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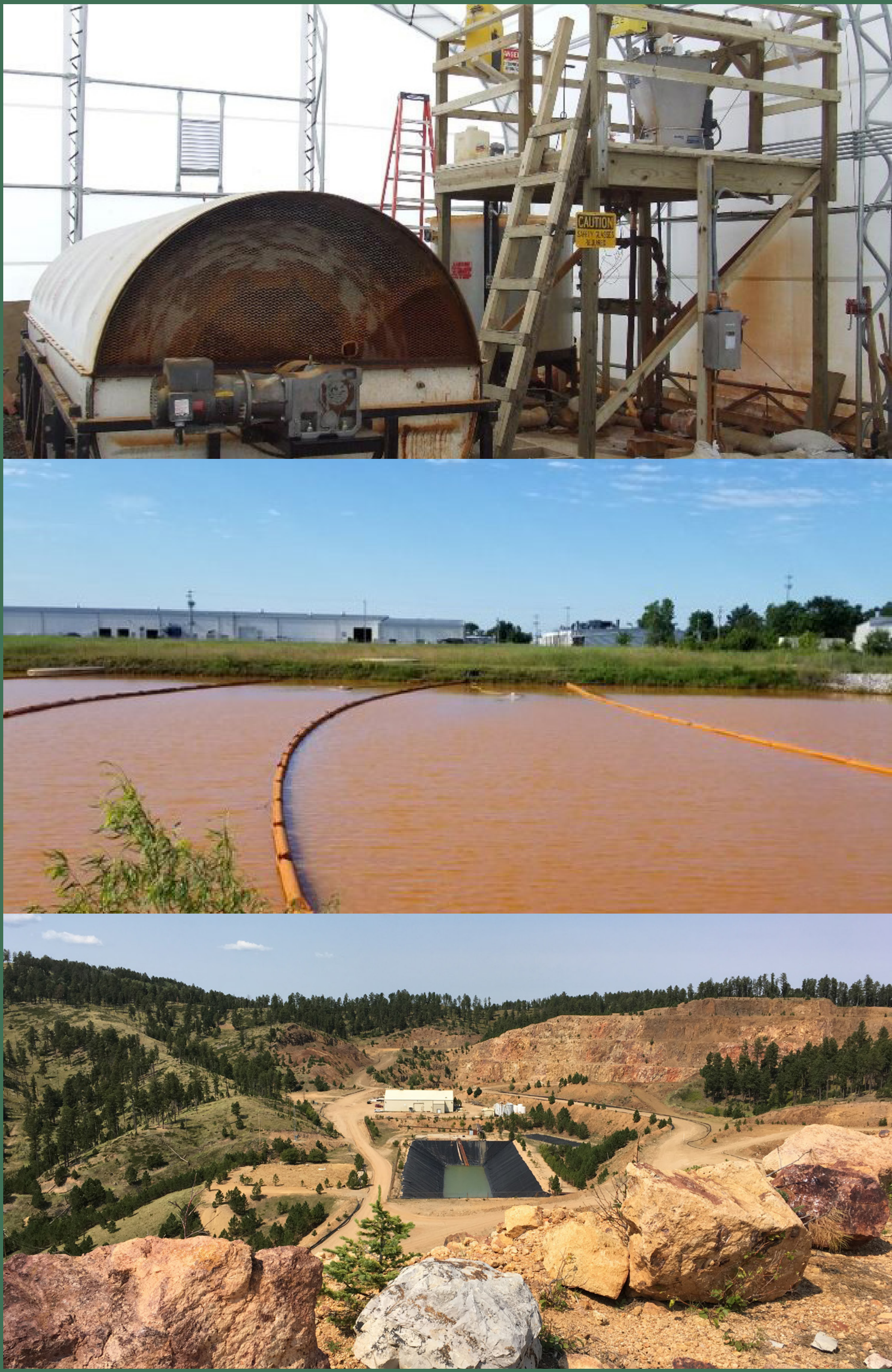

Review of Peer-Reviewed Documents on Treatment Technologies Used at Mining Waste Sites

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Office of Superfund Remediation and Technology Innovation

Notice/Disclaimer Statement

Under U.S. Environmental Protection Agency contract No. EP-C-11-036 through its Office of Research and Development, an initial contractor, RTI, conducted the literature research under an approved Quality Assurance Project Plan (Quality Assurance Identification Number L-300010-QP-1-0). Under EPA Contract No. GS-10F-0309N, a second contractor, Skeo Solutions, Inc., conducted data analyses and interpretation under a Quality Assurance Project Plan approved with U.S. Environmental Protection Agency Office of Superfund Remediation and Technology Innovation. The primary authors of this report are Michele Mahoney, U.S. EPA, Office of Land and Emergency Management, Office of Superfund Remediation and Technology Innovation, Technology Innovation & Field Services Division, and Barbara A. Butler, U.S. EPA, Center for Environmental Solutions and Emergency Response, Land Remediation and Technology Division.

This review provides information about numerous technologies used in remediation of various mining wastes from existing case studies. The data reported and/or summarized in sources referenced are assumed to have been evaluated for quality by the reporting entity and has not been evaluated independently by EPA. However, calculated values using the secondary data have been verified to have been accurately calculated. Any mention of trade names, products, or services does not imply an endorsement by the U.S. Government or the U.S. Environmental Protection Agency. The EPA does not endorse any commercial products, services, or enterprises. This report has undergone U.S. Environmental Protection Agency and external review by subject matter experts and has been approved for publication.

Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The Office of Superfund Remediation and Technology Innovation (OSRTI) within the Office of Land and Emergency Management (OLEM) administers the Superfund Program, the federal government's program to clean up the nation's uncontrolled hazardous waste sites. OSRTI is committed to ensuring that the hazardous waste sites on the National Priorities List are cleaned up to protect the environment and the health of all Americans. The Technology Innovation and Field Services Division (TIFSD) within OSRTI advocates for the innovative use of technologies to assess and clean up Superfund sites as well as other contaminated sites. TIFSD provides national leadership for the delivery of analytical, science-based services for regions and states, and supports the use of technologies that are safe, effective and economically feasible. This type of valuable technical assistance and research supports advancements in the field and aids in environmental emergency responses.

Documenting studies of treatment technologies at Superfund and other sites is important in providing an understanding of how these technologies remove contaminants and can aid a reader, such as a site manager, in determining if the technology would be effective under the conditions at their site of interest. This report is published and made available by US EPA's Office of Land and Emergency Management Office of Superfund Remediation and Technology Innovation to assist readers in the remediation community in understanding the capabilities and limitations of remedial technologies employed at mining sites.

Contents

Tables

Acronyms and Abbreviations

ALD	Anoxic Limestone Drain
AML	Abandoned Mine Lands
ARD	Acid Rock Drainage
BCR	Biochemical Reactor
BOD	Biological Oxygen Demand
Clu-In	Contaminated Site Clean-up Information
cm	Centimeter
DAS	Dispersed Alkaline Substrate
DL	Detection Limit
FRTR	Federal Remediation Technologies Roundtable
HDS	High-density Sludge
ITRC	Interstate Technology and Regulatory Council
kg	Kilogram
LD	Limestone-dosed
LF	Limestone-free
L/min	Liters per minute
m^2	Square meter
mg/L	Milligrams per liter
MIW	Mining-influenced Water
NA	Not Applicable
ND	Not Detected
NFOL	Natural Iron (Fe)-Oxidizing Lagoon
NS	Not Stated
O&M	Operation and Maintenance
PRB	Permeable Reactive Barrier
RAPS	Reducing and Alkalinity Producing System
RL	Reporting Limit
SME	Silica Microencapsulation
SRB	Sulfate-reducing Bacteria

SRBR	Sulfate-reducing Bioreactor
TCLP	Toxicity Characteristic Leaching Procedure
VFP	Vertical Flow Pond
WTP	Water Treatment Plant
µg/l	Micrograms per liter
µm	Micrometer

Acknowledgments

Discussions with the EPA's National Mining Team prompted development of this report to add to the knowledgebase of treatment technologies for cleanup at Superfund sites. The following individuals are acknowledged for their technical reviews of this report: Kathleen Adam of the U.S. Forest Service, Dr. Robert Ford of U.S. EPA Office of Research and Development, Ed Hathaway of the U.S. EPA Region 1, and Dr. Robert Seal of the U.S. Geological Survey.

Conversion Factors

Area				
1	acre	=	4046.86	square meters (m^2)
1	square meters (m^2)	=	0.000247105	acre
Concentration				
1	milligram per liter (mg/l)	=	1000	micrograms per liter (µg/l)
1	micrograms per liter (µg/l)	=	0.001	milligrams per liter (mg/l)
Flow				
1	liter per minute (L/min)	=	0.000588578	cubic feet per second (ft^3/s, or cfs)
1	cubic foot per second (ft^3/s, or cfs)	=	1,699	liters per minute (L/min)
1	liter per minute (L/min)	=	1.6667 x 10^{-5}	cubic meters per second (m^3/s)
1	cubic meter per second (m^3/s)	=	60,000	liters per minute (L/min)
1	liter per minute (L/min)	=	0.264172	gallons per minute (gal/min or gpm)
1	gallon per minute (gal/min, or gpm)	=	3.78541	liters per minute (L/min)
1	cubic meter per second (m^3/s)	=	15,850	gallons per minute (gal/min, or gpm)
1	gallons per minute (gal/min, or gpm)	=	6.309x10^{-5}	cubic meter per second (m^3/s)
Length				
1	foot (ft)	=	0.3048	meters (m)
1	meter (m)	=	3.28084	feet (ft)
Volume				
1	cubic meter (m^3)	=	264.171928	gallons (gal)
1	gallon (gal)	=	0.00378541	cubic meter (m^3)
1	liter (L)	=	0.264172	gallon (gal)
1	gallon (gal)	=	3.78541	liter (L)

1 Introduction

The U.S. Environmental Protection Agency conducts and supervises investigation and cleanup actions at a variety of abandoned mine lands (AMLs). AMLs are those lands, waters and surrounding watersheds where extraction, beneficiation, or processing of ores and minerals has occurred. EPA's AML Program identifies ways to protect human health and the environment by pursuing opportunities to explore innovative site cleanup and reuse opportunities at these sites. The research in this report was conducted to identify information related to treatment technologies being used for mining site cleanup.

Case studies examining treatment technologies used for remediating mining-influenced water (MIW) and mining wastes have been conducted at many hard rock mining sites and range in type from bench studies to full-scale field studies. The research in this report was conducted to capture the capabilities, efficiencies, technological and site-specific requirements, and lessons learned for technologies and methods used. EPA's goals for the work presented in this document were to 1) determine if there are any trends in treatments or methods used; 2) understand successes and failures of the technologies and methods to evaluate whether there are gaps where future technologies could be developed or current ones refined; and 3) provide information in one place to aid decision of whether a given technology or method might be appropriate for use at a particular site, based on information obtained from the case studies.

To work toward meeting these goals, EPA conducted a literature search in order to accumulate, evaluate, and consolidate case studies that documented active or passive treatment systems or methods being used (or previously used) at active and inactive hard rock mining sites for remediating contaminants from various mining wastes and MIW. While not truly a treatment, literature that documented source control through capping and covering of mining wastes was included. The media types of interest included waste rock, tailings, soil, pit lakes, water from adits, underground workings, leachate, groundwater, and surface water.

Technologies presented in this review are organized such that each chapter can be read alone. This chapter lays out the goals and approach for developing this document and limitations in accomplishing those goals.

1.1 Methodology

1.1.1 Scientific Literature Review Approach

The literature search focused on peer-reviewed case studies originating from governmental organizations, non-governmental organizations, academia and contractors or consultants that contained data from field studies assessing the effectiveness of various treatment technologies. Major bibliographic databases were searched as part of this effort, including Science Direct, Web of Science, EBSCOhost Science & Technology Collection, Environmental Sciences and Pollution Management, Conference Papers Index, Pollution Abstracts, PubMed, and Google Scholar. Additional specific sources searched included EPA's Contaminated Site Clean-Up Information (Clu-In) webpage for mining site case studies, EPA Mine Waste Technology Program references on source control or remediation methods, the Interstate Technology and Regulatory Council (ITRC) webpage for mining waste treatment and webpages for international and national mining associations and organizations, including: American Society of Mining and Reclamation, International Mine Water Association, Society for Mining, Metallurgy, and Exploration, the International Network for Acid Prevention, and International Conference on Acid Rock Drainage (ICARD) proceedings, each of whom peer-review conference papers for publication in proceedings. The literature search was completed in 2017.

The literature search used the following tier 1 screening criteria:

- Field-scale (pilot or full) case studies documented in 1980 or later with the technology operating and monitored for a minimum of six months for remediation purposes at active or inactive hard rock mining sites.
- Field-scale studies that were intended to remove metals, metalloids and/or other inorganic contaminants (e.g., sulfate) from media impacted by hard rock mining such as MIW, or abatement of leachate or seepage through source control.

References meeting the first-level screening criteria were then grouped by case study site name and further prioritized based on the following tier 2 criteria:

Required:

- Treatment technology or method clearly identified, as an independent system or part of a treatment train.
- Geographical conditions/constraints (e.g., topography, climate, remoteness, footprint) provided.
- Scale of technology (pilot or full-scale application) indicated.
- Media treated clearly identified.
- Constituents treated identified.
- Process type (physical, chemical, biological or a combination of process types; active, passive or semi-passive) discernable.
- Technology requirements clearly noted (e.g., power needs, temperature constraints, specific microorganisms, etc.).
- If water, influent and effluent concentrations (averages over time or time-dependent data) provided.
- If a solid medium, starting and ending concentrations provided in water source, such as leachate.
- If a solid medium, area or mass of solid treated provided.
- Cleanup goals or other performance criteria provided.
- Statement or indication of whether the treatment method met or did not meet performance goals.

Desired:

- Site name and location (unless confidential).
- If water, influent and effluent loads.
- If water, flows treated provided.
- Issues and lessons learned (technical, regulatory, logistical).
- Costs provided.

If the required tier 2 criteria were not present, EPA excluded the case study from quantitative data evaluation; however, information from the study may have been used in qualitative discussions of the given technology. All primary sources of data used were EPA reports, peer-reviewed conference proceedings, or journal articles.

Concerted effort was made to comprehensively search for a range of studies that encompass the potential variability in mine waste types, contaminants present, and potential treatment technologies. However, EPA acknowledges data gaps may exist and that this report may not include the universe of data on this topic. Contaminants other than those presented in this report may be treatable by the technologies evaluated, but were not presented in the studies examined.

EPA is aware of studies conducted at EPA sites that are not included in this report due to the lack of data published for such studies. The Agency is working toward reporting these data in a form that can be used for future analyses. EPA provides current information on contaminated mining site cleanup treatment technologies at EPA's Cleanup Information Network (www.clu-in.org/mining).

1.1.2 Data Evaluation Procedures

Case studies meeting the second-tier criteria were organized by technology, media type, and primary constituents assessed. For each technology, the following data were extracted for each case study that documented successful treatment (i.e., performance goals were stated as having been attained or constituent concentrations were decreased):

- Identity of each constituent (including pH) assessed and:
    - Minimum and maximum pre-treatment concentration and corresponding post-treatment concentration.
    - Average pre-treatment and average post-treatment concentrations.
    - Minimum, maximum, and average removal efficiency.
- Flows treated
- Costs
- Lessons learned

For MIW, concentrations correspond to the water being treated directly. For technologies treating solid mining wastes, concentrations reported correspond to water leached from a waste pile before and after treatment of the waste, or water from a source upgradient and downgradient (groundwater), or upstream and downstream (stream water or seeps) of the waste pile being treated. Concentration and removal efficiency data obtained in this step are presented in the technology-specific appendices, whereas flows treated, costs, and lessons learned are presented within each technology chapter, where available. Flows treated in case study references were converted to a consistent unit of measure (liters per minute, L/min) across all technologies within this document.

Minimum and maximum pre-treatment and corresponding post-treatment data were obtained from evaluation of tables, graphs, or narratives. In instances where only graphs were provided, data are noted as being estimated from those graphs. Data were chosen from periods over which a case study reported a technology as operating as intended, excluding start-up or equilibration periods. If operation versus start-up or equilibration periods were not stated, data were chosen across the entire period presented. Minimum pre-treatment concentrations chosen were the lowest concentrations reported that exceeded a case study's reported detection limit (DL) for each constituent.

Unless otherwise noted in tables, average pre-treatment and post-treatment concentrations were reported by the authors of the case studies. In the absence of reported averages, where time-specific data from multiple sampling events were available, EPA calculated average values from the reported data. For calculations, one-half of the reported detection limit was used for samples reported as below the detection limit; if no detection limit was provided, the average was not calculated. The average pH presented in the tables represents the average of pH values, rather than an average pH calculated from hydrogen ion activities. Unless otherwise noted, minimum, maximum, and average removal efficiencies were reported by the authors of the case studies. Concentrations reported in case study references were converted to a consistent unit of measure (milligrams per liter [mg/L]) across all technologies within this document, where applicable.

For each technology, data in the appendices were examined across all case studies for each of the constituents treated to choose the technology-based minimum and maximum pre-treatment concentrations and their corresponding post-treatment concentrations, the minimum and maximum average pre-treatment and post-treatment concentrations, and the minimum and maximum removal efficiencies. These data are presented in tables and discussed in the capability section of each technology chapter.

Many case studies presented treatment results from treatment trains, i.e., multiple technologies conducted in series. Some of these studies provided data for each part of the treatment train, and these data were included in individual technology discussions, as well as being discussed in the Treatment Trains chapter (Section 10). Case studies that did not provide data for each unit in the treatment train are discussed only in Section 10.

1.2 Limitations

When reviewing the capabilities of the technologies within this document, it is important to note that average influent concentrations in tables do not correspond directly with the average effluent concentrations. It also should be noted that, although the data from the case studies were examined in aggregate within each technology, the case studies may not have been conducted in the same way, may have had different detection limits for the same constituents examined, or may have had different overall water chemistries, any of which may have influenced case study reported results in unknown ways. For some technologies, the data reported in a case study may not be the most telling data for evaluating successful treatment. For caps and covers, contaminant load reduction is often a pertinent measure of performance yet the case studies examined did not present discussion in terms of loads reduced.

For some technologies, this report only includes one or two case studies that met the required criteria; therefore, the ability to determine general capability of those technologies is limited. In instances when a given constituent may have been monitored in only one case study, generalized capability of the technology with respect to that constituent is limited. Limitations for the technologies as presented in each chapter were stated as such by the references cited and those limitations noted are not intended to reflect all potential limitations of the given technology. Constraints noted for each technology are also presented as stated in the references cited and are not intended to be inclusive of all the constraints that may exist for a given technology.

An additional challenge to comparing technologies across multiple case studies is that not all studies report the same type of data, such as the type of water sample (total or dissolved) for which a constituent concentration was reported. This work aimed to capture as many case studies as possible that met the criteria indicated above and to compare as many constituents reported within each technology as possible. Some studies reported total concentrations but may not have indicated the method used to determine the total concentration. For example, it is unknown if studies conducted a total digestion of the raw water sample (total-recoverable), of if they used a modified digestion method. Some studies report dissolved concentrations, but without indication of the filtration size, and it is well-known that colloidal particles will pass through a 0.45 micrometer (µm) filter and report as dissolved concentrations. Further, some studies did not indicate whether constituent concentration results were dissolved or total. Because case studies meeting this study's criteria were limited, it was necessary to examine aggregated data in the appendices from different water sample types. Tables within each chapter indicate total or dissolved concentrations for each constituent being discussed.

Each chapter includes a Lessons Learned section of technology constraints. These sections relied on information presented in the available references. These constraints are not discussed at length in this report but are intended to provide insights to the limitations of certain technologies. In addition, although the treatment technologies presented in this report may have been tested or used at additional sites, only those sites with information obtained through the literature search are included in this report.

2 Use of this Review

The main goal of this work was to provide a single place where a project manager or practitioner could find information to determine if a given technology would be applicable to their specific needs, based on information aggregated across as many case studies of each technology as possible. An additional goal was to identify if there were any trends in treatments or methods used. Unfortunately, many case studies reviewed did not provide the information needed to meet these goals. Additionally, many studies had different site-specific characteristics and constituents to treat within a given technology. Therefore, the aggregated information provided in this report is limited, limiting the ability to identify trends in treatment methods to better capture the full utility of a technology. However, EPA believes the information presented in this report will prove a valuable resource for site managers as a complement to Reference Guide to Treatment Technologies for Mining-Influenced Water (U.S. EPA, 2014) which provides information on how several of the treatment technologies evaluated in this review work.

EPA recognizes that information presented in journal articles and conference proceedings typically is constrained by page limits. For journal articles, supplementary information may be provided, and appendices provided for reports, but readers may not have the time to process those data themselves. It is also recognized that cost information may not be presented in peer-reviewed case studies due to competition amongst vendors or consultants, especially costs associated with labor. If literature included costs of the technology itself (i.e., capital costs, plus materials over time) and then provided an estimate of the numbers of hours necessary for monitoring, maintenance, or other activities, a practitioner or project manager could compare suitable technologies based on capital costs and labor hours. Presentation of costs and labor hours normalized to volume of water treated would be most beneficial for comparison across technologies. Cost information in this document is presented as reported in the case studies and has not been adjusted for inflation.

EPA may provide updated information as additional information or case studies become available.

2.1 References

U.S. Environmental Protection Agency (U.S. EPA). 2014. *Reference Guide to Treatment Technologies for Mining-Influenced Water*. (EPA/542/R-14/001). 94 pp. https://cluin.org/download/issues/mining/Reference_Guide_to_Treatment_Technologies_for_MIW.pdf

3 Biochemical Reactors

Biochemical reactors (BCRs), sometimes called bioreactors, are engineered systems that use organic materials and natural processes to decrease concentrations of a variety of metals, metalloids and sulfate, and to increase pH in mining-influenced water (MIW). Treatment occurs through microbial, chemical and physical processes, including reduction/oxidation, precipitation, adsorption and retention within the substrate (Nordwick and Bless, 2008). Substrate materials used in these systems, such as wood chips, straw, or biosolids, are often obtained locally. Organic waste materials such as biosolids or manure are put to new use when employed as part of the treatment system within a BCR (Gusek, 2002).

BCR design varies based on site-specific characteristics such as water chemistry (including pH, metals type and concentration), influent water flow rates, climate, temperature, land and power source availability, and treatment goals (Doshi, 2006; Butler et al., 2011). BCRs using solid substrates are considered *passive* systems, meaning that they require minimal human interaction to operate once the microbial community is established; they are also referred to as *semi-passive* systems since it is required that they be maintained over time. BCRs using liquid substrates can be considered active systems because they require more frequent human interaction to replace the carbon source and may also have greater power needs that require more frequent maintenance visits. Passive BCR systems rely on gravity feeds, which require minimal maintenance, whereas a BCR requiring some power for conveying water may be considered a semi-passive system that requires occasional human interaction. BCRs can be placed inside mine shafts or other mining site features (in situ). They can also be in-ground systems or above-ground containerized systems. A polishing step generally follows BCR treatment to remove constituents introduced by microbial activity and settle out any solids released during the process.

