion, and carbon dioxide to maintain blood pH levels. Acid mine drainage also leads to an increase in the concentrations of solluble metals in waterbodies, as well as an increase in metal particulate matter in the environment (Gray, 1997). Physically, acid mine drainage leads to substrate modification, which is the soil that plants and other organisms are located on. Acid mine drainage also leads to increased velocities and turbidity, in streams, due to the increase in material suspended in the water currents, sedimentation of the toxic contaminants into the sediment at the bottom of the water body, as well as a decrease in the penetration of light (Gray, 1997). Biologically, acid mine drainage is best known for causing the following effects on species: behavioral effects from neurotoxins, respiratory issues from inhalation of high quantities of material, acute and chronic toxicity leading to various adverse effects or death, the overwhelming of organisms’ acid-base balance, as well as migration, and avoidance of contaminated areas (Gray, 1997). Ecologically, acid mine drainage can result in habitat modification either physically or biologically, the loss of niches for various species, bioaccumulation through the food chain, which could eventually reach human populations through consumption of contaminated fish species, the elimination of prey and food sources, elimination of sensitive species, a reduction in the primary productivity in food chains, as well as complete modification of food chains (Gray, 1997). One of the challenges with trying to document and predict the effects of acid mine drainage is the variability in terms of releases from underground mine tunnels and open pits. This challenge is documented in a case study of acid mine drainage in the Witwatersrand Basin in South Africa. The variability in this case was attributed to the seasonal variability between the wet and dry seasons, where higher levels of electrical conductivity and Iron were observed in the wet season. This was determined to be caused by the increased inflow of water into the mine tunnels or from a rise in the water table leading to water seaping into the polluted areas (Tutu et al., 2008). Acid mine drainage is one of the primary concerns regarding the clean up and remediation of old mine operations (Gray, 1997; Liang & Thomson, 2009; Salomons, 1995).

1.4.4.1. Possible Treatment Options

There are several different possible options for the treatment of acid mine drainage, with prevention being the best option. One of the many options for reducing the impact of acid mine drainage is to reduce the amount produced. There are several methods to minimize the production of acid mine drainage. One such way is through the flooding and sealing of deeper portions of mine tunnels. The dissolved oxygen in the water will be taken up by oxidizing micro-organisms and the sealing of the tunnel will prevent more dissolved oxygen from entering into a reaction. This is only fully effective if all tunnels and compartments are known and sealed, otherwise oxygen will still be able to enter the area and react with the sulfide (Akcil & Koldas, 2006; Johnson & Hallberg, 2005).

Another possible method for the minimization of acid mine drainage is disposal of potentially acid producing mine tailings into underwater storage. Shallow waters can be applied along with covering the tailings with sediment and/or biological material which will help in reducing the amount of oxygen reaching the acid producing material below (Johnson & Hallberg, 2005). Another potential option for minimizing the production of acid mine drainage is through the combining of acid producing material with acid consuming material. This in turn will create material that is non-threatening to the environment. While these methods appear effective in theory, the practicality and feasability of their application gives rise to difficulty. This makes the only effective method regarding acid mine drainage the reduction and minimization of the impacts of the drainage (Johnson & Hallberg, 2005).

There are two categories of processes for the mitigation of acid mine drainage: abiotic and biotic. In abiotic mitigation there are active and passive technologies. The active tecchnologies make up the most popular methods in mitigating acid mine drainage (Johnson & Hallberg, 2005). This involves the active treatment of drainage with a chemical neutralizing agent. By adding alkaline materials to acid mine drainage the pH is raised, the rate of oxidization of iron is increased, as well as causing many of the other metals present in the sollution to precipitate. This results in the creation of a sludge with very high iron concentrations, along with other metals. Some of the agents that can be used for neutralization inlude lime, slaked lime, calcium carbonate, sodium carbonate, sodium hydroxide, magnesium oxide, and hydroxide (Johnson & Hallberg, 2005).