BCRs can be aerobic (oxic) or anaerobic (anoxic). Anaerobic BCRs are more commonly used to treat MIW. Anaerobic BCRs are also sometimes called sulfate-reducing bioreactors (SRBRs), compost bioreactors, or vertical flow ponds (VFPs), although the primary goal of a VFP is to add alkalinity and create reducing conditions rather than facilitating microbially-mediated precipitation (Hedin et al., 2013). For this review, engineered bioreactors using anaerobic biochemical processes are called “anaerobic BCRs” and engineered bioreactors using aerobic biochemical processes are called “aerobic BCRs.”

Anaerobic BCRs harness the microbial ability of dissimilatory sulfate-reducing bacteria (SRB) to reduce dissolved sulfate in MIW to hydrogen sulfide (Equation 1, using acetic acid as an example carbon source). Dissolved hydrogen sulfide dissociates into hydrogen and bisulfide ions (Equation 2), and the bisulfide then reacts with dissolved metal contaminants in MIW to precipitate metal sulfides, as shown in Equation 3, which are retained within the BCR substrate.

$$CH_3COOH + SO_4^{2-} \leftrightarrow 2HCO_3^- + H_2S \qquad Equation\ 1$$

$$H_2S(aq) \leftrightarrow HS^- + H^+, pka\ \cong 7 \qquad Equation\ 2$$

$$HS^- + Me^{2+} \leftrightarrow MeS + H^+, where\ Me^{2+} = any\ divalent\ metal \qquad Equation\ 3$$

The metabolic process also produces bicarbonate (Equation 1) that can neutralize acidity (Bless et al., 2008; Nordwick and Bless, 2008). SRB need an anoxic, reducing environment and an electron donor (carbon substrate) to function (Doshi, 2006).

Aerobic BCRs often rely on precipitation of metals as oxides and hydroxides under aerobic conditions to decrease metals concentrations (Gusek, 2002); the precipitates also sequester trace elements, such as cadmium, copper, and zinc through sorption. In one case study in this chapter, manganese-oxidizing bacteria were used to induce manganese oxidation (Nordwick and Bless, 2008). BCRs are often used as part of a treatment train (see Section 10).

3.1 Case Studies Evaluated

This chapter provides an evaluation of case studies in which a BCR was the primary component of MIW treatment. The case studies were selected based on the criteria presented in Section 1.1.1. The case studies examined included aerobic and anaerobic BCRs in pilot-scale and full-scale installations at mine sites across the United States, Canada and the United Kingdom. Table 3-1 summarizes site names and locations, BCR design information, and references for each of the case studies. The chapter presents technology-wide considerations for constraints, treatability of contaminants, capability, technological and site-specific requirements and lessons learned for BCR treatment from evaluation of case study results.

Table 3-1: Bioreactor Case Study Sites

Site Name and Location	BCR Type	System Description	Study Type	Reference	Reference Type
Calliope Mine Butte, Montana	Anaerobic, solid substrate	Three horizontal flow units in parallel: two below ground with one having pretreatment and one aboveground with pretreatment; each unit contained organic matter (cow manure and straw) and cobbles; pre-treatment units contained additional organic matter and limestone.	Pilot scale (technology demonstration)	Wilmoth, 2002*	Report
				Bless et al., 2008	Journal paper
				Nordwick et al., 2006	Conference paper

Table 3-1: Bioreactor Case Study Sites

Site Name and Location	BCR Type	System Description	Study Type	Reference	Reference Type
Confidential Mine, Montana	Anaerobic, solid substrate	BCR followed by an aerobic polishing cell (a series of vegetated ponds); BCR substrate consisted of 46 percent wood chips, 10 percent hay, 30 percent limestone, 10 percent animal manure and 4 percent crushed basalt.	Pilot scale (technology demonstration)	Blumenstein and Gusek, 2009*	Conference paper
Cwm Rheidol Mine Wales, United Kingdom	Anaerobic, solid substrate	Vertical-flow bioreactor contained shells, wood chips, compost and anaerobic digested sludge.	Pilot scale	Jarvis et al., 2014*	Report
Force Crag Cumbria, United Kingdom	Anaerobic, solid substrate	Parallel vertical-flow ponds contained compost, woodchips and dried activated sewage sludge, followed by an aerobic wetland.	Full scale	Jarvis et al., 2015*	Conference paper
Keno Hill Yukon, Canada	Anaerobic, liquid substrate	Liquid BCR filled with adit water supplemented with sucrose, methanol and dried milk solids; continuous methanol once established.	Pilot scale	Harrington et al., 2015*	Conference paper
Leviathan Mine		System consisted of a pretreatment	Full scale	Doshi, 2006	Report

Table 3-1: Bioreactor Case Study Sites

Site Name and Location	BCR Type	System Description	Study Type	Reference	Reference Type
Alpine County, California	Anaerobic, liquid substrate	pond (using 25 percent sodium hydroxide and ethanol), two BCRs in series, two continuous flow-settling ponds, and an aeration channel; BCRs were lined with high-density polyethylene, river rock and manure.		U.S. EPA, 2006a*	Report
Lilly Orphan Boy Mine Elliston, Montana	Anaerobic, solid substrate	In-situ BCR built within the mine shaft and containing 70 percent cow manure, 20 percent decomposed wood chips and 10 percent alfalfa straw.	Pilot scale (technology demonstration)	Bless et al., 2008*	Journal paper
				Doshi, 2006	Report
Nenthead Cumbria, United Kingdom	Anaerobic, solid substrate	Vertical flow bioreactor containing compost, wood chips and activated digested sludge.	Pilot scale	Jarvis et al., 2014*	Report
Standard Mine Crested Butte, Colorado	Anaerobic, solid substrate	System comprised a BCR followed by aerobic polishing cells; BCR contained hay, wood chips, limestone and cow manure.	Pilot scale	Gallagher et al., 2012*	Conference paper
				Reisman et al., 2009*	Conference paper
				Butler et al., 2011	Journal paper

Table 3-1: Bioreactor Case Study Sites

Site Name and Location	BCR Type	System Description	Study Type	Reference	Reference Type
Surething Mine Helena, Montana	Anaerobic and aerobic, solid substrates	System comprised an anaerobic BCR followed by an anoxic limestone drain, followed by another anaerobic BCR, followed by an aerobic BCR containing manganese-oxidizing bacteria.	Pilot scale (technology demonstration)	Nordwick and Bless, 2008*	Report
Notes: *Primary source(s) of data for evaluation in this chapter					

3.2 Constraints

Constraints associated with BCRs include the need for space and suitable topography to accommodate system components, operating issues due to clogging of pipes or substrates, the unknown longevity of substrates, and variable seasonal flow (U.S. EPA, 2006a; Doshi, 2006; Harrington et al, 2015). Lack of an accessible source of electricity (if pumping is required), limited site access during winter months and cold temperatures may also be constraints (Reisman et al., 2009; U.S. EPA, 2006a). For example, at the Leviathan Mine in California, only snowmobiles could reach the site's remote location during winter months, requiring detailed planning to ensure the BCR's continued operation (U.S. EPA, 2006a). Another example is the Standard Mine site in Colorado, which is only accessible via snowshoes and skis during winter months (Reisman et al., 2009).

Liquid substrate BCRs face an additional constraint – the need to transport and maintain an adequate supply of liquid reagents (e.g., ethanol or molasses), fuels (to maintain generators) and other supplies to ensure consistent system operations, even when site access may be limited. Liquid substrates are often consumed much faster by SRB than are solid substrates (Gusek, 2002). Personnel may also need to be on site more often to deliver supplies and conduct operation and maintenance activities (Doshi, 2006).

Challenges or concerns may arise from siting BCRs at locations near populated areas, such as stakeholder concerns about a rotten egg odor caused by the BCR's production of hydrogen sulfide gas, additional permitting requirements, and worries about damages to the system or injury to individuals due to trespassing (Interstate Technology & Regulatory Council [ITRC], 2013). Additionally, at the end of a BCR's lifetime, accumulated precipitates and residual media may be determined to require disposal as a hazardous waste, depending on the results of the toxicity characteristic leaching procedure (TCLP) (ITRC, 2013).

In most cases, careful planning and coordination with stakeholders during BCR design can address their concerns. To some extent, BCR design and operation can also be modified over time as technical issues affecting operation or efficiency arise. Section 3.8 of this chapter discusses lessons learned from the case studies examined.

3.3 Treatable Contaminants

BCRs can treat a variety of metals, metalloids, non-metals and increase pH in MIW.

3.3.1 Anaerobic, Solid Substrate BCRs

Although many anaerobic BCR case studies evaluated targeted treatment of a small number of site-specific chemicals of concern, some provided results of additional metals, metalloids or non-metals present in the MIW that also were decreased in concentration. When examined in aggregate, the studies show the following metals, metalloids and non-metals are treatable using anaerobic BCRs: aluminum, arsenic, cadmium, copper, iron, lead, manganese, nitrate, selenium, sulfate, thallium and zinc. Although iron and manganese concentrations can be decreased in anaerobic BCRs, removal may be less efficient than with other elements, and inconsistent (Nordwick and Bless, 2008; Reisman et al., 2009). An increase in pH is also attainable by anaerobic BCRs. Other elements (e.g., cobalt, mercury, nickel, tin) also may be treatable by anaerobic, solid substrate BCRs, but were not presented in the studies examined.

3.3.2 Anaerobic, Liquid BCRs

Based on two case studies meeting the criteria included in this report (U.S. EPA, 2006a; Harrington et al., 2015), liquid BCRs can treat aluminum, antimony, arsenic, cadmium, chromium, copper, iron, lead, nickel, sulfate, sulfide, selenium and zinc.

3.3.3 Aerobic, Solid Substrate BCRs

An aerobic BCR can treat manganese and increase pH, based on a single case study (Nordwick and Bless, 2008) included that met the criteria for this work.

3.4 Capability – Anaerobic, Solid Substrate

3.4.1 Ranges of Applicability

Concentrations of metals tend to be inversely related to the pH, with higher concentrations associated with a lower pH and lower concentrations associated with a higher pH. Tables 3-2 and 3-3 show the ranges of applicability for each constituent – the maximum influent concentration (and the lowest influent pH) and the corresponding effluent concentration, and the minimum influent concentration (and the highest influent pH) and the corresponding effluent concentration, respectively. The ranges were determined by comparisons of data in Table A-1, Appendix A, developed as discussed in Section 1.1.2. For studies having multiple BCRs in series, results from only the first BCR were compared because concentrations of multiple constituents often were below reported detection limits in influent to subsequent BCRs, and therefore are not representative of treatment capability. Additionally, case studies having pretreatment without reporting the concentrations following pretreatment (i.e., influent concentrations to the BCR step; examples are Golden Sunlight in Nordwick and Bless, 2008 and Bioreactors II and IV at Calliope Mine in Wilmoth, 2002) were excluded from data comparison to allow evaluation of strictly the capability of the BCR technology, but are discussed in the Treatment Trains chapter (Section 10).

Table 3-2: Maximum Influent and Corresponding Effluent Concentrations

Constituent	Maximum Influent Concentration	Corresponding Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard unit				
Aluminum[a, b]	14.1	0.0453	Calliope (BCR III)	Wilmoth, 2002
Arsenic[c]	1.25	0.01	Surething (Reactor 1)	Nordwick and Bless, 2008
Cadmium[c]	0.385	0.005	Surething (Reactor 1)	Nordwick and Bless, 2008
Copper[c]	4.25	<0.003	Surething (Reactor 1)	Nordwick and Bless, 2008
Iron[a]	89.8	0.7	Standard	Gallagher et al., 2012
Lead[a,d]	6	<0.008	Standard	Reisman et al., 2009
Manganese[c]	65	20	Surething (Reactor 1)	Nordwick and Bless, 2008
Nitrate[e,f]	7.9	ND	Confidential	Blumenstein and Gusek, 2009
Selenium[e,f]	0.025	ND	Confidential	Blumenstein and Gusek, 2009
Sulfate[c]	900	450	Surething (Reactor 1)	Nordwick and Bless, 2008
Thallium[e,f]	1.6	<0.001	Confidential	Blumenstein and Gusek, 2009
Zinc[c]	39	<0.007	Surething (Reactor 1)	Nordwick and Bless, 2008
pH	3.29	7.56	Calliope (BCR III)	Wilmoth, 2002

Notes:
ND = Assumed not detected based on figures referenced in Appendix A, Table A-1; detection limits unknown
a = Total
b = Aluminum was reported only for the Calliope Mine site
c = Dissolved
d = Lead was reported only for the Standard Mine site
e = Total or dissolved not stated
f = Nitrate, selenium and thallium were reported only for the Confidential Mine site

Table 3-3: Minimum Influent and Corresponding Effluent Concentrations

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Aluminum[a, b]	0.011	0.0094	Calliope (BCR III)	Wilmoth, 2002
Arsenic[c]	0.0051	< 0.005	Calliope (BCR III)	Wilmoth, 2002
Cadmium[c]	0.0051	0.0056	Calliope (BCR III)	Wilmoth, 2002
Copper[c]	0.003	0.0013	Standard	Gallagher et al., 2012
Iron[a]	0.008	0.031	Calliope (BCR III)	Wilmoth, 2002
Lead[c,d]	0.011	0.0009	Standard	Gallagher et al., 2012
Manganese[a]	0.69	0.076	Calliope (BCR III)	Wilmoth, 2002
Nitrate[e,f]	2.9	0.1	Confidential	Blumenstein and Gusek, 2009
Selenium[e,f]	0.01	ND	Confidential	Blumenstein and Gusek, 2009

Table 3-3: Minimum Influent and Corresponding Effluent Concentrations

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Sulfate[c,g]	40	106	Surething (Reactor 1)	Nordwick and Bless, 2008
Thallium[e]	0.25	<0.001	Confidential	Blumenstein and Gusek, 2009
Zinc[c]	1.7	0.2	Nenthead	Jarvis et al., 2014
pH	8.0	7.2	Confidential	Blumenstein and Gusek, 2009

Notes:
ND = Assumed not detected based on figures referenced in Appendix A, Table A-1; detection limits unknown
a = Total
b = Aluminum was reported only for the Calliope site
c = Dissolved
d= Lead was reported only for the Standard Mine site
e = Total or dissolved not specified
f = Nitrate, selenium and thallium were reported only for the Confidential Mine site
g = Force Crag had the lowest influent sulfate concentration (19.3 mg/L), but did not provide a corresponding effluent concentration

Table 3-2 shows that based on the studies examined, anaerobic BCRs can decrease concentrations of aluminum, arsenic, cadmium, copper, iron, lead, thallium and zinc by at least two orders of magnitude when starting with concentrations exceeding 1 mg/L (> 0.300 mg/L for cadmium). Treatment of zinc appears most effective, with the greatest decrease of four orders of magnitude as compared to the other constituents. Aluminum, copper and lead also are effectively treated with decreases in concentrations of three orders of magnitude. Treatment of nitrate and selenium is also effective, with concentrations decreasing to the assumed detection limit when starting with concentrations less than 10 mg/L nitrate and less than 0.03 mg/L selenium at the single site where monitored. Manganese and sulfate are less effectively treated at the maximum influent concentrations, with 69 percent and 50 percent decreases between the maximum influent and corresponding effluent concentrations, respectively. The pH was also increased when influent pH was below 4.

Table 3-3 shows that based on the studies examined, anaerobic BCRs are also able to decrease concentrations of aluminum, arsenic, copper, lead, manganese, nitrate, selenium, thallium and zinc when influent concentrations are low (< 1 mg/L; 1.7 mg/L for zinc; 2.9 mg/L for nitrate). Thallium concentration had the greatest decrease of two orders of magnitude and was decreased to below the detection limit for the single site where monitored. Influent concentrations of arsenic, cadmium and copper were near the detection limit values, so removal (or lack thereof, in the case of cadmium) observed may be due simply to inherent instrumental errors associated with measurements of values close to detection capabilities. Removal was poor for iron and sulfate at minimum influent concentrations, with each having effluent concentrations greater than influent concentrations and this may be an artifact of sampling not corresponding to BCR retention times for systems having a wide range in influent concentrations (see Appendix A, Table A-1 for maximum and minimums for each site).

3.4.2 Average Influent and Effluent Concentrations

Tables 3-4 and 3-5 list the highest and lowest average influent concentrations treated for each constituent, respectively. Tables 3-6 and 3-7 list the highest and lowest average effluent concentrations attained for each constituent, respectively. Values in these tables were determined by looking across data in Appendix A, Table A-2. As discussed in the Introduction, Section 1.1.2, average maximum or minimum influent concentrations do not correspond directly with the average effluent concentrations in Tables 3-4 or 3-5, respectively, and attainment of a given constituent average maximum or minimum effluent concentration may not require treating the same average influent concentration shown in the Tables 3-6 or 3-7, respectively.

Table 3-4: Maximum Average Influent Concentration Treated

Constituent	Maximum Average Influent Concentration	Average Effluent Concentration	Mine	Source
Concentrations reported in mg/L and as dissolved, except nitrate, selenium and thallium (total or dissolved not stated); pH reported in standard units				
Aluminum	9.7	<0.02	Lilly/Orphan Boy[a]	Bless et al., 2008
Arsenic	1.07[b]	0.075	Lilly/Orphan Boy[a]	Bless et al., 2008
Cadmium	0.33	<0.005	Lilly/Orphan Boy[a]	Bless et al., 2008
Copper	0.4078	0.0546	Calliope	Wilmoth, 2002
Iron	27.7	11.25	Lilly/Orphan Boy[a]	Bless et al., 2008
Lead[b]	0.54	0.01	Standard	Reisman et al., 2009
Manganese	10.99	10.53	Standard	Reisman et al., 2009
Nitrate[c]	5.1	0.08	Confidential	Blumenstein and Gusek, 2009
Selenium[c]	0.013	0.001	Confidential	Blumenstein and Gusek, 2009
Sulfate	281	119	Standard	Gallagher et al., 2012
Thallium[c]	1.25	0.007	Confidential	Blumenstein and Gusek, 2009
Zinc	26.46	0.55	Standard	Reisman et al., 2009
pH	3.0	7.2	Lilly/Orphan Boy	Bless et al., 2008
Notes: a = Average influent concentration provided was from 1993-1994; average effluent concentration calculated by EPA from data provided in the reference for two sampling dates in 2001 b = Lead was monitored only at the Standard Mine c = Nitrate, selenium and thallium were monitored only at the Confidential Mine site				

Table 3-5: Minimum Average Influent Concentration Treated

Constituent	Minimum Average Influent Concentration	Average Effluent Concentration	Mine	Source
Concentrations reported in mg/L and as dissolved, except nitrate, selenium and thallium (total or dissolved not stated); pH reported in standard units				
Aluminum	1.2229	0.0616	Calliope	Wilmoth, 2002
Arsenic	1.07[a]	0.075[a]	Lilly/Orphan Boy[b]	Bless et al., 2008
Cadmium	0.0112	<0.005	Calliope	Wilmoth, 2002
Copper	0.26	<0.0038	Standard	Reisman et al., 2009
Iron	0.4556	0.4143	Calliope	Wilmoth, 2002
Lead	0.54	0.01	Standard	Reisman et al., 2009
Manganese	1.4581	1.0073	Calliope	Wilmoth, 2002
Nitrate[c]	5.1	0.08	Confidential	Blumenstein and Gusek, 2009
Selenium[c]	0.013	0.001	Confidential	Blumenstein and Gusek, 2009
Sulfate	0.1029	0.1039	Calliope	Wilmoth, 2002
Thallium[c]	1.25	0.007	Confidential	Blumenstein and Gusek, 2009
Zinc	2.8406	0.7944	Calliope	Wilmoth, 2002
pH	6.05	7.16	Calliope	Wilmoth, 2002
Notes: a = Average influent arsenic concentration was reported above the detection limit only in the Lilly/Orphan Boy study b = Average influent concentration provided was from 1993-1994; average effluent concentration calculated by EPA from data provided in the reference for two sampling dates in 2001 c = Nitrate, selenium and thallium were monitored only at the Confidential Mine site				

Table 3-6: Maximum Average Effluent Concentration Attained

Constituent	Maximum Average Effluent Concentration	Average Influent Concentration	Mine	Source
Concentrations reported in mg/L and as dissolved, except nitrate, selenium and thallium (total or dissolved not stated; pH reported in standard units				
Aluminum	0.0616	1.2229	Calliope	Wilmoth, 2002
Arsenic	0.075	1.07[a]	Lilly/Orphan Boy[b]	Bless et al., 2008
Cadmium	<0.005	0.0112	Calliope	Wilmoth, 2002
Copper	0.0546	0.4078	Calliope	Wilmoth, 2002
Iron	11.25	27.7	Lilly/Orphan Boy[b]	Bless et al., 2008

Table 3-6: Maximum Average Effluent Concentration Attained

Constituent	Maximum Average Effluent Concentration	Average Influent Concentration	Mine	Source
Lead	0.01	0.54	Standard	Reisman et al., 2009
Manganese	10.53	10.99	Standard	Reisman et al., 2009
Nitrate[c]	0.08	5.1	Confidential	Blumenstein and Gusek, 2009
Selenium[c]	0.001	0.013	Confidential	Blumenstein and Gusek, 2009
Sulfate	136.5	277	Lilly/Orphan Boy[b]	Bless et al., 2008
Thallium[c]	0.007	1.25	Confidential	Blumenstein and Gusek, 2009
Zinc	0.7944	2.8406	Calliope	Wilmoth, 2002
pH[d]	7.16	6.05	Calliope	Wilmoth, 2002

Notes:
a = Average influent arsenic concentration was reported above the detection limit only in the Lilly/Orphan Boy study
b = Average influent concentration provided was from 1993-1994; average effluent concentration calculated by EPA from data provided in the reference for two sampling dates in 2001
c = Nitrate, selenium and thallium were monitored only at the Confidential Mine site
d = Lower average effluent pH correlates with higher average effluent constituent concentrations

Table 3-7: Minimum Average Effluent Concentration Attained

Constituent	Minimum Average Effluent Concentration	Average Influent Concentration	Mine	Source
Concentrations reported as dissolved in mg/L; pH reported in standard units				
Aluminum	<0.02	9.7	Lilly/Orphan Boy[a]	Bless et al., 2008
Arsenic	0.075	1.07[b]	Lilly/Orphan Boy[a]	Bless et al., 2008
Cadmium	0.00019	0.095[c]	Standard	Gallagher et al., 2012
Copper	0.0014	0.1[c]	Standard	Gallagher et al., 2012
Iron	0.4143	0.4556	Calliope	Wilmoth, 2002
Lead	0.00215	0.134[c]	Standard	Gallagher et al., 2012
Manganese	1.0073	1.4581	Calliope	Wilmoth, 2002
Nitrate[d]	0.08	5.1	Confidential	Blumenstein and Gusek, 2009
Selenium[d]	0.001	0.013	Confidential	Blumenstein and Gusek, 2009
Sulfate	0.1039	0.1029	Calliope	Wilmoth, 2002

Table 3-7: Minimum Average Effluent Concentration Attained

Constituent	Minimum Average Effluent Concentration	Average Influent Concentration	Mine	Source
Thallium[d]	0.007	1.25	Confidential	Blumenstein and Gusek, 2009
Zinc	0.032	26.1	Lilly/Orphan Boy[a]	Bless et al., 2008
pH	7.2	3.0	Lilly/Orphan Boy[b]	Bless et al, 2008

Notes:
a = Average influent concentration provided was from 1993-1994; average effluent concentration calculated by EPA from data provided in the reference for two sampling dates in 2001
b = Average influent arsenic concentration was reported above the detection limit only in the Lilly/Orphan Boy study
c = Calculated by EPA from average effluent concentration and percent removal provided: 100* (avg in – avg out)/avg in = % removal
d = Nitrate, selenium and thallium were monitored only at the Confidential Mine site

Although they are not directly comparable, both the highest and lowest average influent concentrations are able to be treated to some degree in anaerobic BCRs, as shown in Tables 3-4 and 3-5 with average effluent concentrations of aluminum, arsenic, cadmium, copper, iron, lead, nitrate, selenium, thallium and zinc being lower than average influent concentrations. Comparison of Tables 3-4 and 3-5 with Table 3-6 suggests that, on average, there is minimal or no treatment of manganese with average influent and average effluent concentrations being similar. Average iron and sulfate concentrations are decreased; however, the magnitude of decrease is less than that for other analytes and the decrease is less for lower average influent concentrations. Metal sulfides having higher solubility constants (lower pKs) form more slowly and are dissolved more quickly than metal sulfides having lower solubility constants (higher pKs); solubility constants also are dependent on temperature and pH. The pKs values for manganese and iron sulfide precipitates at 25 °C are 17.2, 9.6, and 12.6 for FeS, MnS (pink) and MnS (green), respectively; for comparison, the pKs values for CdS, CuS, and ZnS (as sphalerite) are 26.1, 35.2, and 23.0, respectively (Blais et al., 2008). Precipitation also is competitive and higher concentrations of more stable sulfides will outcompete those that are less stable; therefore, lesser decreases, or no decreases in concentrations of iron and manganese, on average, are therefore not surprising. Table 3-7 shows that, on average, anaerobic BCRs are capable of decreasing aluminum concentrations to levels below detection limits. Table 3-6 also shows that, on average, anaerobic BCRs are capable of decreasing cadmium concentrations to below detection limits, but comparison with cadmium in Table 3-7 shows that detection limits vary between studies.

3.4.3 Removal Efficiency

The maximum and minimum removal efficiencies in Tables 3-8 and 3-9, respectively, were determined by comparing values in Appendix A, Table A-3. Each constituent's maximum removal efficiency in Table 3-8 is the higher percentage of either the average or the maximum removal efficiency in Table A-3, and each minimum removal efficiency in Table 3-9 is the lower percentage of either the average or the minimum removal efficiency in Table A-3. Comparison of minimum and maximum removal efficiencies also was determined by sample type – total or dissolved. Several case studies had multiple treatment components and reported removal efficiencies for the overall treatment train and those are not included in this section or in Table A-3 because they do not reflect removal efficiencies specific to the BCRs.

Table 3-8: Maximum Removal Efficiencies

Constituent	Maximum Removal Efficiency	Mine	Source
Aluminum[a]	99.73%	Calliope – BCR III[b,c]	Wilmoth, 2002
Arsenic[a]	86.89%	Calliope – BCR III[b,c]	Wilmoth, 2002
Cadmium	99.80%	Standard[d]	Gallagher et al., 2012
Copper	99.37%	Calliope – BCR III[b,c]	Wilmoth, 2002
Iron	97.94%	Calliope – BCR III[b,c]	Wilmoth, 2002
Lead[e]	98.40%	Standard[d]	Gallagher et al., 2012
Manganese[a]	98.05%	Calliope – BCR III[b,c]	Wilmoth, 2002
Nitrate[f]	>99%	Confidential[g]	Blumenstein and Gusek, 2009
Selenium[f]	>99%	Confidential[g]	Blumenstein and Gusek, 2009
Sulfate	57.20%	Standard[d]	Gallagher et al., 2012
Thallium[f]	99.97%	Confidential[h]	Blumenstein and Gusek, 2009
Zinc	100.00%	Cwm Rheidol[d]	Jarvis et al., 2014

Notes:
a = Only monitored at Calliope
b = Values calculated by EPA from data provided in Table 5-6
c = Total
d = Dissolved
e = Only monitored at Standard Mine
f = Only monitored at the Confidential Mine site; total or dissolved not stated
g = Assumed to be greater than 99 percent based on corresponding effluent data assumed to be at or below detection limits based on figures referenced in Appendix A, Table A-3
h = Value calculated by EPA from data in Figure 7 of Blumenstein and Gusek, 2009; for non-detect results, EPA used ½ the detection limit for calculations

Table 3-9: Minimum Removal Efficiencies

Constituent	Minimum Removal Efficiency	Mine	Source
Aluminum[a]	-650.00%	Calliope – BCR III[b,c]	Wilmoth, 2002
Arsenic[a]	-95.38%	Calliope – BCR III[b,c]	Wilmoth, 2002
Cadmium	-9.80%	Calliope – BCR III[b,c]	Wilmoth, 2002
Copper	-189.59%	Calliope – BCR III[b,c]	Wilmoth, 2002
Iron	-14275.00%	Calliope – BCR III[b,c]	Wilmoth, 2002
Lead[d]	98.10%	Standard[e]	Reisman et al., 2009

Table 3-9: Minimum Removal Efficiencies

Constituent	Minimum Removal Efficiency	Mine	Source
Manganese[a]	-108.22%	Calliope – BCR III[b,c]	Wilmoth, 2002
Nitrate[f]	96.55%	Confidential[e,g]	Blumenstein and Gusek, 2009
Selenium[f]	>99%	Confidential[e,h]	Blumenstein and Gusek, 2009
Sulfate	-68.63%	Calliope – BCR III[b,c]	Wilmoth, 2002
Thallium[f]	99.8%	Confidential[e,g]	Blumenstein and Gusek, 2009
Zinc	-11.97%	Calliope – BCR III[b,c]	Wilmoth, 2002

Notes:
a = Only reported for Calliope
b = Values calculated by EPA from data provided in Table 5-6
c = Total
d = Only monitored at Standard Mine
e = Total or dissolved not stated in reference
f = Only monitored at the Confidential Mine site
g = Values calculated by EPA from data provided in figures referenced in Appendix A, Table A-3
h = Assumed to be greater than 99 percent based on corresponding effluent data assumed to be at or below detection limits based on figures referenced in Appendix A, Table A-3

As shown by comparing data in both tables, removal efficiencies from anaerobic BCR treatment in the studies examined span a wide range for most constituents. When comparing constituents where this information was available from more than one case study, the widest range (~126 percent) occurs for sulfate, while the smallest range (~110 percent) occurs for cadmium. Selenium and thallium had greater than 99 percent removal efficiencies at the single case study included in this report that reported results for these constituents.

The negative removal efficiencies for multiple constituents in Table 3-9 were from a single case study in which EPA calculated the sampling date specific removal efficiencies from the corresponding influent and effluent data provided in the study (Wilmoth, 2002). Some sampling dates had concentrations of aluminum, arsenic, cadmium, copper, iron, manganese, sulfate and zinc in the effluent samples that were higher than the corresponding influent samples used for calculating removal efficiencies. Wilmoth (2002) hypothesizes that higher concentrations of constituents in the effluent samples may have occurred for a variety of constituent specific reasons.

3.4.4 Flow Rates

Table 3-10 presents flow rates for anaerobic BCRs using solid substrates.

Table 3-10: Flow Rate – Anaerobic, Solid Substrate

Operational Flow Rate	Mine	Source
All rates are in liters per minute (L/min)		

Table 3-10: Flow Rate – Anaerobic, Solid Substrate

Operational Flow Rate	Mine	Source
3.8[a]	Calliope	Wilmoth, 2002
3.8 – 19.3[b]	Confidential	Blumenstein and Gusek, 2009 (Figure 6, text)
1.9 – 4.5	Cwm Rheidol	Jarvis et al., 2014
1.1	Nenthead	Jarvis et al., 2014
7.6	Lilly Orphan Boy	Bless et al., 2008
3.8	Standard	Gallagher et al., 2012
< 7.6[c]	Surething	Nordwick and Bless, 2008

Notes:
a = Operated at 7.6 L/min for four months
b = Typically operated at or below design flow rate of 18.9 L/min
c = Operational flow stated as below the design flow of 7.6 L/min

As shown in Table 3-10, anaerobic, single-unit solid substrate BCRs can treat flows of 3.8-19.3 L/min in the studies examined. Anaerobic BCRs (or SRBRs) commonly are included as part of a treatment train, with higher influent flows able to be treated over the entire system; for example, see discussions of case studies in Chapter 5 of Doshi (2006). One evaluated case study reported a higher design flow rate of 180 L/min for a single unit solid substrate BCR (Jarvis et al., 2015).

Additionally, all the studies providing operational flow rate information were pilot-scale studies (some were demonstration type) and may not be representative of actual treatable flow capability of full-scale BCRs.

3.5 Capability – Anaerobic, Liquid Substrate

Only two case studies using liquid substrates for their anaerobic BCRs met the screening criteria for inclusion in this report (see Introduction): Leviathan Mine and Keno Mine. Additionally, differences between the two studies (Table 3-1) and limited data restrict the ability to compare results to determine the general capability for the liquid substrate anaerobic BCR technology. This is due to the Leviathan site having 1) pretreatment with sodium hydroxide to raise influent pH from 3.1 to 4 and to precipitate some metals (Doshi, 2006; U.S. EPA, 2006a), 2) two different operating designs (modes), and 3) that the case study reported results for only a single sampling date for each of the two design configurations (one when operated in a recirculation mode and one when operated in a gravity-fed mode).

3.5.1 Ranges of Applicability

Although the technology's range of applicability cannot be evaluated by comparison of solely the two studies, maximum and minimum influent and corresponding effluent concentration data for both case studies are provided in Table A-1, Appendix A and a limited discussion of the technology is presented in this section. Tables 3-11 and 3-12 list the maximum and minimum influent constituent concentrations, respectively, from comparison of data in Appendix A, Table A-1 across the two operating modes at Leviathan. Tables 3-13 and 3-14 list the maximum and minimum influent constituent concentrations, respectively, for Keno Hill.

Table 3-11: Maximum Influent and Corresponding Effluent Concentrations – Leviathan

Constituent	Maximum Influent Concentration	Corresponding Effluent Concentration	Mode	Source
All concentrations reported in mg/L; pH reported in standard units				
Aluminum[a]	36.3	28.3	Gravity	U.S. EPA, 2006a
Arsenic[b]	0.0059	0.005	Recirculation	U.S. EPA, 2006a
Cadmium[a]	0.00042	< 0.00023	Gravity	U.S. EPA, 2006a
Chromium[a]	0.0147	0.0139	Gravity	U.S. EPA, 2006a
Copper[a]	0.653	0.0676	Gravity	U.S. EPA, 2006a
Iron[a]	87	77.7	Gravity	U.S. EPA, 2006a
Lead[a]	0.0059	0.0055	Gravity	U.S. EPA, 2006a
Nickel[a]	0.475	0.37	Gravity	U.S. EPA, 2006a
Selenium[b]	0.0114	0.0116	Recirculation	U.S. EPA, 2006a
Sulfate[a]	1520	1480	Gravity	U.S. EPA, 2006a
Zinc[a]	0.714	0.125	Gravity	U.S. EPA, 2006a
pH	3.6	4.7	Gravity	U.S. EPA, 2006a
Notes: a = Total b = Dissolved				

Table 3-12: Minimum Influent and Corresponding Effluent Concentrations – Leviathan

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mode	Source
Concentrations reported in mg/L and as dissolved, except sulfate (total); pH reported in standard units				
Aluminum	0.104	0.108	Recirculation	U.S. EPA, 2006a
Arsenic	0.0028	<0.0023	Gravity	U.S. EPA, 2006a
Cadmium	0.00021	0.00041	Recirculation	U.S. EPA, 2006a
Chromium	0.0118	0.012	Recirculation	U.S. EPA, 2006a
Copper	0.0057	0.0061	Gravity	U.S. EPA, 2006a
Iron	0.266	0.247	Recirculation	U.S. EPA, 2006a
Nickel	0.0117	0.0102	Recirculation	U.S. EPA, 2006a
Lead	0.0042	0.0040	Recirculation	U.S. EPA, 2006a
Selenium	0.0075	0.0114	Recirculation	U.S. EPA, 2006a
Sulfate	1160	1090	Recirculation	U.S. EPA, 2006a
Zinc	0.0063	0.0104	Recirculation	U.S. EPA, 2006a
pH	7.2	7.3	Recirculation	U.S. EPA, 2006a

Table 3-13: Maximum Influent and Corresponding Effluent Concentrations – Keno Hill

Constituent	Maximum Influent Concentration	Corresponding Effluent Concentration	Mine	Source
Concentrations reported as total in mg/L				
Arsenic	0.07	0.008	Keno Hill[a]	Harrington et al., 2015
Cadmium	0.0016	<0.0001	Keno Hill[a]	Harrington et al., 2015
Manganese	19	20	Keno Hill[a]	Harrington et al., 2015
Zinc	6.2	0.01	Keno Hill[a]	Harrington et al., 2015
Notes: a = Keno Hill data used were from post-August 2009, which corresponds to the start of sulfate-reducing conditions in the BCR; data were approximated from figures				

Table 3-14: Minimum Influent and Corresponding Effluent Concentrations – Keno Hill

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mine	Source
Concentrations reported as total in mg/L				
Arsenic	0.018	0.001	Keno Hill[a]	Harrington et al., 2015
Cadmium	0.0011	<0.0001	Keno Hill[a]	Harrington et al., 2015
Manganese	15	16	Keno Hill[a]	Harrington et al., 2015
Zinc	4.8	0.055	Keno Hill[a]	Harrington et al., 2015
Notes: a = Keno Hill data used were from post-August 2009, which corresponds to the start of sulfate-reducing conditions in the BCR; data were approximated from figures				

The highest constituent influent concentrations between the two operating configurations at Leviathan (Table 3-11) show some decreases from treatment, but only copper is decreased by an order of magnitude. Minimum influent concentrations (Table 3-12) also show little removal, with some constituent concentrations even being increased in the effluent versus the influent (e.g., aluminum, cadmium, copper). The liquid anaerobic BCR study at Keno Hill demonstrated that treatment can decrease concentrations of constituents by greater than one order of magnitude for arsenic, cadmium and zinc, at both the highest (Table 3-13) and lowest (Table 3-14) influent concentrations of the constituents. However, manganese is not decreased by the technology. Notable differences in ranges of applicability observed from each study further support the need for additional studies to be assessed to evaluate applicability for the technology.

3.5.2 Average Influent and Effluent Concentrations

Average influent and effluent concentrations were not provided for either case study examined.

3.5.3 Removal Efficiency

Maximum and minimum removal efficiencies for both total and dissolved concentrations of multiple constituents were provided for the two operating modes (gravity and recirculation modes) for single sampling dates at Leviathan, and averages were provided for Keno Hill (Appendix A, Table A-3). Table 3-15 and Table 3-16 list the maximum and minimum removal efficiencies, respectively, as compared across the two operating modes and two sample types at Leviathan. Table 3-17 lists the average removal efficiencies for Keno Hill.

Table 3-15: Maximum Removal Efficiencies – Leviathan

Constituent	Maximum Removal Efficiency	Mode	Source
Aluminum[a]	66.80%	Recirculation	U.S. EPA, 2006a
Cadmium[a]	45.20%	Gravity	U.S. EPA, 2006a
Chromium[a]	7.90%	Gravity	U.S. EPA, 2006a
Copper[b]	99.10%	Gravity	U.S. EPA, 2006a
Iron[b]	94.60%	Recirculation	U.S. EPA, 2006a
Lead[a]	20.00%	Gravity	U.S. EPA, 2006a
Nickel[b]	83.90%	Recirculation	U.S. EPA, 2006a
Selenium[b]	23.90%	Gravity	U.S. EPA, 2006a
Sulfate[a]	11.50%	Gravity	U.S. EPA, 2006a
Zinc[b]	95.20%	Gravity	U.S. EPA, 2006a

Notes:
a = Total
b = Dissolved
Minimum and maximum values from Leviathan gravity flow configuration data March 24, 2004
Minimum and maximum recirculation flow configuration data August 19, 2004

Table 3-16: Minimum Removal Efficiencies – Leviathan

Constituent	Minimum Removal Efficiency	Mode	Source
Aluminum[a]	0.00%	Recirculation	U.S. EPA, 2006a
Cadmium[a,b]	0.00%	Recirculation and Gravity	U.S. EPA, 2006a
Chromium[a,b]	0.00%	Recirculation and Gravity	U.S. EPA, 2006a
Copper[a]	-6.50%	Recirculation and Gravity	U.S. EPA, 2006a
Iron[a]	1.90%	Gravity	U.S. EPA, 2006a
Lead[b]	-9.30%	Recirculation	U.S. EPA, 2006a
Nickel[a]	12.80	Recirculation	U.S. EPA, 2006a
Selenium[a]	0.00%	Recirculation and Gravity	U.S. EPA, 2006a
Sulfate[b]	2.50%	Recirculation	U.S. EPA, 2006a
Zinc[a]	-6.60%	Recirculation	U.S. EPA, 2006a

Table 3-16: Minimum Removal Efficiencies – Leviathan

Constituent	Minimum Removal Efficiency	Mode	Source
Notes: a = Dissolved b = Total Minimum and maximum values from Leviathan gravity flow configuration data March 24, 2004 Minimum and maximum Recirculation flow configuration data August 19, 2004			

Table 3-17: Average Removal Efficiencies – Keno Hill

Constituent	Average Removal Efficiency	Mine	Source
All results reported as total			
Antimony	80.00%	Keno Hill	Harrington et al., 2015
Arsenic	80.00%	Keno Hill	Harrington et al., 2015
Nickel	80.00%	Keno Hill	Harrington et al., 2015
Zinc	99.00%	Keno Hill	Harrington et al., 2015

The liquid BCRs in the case studies examined demonstrated more than 94 percent removal efficiencies for dissolved copper, iron and zinc when influent water was previously treated with alkali (Table 3-15). Liquid BCR treatment appears less effective for chromium, lead, selenium and sulfate than for the other elements, with removal efficiencies <24 percent. The removal efficiency for all constituents (except for nickel and sulfate) was also as low as zero, suggesting the removal efficiency of the liquid BCR technology with alkali pretreatment is highly variable. On average, a liquid anaerobic BCR without an alkaline pretreatment appears capable of providing 80 percent removal efficiency on average for total antimony, arsenic and nickel, and an even higher 99 percent removal efficiency for total zinc (Table 3-17). However, because of limited studies, these data may not reflect the true capabilities of a liquid anaerobic BCR.

3.5.4 Flow Rates

U.S. EPA (2006) reported that up to 91 L/min was treated at Leviathan, whereas Harrington et al. (2015) reported an operational flow rate ranging from 30 to 60 L/min at Keno Hill.

3.6 Capability – Aerobic, Solid Substrate

The inclusion of only one case study (Nordwick and Bless, 2008 - Surething Mine) that met the screening criteria (Section 1.1.1) for this work limits the ability to determine general capability of aerobic BCRs.

3.6.1 Ranges of Applicability

A shallow (30.5 cm (1 foot) depth) aerobic BCR decreased a maximum influent concentration of manganese from 24 mg/L to 2.3 mg/L and a minimum influent concentration of 17 mg/L to 10.5 mg/L on one date and to <0.30 mg/L on another date (Nordwick and Bless, 2008).[1] The pH was also increased by the limestone in the aerobic BCR and manganese removal increased as pH increased.

3.6.2 Average Influent and Effluent Concentrations

Average influent and effluent concentrations were not provided for the aerobic BCR at the Surething Mine.

3.6.3 Removal Efficiency

Removal efficiency for the aerobic BCR part of the treatment train was not provided by Nordwick and Bless (2008); however, using the maximum and minimum influent (see Ranges of Applicability, above), the calculated efficiency of a manganese-oxidizing bacteria aerobic BCR ranges from about 38-98 percent.

3.6.4 Flow Rates

Flow rate specific to the aerobic BCR was not provided by Nordwick and Bless (2008); however less than 7.6 L/min was treated by the treatment train at Surething Mine.

3.7 Costs

Costs were provided for only two case studies reviewed; therefore, no technology-specific costs can be determined. The total capital and equipment cost for the anaerobic BCR with a liquid substrate at Leviathan was $548,431 for gravity flow mode and $554,551 for the recirculation flow mode; site preparation costs were $288,186 and $309,568 for the gravity and recirculation flow modes, respectively; and operational costs (including sludge disposal, analytical services for weekly sampling, and maintenance/modification) were $104,613 and $98,353 for the gravity and recirculation flow modes, respectively (Table 4.2 in U.S. EPA, 2006a). The first-year costs for the liquid BCR in each of the flow-modes was approximately $190 per 3.79 m^3 (1,000 gallons) of water treated (U.S. EPA, 2006a). The construction costs for the treatment train at the Surething Mine, consisting of two anaerobic BCRs with solid substrates, an anoxic limestone drain, and an aerobic BCR with solid substrate, was $250,000 (Doshi, 2006).

3.8 Lessons Learned

- Suitability of BCR substrate mixture for treatment at a site is best determined through bench-scale testing. The ideal substrate consists of both long- and short-term sources of carbon and nutrients (i.e., sources that do and do not biodegrade easily) and provides good permeability and structural stability of the BCR over time (Bless et al., 2008; Blumenstein and Gusek, 2009). A short-term substrate is easily biodegradable and essential for startup, while a substrate with low biodegradation rate enhances long-term performance (Bless et al., 2008).

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[1] Maximum and minimum influent and effluent manganese concentrations are estimates, based on review of Figure 4-7, SP4 and effluent post June 2004, in Nordwick and Bless, 2008.

- BCR system components may plug due to high iron and aluminum concentrations (Jarvis et al., 2014; Bless et al., 2008) or due to decreased permeability or lack of stability over time (Wilmoth, 2002). Systems can incorporate design components to minimize sediment and iron hydroxide precipitants from entering the system (Reisman et al., 2009).
- Use of liquid BCRs in remote locations can be challenging due to frequent maintenance requirements and storage of chemicals and fuel (Doshi, 2006; U.S. EPA, 2006a).
- Neutralizing pH in MIW as a pretreatment step prior to circulation through an anaerobic BCR may reduce stress on the SRB and increase metal removal efficiency in liquid and solid substrate BCRs (U.S. EPA, 2006a; Bless et al., 2008).
- Effluents from anaerobic BCR treatment may be acutely or sub-chronically toxic, although toxicity is reduced from that observed in BCR influents (Lazorchak et al., 2002; Butler et al., 2011). Inclusion of an aeration step following BCR treatment to remove secondary contaminants formed through microbial activity, such as hydrogen sulfide or ammonia, and to decrease biochemical oxygen demand may eliminate aquatic toxicity (Butler et al., 2011). Aeration is also necessary to re-oxidize the water and precipitate and settle out any residual metals (Nordwick and Bless, 2008; U.S. EPA, 2006a).
- A shallow aerobic BCR is more effective than a deeper system for providing a sufficiently oxic environment for manganese removal following anaerobic treatment (Nordwick and Bless, 2008).
- Colder temperatures may prolong the time needed for an SRB population to become established and may also decrease BCR efficiency (Harrington et al., 2015; Jarvis et al., 2014). However, systems can incorporate design components to minimize the effects, such as by keeping reactors at a depth below the frost line, providing extra capacity, covering with plastic to insulate the cells, and controlling winter flows (Butler et al., 2011; Doshi, 2006; Wilmoth, 2002; Blumenstein and Gusek, 2009).
- Covering anaerobic BCRs with plastic may insulate the cells from low temperatures and minimize oxygen infiltration, which leads to more reducing conditions and increased efficiency (Wilmoth, 2002; Bless et al, 2008; Butler et al., 2011).
- Solar power can be used to power pumps and monitoring equipment in locations where access to electricity is limited, although issues may arise if persistent cloudy weather prevents recharging of batteries (Gallagher et al., 2012; Reisman et al., 2009).
- Effluent from in-situ BCRs may become re-contaminated with metals if not isolated from untreated tunnel drainage post-treatment (Bless et al., 2008; Doshi, 2006).
- Variable flows may negatively impact BCR performance (Doshi, 2006; Harrington et al., 2015).
- BCR lifetime is limited by high concentrations of constituents and acidity (Doshi, 2006).
- At the end of a BCR's lifetime, substrate materials that have retained the contaminants need to be tested to determine appropriate disposal options (Jarvis et al., 2014; Doshi, 2006; U.S. EPA, 2006a).
- Coarse rock materials are unable to retain zinc sulfide particulates formed in liquid BCRs (Harrington et al., 2015). Gammons and Frandsen (2001) documented similar observations of particulate zinc sulfide in effluent from a constructed anaerobic wetland having less coarse substrate, as well as noting the presence of particulate copper and cadmium in effluent.