The passive approach to abiotic mitigation is also through the addition alkaline material to the drainage. The process for this approach, however, is the use of anoxic limestone drains. The use of this system allows for the addition alkaline material while maintaining the iron as its reduced form to minimize the possibility of oxidization (Johnson & Hallberg, 2005). In this system, acid mine water flows through limestone gravel in the drain which is designed to keep outside air and water out of the drain. Anoxic limestone drains are effective in short time periods as buildup of hydroxide particles decreases drain permeability leading to failure after just six months. These drain systems are commonly found as part of a whole passive treatment system usually including aerobic or compost wetlands (Johnson & Hallberg, 2005).

The biological remediation strategies are based on the working of different microorganisms to create alkaline conditions, essentially reversing the original acidification reactions. These methods of biological remediation are passive processes and are advantageous for their low operating costs (Johnson & Hallberg, 2005).

The first method of biological remediation is aerobic wetlands, which involve the use of oxygen. These are construtced to treat mine drainage that is net alkaline with the main remediation process being the oxidation of iron within the wetlands. The alkalinity of the water prevents a drop in the pH in the mine water and, if levels are not where needed, anoxic lime drains are incorporated into the system (Johnson & Hallberg, 2005). These wetlands are shallow and operate based on surface flow of the mine water. Various aquatic species are planted throughout the wetland to help naturally control water flow and provide additional surface area for the precipitation and filtration of iron compounds and minerals. Plants may also contribute to the oxidization of the main water due to transport of oxygen from the upper portions of the plant down through the roots. Another process that takes place in the aerobic wetlands is the removal of arsenic from the acid mine drainage. This occurs primarily through the absorption on to positively charged iron colloids within the aerobic wetlands (Johnson & Hallberg, 2005).

The second method for biological remediation is through anaerobic wetlands or compost bioreactors. These anaerobic wetlands do not require oxygen for their processes. One of the key features of this method is these wetlands are built completely underground and have no aquatic plant life associated with them (Johnson & Hallberg, 2005). The processes of the compost bioreactors involve reactions initiated by microorganisms. These reactions create alkaline conditions and biogenic sulfide and, in turn, are used to treat waters that are net acidic and have high concentrations of metals. These pools are filled with organic material compost that are the source of the electrons needed to react with the acidic materials. The compost itself is usually composed of biodegradable material such as manure, and less degradable materials such as saw dust. The less biodegradable materials are assumed to have a major role in the remediation of acid mine drainage through their presence in the pools (Johnson & Hallberg, 2005).

The third method of biological remediation involves both aerobic and anaerobic wetlands. An example of this method is the "Acid Reduction Using Microbiology" ("ARUM"). This method uses two oxidation cells where iron is both oxidized and precipitated. After passing through these two oxidation cells, the acid mine drainage makes its way through two ARUM cells where alkali and sulfide are created. Aquatic plants generate the sulfate reduction. These remediation operations tend to be successful in high latitude and subtropical regions (Johnson & Hallberg, 2005).

The fourth biological remediation method is permeable reaective barriers. These systems involve the construction of a trench of sorts within the natural flow line of the acid mine drainage. These trenches are then filled with reactive material, which tend to be comprised of organic solids and limestone gravels. The microbiological processes within these systems create alkalinity and removal of metals (Johnson & Hallberg, 2005). The final passive biological system is an iron-oxidizing bioreactor. These systems utilize mostly autotrophic prokartyotes. The main factor affecting the efficiency of this system is the number of organisms present within the system (Johnson & Hallberg, 2005).