3.9 References

3.9.1 Case Study References

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3.9.2 General BCR References

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4 Caps and Covers

Caps and covers are well-proven technologies that are often employed at mine sites. Typically, caps and covers are used to isolate solid mining waste to prevent or limit infiltration of water, ingress of oxygen, control dust migrations, prevent erosion and eliminate the potential for direct contact with the waste. Decreased infiltration from use of caps and covers could decrease loads of constituents sufficiently to allow for passive treatment. While not directly treatment technologies, studies were sought where caps and covers influenced leachate concentrations. Various materials are utilized for caps and covers, including soil, clay, amendments, membrane liners and rock, vegetation, as well as a combination of these materials based on the conditions and needs at specific mine sites (Interstate Technology and Regulatory Council [ITRC], 2010).

4.1 Case Studies Evaluated

This chapter provides an evaluation of case studies in which caps and covers were the primary components in treating or managing mining wastes to mitigate mining-influenced water (MIW) formation. The case studies were selected based on the criteria presented in Section 1.1.1. Due to the frequent use of liners, few studies are available where the influence of cap or cover can be isolated from the influence of a liner. The case studies examined include three mining sites: one in the United States, one in Australia and one in Sweden. Table 4-1 summarizes site names and locations, treatment design information, and references for each of the case studies. The Dunka Mine case study (Eger and Eger, 2005) examined the effectiveness of wetland treatment combined with capping of waste piles; data incorporated into this chapter's evaluation address the capping component, whereas the Constructed Wetlands chapter (Section 7) addresses the whole system. The chapter presents technology-wide considerations for constraints, treatability of contaminants, capability, technological and site-specific requirements, and lessons learned for caps and covers from evaluation of case study results.

Table 4-1: Caps and Covers Case Study Sites

Site Name and Location	Type	Description	Study Type	Reference	Reference Type
Kristineberg Mine, Northern Sweden	Composite cover consisting of till (protective layer) and sewage sludge (sealing layer)	Sewage sludge was used as a sealing layer in a composite dry cover. Composite dry covers consist of a protective layer and a sealing layer.	Pilot scale	Nason et al., 2013*	Journal paper
				Nason, 2013	Conference proceedings
				Nason et al., 2010	Conference proceedings

Table 4-1: Caps and Covers Case Study Sites

Site Name and Location	Type	Description	Study Type	Reference	Reference Type
Savage River Mine, Tasmania, Australia	Water-shedding top cover and alkaline (calcite-chlorite schist) side cover	To control acid rock drainage (ARD), a combined water-shedding and calcite-chlorite schist cover was placed over a historic dump (B-dump).	Full scale	Li et al., 2012*	Conference proceedings
Dunka Mine, Northeastern Minnesota	Several covers consisting of screened soil, compacted soil and/or flexible membrane liner	Five waste rock stockpiles were covered.	Full scale	Eger and Eger, 2005*	Conference proceedings
				Eger et al., 1998	Conference proceedings
				Eger et al., 1996	Conference proceedings
Notes: *Primary source(s) of data for evaluation in this chapter					

4.2 Constraints

A constraint for caps and covers is the cost for locating, excavating and transporting capping and covering materials to the site being remediated (Nason et al., 2013), with higher transportation costs associated with materials located far from the site (Eger et al., 1998). A limitation to using sewage sludge in cap and cover material is that it is chemically unstable and may contain metals or nitrate that could be leached (Nason, 2013). Another limitation to using sewage sludge is degradation of the organic matter that would limit the long-term capability of the cap, or potential for sewage sludge to contain emerging contaminants that may need to be tested (Nason, 2013).

4.3 Treatable Contaminants

Caps and covers in the studies examined are capable of increasing pH and decreasing the concentrations of dissolved cadmium, copper, iron, lead, sulfur, and zinc, and cobalt, copper, nickel, and zinc in leachate/seepage not indicated as total or dissolved (Eger and Eger, 2005; Nason et al., 2013) relative to pre-capping conditions. Additionally, capping demonstrated a reduction in oxidation of sulfide from waste rock (Li et al., 2012).

4.4 Capability

The three case studies meeting the criteria (Section 1.1.1) differed in the type of materials used for the covers, methodologies for monitoring effectiveness (two analyzed leachate samples, one analyzed waste material). These differences between the studies and limited data reported restrict the ability to compare directly across types of caps/covers. The limited numbers of studies identified limits the assessment of general capability of caps and covers.

4.4.1 Ranges of Applicability

Range of applicability differs in this section, as compared to technologies directly treating water, because results are not based on an influent treated and a corresponding effluent attained at a point in time, but rather are based on differences in concentrations of constituents in affected water sources monitored before and after cap/cover placement or capped versus uncapped wastes. Therefore, applicability is presented as a range in concentrations in leachate before treatment (pre-capping or uncapped control) and a range attained after covering of the waste. Only one examined case study provided non-averaged pre-and post-capping (or capped versus uncapped control) concentration data to address range of applicability and Table 4-2 contains the concentration ranges for constituents from Table B-1 in Appendix B.

Table 4-2: Concentration Range Pre- and Post-Capping – Kristineberg Mine

Constituent	Pre-Capping (or Uncapped Control) Concentration Range	Post-Capping Concentration Range	Media	Source
Concentrations reported as dissolved in mg/L; pH reported in standard units				
Cadmium	ND – 0.03	ND	Leachate	Nason et al., 2013
Copper	0.0005 – 0.04	ND – 0.001	Leachate	Nason et al., 2013
Iron	ND – 0.022	ND – 0.005	Leachate	Nason et al., 2013
Lead	0.0001 – 0.00065	0.0001 – 0.00055	Leachate	Nason et al., 2013
Sulfur	410 – 700	15 – 220	Leachate	Nason et al., 2013
Zinc	2.5 – 40	ND	Leachate	Nason et al., 2013
pH	6.2 – 7.6	6.8 – 8.2	Leachate	Nason et al., 2013
Notes: ND = Not detected Nason et al. (2013) compared capped cells with uncapped control cells				

Table 4-2 shows that the cap at the single case study examined that provided pre- and post-capping concentration ranges can decrease concentrations of cadmium, copper, iron, lead, sulfur, and zinc originating from mining wastes. The magnitude of decrease in concentrations in affected leachate varies among the constituents assessed. The cap in the case study examined also can raise the pH of affected water as shown by comparison of the lowest pH of leachate in the absence of a cap on the waste source with the lowest pH of the leachate after placement of a cap on the waste material source and likewise comparison of the highest pH values in the leachate.

While caps/covers do result in decreased concentrations in affected water sources, a general assessment of applicability of the technology is hindered by data limitations. For example, only dissolved cadmium, copper, iron, lead, zinc, and pH were monitored in the single study examined that provided pre- and post-capping concentration ranges.

4.4.2 Average Pre-Treatment and Post-Treatment Concentrations

This chapter includes a single study that documented average concentrations. Table 4-3 lists the maximum average pre-capping leachate concentrations and the range in average post-capping concentrations (average 1996-1998 and average 1999-2004) and Table 4-4 lists the minimum average pre-capping leachate concentrations and the average post-capping concentrations (1996-1998) for cobalt, copper, nickel, and zinc. Values were determined by looking across data in Appendix B, Table B-2, which includes data from pre- and post-capping of two waste piles.

Table 4-3: Maximum Average Pre-Capping Leachate and Post-Capping Leachate Concentration Range (1996-1998 – 1999-2004) – Dunka Mine

Constituent	Maximum Average Pre-Capping Leachate Concentration	Average Post-Capping Leachate Concentration Range	Stockpile/Wetland	Source
Concentrations reported in mg/L, total or dissolved not specified; pH reported in standard units				
Cobalt	0.036	0.009[a]	8018 and 8031/W1D	Eger and Eger, 2005
Copper	0.068	0.02 – 0.03	8018 and 8031/W1D	Eger and Eger, 2005
Nickel	3.98	0.74 – 0.76	8018 and 8031/W1D	Eger and Eger, 2005
Zinc	0.052	0.019 – 0.021	8018 and 8031/W1D	Eger and Eger, 2005
pH	7	7	8031/W2D/3D	Eger and Eger, 2005
Notes: a = No value given in source for 1999-2004 Post-capping values are influent concentrations to Wetland W1D from Table 1 of the source				

Table 4-4: Minimum Average Pre-Capping Leachate and Post-Capping Leachate Concentrations (1996-1998) – Dunka Mine

Constituent	Minimum Average Pre-Capping Leachate Concentration	Average Post-Capping Leachate Concentration	Stockpile/Wetland	Source
Concentrations reported in mg/L, total or dissolved not specified; pH reported in standard units				
Cobalt	0.02	0.02	8031/W2D/3D	Eger and Eger, 2005
Copper	0.05	0.05	8031/W2D/3D	Eger and Eger, 2005

Table 4-4: Minimum Average Pre-Capping Leachate and Post-Capping Leachate Concentrations (1996-1998) – Dunka Mine

Constituent	Minimum Average Pre-Capping Leachate Concentration	Average Post-Capping Leachate Concentration	Stockpile/Wetland	Source
Concentrations reported in mg/L, total or dissolved not specified; pH reported in standard units				
Nickel	1.9	1.9	8031/W2D/3D	Eger and Eger, 2005
Zinc	0.05	0.05	8031/W2D/3D	Eger and Eger, 2005
pH	7.07	7.26 – 7.3	8018 and 8031/W1D	Eger and Eger, 2005

Although they are not directly comparable (i.e., a given maximum average pre-capping concentration in affected water may not result in a given minimum average post-capping concentration in affected water), on average, cobalt and nickel concentrations are an order of magnitude (Table 4-3) lower than average pre-capping leachate concentrations. Copper and zinc decreased by less than an order of magnitude, on average. Minimum average pre-capping data are identical to average post-capping data (Table 4-4), suggesting that this cap was not effective.

Table 4-5 presents a comparison of the percentage of total sulfur in waste rock materials five years after being capped or not capped, as compared to the initial conditions.

Table 4-5: Savage River Mine – Percent Total Sulfur in Waste Rock, Pre-Cover, Post-Cover and with No Cover Within The B-Dump

	Under Alkaline Cover	No Cover	Pre-Cover	Source
Average Percentage of Total Sulfur (%)	1.9	0.9	3.2[a]	Li et al., 2012
MPA (Sulfur)	57.1	27.2	97.2	Li et al., 2012
Decrease in Percentage of Total Sulfur between 2005 and 2010 (%)	41	72		Li et al., 2012
Notes: Table reproduced from Table 5 in source MPA = maximum potential acidity expressed as kg H_2SO_4/t a = Li et al. (2012) calculated the average sulfur percentage from three samples collected in May 2005; the total sulfur content in the three samples was 3.05 percent, 3.77 percent and 2.71 percent				

On average (over five years), and assuming that sulfur-bearing waste materials are completely homogenized within the waste rock pile and that any oxidized sulfur is leached out of the pile and not retained as precipitated salts (Li et al., 2012), capping with an alkaline cover is effective in decreasing oxidation of pyritic waste rock as seen by the higher percentage of sulfur remaining in the samples obtained under the alkaline cover Table 4-5).

Capping led to 31 percent less oxidation of pyrite as compared to waste rock without a cap, when both were compared to pre-capping conditions. This is reflected also in the capped material retaining more potential acidity (57.1 kilograms (kg) H_2SO_4/t) than the un-capped waste rock (27.2 kg H_2SO_4/t) (Table 4-5).

4.4.3 Percentage Reduction

Table 4-6 presents percentage reductions in concentrations of constituents in leachate from capping/covering of the mine waste source. The maximum and minimum percentage reductions were calculated from the data in Appendix B, Tables B-1 and B-2. Percentage reduction was only calculated when a detected concentration was available for the pre-reclamation condition. The percentage reductions should be considered estimates due to the variability in comparing data from capped and uncapped and pre- and post-reclamation conditions obtained in different time periods.

Table 4-6: Maximum and Minimum Percentage Reduction

Constituent	Water Sample	Maximum Percentage Reduction	Minimum Percentage Reduction	Mine	Notes
Cadmium	Dissolved	>99.00%	>99.00%	Kristineberg[a]	Table B-1
Copper	Dissolved	>99.00%	97.5%	Kristineberg[a]	Table B-1
Iron	Dissolved	>99.00%	77.27%	Kristineberg[a]	Table B-1
Lead	Dissolved	84.62%	0.00%	Kristineberg[a]	Table B-1
Sulfur	Dissolved	97.86%	46.34%	Kristineberg[a]	Table B-1
Zinc	Dissolved	>99.00%	>99.00%	Kristineberg[a]	Table B-1
Cobalt	NS	75.00%	75.00%[b]	Dunka[c]	Table B-2 (Wetland W1D)
Copper	NS	70.59%	55.88%	Dunka[c]	Table B-2 (Wetland W1D)
Nickel	NS	81.41%	80.90%	Dunka[c]	Table B-2 (Wetland W1D)
Zinc	NS	63.46%	59.62%	Dunka[c]	Table B-2 (Wetland W1D)

Notes:
NA = Pre-reclamation concentrations were not detected
NS = Not stated
a = EPA calculated maximum and minimum percent reduction based on the maximum and minimum leachate concentrations in capped and uncapped cells shown in Appendix B, Table B-1. For

Table 4-6: Maximum and Minimum Percentage Reduction

Constituent	Water Sample	Maximum Percentage Reduction	Minimum Percentage Reduction	Mine	Notes
constituents that were not detected in the uncapped cell, EPA assumed a greater than 99 percent reduction. b = Cobalt concentrations in 1999-2004 were not recorded, so only a single set of average pre- and post-capping concentrations were available c = EPA calculated maximum and minimum percent reduction based on pre-capping average concentrations (1992-1994) and post-capping average concentrations (1996-1998 and 1999-2004) for Wetland W1D shown in Appendix B, Table B-2					

Table 4-6 shows that cap/cover placement can reduce concentrations of constituents in affected water sources in the case studies that provided data to calculate percentage reduction and when pre-reclamation concentrations were reported above detection limits. The magnitude of the percentage reduction in affected water sources varies among the constituents and case studies. The range of percentage reduction for constituents within individual case studies also varies. Maximum percentage reduction for all constituents in all case studies included in the evaluation in Table 4-6 was greater than 63 percent; minimum percentage reduction for all constituents in all case studies included in the evaluation in Table 4-6 was greater than 50 percent except for dissolved lead and dissolved sulfur in one study (0 percent and 46 percent reduction, respectively, at Kristineberg).

4.4.4 Flow Rates

Only one case study that was evaluated had flow rates for water flow out of a capped area (Table 4-7). Average flow from capped stockpiles ranged from 38 liters per minute (L/min) to about 76 L/min (Eger and Eger, 2005). Flow rates were decreased by 36 percent for part of the year (May through October) after two years of the cap being in place covering about 60 percent of the total area of the stockpile for W1D (Eger and Eger, 2005).

Table 4-7 Average Flow

Average Flow	Stockpile	Pre- or Post-Capping Date Range
All rates are in L/min		
75	W2D/3D	Pre-capping (1992-1994)
125	W1D	Pre-capping (1992-1994)
45	W2D/3D	Post-capping (1996-1998)
57	W1D	Post-capping (1996-1998)
45	W2D/3D	Post-capping (1999-2004)
38	W1D	Post-capping (1999-2004)
Notes: Source: Eger and Eger, 2005		

4.5 Costs

Costs were provided in only one of the three case studies. Cost per hectare averaged $35,000 for a screened soil cap and was $123,000 for a flexible liner (Eger et al., 1998). Other cap types presented in Eger et al. (1998) included compacted soil at $56,000 per hectare and a combined screened soil and flexible liner at $54,000 per hectare; however, these cap types did not have associated data provided in the case study. Costs are contingent upon site-specific details (e.g. earth moving, contour and grade).

4.6 Lessons Learned

- When using sewage sludge as a sealing layer in a composite cover, degradation of the organic matter in the sludge may limit the length of time a cap or cover is effective and further study of long-term applicability is needed (Nason et al., 2013).
- To prevent pyrite oxidation and formation of a contaminant plume, sewage sludge should be avoided on water-saturated cover types (Nason, 2013).
- Applying sewage sludge to fresh tailings can lead to cracking and can release additional metals into the tailings (Nason, 2013).

4.7 References

4.7.1 Case Study References

Eger, P., Wagner, J., and Melchert, G. 1996. “The Use of Overland Flow Wetland Treatment Systems to Remove Nickel from Neutral Mine Drainage. “Paper presented at the 1996 Annual Meeting of the American Society for Surface Mining and Reclamation (ASSMR), Knoxville, TN, May 18-23. pp. 580-589.

Eger, P., Melchert, G., and Wagner, J. 1998. “Mine closure – Can passive treatment be successful.” In Proceedings of 15th Annual Meeting of American Society for Surface Mining and Reclamation, St. Louis, MO, May 17-21, 1998. pp. 263-271.

Eger, P. and P. Eger. 2005. “Controlling Mine Drainage Problems in Minnesota – Are All the Wetland Treatment Systems Really Above Average?” Paper presented at the 2005 National Meeting of the American Society of Mining and Reclamation, June 19-13, 2005. Published by ASMR, Lexington, KY. pp. 339-359.

Li, J., Kawashima, N., Kaplun, K., Schumann, R.C, Smart, R., Hughes, A, Hutchison, B., and Kent, S. 2012. “Investigation of alkaline cover performance for abatement of ARD from waste rock dumps at Savage River.” Presented at the 9th International Conference on Acid Rock Drainage (ICARD), Ottawa, Canada, May, 2012. pp. 418-429.

Nason, P. 2013. “Advances in using sewage sludge to remediate sulfidic mine tailings – an overview from pilot- and field-scale experiments, Northern Sweden.” In Wolkersdorfer, C., Brown, A., and Figueroa, L. (Eds.), Proceedings of the International Mine Water Association Annual Conference: Reliable Mine Water Technology, Volume 1. Golden, CO, August 6-9, 2013. pp. 681-686. Published by the International Mine Water Association.

Nason, P., Alakangas, L., and Öhlander, B. 2010 “The Effectiveness of Using Sewage Sludge as a Sealing Layer on Sulphide-rich Mine Tailings: A Pilot-scale Experiment, Northern Sweden.” In proceedings from the International Mine Water Association Symposium: *Mine Water and Innovative Thinking*, Sydney, Nova Scotia, September 5-9, 2010. pp. 155-158. Published by Cape Breton University Press, Sydney, Nova Scotia.

Nason, P., Alakangas, L., and Öhlander, B. 2013. Using Sewage Sludge as a Sealing Layer to Remediate *Sulphidic Mine Tailings: A Pilot-Scale Experiment, Northern Sweden. *Environmental Earth Sciences* **70**(7): 3093-3105.

4.7.2 General Capping References

Interstate Technology & Regulatory Council (ITRC) Interstate Technology & Regulatory Council, Mining Waste Team. 2010. “Technology Overview, Capping, Covers and Grading.” Last modified August 2010. https://www.itrcweb.org/miningwaste-guidance/to_capping_covers.htm.

5 Neutralization and Chemical Precipitation

Neutralization and chemical precipitation involve the use of reagents to facilitate the formation of insoluble solids from the mining-influenced water (MIW) that then can be separated from the treated water. Alkaline reagents used for treating MIW include limestone ($CaCO_3$), lime (CaO), hydrated (or slaked) lime ($CaOH_2$), sodium hydroxide (NaOH), and soda ash (Na_2CO_3). Neutralization and chemical precipitation can occur in an active water treatment system or in a passive or semi-passive, flow-through system. In active systems, coagulants and flocculants often are added to facilitate faster separation of the solids from the water column, whereas in passive or semi-passive systems, settling typically occurs over time in a pond or wetland without using additional chemicals. Biogenically-produced or chemical sulfide reagents may be used in active treatment systems to anaerobically precipitate metal sulfides that may be salable (Kratochvil et al, 2015). The active and semi-passive systems evaluated in this chapter utilized hydroxide precipitation with lime. Although active sulfide precipitation technology is being used, at the time of report development no studies using it were identified that met the criteria (see Section 1.1.1) for this work; therefore, that technology was not evaluated.

Passive alkaline neutralization and precipitation treatment systems include anoxic limestone drains (ALD) and reducing and alkalinity producing systems (RAPS) that use limestone to neutralize acidity and provide the alkalinity to allow for precipitation of metals in a settling pond or other structure downstream from the limestone system. Variations in system designs have been explored to reduce passivation or clogging, save space or otherwise improve on the mechanisms of treatment. The passive system evaluated in this chapter uses a dispersed alkaline substrate (DAS). The DAS is a medium that consists of a fine-grained alkaline material such as calcite, limestone sand or magnesium oxide (MgO) mixed with a coarse inert material such as wood chips (Rötting et al., 2008a; Rötting et al., 2008b; Macías et al., 2012a). The small grain size of the alkaline material increases reactivity and reduces passivation with its large reactive surface area, while the coarse material provides porosity and reduces potential for clogging, although clogging may occur if the MIW being treated has high concentrations of aluminum (Rötting et al., 2008a). Limestone-based DAS effectively treats trivalent metals aluminum and iron and MgO-based DAS effectively treats divalent metals like copper, manganese, nickel and zinc (Macías et al., 2012b), which precipitate at higher pH than ferric iron and aluminum.

5.1 Case Studies Evaluated

This chapter provides an evaluation of case studies in which neutralization and chemical precipitation was a primary component of MIW treatment. The case studies evaluated were selected based on the criteria presented in Section 1.1.1 and include three active lime treatment systems (one of which was operated in two separate modes and one that utilized a Rotating Cylinder Treatment System^{TM} (RCTS)), a semi-passive system and a passive limestone DAS (Table 5-1). This chapter provides considerations for constraints, treatability of contaminants, capability, technological and site-specific requirements, costs and lessons learned for neutralization and chemical precipitation treatment from evaluation of these case studies.

Table 5-1: Neutralization and Chemical Precipitation Case Study Sites

Site Name and Location	Type	System Description	Study Type	Reference	Reference Type
Leviathan Mine, Alpine County, California	Active lime treatment	Two modes employed: single-stage and dual-stage mode (1st stage for arsenic removal and 2nd stage for removing remaining constituents)	Pilot scale	U.S. EPA, 2006a*	Report
	Semi-passive alkaline lagoon	Continuous flow lime contact system			
Britannia Mine, Vancouver, British Columbia	Active lime treatment	High-density sludge (HDS)	Full scale	Madsen et al., 2012*	Conference proceedings
Monte Romero Mine Southwestern Spain	Passive limestone DAS	Two, three-cubic meter tanks (Tank 1 and Tank 2) filled with coarse wood chips mixed with limestone sand and operated in series separated by two aeration cascades and two decantation ponds	Pilot scale	Macías et al., 2012a*	Journal paper
				Macías et al., 2012b	Journal paper
				Rötting et al., 2008a	Journal paper
Elizabeth Mine, Strafford, Vermont	Active lime treatment in Rotating Cylinder Treatment System™ (RCTS)	An RCTS™ system followed by a sedimentation basin	Full scale	Butler and Hathaway, 2020*[a]	Report

Notes:
*Primary source(s) of data for evaluation in this chapter
a. Although published outside of the established literature search timeframe, report is included due to its authors' involvement in drafting this report.

The DAS at Monte Romero Mine was part of a larger treatment train, which consisted of water flowing from the mine shaft to a natural Fe-oxidizing lagoon (NFOL) to reduce high iron concentrations, followed by a limestone-DAS tank, two aeration structures and settling ponds, a second limestone-DAS tank followed by two more aeration structures and settling ponds, and then to a MgO-DAS tank (Macías et al., 2012b). The multi-step system is evaluated in the Treatment Trains chapter (Section 10). This chapter evaluates only the two limestone-DAS tanks (Tank 1 and Tank 2). Water quality data specific to the MgO-DAS tank were unavailable in the references reviewed.

5.2 Constraints

A constraint for typical active lime treatment systems is that they require a large amount of space to store sludge, water and other reagents, as well as filter presses, pumps and piping (U.S. EPA, 2006a). The RCTS™ system is more compact and does not require conventional agitators, compressors, diffusers and reactions vessels (Butler and Hathaway, 2020). Utilities such as electricity are required to operate the systems and cellular or satellite phone service may be required to monitor remote sites (U.S. EPA, 2006a). Active lime treatment also requires high maintenance and regular monitoring, and systems are prone to scaling from gypsum formation ($CaSO_4 \bullet 2H_2O$) and plugging from clumps of lime (U.S. EPA, 2006a; Butler and Hathaway, 2020). Lime treatment may also increase pH above regulatory limits for discharge to receiving waters; secondary treatment to decrease pH may be needed to meet water quality criteria. Additionally, capacity can be limited in the treatment system and high flow events may occur, leaving some MIW untreated or unable to meet effluent limits (Madsen, et al., 2012).

In cold climates, operation may not be possible in winter months, requiring yearly shutdown procedures which are time-consuming and intensive, or alternatively requiring the treatment system to be housed in a heated structure, increasing costs and energy usage (Butler and Hathaway, 2020). Climate also may influence land space required for the system if a large holding pond is needed to accommodate both MIW and precipitation. Operation in remote areas requires increased planning and organization (U.S. EPA, 2006a).

A constraint of the DAS technology is that precipitates accumulate in the tanks containing the substrate and this eventually causes clogging, which will lead to a need to either remove surface precipitates or to replace the substrate (Rötting et al., 2008a). According to Rötting et al. (2008a), the need to remove precipitates or replace substrate will occur more frequently than in a RAPS or ALD.

5.3 Treatable Contaminants

Lime treatment can increase pH and treat aluminum, arsenic, cadmium, chromium, copper, iron, lead, manganese, nickel, selenium and zinc (U.S. EPA, 2006a; Madsen et al., 2012; Butler and Hathaway, 2020). Semi-passive alkaline treatment also can reduce concentrations of aluminum, arsenic, chromium, copper, iron, lead, nickel, selenium and zinc and increase pH (U.S. EPA, 2006a). Limestone-DAS can treat aluminum, arsenic, copper, iron, lead, silicon, zinc and increase pH (Macías et al., 2012a). Future case study comparisons may provide additional information on treatable contaminants.

5.4 Capability – Active

Because only three studies were identified that met the screening criteria, limited data restrict the ability to determine the general capability for active lime treatment.

5.4.1 Ranges of Applicability

Two case studies included corresponding influent and effluent data. Concentrations of metals tend to be inversely related to the pH, with higher concentrations associated with a lower pH and lower concentrations associated with a higher pH. Tables 5-2 and 5-3 show the maximum influent concentration (and the minimum pH) and corresponding effluent concentration, and the minimum influent concentration (and the maximum pH) and corresponding effluent concentration, respectively from comparison of data in Table C-1, Appendix C.

Table 5-2: Maximum Influent and Corresponding Effluent Concentrations – Active Treatment

Constituent	Maximum Influent Concentration	Corresponding Effluent Concentration	Mine / Mode	Source
Concentrations reported in mg/L and as dissolved, except iron is reported as total; pH reported in standard units				
Aluminum	486	1.09	Leviathan/Dual-stage	U.S. EPA, 2006a
Arsenic	4.05	0.0101	Leviathan/Dual-stage	U.S. EPA, 2006a
Cadmium	0.0683	0.0007	Leviathan/Dual-stage	U.S. EPA, 2006a
Chromium	1.24	0.0024	Leviathan/Dual-stage	U.S. EPA, 2006a
Copper	2.99	0.0101	Leviathan/Dual-stage	U.S. EPA, 2006a
Iron	1,710	23.6[a]	Elizabeth Mine	Butler and Hathaway, 2020
Lead	0.0122	<0.0014	Leviathan/Dual-stage	U.S. EPA, 2006a
Nickel	8.77	0.0389	Leviathan/Dual-stage	U.S. EPA, 2006a
Selenium	0.0323	<0.0018	Leviathan/Single-stage	U.S. EPA, 2006a
Zinc	1.81	0.0307	Leviathan/Dual-stage	U.S. EPA, 2006a
pH	4.63	8.65 [a]	Elizabeth Mine	Butler and Hathaway, 2020
Notes: Dual-stage data come from 12 sampling dates in 2002 and 1 in 2003 and the single-stage data come from 7 sampling dates in 2003 a = Effluent data from the RCTS™ system				

Table 5-3: Minimum Influent and Corresponding Effluent Concentrations – Active Treatment

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mine / Mode	Source
Concentrations reported in mg/L, and as dissolved, except iron is reported as total; pH reported in standard units				
Aluminum	98.6	0.575	Leviathan/Single-stage	U.S. EPA, 2006a
Arsenic	1.33	0.0096	Leviathan/Dual-stage	U.S. EPA, 2006a
Cadmium	0.0132	<0.00021	Leviathan/Single-stage	U.S. EPA, 2006a
Chromium	0.266	0.0116	Leviathan/Single-stage	U.S. EPA, 2006a
Copper	0.434	<0.0019	Leviathan/Single-stage	U.S. EPA, 2006a

Table 5-3: Minimum Influent and Corresponding Effluent Concentrations – Active Treatment

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mine / Mode	Source
Concentrations reported in mg/L, and as dissolved, except iron is reported as total; pH reported in standard units				
Iron	50	4[a]	Elizabeth Mine	Butler and Hathaway, 2020
Lead	0.0017	0.0044	Leviathan/Dual-stage	U.S. EPA, 2006a
Nickel	2.41	0.0688	Leviathan/Single-stage	U.S. EPA, 2006a
Selenium	0.0046	0.0037	Leviathan/Dual-stage	U.S. EPA, 2006a
Zinc	0.49	0.0031	Leviathan/Single-stage	U.S. EPA, 2006a
pH	6.87	9.6 [a]	Elizabeth Mine	Butler and Hathaway, 2020

Notes:
Dual-stage data come from 12 sampling dates in 2002 and 1 in 2003 and the single-stage data come from 7 sampling dates in 2003
a = Effluent from the RCTS™ system

Active lime treatment can decrease concentrations of all constituents evaluated, with concentrations of aluminum, arsenic, cadmium, chromium, copper, iron, nickel and zinc decreased by two to three orders of magnitude when starting concentrations are high, and lead and selenium can be decreased to below their respective detection limits (Table 5-2). Active lime treatment can also increase pH.

Decreases in aluminum, arsenic, cadmium, copper and nickel concentrations are also two or three orders of magnitude from minimum concentrations treated, whereas chromium and iron concentrations are decreased by one order of magnitude (Table 5-3). The lowest influent lead concentration increased following treatment, but influent and effluent concentrations are on the same order of magnitude as the detection limit (0.0014 mg/L, Table 5-2) and therefore may not be representative of treatment ability. It should be noted that the minimum concentrations of many constituents indicated in Table 5-3 are higher than low concentrations present at many other sites; therefore, the table likely does not represent the capability of lime treatment at lower influent concentrations.

5.4.2 Average Influent and Effluent Concentrations

Tables 5-4 and 5-5 list the highest and lowest average influent concentrations treated for each constituent, respectively. Tables 5-6 and 5-7, respectively, list the highest and lowest average effluent concentrations attained for each constituent. These values were determined by comparing values in Appendix C, Table C-2. It is important to note that the average influent concentrations do not correspond directly with the average effluent concentrations (see Section 1.1.2).

Table 5-4: Maximum Average Influent Concentration Treated – Active Treatment

Constituent	Maximum Average Influent Concentration	Average Effluent Concentration	Mine / Mode	Source
Concentrations reported in mg/L and as dissolved, except iron is reported as total; pH reported in standard units				
Aluminum	381	1.118	Leviathan/Dual-stage	U.S. EPA, 2006a
Arsenic	3.236	0.0063	Leviathan/Single-stage	U.S. EPA, 2006a
Cadmium	0.097	0.001	Britannia	Madsen et al., 2012
Chromium	0.877	0.0057	Leviathan/Dual-stage	U.S. EPA, 2006a
Copper	16.8	0.01	Britannia	Madsen et al., 2012
Iron	879.55 ± 181.09	0.37 ± 0.29[a]	Elizabeth Mine	Butler and Hathaway, 2020
Lead	0.0082	0.002	Leviathan/Dual-stage	U.S. EPA, 2006a
Manganese	4.8	0.3	Britannia	Madsen et al., 2012
Nickel	7.024	0.0342	Leviathan/Dual-stage	U.S. EPA, 2006a
Selenium	0.0271	0.00214	Leviathan/Single-stage	U.S. EPA, 2006a
Zinc	19.7	0.03	Britannia	Madsen et al., 2012
pH	3.71	9.2[b]	Britannia	Madsen et al., 2012

Notes:

a = Effluent from the RCTS™ system

b = The average effluent pH was reported in the text as “consistently 9.2”

Data from Butler and Hathaway, 2020, include average concentrations and standard deviations

Table 5-5: Minimum Average Influent Concentration Treated – Active Treatment

Constituent	Minimum Average Influent Concentration	Average Effluent Concentration	Mine / Mode	Source
Concentrations reported as dissolved in mg/L				
Aluminum	16.08	0.5	Britannia	Madsen et al., 2012
Arsenic	2.239	0.00859	Leviathan/Dual-stage	U.S. EPA, 2006a
Cadmium	0.0261	ND	Leviathan/Single-stage	U.S. EPA, 2006a
Chromium	0.341	0.00304	Leviathan/Single-stage	U.S. EPA, 2006a
Copper	0.502	0.00307	Leviathan/Single-stage	U.S. EPA, 2006a
Iron	0.66	0.01	Britannia	Madsen et al., 2012
Lead	0.0071	0.00156	Leviathan/Single-stage	U.S. EPA, 2006a
Manganese	3.45	0.3	Britannia	Madsen et al., 2012
Nickel	2.56	0.0468	Leviathan/Single-stage	U.S. EPA, 2006a
Selenium	0.0088	0.00378	Leviathan/Dual-stage	U.S. EPA, 2006a
Zinc	0.538	0.00561	Leviathan/Single-stage	U.S. EPA, 2006a

Table 5-5: Minimum Average Influent Concentration Treated – Active Treatment

Constituent	Minimum Average Influent Concentration	Average Effluent Concentration	Mine / Mode	Source
Concentrations reported as dissolved in mg/L				
pH	4.2	9.2[a]	Britannia	Madsen et al., 2012
Notes: ND = Not detected, detection limit not reported a = The average effluent pH was reported in the text as "consistently 9.2"				

Table 5-6: Maximum Average Effluent Concentration Attained – Active Treatment

Constituent	Maximum Average Effluent Concentration	Average Influent Concentration	Mine / Mode	Source
Concentrations reported in mg/L and as dissolved, except iron that is reported as total; pH reported in standard units				
Aluminum	1.118	381	Leviathan/Dual-stage	U.S. EPA, 2006a
Arsenic	0.00859	2.239	Leviathan/Dual-stage	U.S. EPA, 2006a
Cadmium	0.002	0.087	Britannia	Madsen et al., 2012
Chromium	0.0057	0.877	Leviathan/Dual-stage	U.S. EPA, 2006a
Copper	0.02	13.9	Britannia	Madsen et al., 2012
Iron	12.28 ± 12.74	199.15 ± 64.75	Elizabeth Mine	Butler and Hathaway, 2020
Lead	0.002	0.0082	Leviathan/Dual-stage	U.S. EPA, 2006a
Manganese	0.4	3.94/4.1[a]	Britannia	Madsen et al., 2012
Nickel	0.0468	2.56	Leviathan/Single-stage	U.S. EPA, 2006a
Selenium	0.00378	0.0088	Leviathan/Dual-stage	U.S. EPA, 2006a
Zinc	0.04	14.8	Britannia	Madsen et al., 2012
pH	9.2[b]	3.7 – 4.2[b]	Britannia	Madsen et al., 2012
Notes: a = The average annual effluent reported was 0.4 in two different years; the average annual influent concentrations are provided for both years b = The average effluent pH was reported in the text as "consistently 9.2"; the range in average influent pH is provided Data from Butler and Hathaway, 2020, include average concentrations and standard deviations				

Table 5-7: Minimum Average Effluent Concentration Attained – Active Treatment

Constituent	Minimum Average Effluent Concentration	Average Influent Concentration	Mine / Mode	Source
Concentrations reported as dissolved in mg/L; pH reported in standard units				
Aluminum	0.4	19.3	Britannia	Madsen et al., 2012
Arsenic	0.0063	3.236	Leviathan/Single-stage	U.S. EPA, 2006a
Cadmium	ND	0.0261	Leviathan/Single-stage	U.S. EPA, 2006a
Chromium	0.00304	0.341	Leviathan/Single-stage	U.S. EPA, 2006a
Copper	0.00307	0.502	Leviathan/Single-stage	U.S. EPA, 2006a
Iron	<0.01	0.95	Britannia	Madsen et al., 2012
Lead	0.00156	0.0071	Leviathan/Single-stage	U.S. EPA, 2006a
Manganese	0.1	4.33	Britannia	Madsen et al., 2012
Nickel	0.0342	7.024	Leviathan/Dual-stage	U.S. EPA, 2006a
Selenium	0.00214	0.0271	Leviathan/Single-stage	U.S. EPA, 2006a
Zinc	0.00561	0.538	Leviathan/Single-stage	U.S. EPA, 2006a
pH	9.2[a]	3.7 – 4.2[a]	Britannia	Madsen et al., 2012

Notes:
ND = Not detected, detection limit not reported
a = The average effluent pH was reported in the text as “consistently 9.2”; the range in average influent pH is provided

Lime treatment can treat both the highest and lowest average influent concentrations of all elements presented, as shown by comparison of Tables 5-4 and 5-5 with Table 5-6, indicating maximum average effluent concentrations are lower than both maximum and minimum influent concentrations. On average, concentrations are decreased by one to three orders of magnitude relative to maximum and minimum influent concentrations. In the case of lead, maximum and minimum average influent concentrations and maximum and minimum average effluent concentrations are on the same order of magnitude, which is true also for the minimum average influent of selenium. Therefore, treatment appears less efficient, on average, but this likely is because concentrations already are low (in the <10 µg/l range). Lead sulfate is insoluble except at very low or very high pH; therefore, in MIW having high concentrations of sulfate, dissolved lead concentrations would be expected to be low. The minimum average influent selenium concentration is an order of magnitude lower than the maximum average influent concentration, but both the minimum and maximum average effluent concentrations are on the same order of magnitude. This suggests that, on average, there is a minimum concentration (~0.002 mg/L) to which selenium can be treated passively with lime. As shown in Table 5-7, lime treatment can reduce cadmium and iron concentrations to below their detection limits. On average, all elements but aluminum, manganese and nickel can be treated to concentrations <0.01 mg/L, whereas those are able to be reduced to <0.4 mg/L. Lime treatment also increases pH.

5.4.3 Average Mass Removed

This chapter includes a single case study that provided yearly influent volumes treated, as well as average influent and effluent concentrations (Madsen et al., 2012). Yearly average mass treated and removed for each of the constituents were calculated from the data provided in the case study. The calculated mass treated and removed for each contaminant is presented in Table C-3 in Appendix C.

Over the entire study, 2006-2010, thousands to hundreds of thousands of kilograms (kg) of total metals were removed by the lime treatment system. Zinc had the highest initial mass at about 103,700 kg and 103,550 kg of zinc were removed. Cadmium had the lowest initial mass at 293 kg and 289 kg were removed.

5.4.4 Removal Efficiency

The maximum and minimum average removal efficiencies in Table 5-8 and Table 5-9, respectively, were determined by a review of data in Appendix C, Table C-4.

Table 5-8: Maximum Removal Efficiencies – Active Treatment

Constituent	Maximum Removal Efficiency	Mine / Mode	Source
All constituents reported as dissolved			
Aluminum	99.9%	Leviathan/Dual-stage	U.S. EPA, 2006a
Arsenic	99.9%	Leviathan/Single-stage	U.S. EPA, 2006a
Cadmium	99.7%	Leviathan/Single-stage	U.S. EPA, 2006a
Chromium	99.9%	Leviathan/Dual-stage	U.S. EPA, 2006a
Copper	100.0%	Britannia[a]	Madsen et al., 2012
Iron	100.0%	Leviathan/Single-stage and Dual-stage	U.S. EPA, 2006a
Lead	89.8%	Leviathan/Single-stage	U.S. EPA, 2006a
Manganese	97.7%	Britannia[a]	Madsen et al., 2012
Nickel	99.9%	Leviathan/Dual-stage	U.S. EPA, 2006a
Selenium	94.4%	Leviathan/Single-stage	U.S. EPA, 2006a
Zinc	99.9%	Britannia[a]	Madsen et al., 2012
Notes: a = EPA calculated removal efficiencies from the average influent and effluent concentrations for each year (2006 to 2010)			

Table 5-9: Minimum Removal Efficiencies – Active Treatment

Constituent	Minimum Removal Efficiency	Mine/Mode	Source
All constituents reported as dissolved			
Aluminum	96.90%	Britannia[a]	Madsen et al., 2012
Arsenic	99.20%	Leviathan/Dual-stage	U.S. EPA, 2006a
Cadmium	97.50%	Leviathan/Dual-stage	U.S. EPA, 2006a
Chromium	93.80%	Leviathan/Dual-stage	U.S. EPA, 2006a
Copper	99%	Leviathan/Single-stage	U.S. EPA, 2006a
Iron	93.40%	Britannia[a]	Madsen et al., 2012
Lead	48.30%	Leviathan/Single-stage	U.S. EPA, 2006a
Manganese	89.80%	Britannia[a]	Madsen et al., 2012
Nickel	95.70%	Leviathan/Single-stage	U.S. EPA, 2006a
Selenium	91%	Leviathan/Single-stage	U.S. EPA, 2006a
Zinc	97.40%	Leviathan/Dual-stage	U.S. EPA, 2006a
Notes: a = EPA calculated removal efficiencies from the average influent and effluent concentrations for each year (2006 to 2010)			

As shown in Table 5-8, the maximum removal efficiencies for active lime treatment ranged from about 90 percent (lead) to 100 percent (copper and iron) in the studies examined. The minimum removal efficiencies ranged from 48 percent (lead) to 99 percent (arsenic and copper) (Table 5-9). With the exceptions of lead and manganese, lime treatment has a minimum removal efficiency of greater than 90 percent for all elements in Table 5-9.

5.4.5 Flow Rates

Flow rates for the three studies are provided in Table 5-10.

Table 5-10: Flow Rate – Active Treatment

Maximum Influent Flow Rate	Minimum Influent Flow Rate	Average Influent Flow Rate	Mine / Mode	Source
All rates are in liters per minute (L/min)				
246	212	223	Leviathan/Single-stage	U.S. EPA, 2006a
662	587	640	Leviathan/Dual-stage	U.S. EPA, 2006a
193.19	100.64	140.34 ± 16.83	Elizabeth Mine (2009)	Butler and Hathaway, 2020
166.13	92.81	122.67 ± 20.67	Elizabeth Mine (2010)	Butler and Hathaway, 2020
218	34	100.00 ± 27.33	Elizabeth Mine (2011)	Butler and Hathaway, 2020
102.23	59.25	85.34 ± 13.17	Elizabeth Mine (2012)	Butler and Hathaway, 2020

Table 5-10: Flow Rate – Active Treatment

Maximum Influent Flow Rate	Minimum Influent Flow Rate	Average Influent Flow Rate	Mine / Mode	Source
117.38	70.35	85.00 ± 8.50	Elizabeth Mine (2013)	Butler and Hathaway, 2020
86.78	63.86	73.17 ± 5.67	Elizabeth Mine (2014)	Butler and Hathaway, 2020
87.41	51.19	65.50 ± 7.17	Elizabeth Mine (2015)	Butler and Hathaway, 2020
96	46.09	76.33 ± 10.00	Elizabeth Mine (2016)	Butler and Hathaway, 2020
114.45	62.14	89.50 ± 9.50	Elizabeth Mine (2017)	Butler and Hathaway, 2020
NS	NS	7,435	Britannia[a] (2006)	Madsen et al., 2012
NS	NS	10,005	Britannia[a] (2007)	Madsen et al., 2012
NS	NS	7,298	Britannia[a] (2008)	Madsen et al., 2012
NS	NS	6,412	Britannia[a] (2009)	Madsen et al., 2012
NS	NS	8,423	Britannia[a] (2010)	Madsen et al., 2012
NS	NS	7,915[b]	Britannia[a] Overall	Madsen et al., 2012

Notes:
NS = Not stated
a = EPA calculated the average flow rate from annual flows presented in Table 4 for 2006-2010
b = Average treatment plant flow rate (2006-2010)
Data from Butler and Hathaway (2020) include average flow rates and standard deviations by year

As shown in Table 5-10, active neutralization and chemical precipitation can treat a wide variety of flows, with average flow rates treated being greater than 10,000 liters per minute (L/min) and a minimum flow as low as 34 L/min.