There is one active biological remediation process for treating acid mine drainage. This process is through a sulfidogenic bioreactor system. While these are not as widely used, they have three potential advantages in the remediation of acid mine drainage. These advantages include a more predictable and easily controlled performance, they allow for some heavy metals to be recovered and reused, and they help reduce the concentrations of sulfate in processed waters (Johnson & Hallberg, 2005). These systems use the biogenic production of hydrogen sulfide to facilitate alkalinity and remove metals from the drainage. There are two systems of this method; the Biosulfide and the Thiopaq systems. The Biosulfide system has both a biological and chemical aspect. The raw drainage enters the chemical component where it interacts with hydrogen sulfide from the biological component. With this interaction and manipulation, selective separation and removal can occur for specific metal sulfides. The remaining water runs through the biological component creating the hydrogen sulfide needed for the chemical component (Johnson & Hallberg, 2005). The Thiopaq system differs from the Biosulfide method in that it uses two microbiological processes. Its process involves the conversion of sulfate to sulfide along with the precipitation of metal sulfides, and the conversion of excess hydrogen sulfide to basic sulfur (Johnson & Hallberg, 2005).

2. Iron Mountain

The previously described impacts are general to the mining industry but are applicable to the events and operations found at Iron Mountain. The following sections will analyze the specific issues and complications found at Iron Mountain Mine that are of special concern to the U.S. government.

2.1. Acid Mine Drainage at Iron Mountain

Iron Mountain Mine was designated a Superfund Site by the USEPA in 1983 (USACE, 2018). Iron Mountain has been the historical source of extremely toxic acid mine drainage in the Sacramento River and other local water bodies. The waters currently found at Iron Mountain are extremely acidic, with pH of negative 3.7. The most acidic water is found in the underground tunnels of the Richmond Mine and has been referred to as some of the most acidic water in the world (Nordstrom & Alpers, 1999).

Iron Mountain is surrounded by several waterbodies including Slickrock Creek, Boulder Creek, Spring Creek, Flat Creek and the Keswick Reservoir. Mining operations left several mine tailings and waste rock piles in the watershed regions of these waterbodies. Once the Keswick reservoir was completed in 1950, a delta was indirectly created behind the dam and a major storm caused a large runoff event. A total of 20 fish kill events have been documented since 1963 in the Sacramento River resulting from uncontrolled flow of acid mine drainage. The acid mine drainage that flows into the Sacramento River affects the drinking water of the inhabitants of Redding, California as well as threatened and endangered fish species such as steelhead trout and Chinook Salmon (Druschel et al., 2004; Finlayson et al., 2000; Nordstrom et al., 2000).

The Richmond Mine at Iron Mountain has been the main source of concern regarding the acid mine drainage from the Superfund Site. The effluent, or waste runoff, from the portals of the Richmond Mine contain high concentrations of sulfate, iron, zinc, copper, arsenic, cadmium and thallium. The acid mine drainage at Iron Mountain is specific to the oxidation of pyrite, which involves the transfer of 15 moles of electrons for every one mole of pyrite (FeS_2). The reaction converts pyritic sulfide to sulfate and Fe^{2+} to Fe^{3+}. While oxygen is the main controller of pyrite oxidation, ferric iron is the most effective and efficient oxidant. Prior to any Superfund remediation activity, over 2,500 tons of pyrite and 300 tons of cadmium, zinc and copper weathered and drained into the Sacramento River annually (Druschel et al., 2004; Finlayson et al., 2000; Nordstrom et al., 1999; Nordstrom et al., 2000).

2.2. Remediation

Remediation at Iron Mountain has been taking place since 1986 after the site was placed on the National Priority List in 1983 (USACE, 2018). The advisory council governing the cleanup is a joint government cooperation called the Iron Mountain Mine Natural Resources Trustee Council. This group is composed of several federal and state agencies including the U.S. Fish and Wildlife Service, U.S. Bureau of Reclamation, U.S. Bureau of Land Management, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, and the California Department of Fish and Wildlife (Council, 2002). The potentially responsible party was determined to be Aventis CropScience USA, formerly known as Rhône-Poulenc Chemical Company. As the potentially responsible party, they are responsible for supplying the work and finances for the cleanup of the Superfund Site per the orders of USEPA. The current property owner is listed as Iron Mountain Mines, Inc (EPA, 2006).