5.5 Capability – Semi-Passive Treatment

The inclusion of only one case study (U.S. EPA, 2006a) that met the criteria (see Section 1.1.1) for this work limits the ability to determine the capability of semi-passive lime treatment, in general. In the single case study evaluated, the treatment system relied on mechanical aeration and lime dosing prior to gravity flow to alkaline treatment lagoons (U.S. EPA, 2006a). Nevertheless, the following sections present capability data for the technology based on the single study.

5.5.1 Ranges of Applicability

Tables 5-11 and 5-12, respectively, show the range of concentrations (maximum influent and corresponding effluent; and minimum influent and corresponding effluent) treated semi-passively with lime from Appendix C, Table C-1 in the single case study (U.S. EPA, 2006a).

Table 5-11: Maximum Influent and Corresponding Effluent Concentrations – Semi-Passive Treatment

Constituent	Maximum Influent Concentration	Corresponding Effluent Concentration	Mine / Mode	Source
Concentrations reported as dissolved in mg/L; pH reported in standard units				
Aluminum	33.6	0.254	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Arsenic	0.545	0.0129	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Chromium	0.0235	0.0038	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Copper	0.0163	0.0061	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Iron	460	0.0172	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Lead	0.0063	0.0026	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Nickel	1.69	0.0472	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Selenium	0.007	<0.0025	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Zinc	0.369	0.019	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
pH	4.59	7.92	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Notes: < = Not detected above laboratory method detection limit shown				

Table 5-12: Minimum Influent and Corresponding Effluent Concentrations – Semi-Passive Treatment

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mine / Mode	Source
Concentrations reported as dissolved in mg/L; pH reported in standard units				
Aluminum	30.9	0.185	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Arsenic	0.485	0.0038	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Chromium	0.0162	0.0014	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Copper	0.0092	0.0031	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Iron	360	0.0881	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Lead	0.0027	<0.0012	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Nickel	1.57	0.0201	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Selenium	0.0022[a]	0.0036	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Zinc	0.35	0.0062	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
pH	4.59	7.92	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Notes: < = Not detected above laboratory method detection limit shown a = Value reported in reference, but is below the reference's reported detection limit				

As shown in Table 5-11 and Table 5-12, aluminum, arsenic, chromium, copper, iron, lead, nickel, selenium and zinc are all treatable to concentrations below about 0.2 mg/L by lime in a semi-passively operated system (U.S. EPA, 2006a). Lead shows the least change between minimum and maximum influent concentrations and corresponding effluent concentrations, owing to low influent concentrations being treated, but was decreased by more than 50 percent. Minimum and maximum influent selenium concentrations and their corresponding effluent concentrations are all close to the detection limit and therefore may or may not represent treatability.

5.5.2 Average Influent and Effluent Concentrations

Data provided were insufficient to determine the maximum and minimum average influents treated and the maximum and minimum effluents attained. Therefore, Table 5-13 lists only the average influent concentrations and average effluent concentrations reported for aluminum, arsenic, cadmium, chromium, copper, iron, nickel, selenium and zinc from Appendix C, Table C-2.

Table 5-13: Average Influent Concentration Treated – Semi-Passive Treatment

Constituent	Average Influent Concentration	Average Effluent Concentration	Mine / Mode	Source
Concentrations reported as dissolved in mg/L; pH reported in standard units				
Aluminum	31.988	0.251	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Arsenic	0.519	0.00584	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Cadmium	ND	0.00038	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Chromium	0.0193	0.00225	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Copper	0.0135	0.00546	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Iron	391.25	0.148	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Lead	0.0051	0.00166	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Nickel	1.631	0.0226	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Selenium	0.0033	0.00324	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Zinc	0.356	0.0142	Leviathan/Alkaline Lagoon	U.S. EPA, 2006a
Notes: ND = Not detected, detection limit not provided				

Although the average influent concentrations are not directly comparable to the average effluent concentrations (i.e., a concentration equal to the average influent concentration may or may not be treated to the average concentration reported for the effluent), the average effluent concentrations lower than the average influent concentrations shown in Table 5-13 indicates these constituents are successfully treatable in a semi-passive system. The one exception is cadmium, where the influent concentrations on all sampling dates were below detection; therefore, no assessment can be made as to whether cadmium is treatable via this method without inclusion of additional studies. Lead and selenium average influent concentrations were less than about 0.005 mg/L, as were average effluent concentrations. On average, lead appears to be able to be decreased further in concentration from a low value, but selenium appears to be untreatable at average concentrations to lower than about 0.0033 mg/L by semi-passive lime treatment.

5.5.3 Removal Efficiency

The maximum and minimum removal efficiencies are provided in Table 5-14, from Appendix C, Table C-4.

Table 5-14: Removal Efficiencies – Semi-Passive Treatment

Constituent	Maximum Removal Efficiency	Minimum Removal Efficiency	Mine	Source
All constituents reported as dissolved				
Aluminum	99.5%	98%	Leviathan Mine / Alkaline Lagoon	U.S. EPA, 2006a
Arsenic	99.5%	97.6%	Leviathan Mine / Alkaline Lagoon	U.S. EPA, 2006a
Chromium	92.3%	83.1%	Leviathan Mine / Alkaline Lagoon	U.S. EPA, 2006a
Copper	74.5%	27.7%	Leviathan Mine / Alkaline Lagoon	U.S. EPA, 2006a
Iron	100%	99.9%	Leviathan Mine / Alkaline Lagoon	U.S. EPA, 2006a
Lead	78.9%	37.7%	Leviathan Mine / Alkaline Lagoon	U.S. EPA, 2006a
Nickel	99.1%	97.2%	Leviathan Mine / Alkaline Lagoon	U.S. EPA, 2006a
Zinc	98.2%	90.6%	Leviathan Mine / Alkaline Lagoon	U.S. EPA, 2006a

As shown in Table 5-14, semi-passive lime treatment in a lagoon has maximum removal efficiencies of over 90 percent for aluminum, arsenic, iron, nickel, chromium and zinc. Maximum removal efficiencies for copper and lead are lower, at 74.5 percent and 78.9 percent, respectively. The range of removal efficiencies is narrow for most elements in Table 5-14, but the technology is more variable for copper and lead, with ranges in removal efficiencies of 27.7 to 74.5 percent for copper and 37.7 to 78.9 percent for lead.

5.5.4 Flow Rates

U.S. EPA (2006a) reported that the semi-passive lime treatment system at Leviathan Mine treated flows between 62 to 120 L/min.

5.6 Capability – Passive Treatment

Because only a single case study was evaluated that met this study's criteria, it is not possible to provide evaluation on a technology-wide basis.

5.6.1 Ranges of Applicability

No non-averaged corresponding influent and effluent concentrations of constituents treated were presented in the single case study; therefore, the range of applicability cannot be determined.

5.6.2 Average Influent and Effluent Concentrations

Because the study presented average concentrations of constituents over the entire sampling period of six months, highest and lowest average influent concentrations and highest and lowest effluent concentrations cannot be determined. Table 5-15 presents the average influent and effluent concentrations from the two limestone-DAS tanks.

Table 5-15: Average Influent and Effluent Concentrations – Tanks 1 and 2

Constituent	Average Influent Concentration	Average Effluent Concentration	Mine	Source	Notes
Concentrations reported as dissolved in mg/L; pH reported in standard units					
Aluminum	100	10	Monte Romero	Macías et al., 2012a	Tank 1
Aluminum	10	<0.2	Monte Romero	Macías et al., 2012a	Tank 2
Arsenic	97	<0.002	Monte Romero	Macías et al., 2012a	Tank 1
Arsenic	<0.002	<0.002	Monte Romero	Macías et al., 2012a	Tank 2
Calcium	252	810	Monte Romero	Macías et al., 2012a	Tank 1
Calcium	790	850	Monte Romero	Macías et al., 2012a	Tank 2
Copper	5	<0.005	Monte Romero	Macías et al., 2012a	Tank 1
Copper	<0.005	<0.005	Monte Romero	Macías et al., 2012a	Tank 2
Iron	171	15	Monte Romero	Macías et al., 2012a	Tank 1
Iron	5	<0.2	Monte Romero	Macías et al., 2012a	Tank 2
Lead	182	<0.001	Monte Romero	Macías et al., 2012a	Tank 1
Lead	<0.001	<0.001	Monte Romero	Macías et al., 2012a	Tank 2
Magnesium	263	279	Monte Romero	Macías et al., 2012a	Tank 1
Magnesium	316	386	Monte Romero	Macías et al., 2012a	Tank 2
Manganese	18	19	Monte Romero	Macías et al., 2012a	Tank 1
Manganese	18	19	Monte Romero	Macías et al., 2012a	Tank 2
Potassium	3	4	Monte Romero	Macías et al., 2012a	Tank 1
Potassium	7	7	Monte Romero	Macías et al., 2012a	Tank 2
Silicon	38	19	Monte Romero	Macías et al., 2012a	Tank 1
Silicon	18	11	Monte Romero	Macías et al., 2012a	Tank 2
Sulfate	3440	3590	Monte Romero	Macías et al., 2012a	Tank 1
Sulfate	3870	3770	Monte Romero	Macías et al., 2012a	Tank 2
Zinc	443	436	Monte Romero	Macías et al., 2012a	Tank 1
Zinc	430	414	Monte Romero	Macías et al., 2012a	Tank 2
pH	2.7	6.1	Monte Romero	Macías et al., 2012a	Tank 1
pH	6	6.6	Monte Romero	Macías et al., 2012a	Tank 2
Notes: < = Not detected above laboratory method detection limit given Average influent and effluent obtained from Table 1 of Macías et al., 2012a, where NFOL represents Tank 1 influent and influent for Tank 2 is represented by D2 out (second decant pond in reference Figure 1)					

Although the average influent and average effluent values are not directly related, data in Table 5-15 indicate that limestone-DAS is able to decrease average concentrations of copper, arsenic and lead to below their detection limits. On average, high concentrations of aluminum and iron can be treated with average effluent concentrations being an order of magnitude lower than average influent concentrations and pH can be increased from acidic to near neutral. Average influent concentrations of manganese and zinc were similar to average effluent concentrations, indicating that they are not able to be treated with limestone-DAS.

5.6.3 Removal Efficiency

Average removal efficiencies for each limestone-DAS tank are provided in Table 5-16.

Table 5-16: Removal Efficiencies – Tanks 1 and 2

Constituent	Tank 1 Average Removal Efficiency	Tank 2 Average Removal Efficiency	Source
All constituents reported as dissolved			
Aluminum	90%	99%	Macías et al., 2012a
Arsenic	100%	NA	Macías et al., 2012a
Calcium	-221%	-8%	Macías et al., 2012a
Copper	100%	NA	Macías et al., 2012a
Iron	91%	98%	Macías et al., 2012a
Lead	100%	NA	Macías et al., 2012a
Magnesium	-6%	-22%	Macías et al., 2012a
Manganese	-6%	-6%	Macías et al., 2012a
Potassium	-33%	0%	Macías et al., 2012a
Silicon	50%	39%	Macías et al., 2012a
Sulfate	-4%	3%	Macías et al., 2012a
Zinc	2%	4%	Macías et al., 2012a

Notes:
NA = not applicable, because effluent concentration from Tank 1 (and influent to Tank 2) was below detection
EPA calculated removal efficiency based on data in Table 1 of the reference
For non-detect results, EPA used ½ the detection limit for calculations

On average, arsenic, copper and lead were removed to below their detection limits by the first limestone-DAS unit without need for aeration or the second DAS unit. Aluminum and iron also were able to be treated to below their detection limits, but not by a single pass through the limestone-DAS unit. Therefore, it appears the limestone-DAS technology is effective for aluminum and iron, but that greater than 90 mg/L aluminum or greater than about 150 mg/L iron the water may require an additional pass through a limestone-DAS. The average pH achieved is typical of limestone-based treatments where carbon dioxide is in equilibrium with bicarbonate. Manganese and zinc were not treatable by the limestone-DAS technology, which most likely is because pH is not increased sufficiently to facilitate precipitation of the ions as either carbonates or hydroxides.

5.6.4 Flow Rates

The flow rate for the technology is set to meet the residence time desired. In the single case study evaluated, the flow was set to 1 L/min to obtain a residence time of 24 hours for Tanks 1 and 2 and 4 days for each settling pond (Macías et al., 2012a).

5.7 Costs

The costs for an active lime treatment system vary from about $200,000 to $1,480,000 per year (U.S. EPA, 2006a; Madsen, 2012; Butler and Hathaway, 2020). U.S. EPA (2006a) found that operating in a two-stage system, to first remove arsenic and then to remove remaining constituents, resulted in reduced materials handling and sludge disposal costs due to arsenic being concentrated in a smaller volume of sludge requiring disposal as a hazardous waste. Based on a single study (U.S. EPA, 2006a), costs approach $470,000 for construction and first year operation of a semi-passive lime treatment system, with nearly $280,000 of the total for site preparation, capital and equipment. First year costs for the semi-passive system were approximately $40 per 1,000 liters; first year costs for active lime treatment were between $112 and $128 per 1,000 liters (U.S. EPA, 2006a). Costs were not provided in the single passive treatment case study evaluated.

As additional case studies meeting the project's criteria are identified, future comparisons may provide additional information on treatment costs.

5.8 Lessons Learned

- Major performance issues (and increased maintenance costs) arise from gypsum scale and lime feed and delivery issues that cause plugging of pumps, outlets from holding and reaction tanks, monitoring probes, and pipes. Potential remedies are the use of a higher purity lime, mechanical mixing, or better pumping systems (U.S. EPA, 2006a; Butler and Hathaway, 2020).
- Cold weather operation may be hindered by icing of the fabric of bag filters that creates backpressure (U.S. EPA, 2006a).
- The pre-existing iron terraces, cascades, and lagoon (the NFOL) aided in efficiency of iron and aluminum removal by the limestone DAS (Macías et al., 2012a).
- System design should consider ease of access for maintenance, potential for upgrades and use of universal motors (Butler and Hathaway, 2020).

5.9 References

5.9.1 Case Study References

Butler, B.A. and E. Hathaway. 2020. *Evaluation of the Rotating Cylinder System™ at Elizabeth Mine, Vermont.* US Environmental Protection Agency (U.S. EPA), Land Remediation and Technology Division Center for Environmental Solutions and Emergency Response. (EPA/600/R-19/194). 42 pp.

Macías, F., Caraballo, M.A., Nieto, J.M., Rötting, T.S., and Ayora, C. 2012a. Natural pretreatment and passive remediation of highly polluted acid mine drainage. *Journal of Environmental Management,* **104**:93-100.

Macías, F., Caraballo, M.A., Rötting, T.S., Pérez-López, R., Nieto, J.M., and Ayora, C. 2012b. From highly polluted Zn-rich acid mine drainage to non-metallic waters: Implementation of a multi-step alkaline passive treatment system to remediate metal pollution. *Science of the Total Environment,* **433**:323-330.

Madsen, C., O'Hara, G., and Sinnet, G. 2012. "Management of Acid Rock Drainage at Britannia Mine, BC, Part 2: Water Treatment Plant Implementation and Operations." In Proceedings from the 9th International Conference on Acid Rock Drainage (ICARD), Volume 1 of 2, Ottawa, Canada, May 20-26, 2012. pp. 295-306. Eds. Price, W.A., Hogan, C., and Tremblay.

Rötting, T.S., Caraballo, M.A., Serrano, J.A., Ayora, C., and Carrera, J. 2008a. Field application of calcite Dispersed Alkaline Substrate (calcite-DAS) for passive treatment of acid mine drainage with high Al and metal concentrations. *Applied Geochemistry*, **23**(6):1660-1674.

Rötting, T.S., Thomas, R.C., Ayora, C., and Carrera, J. 2008b. Passive treatment of acid mine drainage with high metal concentrations using Dispersed Alkaline Substrate. *Journal of Environmental Quality*, **37**:1741-1751.

U.S. Environmental Protection Agency (U.S. EPA). 2006a. *Active and Semi-Passive Lime Treatment of Acid Mine Drainage at Leviathan Mine, Innovative Technology Evaluation Report*. (EPA/540/R-05/015). 92 pp.

5.9.2 General Neutralization Chemical Precipitation Treatment References

Kratochvil, D., Ye, S., and Lopez, O. 2015. “Commercial Case Studies of Life Cycle Cost Reduction of ARD Treatment with Sulfide Precipitation.” Paper presented at 10th International Conference on Acid Rock Drainage and IMWA Annual Conference, Santiago, Chile, April 21-24, 2015. 11 pp.

6 Chemical Stabilization

Chemical stabilization technologies use a variety of amendments to reduce the mobility of metals in solid mining wastes, which limits the formation of metal-contaminated leachate or runoff. Alkaline materials, such as limestone, are common amendments that neutralize acidity produced by the oxidation of sulfide minerals in mining wastes. Phosphate, silicate or other coating materials can be applied to the surfaces of mining wastes to prevent oxidation of sulfidic minerals in the wastes through isolation (Trudnowski, 2004; Nordwick et al, 2006). Isolation includes passivation and microencapsulation.

Solid mine wastes can be treated either in situ or ex situ, with ex situ typically being associated with removal of the mining wastes to an off-site repository (Interstate Technology and Regulatory Council [ITRC], 2010). In theory, some types of chemical stabilization technologies that immobilize sulfide or metals or create a barrier to leaching should last indefinitely; therefore, only one application of the treatment would be needed to permanently stabilize the mining waste (Trudnowski, 2004; Nordwick et al., 2006).

6.1 Case Studies Evaluated

This chapter provides an evaluation of one case study where chemical stabilization was the primary component of treatment. The case study was selected based on the screening criteria presented in Section 1.1.1 and examined four types of chemical stabilization technologies applied to waste rock at a site in South Dakota. An additional case study meeting the selection criteria was identified, but data were unavailable at the time of this report compilation. Table 6-1 summarizes the site name and location, design information, and reference for the case study. The chapter provides considerations for constraints, treatability of contaminants, capability, technological and site-specific requirements and lessons learned for chemical stabilization treatment from evaluation of the case study results.

Table 6-1: Chemical Stabilization Case Study Site

Site Name and Location	Type	System Description	Study Type	Reference	Reference Type
Gilt Edge Mine, South Dakota	Envirobond (Metals Treatment Technologies, MT2)[a]	Applied as a liquid spray onto waste rock in two above-ground treatment cells; used phosphate stabilization chemistry	Pilot scale	Trudnowski, 2004* Nordwick et al., 2006	Report

Table 6-1: Chemical Stabilization Case Study Site

Site Name and Location	Type	System Description	Study Type	Reference	Reference Type
	Potassium Permanganate Passivation Technology (University of Nevada-Reno)	Applied in two phases: 1) waste rock, magnesium oxide and calcium oxide (lime) were mixed ex situ, 2) a mixture of water, caustic soda and potassium permanganate were applied to the waste rock mixture in two above-ground treatment cells			
	Silica Microencapsulation (SME) Technology (Klean Earth Environmental Company, KEECO)	Applied as a liquid spray onto waste rock in two above-ground treatment cells			
	Lime	Waste rock was mixed with calcium oxide ex situ and placed into three above-ground treatment cells			

Notes:
a = MT2's Envirobond product is no longer available. The current MT2 ECOBOND® brand supersedes MT2 Envirobond (James M. Barthel, MT2 CEO, personal communication, 2020)
*Primary source(s) of data for evaluation in this chapter

6.2 Constraints

Constraints associated with some chemical stabilization technologies include high costs of large amounts of the chemical reagents needed for successful treatment (Trudnowski, 2004). Effective mixing or coating of reagents with waste materials is necessary.

6.3 Treatable Contaminants

MT2 Envirobond, potassium permanganate passivation, silica microencapsulation, and lime treatment can lower concentrations of aluminum, arsenic, iron, sulfate, zinc and raise pH in leachate from treated waste rock. Lime, potassium permanganate passivation, and silica encapsulation are also able to reduce concentrations of arsenic and sulfate. However, leachate from lime-treated mining wastes may require further treatment to adjust pH to near neutral prior to it reaching a waterbody.

6.4 Capability

Evaluation of only one case study (Trudnowski, 2004) that met the criteria (see Section 1.1.1) for this work limits the ability to determine the capability of the chemical stabilization technologies. Nevertheless, the following sections present capability data for the four technologies used in the single study.

6.4.1 Ranges of Applicability

The Gilt Edge Mine case study evaluated the four chemical stabilization treatment technologies against a control (cells of waste rock with no treatment applied) over two years. Like the Caps and Covers chapter (Section 4), the range of applicability differs in this section as compared to other technologies, because results are not based on an influent treated and a corresponding effluent attained, but rather are based on general differences between concentrations of constituents in waste rock leachate originating from treated versus untreated cells. Table 6-2 provides the ranges in average (replicated samples) concentrations of constituents in leachate from treated and untreated cells.

Table 6-2: Average Leachate Concentration Ranges from Treated and Untreated Cells of Waste Rock – All Treatment Types

Constituent	Concentration Range – Untreated Cells[a]	Concentration Range – Treated Cells[b]	Technology	Source	Notes (location within source)
Concentrations reported as dissolved in mg/L; pH reported in standard units					
Aluminum	198.545 – 2,796.667	0.22 – 0.422	Lime	Trudnowski, 2004	Table 4-2
		0.005 – 0.264	MT2 Envirobond	Trudnowski, 2004	Table 5-2
		0.011 – 0.326	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-2
		0.401 – 398.0	SME	Trudnowski, 2004	Table 7-2
Arsenic	1.4223 – 123.8027	0.0238 – 0.0481[c]	Lime	Trudnowski, 2004	Appendix A
		8.4950 – 50.20	MT2 Envirobond	Trudnowski, 2004	Appendix A
		0.0059[c] – 2.6148[c]	Potassium Permanganate Passivation	Trudnowski, 2004	Appendix A
		0.0056[c] – 0.04979[c]	SME	Trudnowski, 2004	Appendix A
Iron	535.110 – 21,204.900	0.008 – 0.397	Lime	Trudnowski, 2004	Table 4-3
		0.008 – 0.145	MT2 Envirobond	Trudnowski, 2004	Table 5-3
		0.017 – 0.739	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-3
		0.178 – 528.0	SME	Trudnowski, 2004	Table 7-3
Sulfate	1,106 – 72,667	204 – 1,403	Lime	Trudnowski, 2004	Table 4-4
		8,150 – 26,700	MT2 Envirobond	Trudnowski, 2004	Table 5-4
		1,490 – 8,350	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-4[d]
		1,834 – 7,100	SME	Trudnowski, 2004	Table 7-4
Zinc	11.45 – 71.93	0.0045[c] – 0.0437[c]	Lime	Trudnowski, 2004	Appendix A

Table 6-2: Average Leachate Concentration Ranges from Treated and Untreated Cells of Waste Rock – All Treatment Types

Constituent	Concentration Range – Untreated Cells[a]	Concentration Range – Treated Cells[b]	Technology	Source	Notes (location within source)
Concentrations reported as dissolved in mg/L; pH reported in standard units					
		0.0028[c] – 0.4720[c]	MT2 Envirobond	Trudnowski, 2004	Appendix A
		0.0211[c] – 0.1645	Potassium Permanganate Passivation	Trudnowski, 2004	Appendix A
		0.3555[c] – 21.5333	SME	Trudnowski, 2004	Appendix A
pH[e]	2.49 – 4.52	6.85 – 12.09	Lime	Trudnowski, 2004	Appendix B
		6.78 – 7.95	MT2 Envirobond	Trudnowski, 2004	Appendix B
		7.15 – 8.55	Potassium Permanganate Passivation	Trudnowski, 2004	Appendix B
		2.71 – 6.86	SME	Trudnowski, 2004	Appendix B

Notes:

Average concentrations were not reported for all sampling dates, or for all replicated samples for some dates, due to lack of leachate volume for analysis. Therefore, maximum and minimum average concentrations chosen for this table were obtained from comparison of sampling dates having reported average concentrations based on at least two replicates in the reference tables indicated. EPA calculated date-specific averages from replicated sample data provided in Appendices A and B and data in this table were obtained from comparison of those results across the sampling dates.