Remedial investigations and feasibility studies were completed in 1985, after the site was placed on the National Priority List. Several potential treatment options were discussed including no action, diverting the surrounding creeks away from the site, limestone treatment operations at major point sources to neutralize acidity, capping of the mountain to prevent water infiltration into the underground mine tunnels, expanding the Spring Creek Debris Dam, interception of groundwaters via drainage systems around the ore deposits, plugging of the mine, and leaching and mineral extraction operations on site (USACE, 2018). In one of several Records of Decision, the USEPA implemented five initial recommendations. Some of these included partial capping around the Richmond ore deposit and the diversion of surface waters of Spring Creek, Slickrock Creek and South Fork Spring Creek (EPA, 1986).

The USEPA has ordered multiple different remediation actions to be taken over the years. A total of five Records of Decisions have been made since 1986, each pertaining to a specific aspect of the cleanup. In the 1986 Record of Decision the USEPA ordered the initial recommendations, discussed previously, be enacted on a sitewide basis (EPA, 1986). In the second Record of Decision, in 1992, USEPA decided to treat acid mine drainage from the Richmond and Lawson tunnels with a lime neutralization plant, along with the consolidating and capping of multiple waste piles to a landfill specifically located on site. The disposal of treated sludge was to be directed to the open pit mine at the Brick Flat mine at the top of the mountain (EPA, 1992). In the third Record of Decision, in 1993, the USEPA ordered treatment of acid mine drainage from the Old and No. 8 Mines through the lime neutralization facility (EPA, 1993).

The fourth Record of Decision, in 1997, focused on water management, primarily the Slickrock Creek watershed (EPA, 1997). The USEPA ordered the construction of a 220-acre foot reservoir to capture acid mine drainage that is discharged into the watershed and required a surface water diversion facility, erosion control structures, additional acid mine drainage transport pipelines and a tunnel for gravity discharge of treated water down to Spring Creek. The implementation of these remedies was anticipated to have beneficial effects on water quality that reached the downstream Sacramento River (EPA, 1997; USACE, 2018).

The fifth Record of Decision from 2004 focused on the contaminated soil and sediment around the Iron Mountain site. The focal point of this remedy application was sediment and soil that had the potential for erosion into the Spring Creek Watershed (EPA, 2004). This remedy involved the dredging and disposal of contaminated soil in a confined disposal facility that is located next to the Spring Creek Reservoir. The confined disposal facility was constructed in 2009 and operated sediment removal actions for a total of seven months between 2009 and 2010 (EPA, 2004; USACE, 2018). The operations conducted by the USEPA involved hydraulic dredging of contaminated soil, treatment of dredged material with lime, polymer and coagulant as well as water quality monitoring in the Keswick Reservoir and Sacramento River. The Carr fire that swept through Redding, California has slightly hindered the remediation activities of the site as some of the treatment equipment and infrastructure had been damaged (EPA, 2004; USACE, 2018).

2.3. Results and Ongoing Efforts

The remediation efforts at Iron Mountain have dramatically reduced the amount of acid mine drainage that impacts the surrounding areas. Between January of 2013 and December of 2017, a total of approximately 1.6 billion gallons of acid mine drainage was treated. Of these 1.6 billion gallons, close to 2 million pounds of zinc and 600,000 pounds of copper were removed from the mine drainage. The values are down slightly from 2008 to 2012, where 2 billion gallons of mine drainage was treated, and 3 million pounds of zinc and 870,000 pounds of copper were removed from the waste water. The main source of this reduction in treated and removed quantities is from the overall decrease in acid mine drainage flowing into the treatment facilities. The main treatment plant onsite is the Minnesota Flats Treatment Plant.

2.3.1. Water Quality Improvements

The main goal of remediation efforts at Iron Mountain has been the improvement of water quality in surrounding waterbodies. Monitoring and sampling are conducted at the point of discharge from the Spring Creek Debris Dam and is tested for pH, total copper, zinc and cadmium. The remediation efforts in effect at Iron mountain have significantly reduced the amount of copper and zinc found in the discharged water. Before any remediation efforts were put into effect, the daily zinc concentrations were in excess of the allowable limit of 1500µg/L as well as above the allowable limit for copper, which is 300 µg/L. Within the last five year the concentrations of zinc have been reduced to a range of 90µg/L to 800µg/L, and copper has been reduced to range of 50µg/L to 150µg/L. A total decrease of 97% of metal concentration has been observed in discharged water from Iron Mountain (USACE, 2018). Arsenic was dealt with primarily through an erosion control action, which involved the excavating and removal of contaminated soils around the site and disposal in a waste facility onsite (EPA, 2006)

3. Modern Regulations

The mining industry has been a befitted society a number of ways both from production and an economic standpoint. While these operations are beneficial to the society, they can be detrimental to the environment (Power, 2007). There are multiple regulations that came into effect several years after the Iron Mountain Mine was abandoned to help prevent environmental damage from occurring due to mining operations. Some of these regulations include the Surface Mining and Reclamation Act of 1975, The Department of Conservation’s Water Code, as well as the California Environmental Quality Act and the National Environmental Policy Act. Each of these regulations and policies require the careful analysis, prior to any operations taking place, of the potential impacts that could be caused by the mining operations.

The Surface Mining and Reclamation Act of 1975 ("SMARA") is one of the most important regulations in the mining industry. SMARA requires a multiple step review process and action plan that must be strictly adhered to. One of the most important aspects that it requires is the mining company to submit a reclamation plan. In this case a reclamation plan is a land use permit, separate from property ownership, that obligates the mine operators to mitigate the environmental impacts associated with their operation (California, 1975). The reclamation plan is the mine operator's way of determining what land use the mined area will become once extraction operations have ceased. These land uses can include open space, lakes or water storage, residential or commercial development, energy projects such as solar farms, or backfill operations (California, 1975). Another aspect of SMARA is the financial assurance where the operating company is required to submit a financial assurance cost estimate that creates an estimate as to what it would cost to conduct the proposed reclamation actions. This is to include the cost and hours of operations for laborers, operation costs for the equipment need, as well as the cost of materials needed to complete the work. The financial assurance is money set aside to ensure that the reclamation activities are completed as laid out in the reclamation plan (California, 1975). The assurance estimates must be updated each year to account for inflation, new disturbances in the area of operations, or the completion of the reclamation. This financial capital will either be released back to the operators once the reclamation has been completed, or kept by the Department of Conservation, or other lead agency, and used to complete reclamation if the mine is abandoned. SMARA, on many occasions works hand in hand with the California Environmental Quality Act (California, 1975).

The California Environmental Quality Act ("CEQA") and the National Environmental Policy Act ("NEPA") play major roles in the mining industry in the modern day. Both acts are process based and have no decision-making power within them. They are designed solely to provide as much information as possible as to the potential environmental, social and economic effects the proposed operation could cause. Both require investigations and studies into all possible effects, including those described previously. The information gathered would then be presented to the decision-making body and public input would be given with a final decision made based on all options, alternatives and comments made on the project. These policies and regulations have helped shape the mining industry to protect the environment as much as possible and hold those responsible for damages accountable for their actions, like that of the Superfund Program (Environmental Quality, 2014).

4. Conclusion

The Iron Mountain Mine Superfund Site is an example of the impacts of metal ore mining. The effects of the acid mine drainage have been detrimental to aquatic species and the environment around the site. The Superfund program has played a pivotal part in the remediation and stabilization of the site. Over the years water quality has improved substantially from the removal of toxic contaminants that could have been released downstream. Having been a historical mine operation, which means that it was operated prior to any environmental regulations being in place, the mine had no environmental review and the impacts were never anticipated. With modern regulations and policy in place, all possible impacts are brought to light prior to any mining operation taking place. There is still work to be done at Iron Mountain as it was estimated that there is a total of 13 million tons of reserve still in the mountain. This provides 13 million tons of material to be oxidized and acid mine drainage created, which in turn will be treated before being discharged. Iron Mountain Mine is a prime example of what could happen when environmental regulations are not in place or followed and shows the importance of maintaining the Superfund Program and treating extremely toxic sites across the country.

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