RL = reporting limit (reference did not provide the value for the limit)

Date range = 2001-2002

a = The study included three untreated control cells

b = Lime treatment included three cells, whereas the other three treatments included two treatment cells

c = Calculated from values provided in the reference where one or more values was noted as being estimated

d = Reference table has incorrect units for sulfate in title

e = Average of the pH values provided by the source

Lime, MT2 Envirobond and potassium permanganate passivation treatments all can reduce aluminum and iron concentrations in leachate by three to five orders of magnitude, on average, with MT2 Envirobond appearing to be the most effective for minimizing the leachate concentration of aluminum. Silica microencapsulation treatment appears less effective as compared to the other three technologies, but the lower end of the range falls within, or close to, the ranges for the other technologies.

Lime, potassium permanganate passivation and silica microencapsulation treatments reduce average arsenic concentrations in leachate by three to four orders of magnitude, as compared to leachate from untreated waste rock. MT2 Envirobond can reduce average arsenic concentrations by two orders of magnitude, but the range of concentrations in the leachate is higher than for the other technologies. This could be due to changes in the waste rock over time, because concentrations of arsenic in leachate from untreated waste rock was higher in some control units in 2002 versus in 2001 and lowest in MT2 Envirobond treated units in 2002 versus 2001 (Trudnowski, 2004). The lowest leachate concentrations were achieved with potassium permanganate and silica microencapsulation treatments.

All four treatment technologies can decrease the amount of sulfate leached by one to two orders of magnitude. Lime treatment is most effective at reducing concentrations of sulfate leached with the highest concentration being lower than the lowest concentrations in the ranges for the other treatments. MT2 Envirobond appears least effective.

Relative to control ranges in leachate concentrations, average zinc concentrations are decreased by two to four orders of magnitude by lime treatment, MT2 Envirobond and potassium permanganate, with average leachable amounts following lime treatment reduced to below the reporting limit, or near to it (estimated data). Silica microencapsulation treatment appears minimally effective in attenuating leaching of zinc, with differences between control and treatment upper range average leachate concentrations on the same order of magnitude.

Relative to the range of average control leachate pH values (2.49-4.52), the range of average pH values in leachate from all but the silica microencapsulation treated cells is higher (6.78 to 12.09). The highest pH is attained by lime treatment, which is expected due to lime being a caustic material.

6.4.2 Average Leachate Concentrations from Untreated and Treated Cells of Waste Rock

Table 6-3 presents average leachate concentrations over all sampling dates and replicates from untreated cells of waste rock and treated cells of waste rock for the four technologies.

Table 6-3: Average Leachate Concentrations from Treated and Untreated Cells of Waste Rock – All Treatment Types

Constituent	Average Concentration from Untreated Cells[a]	Average Concentration from Treated Cells[b]	Technology	Source	Notes (location within source)
Concentrations reported as dissolved in mg/L; pH reported in standard units					
Aluminum	687.800	0.1691	Lime	Trudnowski, 2004	Table 4-2
		0.135	MT2 Envirobond	Trudnowski, 2004	Table 5-2
		0.107	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-2
		192.497	SME	Trudnowski, 2004	Table 7-2
Arsenic[c]	26.6829	0.0287	Lime	Trudnowski, 2004	Appendix A
		36.8332	MT2 Envirobond	Trudnowski, 2004	Appendix A
		0.2489	Potassium Permanganate Passivation[d]	Trudnowski, 2004	Appendix A
		1.6265	SME[d]	Trudnowski, 2004	Appendix A
Iron	4,237.946	0.0792	Lime	Trudnowski, 2004	Table 4-3
		0.075	MT2 Envirobond	Trudnowski, 2004	Table 5-3
		0.151	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-3
		763.211	SME	Trudnowski, 2004	Table 7-3
Sulfate	22,406	444.3	Lime[d]	Trudnowski, 2004	Table 4-4
		18,425	MT2 Envirobond	Trudnowski, 2004	Table 5-4
		2,443	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-4
		6,026	SME	Trudnowski, 2004	Table 7-4
Zinc[c]	36.3993	0.0329	Lime[d]	Trudnowski, 2004	Appendix A
		0.1398	MT2 Envirobond[d]	Trudnowski, 2004	Appendix A
		0.0609	Potassium Permanganate Passivation[d]	Trudnowski, 2004	Appendix A
		5.4349	SME	Trudnowski, 2004	Appendix A
pH[e]	3.52	10.56	Lime	Trudnowski, 2004	Appendix B
		7.39	MT2 Envirobond	Trudnowski, 2004	Appendix B

Table 6-3: Average Leachate Concentrations from Treated and Untreated Cells of Waste Rock – All Treatment Types

Constituent	Average Concentration from Untreated Cells[a]	Average Concentration from Treated Cells[b]	Technology	Source	Notes (location within source)
Concentrations reported as dissolved in mg/L; pH reported in standard units					
		7.18	Potassium Permanganate Passivation	Trudnowski, 2004	Appendix B
		5.32	SME	Trudnowski, 2004	Appendix B

Notes:
Calculated from averages provided for all individual sampling dates in the tables indicated in the Notes column, or from those that EPA calculated from data in the appendices indicated in the Notes column.
Date range = 2001-2002
a = The study included three control cells
b = Lime treatment included three cells, while the other three treatments included two treatment cells
c = Values calculated from all data provided by the source, including for sampling dates having results reported as estimated or below the reporting limit
d = Majority of data provided by the source was indicated as estimated or below the reporting limit
e = Average of the pH values provided by the source

Lime, MT2 Envirobond and potassium permanganate passivation treatments reduce average aluminum and iron concentrations over two years in leachate from treated waste rock by three to five orders of magnitude, relative to leachate from untreated waste rock. Silica microencapsulation technology reduces average aluminum and iron concentrations in treated leachate to a lesser degree, with average aluminum concentration being on the same order of magnitude as in the leachate from untreated waste rock and iron concentrations being decreased by only one order of magnitude.

Lime, potassium permanganate passivation and silica microencapsulation technologies reduce average arsenic concentrations in leachate from treated waste rock by one to three orders of magnitude, relative to leachate from untreated waste rock, with most samples contributing to the averages for potassium permanganate and silica microencapsulation being below or near the reporting limit. Average arsenic concentration in leachate from the MT2 Envirobond-treated rock over the two years was increased relative to leachate from the untreated control, suggesting ineffective treatment. However, average concentrations across individual dates in 2002 were an order of magnitude lower than those in 2001, suggesting that MT2 Envirobond may be a source of arsenic (Trudnowski, 2004). Average arsenic concentration in leachate from waste rock treated with the silica microencapsulation technology was increased in 2002 versus 2001.

All four technologies decreased average sulfate concentrations leached. Lime treatment provided the greatest decrease (two orders of magnitude). MT2 Envirobond treatment resulted in the smallest average decrease in sulfate concentrations leached.

Lime, MT2 Envirobond and potassium permanganate passivation reduced average zinc concentrations in leachate from treated waste rock by two to three orders of magnitude; silica microencapsulation treatment reduces average zinc concentrations by an order of magnitude. Similar to arsenic, average concentrations of zinc in leachate from waste rock treated with silica microencapsulation were higher in 2002 than in 2001.

All four treatments provided increased pH (averaged over the two years) as compared to the pH of leachate from untreated waste rock. The average pH in leachate from lime treatment was basic (pH 10.5), whereas it was neutral (7.39 and 7.18) in leachate from waste rock treated with MT2 Envirobond and potassium permanganate, respectively. The average pH over the two years in leachate from the silica microencapsulation treatment was slightly acidic at pH 5.32; however, the average over the first year was near neutral at 6.51 and the second year was acidic at 2.55. The lower average pH corresponds with the higher average concentrations of arsenic and zinc in leachate from silica encapsulation treated waste rock.

6.4.3 Percent Reduction

Table 6-4 presents percentage reductions in leachate concentrations from chemical stabilization treated cells as compared to leachate concentrations from untreated cells.

Table 6-4: Percent Reduction – All Treatment Types

Constituent	Average Percent Reduction	Minimum Percent Reduction	Maximum Percent Reduction	Technology	Source	Notes (location within source)
All constituents reported as dissolved						
Aluminum	99.96%	99.80%	99.99%	Lime	Trudnowski, 2004	Table 4-2
Arsenic	99.89%	97.19%	99.98%	Lime	Trudnowski, 2004	Appendix A
Iron	100.00%	99.99%	100.00%	Lime	Trudnowski, 2004	Table 4-3
Sulfate	95.32%	74.14%	99.52%	Lime	Trudnowski, 2004	Table 4-4
Zinc	99.91%	99.72%	99.99%	Lime	Trudnowski, 2004	Appendix A
Aluminum	99.98%	99.91%	100.00%	MT2 Envirobond	Trudnowski, 2004	Table 5-2
Arsenic	-38.04%	-2,032.45%	93.14%	MT2 Envirobond	Trudnowski, 2004	Appendix A
Iron	99.99%	99.95%	100.00%	MT2 Envirobond	Trudnowski, 2004	Table 5-3
Sulfate	-275.04%	-2,313.89%	88.37%	MT2 Envirobond	Trudnowski, 2004	Table 5-4
Zinc	99.62%	97.99%	99.99%	MT2 Envirobond	Trudnowski, 2004	Appendix A

Table 6-4: Percent Reduction – All Treatment Types

Constituent	Average Percent Reduction	Minimum Percent Reduction	Maximum Percent Reduction	Technology	Source	Notes (location within source)
Aluminum	99.97%	99.91%	100.00%	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-2
Arsenic	99.07%	99.20%	99.99%	Potassium Permanganate Passivation	Trudnowski, 2004	Appendix A
Iron	99.99%	99.91%	100.00%	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-3
Sulfate	73.43%	-34.71%	96.20%	Potassium Permanganate Passivation	Trudnowski, 2004	Table 6-4
Zinc	99.83%	98.52%	99.99%	Potassium Permanganate Passivation	Trudnowski, 2004	Appendix A
Aluminum	88.14%	5.78%	99.87%	SME	Trudnowski, 2004	Table 7-2
Arsenic	93.90%	84.12%	99.95%	SME	Trudnowski, 2004	Appendix A
Iron	94.82%	53.81%	99.99%	SME	Trudnowski, 2004	Table 7-3
Sulfate	33.18%	-316.78%	90.23%	SME	Trudnowski, 2004	Table 7-4
Zinc	85.19%	-17.03	98.69%	SME	Trudnowski, 2004	Appendix A

Notes:
Date range = 2001-2002
Minimum and maximum percent reductions for aluminum, iron, and sulfate were obtained from comparison of values for each of the sampling dates having reported values in the tables indicated; average percent reductions were stated in the tables. Data reported in Appendix A were used to calculate date-specific percentage reductions for arsenic and zinc and those were compared across the sampling dates to determine the minimum and maximum percentage reductions; average percentage reductions were calculated from all data reported.

Lime treatment can reduce the concentrations of aluminum, arsenic, and iron leached from waste rock by more than 95 percent, relative to leachate from untreated waste rock; reduction in sulfate leachate concentrations ranges from 74 to 99.5 percent. Greater than 98 percent reduction in leachate concentrations of aluminum, iron and zinc are evident with MT2 Envirobond treatment; however, MT2 Envirobond is not able to achieve positive reductions of leachate concentrations of either arsenic or sulfate. Potassium permanganate treatment can achieve reductions of leachate concentrations for aluminum, arsenic, iron and zinc of greater than 98 percent, relative to untreated waste rock leachate. However, reduction in leachate concentration of sulfate by potassium permanganate treatment is more variable, with a range from below zero to 96 percent. Percentage reductions in leachate concentrations from silica microencapsulation are the most varied of the treatments, with maximum reductions greater than 90 percent for all constituents, but minimum reductions below zero for sulfate and zinc, < 10 percent for aluminum, 54 percent for iron and 84 percent for arsenic.

6.4.4 Flow Rates

Flow rates were not provided in the case study evaluated.

6.5 Costs

Conceptual design costs for each of the four treatment technologies, based on hypothetical treatment of 750,000 tons of waste rock, are as follows: silica microencapsulation = $12,682,998; potassium permanganate passivation = $3,241,408; MT2 Envirobond = $4,034,750; and lime = $4,774,438 (Trudnowski, 2004).

6.6 Lessons Learned

- Some chemicals used in the chemical stabilization technology are more effective than others (Trudnowski, 2004; Nordwick et al., 2006).
- Lime treatment may need multiple applications to maintain effectiveness because it is soluble and will dissolve over time (Trudnowski, 2004; Nordwick et al., 2006).
- Chemical stabilization treatment performance can vary over time.
    - Silica microencapsulation performed well in the short-term. Increasing the dosage may solve the longevity issue; however it would increase costs for an already expensive treatment (Trudnowski, 2004; Nordwick et al., 2006).
- Although chemical stabilization treatments reduce concentrations of elements and acidity leached from waste rock, concentrations in leachate may still exceed site-specific discharge criteria (Trudnowski, 2004; Nordwick et al., 2006).
- Some of the chemical stabilization technologies evaluated may result in unfavorable conditions that may require treatment modification. MT2 Envirobond application may increase arsenic and sulfate levels; lime treatment may result in pH values that exceed site-specific discharge criteria and require adjustment prior to discharge (Trudnowski, 2004; Nordwick et al., 2006).

6.7 References

6.7.1 Case Study References

Nordwick, S., Zaluski, M., Park, B., and Bless, D. 2006. “Advances in Development of Bioreactors Applicable to the Treatment of ARD.” Paper presented at the 7th International Conference on Acid Rock Drainage (ICARD), St. Louis, MO, March 26-30, 2006. pp. 1410-1420. R.I. Barnhisel (Ed.), Published by ASMR, Lexington, KY.

Trudnowski, J. 2004. *Mine Waste Technology Program, Remediation Technology Evaluation at Gilt Edge Mine, South Dakota*. US Environmental Protection Agency (U.S. EPA) National Risk Management Research Laboratory. (EPA/600/R-05/002). 38 pp.

6.7.2 General Chemical Stabilization References

Interstate Technology and Regulatory Council (ITRC) Mining Waste Team. 2010. *Chemical Stabilization: Phosphate and Biosolids Treatment*. Washington, D.C. www.itrcweb.org.

7 Constructed Wetlands

Characteristics of wetlands include saturated soil conditions (hydric soil), a water cover at or near the surface for at least part of the year, and vegetation that is adapted to surviving in hydric soils. Constructed wetlands are created specifically to treat metals or other contaminants present in groundwater or surface water that is directed to flow through them (U.S. EPA, 1994).

There are two primary types of constructed wetlands: aerobic and anaerobic. Aerobic, or surface-flow wetlands, consist of wetland vegetation planted in shallow (<30 centimeter [cm]) organic substrates and treat net-alkaline water, whereas anaerobic, or sub-surface flow wetlands, have vegetation planted in deeper (>30 cm) substrates and treat net acidic water. Both types of constructed wetlands may include limestone either as a base or mixed in with the organic substrate (Skousen and Ziemkiewicz, 2005).

The primary function of an aerobic wetland is to allow oxidation and precipitation of high concentrations of iron to ferric oxyhydroxides in net-alkaline or slightly acidic water (Zipper et al., 2011). Anaerobic wetlands are similar to biochemical reactors (BCRs), although BCRs do not contain vegetation. Anaerobic wetlands are designed to include limestone specifically to provide alkalinity to neutralize acidity of the mining-influenced water (MIW) (Zipper et al., 2011) and treat metals present through reactions occurring under reducing conditions, such as by the formation of metal sulfides (Skousen and Ziemkiewicz, 2005).

Constructed wetlands are designed to treat contaminants over a long period and can be used as the sole technology or as part of a larger treatment approach, such as an aerobic wetland operating as a polishing step for effluents from BCRs or other anaerobic or alkalinity-producing processes. Contaminants may be removed from MIW through plant uptake, volatilization (e.g., arsenic, mercury, selenium), oxidation/reduction (chemical and/or microbial), precipitation, and adsorption. Some treatment systems use both aerobic and anaerobic wetlands for complete treatment of a variety of metals and acidity in MIW. Constructed wetlands are often used as part of a treatment train (see Section 10).

7.1 Case Studies Evaluated

This chapter provides an evaluation of case studies in which a constructed wetland was the sole treatment for MIW (i.e., not part of a treatment train). The case studies evaluated were based on the criteria presented in Section 1.1.1. The case studies include two mine sites: one having an aerobic constructed wetland and the other having an anaerobic constructed wetland (Table 7-1). This chapter provides considerations for constraints, treatability of contaminants, capability, technological and site-specific requirements, costs, and lessons learned for constructed wetlands treatment from evaluation of these case studies. Because only a single study was evaluated for each type of wetland that met this study's criteria and the criteria of having data specifically for a wetland component, it is not possible to provide evaluation of either anaerobic or aerobic wetlands on a technology-wide basis.

Table 7-1: Constructed Wetlands Case Study Sites

Site Name and Location	Wetland Type	Description	Study Type	Reference	Reference Type
Copper Basin Mining District, Copper Hill, Tennessee	Anaerobic followed by aerobic	Two-acre anaerobic wetland constructed with a geosynthetic clay liner overlain with lime-enriched soil, crushed limestone, hay, mushroom compost and planted with cattails. After four years, two aerobic cells and an aerobic limestone rock filter were added.	Pilot scale	Federal Remediation Technologies Roundtable (FRTR), 2007	FRTR Case Study summary (online document)
				U.S. EPA, 2006b	Report
				Faulkner and Miller, 2002 (anaerobic only)*	Conference paper
Dunka Mine, Babbitt, Minnesota	Aerobic	Five unconnected surface flow wetland treatment systems. Each system included a series of soil berms, covered in local peat and peat screenings, built to control water levels and maximize contact between the drainage and the substrate. The berms were hand-seeded with Japanese millet, while open water areas were seeded with cattails.	Full scale	Eger and Eger, 2005*	Conference paper
				Eger et al., 1996	Conference paper
				Eger et al., 1998	Conference paper
				ITRC, 2010*	Report
				Eger and Beatty, 2013	Journal paper

Notes:
* Primary source(s) of data for evaluation in this chapter

7.2 Constraints

A primary constraint associated with constructed wetlands treatment is the need for suitable land space and topography to accommodate the wetland system. A wetland's effective treatment area needs to be large enough to allow enough time for the reactions to occur at the anticipated influent flow rate and constituent concentrations (Eger and Eger, 2005).

Additional constraints of constructed wetlands treatment include:

- Some locations might be unsecured and have a potential for vandalism, which would need to be considered in the wetland design (Faulkner and Miller, 2002).
- Treatment may be insufficient to meet numeric effluent limits consistently (Interstate Technology and Regulatory Council [ITRC], 2010).
- A challenge specific to anaerobic wetlands is the need to maintain appropriate water levels and deep subsurface flow to facilitate anaerobic processes (Faulkner and Miller, 2002).

- Depending on the waste stream, there may be a need to limit human or ecological exposure to the metals sequestered in the wetland.

7.3 Treatable Contaminants

Anaerobic constructed wetlands can treat aluminum, copper, iron, zinc and sulfate, and raise pH (Faulkner and Miller, 2002), although based on a single study. Constructed aerobic wetlands can treat cobalt, copper, nickel and zinc (Eger and Eger, 2005; ITRC, 2010).

7.4 Capability – Anaerobic

7.4.1 Ranges of Applicability

The single case study evaluated did not provide date-specific corresponding influent and effluent concentrations for the constructed wetlands. Therefore, the range of applicability for anaerobic constructed wetlands could not be ascertained.

7.4.2 Average Influent and Effluent Concentrations

Table 7-2 lists the average influent concentration treated for each constituent from Appendix D, Table D-1.

Table 7-2: Average Influent Concentration Treated

Constituent	Average Influent[a] Concentration	Average Effluent[a] Concentration	Mine	Source
Concentrations reported as total in mg/L, except total or dissolved not stated for sulfate; pH reported in standard units				
Aluminum	2.351	0.073	Copper Basin	Faulkner and Miller, 2002
Copper[b]	0.311	0.008	Copper Basin	Faulkner and Miller, 2002
Iron	1.07	0.353	Copper Basin	Faulkner and Miller, 2002
Manganese	1.52	1.64	Copper Basin	Faulkner and Miller, 2002
Zinc	1.094	0.045	Copper Basin	Faulkner and Miller, 2002
Sulfate	142	128	Copper Basin	Faulkner and Miller, 2002
pH	4.2	7.1	Copper Basin	Faulkner and Miller, 2002
Notes: a = From 9/8/1999 to 1/1/2002 b = Average influent and effluent concentrations of 0.43 mg/L and less than 0.025 mg/L, respectively, during the first six months of operation, from 10/1998 through 3/1999				

Although the average influent and effluent concentrations are not corresponding concentrations, on average, concentrations of aluminum, iron, copper and zinc are decreased by one to two orders of magnitude from treatment by an anaerobic wetland. Anaerobic constructed wetlands also can raise pH from acidic (4.2) to neutral levels (7.1). In the study examined, Table 7-2 shows that, on average, there is minimal or no treatment of sulfate and manganese, with their average effluent concentrations being greater than (manganese) or within 10 percent of (sulfate) their average influent concentrations.

7.4.3 Removal Efficiency

Table 7-3 summarizes average removal efficiencies, calculated by EPA using the average influent and effluent concentrations presented in Table 7-2.

Table 7-3: Average Removal Efficiencies

Constituent	Average Removal Efficiency[a]	Mine	Source
All results reported as total except sulfate (not stated)			
Aluminum	96.9%	Copper Basin	Faulkner and Miller, 2002
Copper	97.4%	Copper Basin	Faulkner and Miller, 2002
Copper[b]	94.2%	Copper Basin	Faulkner and Miller, 2002
Iron	67.0%	Copper Basin	Faulkner and Miller, 2002
Manganese	-7.9%	Copper Basin	Faulkner and Miller, 2002
Zinc	95.9%	Copper Basin	Faulkner and Miller, 2002
Sulfate	9.9%	Copper Basin	Faulkner and Miller, 2002

Notes:
a = Average removal efficiencies calculated by EPA
b = Based on influent and effluent averages provided for first six months of operation, beginning 10/1998

As shown in Table 7-3, average removal efficiencies from anaerobic constructed wetlands treatment for aluminum, copper and zinc exceed 94 percent. The anaerobic constructed wetlands did not treat manganese and average removal efficiency for sulfate is low (<10 percent).

7.4.4 Flow Rates

Maximum and minimum average flow rates treatable in a constructed anaerobic wetland are not known from the currently available data. Average influent flow treatable by a constructed anaerobic wetland is 992 L/min (Faulkner and Miller, 2002).

7.5 Capability - Aerobic

Only a single case study (Eger and Eger, 2005) was evaluated that met the screening criteria (see Section 1.1.1) for this work. The case study examined five unconnected wetlands; however, only one wetland and its expansion could be considered as sole treatment systems. Therefore, the discussion of the capability of aerobic wetlands is limited.

7.5.1 Ranges of Applicability

The range of applicability for aerobic constructed wetlands treatment of nickel is provided in Table 7-4, based on the single case study examined (Eger and Eger, 2005). No corresponding influent and effluent concentrations were provided for other constituents.

Table 7-4: Maximum and Minimum Influent and Corresponding Effluent Concentrations

Constituent	Maximum Influent Conc.	Corresponding Effluent Conc.	Minimum Influent Conc.	Corresponding Effluent Conc.	Mine – Wetland	Source
Concentrations reported in mg/L, total or dissolved not stated						
Nickel	8	0.006	0.15	0.04	Dunka – W1D	Eger and Eger, 2005
Notes: Values extracted from a line graph (Figure 8, Eger and Eger, 2005)						

As shown in Table 7-4, aerobic constructed wetland treatment is capable of reducing nickel concentrations from both maximum and minimum influent concentrations and can decrease nickel concentrations by one to three orders of magnitude.

7.5.2 Average Influent and Effluent Concentrations

Concentrations of metals tend to be inversely related to the pH, with higher concentrations associated with a lower pH and lower concentrations associated with a higher pH. Tables 7-5 and 7-6 list the highest and lowest average influent concentrations (and lowest and highest pH) treated for each constituent, respectively. Tables 7-7 and 7-8 list the highest and lowest average effluent concentrations (and lowest and highest pH) attained for each constituent, respectively. Values in Tables 7-5 through Table 7-8 were determined by comparison of values in Appendix D, Table D-1, developed as discussed in Section 1.1.2. As discussed in Section 1.1.2 of the Introduction, it is important to note that the average influent concentrations do not correspond directly with the average effluent concentrations.

Table 7-5: Maximum Average Influent Concentration Treated

Constituent	Maximum Average Influent Concentration	Average Effluent Concentration	Mine – Wetland	Source(s)
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units				
Cobalt[a]	0.036	0.008	Dunka – W1D	Eger and Eger, 2005; ITRC, 2010
Copper[b]	0.068	0.008/0.010	Dunka – W1D	Eger and Eger, 2005; ITRC, 2010
Nickel[b]	3.98	0.36/0.700	Dunka – W1D	Eger and Eger, 2005; ITRC, 2010
Zinc[a]	0.052	0.013	Dunka – W1D	Eger and Eger, 2005; ITRC, 2010
pH	7.07	7.18	Dunka – W1D Expanded	Eger and Eger, 2005; ITRC, 2010
Notes: a = Two sampling periods had the same maximum average influent concentration reported and the same average effluent concentration reported				

Table 7-5: Maximum Average Influent Concentration Treated

Constituent	Maximum Average Influent Concentration	Average Effluent Concentration	Mine – Wetland	Source(s)
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units				
b = Two sampling periods had the same maximum average influent concentration reported, but different average effluent concentrations reported				

Table 7-6: Minimum Average Influent Concentration Treated

Constituent	Minimum Average Influent Concentration	Average Effluent Concentration	Mine – Wetland	Source(s)
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units				
Cobalt[a]	0.009	0.001	Dunka – W1D; Dunka – W1D Expanded	Eger and Eger, 2005
Copper[a]	0.02	0.002	Dunka – W1D; Dunka – W1D Expanded	Eger and Eger, 2005
Nickel[a]	0.74	0.19/0.18	Dunka – W1D; Dunka – W1D Expanded	Eger and Eger, 2005
Zinc	0.017	0.011	Dunka – W1D Expanded	ITRC, 2010
pH	7.30	7.48	Dunka – W1D	Eger and Eger, 2005
Notes: a = Dunka – W1D and Dunka – W1D Expanded had identical concentrations reported for some sampling periods				

Table 7-7: Maximum Average Effluent Concentration Attained

Constituent	Maximum Average Effluent Concentration	Average Influent Concentration	Mine – Wetland	Source(s)
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units				
Cobalt[a]	0.008	0.036	Dunka – W1D	Eger and Eger, 2005; ITRC, 2010
Copper	0.010	0.068	Dunka – W1D	ITRC, 2010
Nickel	0.700	3.98	Dunka – W1D	ITRC, 2010

Table 7-7: Maximum Average Effluent Concentration Attained

Constituent	Maximum Average Effluent Concentration	Average Influent Concentration	Mine – Wetland	Source(s)
Zinc[a]	0.013	0.052	Dunka – W1D	Eger and Eger, 2005; ITRC, 2010
pH	7.18	7.07	Dunka – W1D Expanded	Eger and Eger, 2005; ITRC, 2010
Notes: a = Two sampling periods had the same maximum average effluent concentration reported and the same average influent concentration reported				

Table 7-8: Minimum Average Effluent Concentration Attained

Constituent	Minimum Average Effluent Concentration	Average Influent Concentration	Mine – Wetland	Source(s)
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units				
Cobalt[a]	0.001	0.009/0.023	Dunka – W1D and W1D Expanded	Eger and Eger, 2005; ITRC, 2010
Copper[b]	0.002	0.02	Dunka – W1D and W1D Expanded	Eger and Eger, 2005
Nickel	0.099	0.76	Dunka – W1D Expanded	Eger and Eger, 2005
Zinc[a]	0.006	0.019/0.021	Dunka – W1D	Eger and Eger, 2005; ITRC, 2010
pH	7.48	7.30	Dunka – W1D	Eger and Eger, 2005
Notes: a = Some sampling periods and locations had the same minimum average effluent concentration reported, but different average influent concentrations reported b = Dunka – W1D and Dunka – W1D Expanded had identical concentrations reported for some sampling periods				

Aerobic constructed wetlands in the examined study can treat both the highest and lowest average influent concentrations of all constituents, as shown by the maximum average effluent concentrations (Table 7-7) being lower than both maximum (Table 7-5) and minimum (Table 7-6) average influent concentrations. On average, cobalt and copper are decreased by one order of magnitude relative to both maximum and minimum average influent concentrations when comparing data in Tables 7-5 and 7-6 with Table 7-7. On average, decreases in nickel concentration are less than an order of magnitude to more than an order of magnitude, relative to lower and higher average influent concentrations, respectively. Aerobic constructed wetlands treatment can reduce cobalt, copper and zinc concentrations, on average, to 13 µg/l or below and nickel to 700 µg/l or below, as shown by the maximum and minimum average effluent concentrations in Tables 7-7 and 7-8, respectively. Aerobic constructed wetlands do not generally affect pH when influent concentrations are near neutral (pH ~7), as indicated by both maximum and minimum average pH values being similar (pH 7.2 to ~7.5).

7.5.3 Removal Efficiency

Tables 7-9 and 7-10 present the maximum and minimum average removal efficiencies, respectively, determined from comparison of values in Appendix D, Table D-2.

Table 7-9: Maximum Average Removal Efficiencies

Constituent	Maximum Average Removal Efficiency[a]	Mine – Wetland	Source
Total or dissolved not stated			
Cobalt	95.7%	Dunka – W1D Expanded	ITRC, 2010
Copper	91.5%	Dunka – W1D Expanded	ITRC, 2010
Nickel	91%	Dunka – W1D	Eger and Eger, 2005
Zinc	75%	Dunka – W1D	Eger and Eger, 2005
Notes: a = Average removal efficiencies calculated by EPA			

Table 7-10: Minimum Average Removal Efficiencies

Constituent	Minimum Average Removal Efficiency[a]	Mine – Wetland	Source
Total or dissolved not stated			
Cobalt	77.8%	Dunka – W1D	Eger and Eger, 2005; ITRC, 2010
Copper	83.3%	Dunka – W1D Expanded	Eger and Eger, 2005
Nickel	74.3%	Dunka – W1D	Eger and Eger, 2005
Zinc	35.3%	Dunka – W1D Expanded	ITRC, 2010
Notes: a = Average removal efficiencies calculated by EPA			

The maximum average removal efficiencies for aerobic constructed wetlands treatment range from 75 percent (zinc) to about 96 percent (cobalt) (Table 7-9). The minimum average removal efficiencies range from about 35 percent (zinc) to about 83 percent (copper) (Table 7-10). Except for zinc, aerobic constructed wetlands treatment has a minimum removal efficiency of greater than 74 percent for all metals in Table 7-10. Aerobic constructed wetlands treatment is less efficient and the most varied for zinc relative to the other metals examined, with average removal efficiencies ranging from 35 percent to 75 percent.

Average removal efficiencies for cobalt, copper and nickel decrease after the first one to five years of treatment but rebound to similar or higher average removal efficiencies after nearly a decade of treatment (Appendix D, Table D-2). Because only the one site was evaluated, this trend may or may not be typical of aerobic wetlands.

7.5.4 Flow Rates

Average flow rates over time for the aerobic constructed wetlands are provided in Table 7-11.

Table 7-11: Average Flow Rates

Average Flow Rate	Time Period	Mine – Wetland	Source
All rates are in L/min			
125	1992 to 1994	Dunka – W1D	Eger and Eger, 2005
150	1992 to 1997	Dunka – W1D	ITRC, 2010
57	1996 to 1998	Dunka – W1D	Eger and Eger, 2005
38	1999 to 2004	Dunka – W1D	Eger and Eger, 2005
130	1995 to 1997	Dunka – W1D Expanded	ITRC, 2010
57	1996 to 1999	Dunka – W1D Expanded	Eger and Eger, 2005

Average influent flow treatable by aerobic constructed wetlands ranges between 38 L/min and 150 L/min (Eger and Eger, 2005; ITRC, 2010). Future case study comparisons may provide additional information on the flow capabilities of the treatment.

7.6 Costs

Costs specific to anaerobic constructed wetlands were unavailable in the case studies reviewed. Costs for aerobic constructed wetlands range from about \$18 per square meter (m^2) to \$28/m^2 (ITRC, 2010). Costs for aerobic constructed wetlands vary by size, design and material construction of the wetland.

7.7 Lessons Learned

- Performance of wetlands is highly dependent on size, reactive surface area and metal loading rates (flow x concentration), where adequate retention time to ensure metal removal governs wetland size requirements (ITRC, 2010; Eger et al., 1998).
- Efficiency of aerobic wetlands treatment may decrease when temperatures decrease (ITRC, 2010).
- Anaerobic wetlands treatment is ineffective for manganese removal, but reduction in the concentration of manganese is possible through use of aerobic wetlands and limestone rock-filters (e.g., Copper Basin,FRTR, 2007).
- Limestone rock-filters placed downstream from anaerobic wetlands are useful for allowing gases produced in anaerobic systems to volatilize, providing for oxygen diffusion to the water and oxidation of metals that are more easily removed in aerobic processes, and settling of oxidized precipitates (FRTR, 2007).

7.8 References

7.8.1 Case Study References

Eger, P., Wagner, J., and Melchert, G. 1996. “The Use of Overland Flow Wetland Treatment Systems to Remove Nickel from Neutral Mine Drainage. “Paper presented at the 1996 Annual Meeting of the American Society for Surface Mining and Reclamation (ASSMR), Knoxville, TN, May 18-23. pp. 580-589.

Eger, P., Melchert, G., and Wagner, J. 1998. “Mine closure – Can passive treatment be successful.” In Proceedings of 15th Annual Meeting of American Society for Surface Mining and Reclamation, St. Louis, MO, May 17-21, 1998. pp. 263-271.

Eger, P. and Beatty, C.L.K. 2013. “Constructed Wetland Treatment Systems for Mine Drainage – Can They Really Provide Green and Sustainable Solutions?” Paper presented at the 2013 International Mine Water Conference. pp. 545-550. Wolkersdorfer, Brown & Figueroa (Ed.).

Eger, P. and P. Eger. 2005. “Controlling Mine Drainage Problems in Minnesota – Are All the Wetland Treatment Systems Really Above Average?” Paper presented at the 2005 National Meeting of the American Society of Mining and Reclamation, June 19-13, 2005. Published by ASMR, Lexington, KY. pp. 339-359.

Faulkner, B.B. and F.K. Miller. 2002. “Improvement of Water Quality by Land Reclamation and Passive Systems at an Eastern U.S. Copper Mine.” Paper presented at the 2002 National Meeting of the American Society of Mining and Reclamation, Lexington, KY, June 9-13, 2002. pp. 830-841.

Federal Remediation Technologies Roundtable (FRTR). 2007. “Constructed Wetland at Copper Basin Mining District, in Cost and Performance Case Studies.” Accessed August 22, 2019. https://frtr.gov/costperformance/pdf/20070522_397.pdf.

Interstate Technology and Regulatory Council (ITRC) Mining Waste Team. 2010. *Dunka Mine, Minnesota. Mining Waste Treatment Technology Selection Web*. Washington, D.C., 2010. www.itrcweb.org.

U.S. Environmental Protection Agency (U.S. EPA). 2006b. *Abandoned Mine Lands Innovative Technology Case Study, Copper Basin Mining District*. 2006. https://semspub.epa.gov/work/04/11121242.pdf.

7.8.2 General Constructed Wetlands References

Skousen, J. and Ziemkiewicz, P. 2005. “Performance of 116 Passive Treatment Systems for Acid Mine Drainage.” In proceedings of 2005 National Meeting of the American Society of Mining and Reclamation, Breckenridge, CO, June 19-23, 2005. Published by the ASMR, Lexington, KY. pp. 1100-1133. http://www.asmr.us/Portals/0/Documents/Conference-Proceedings/2005/1100-Skousen.pdf.

U.S. Environmental Protection Agency (U.S. EPA). 1994. *A Handbook of Constructed Wetlands: A Guide to Creating Wetlands for: Agricultural Wastewater, Domestic Wastewater, Coal Mine Drainage, Stormwater in the Mid-Atlantic Region*. 46 pp. https://www.epa.gov/sites/production/files/2015-10/documents/constructed-wetlands-handbook.pdf.

Zipper, C., Skousen, J., and Jage, C. 2011. Passive treatment of acid mine drainage, Powell River Project. *Virginia Cooperative Extension*, 460-133.

https://vtechworks.lib.vt.edu/bitstream/handle/10919/56136/460-133.pdf?sequence=1. Last accessed 10/22/18.

8 In-Situ Treatment of Mine Pools and Pit Lakes

In-situ treatment of mine pools and pit lakes includes physical (e.g., stratification), chemical (e.g., adding lime) and/or biological (e.g., enhancing sulfate-reducing bacterial activity) mechanisms (McCullough, 2008; ITRC, 2010; Fisher and Lawrence, 2006). Addition of lime is proven and effective but may be too expensive to maintain long-term (McCullough, 2008). Biological in-situ treatment involves adding carbon and/or nutrient amendments to encourage growth of plankton that will adsorb constituents and then carry them to the sediments as they sink after death (Poling et al., 2003; Fisher and Lawrence, 2006) or sulfate-reducing bacteria that facilitate precipitation of metal sulfides (Harrington et al., 2015). Depending on site-specific conditions, delivery of organic carbon can be at an upgradient area of the mine, where treatment would then occur along the flow path, directly into a pit lake, or added to water pumped from mine workings, mixed at the surface and recirculated back into the mine workings (Harrington et al., 2015). The form of organic carbon chosen is generally based on residence time of the water in the pit or pool, with alcohol-base reagents, such as methanol, used for residence times on the order of weeks and slower degrading sugar or starches (molasses) used for mine pools with longer residence times (several months or longer) (Harrington, 2015). The injection frequency ranges from months to years based on water quality improvements observed and the rate of re-oxidation of water or constituents (Harrington et al., 2015). Water treatment plant sludge containing ferric oxyhydroxide precipitates can also be applied to enhance mine pool treatment (Harrington et al., 2015). Mine pool treatments have to take into consideration whether there is a surface water discharge or a connection with groundwater serving public water supplies.

8.1 Case Studies Evaluated

This chapter provides an evaluation of case studies in which mine pool or pit lake water was treated primarily in situ. The case studies were selected based on the criteria presented in Section 1.1.1. The case studies examined included one mining site in the United States and one in Canada. Table 8-1 summarizes site names and locations, treatment design information, and references for each of the case studies. The chapter provides considerations for constraints, treatability of contaminants, capability, technological and site-specific requirements, and lessons learned for in-situ mine pool and pit lake treatment from evaluation of case study results.

Capability considerations for pit lakes and mine pools are evaluated separately in this chapter as they likely have different chemistries. Pit lakes are exposed to oxygen and may be stratified. Mine pools are underground and usually have less exposure to oxygen. Delivery to a mine pool can be complicated as is the ability to characterize if the mine in inaccessible and old.

Table 8-1: In Situ Mine Pools and Pit Lakes Case Study Sites

Site Name and Location	Type	Description	Study Type	Reference	Reference Type
Island Copper Mine	Pit Lake	Seawater and freshwater capping (stratification); liquid fertilizer, applied across the	Full scale	Poling et al., 2003*	Conference paper
				Fisher and Lawrence, 2006*	Journal paper

Table 8-1: In Situ Mine Pools and Pit Lakes Case Study Sites

Site Name and Location	Type	Description	Study Type	Reference	Reference Type
British Columbia, Canada		surface of the lake during summer 1997-2000 and then every 7-10 days from June 2001[a]			
Platoro Mine Colorado, United States	Underground Mine Pool	Single annual soluble carbon injections supplemented with metal hydroxide sludge from a lime-based water treatment plant (WTP) mixed with potato or corn starch	Full scale	Harrington et al., 2015*	Conference paper

Notes:
* Primary source(s) of data for evaluation in this chapter
a = It is not clear from the sources if the applications in 1997-2000 were daily over the summer months or at some interval

8.2 Constraints

The case studies exampled did not identify constraints.

8.3 Treatable Contaminants

Based on the two studies examined, in-situ treatment of mine pools and pit lakes can decrease concentrations of arsenic, cadmium, copper, zinc and sulfate. Future case study comparisons may provide additional information on treatable contaminants.

8.4 Capability – Pit Lakes

The inclusion of only two case studies (Poling et al., 2003; Fisher and Lawrence, 2006) that met the criteria (see Section 1.1.1) for this work limits the ability to determine the capability of pit lake treatment, in general. Nevertheless, the following sections present capability data for the technology based on the two case studies at a single site.

8.4.1 Ranges of Applicability

In order to assess the range of applicability, Table 8-2 presents the ranges in constituent concentrations in the upper layer of the Island Copper pit lake prior to each amendment application, during the application periods, and post applications (i.e., interim period between applications), based on the data available in the two examined case studies.

Table 8-2: Constituent Concentration Ranges Pre-, During and Post-Treatment – Island Copper Mine Pit Lake

Constituent	Pre-treatment Concentration Range	During Treatment Concentration Range	Post-treatment (between applications) Concentration Range	Treatment Event	Source
Concentrations reported as dissolved in mg/L					
Cadmium	0.004[a] – 0.0051[a]	0 – 0.006	NA	2001 – 2002	Poling et al., 2003, Figure 8
Copper	0.0065 – 0.055	0.0055 – 0.014	0.006 – 0.011	1997	Fisher and Lawrence, 2006, Figure 7
	0.006 – 0.011	0.007 – 0.0135	0.0045 – 0.008	1998	Fisher and Lawrence, 2006, Figure 7
	0.0045 – 0.008	0.002 – 0.006	0.005 – 0.013	1999	Fisher and Lawrence, 2006, Figure 7
	0.005 – 0.013	0.001 – 0.010	0.003[b]	2000	Fisher and Lawrence, 2006, Figure 7
	0.003[a] – 0.008	0.001 – 0.006	NA	2001 – 2002	Poling et al., 2003, Figure 7
Zinc	0.3 – 0.6	0.01 – 0.59	0.01 – 0.25	1997	Fisher and Lawrence, 2006, Figure 7
	0.01 – 0.025	0.01 – 0.42	0.15 – 0.38	1998	Fisher and Lawrence, 2006, Figure 7
	0.15 – 0.38	0.01 – 0.18	0.17 – 0.24	1999	Fisher and Lawrence, 2006, Figure 7
	0.17 – 0.24	0.08 – 0.22	0.20[b]	2000	Fisher and Lawrence, 2006, Figure 7
	0.41[a] – 0.51[a]	0 – 0.2	NA	2001 – 2002	Poling et al., 2003, Figure 6

Notes:

a = March through May 2001 represents concentration prior to start of the continuous (treatment every 10 days) treatment at 1-meter depth

b = Only one sampling date following application

NA = Not available; figures in source do not allow determining dates associated with post application

As shown by differences between the pre- and during treatment ranges in Tables 8-2 in-situ treatment to stimulate biological activity can decrease zinc concentrations over time in pit lake water. Results suggest that consistent and continued in-situ treatment is necessary to sustain decreased concentrations of constituents.

8.4.2 Average Pre-Treatment and Post-Treatment Concentrations

Average pre- and post-treatment concentrations were not provided in the references and were not calculated from sources by EPA.

8.4.3 Removal Efficiency

Table 8-3 presents average removal efficiencies observed.

Table 8-3: Average Removal Efficiencies

Constituent	Average Removal Efficiency	Mine	Source	Notes
All constituents reported as dissolved				
Cadmium	>90%	Island Copper	Poling et al., 2003	Based on the results of the 18-month study
Copper	>90%	Island Copper	Poling et al., 2003	Based on the results of the 18-month study
Zinc	>90%	Island Copper	Poling et al., 2003	Based on the results of the 18-month study
Notes: Cadmium and copper removal efficiencies stated in conclusion section of source Zinc removal efficiency stated in text of source				

As shown in Table 8-3, in-situ treatment of a pit lake can achieve an average removal efficiency of greater than 90 percent for dissolved cadmium, copper and zinc.

8.4.4 Flow Rates

Pit lakes contain water from direct precipitation, groundwater inflow, and runoff and leachate from mining wastes. Average annual daily and peak daily flow rates for the acid rock drainage (ARD) input to the Island Copper pit lake are presented in Table 8-4.

Table 8-4: Average Flow Rate

Average Flow	Notes	Source
All rates are in liters per minute (L/min)		
13.7	Annual Daily Average (North Injection System)	Fisher and Lawrence, 2006
8.8	Annual Daily Average (South Injection System)	Fisher and Lawrence, 2006

Table 8-4: Average Flow Rate

Average Flow	Notes	Source
143	Peak Daily Flow (North Injection System)	Fisher and Lawrence, 2006
137	Peak Daily Flow (South Injection System)	Fisher and Lawrence, 2006

The average yearly ARD inflow to the pit lake was 4,321,600 million cubic meters ([7,190 + 4,650] x 365). Fisher and Lawrence (2006) reported that flows to the Island Copper pit lake are “highly seasonal”, which can be seen by the order of magnitude difference between the annual daily average flows and the peak daily flows in Table 8-4. It is not known if this behavior is typical of all pit lakes.

8.5 Capability – Mine Pools

The inclusion of only one case study (Harrington et al., 2015) that met the criteria (see Section 1.1.1) for this work limits the ability to determine the capability of in situ mine pool treatment, in general. Nevertheless, the following sections present capability data for the technology based on the single case study.

8.5.1 Ranges of Applicability

In order to assess the range of applicability, Table 8-5 presents the ranges in constituent concentrations in the Platoro mine pool prior to amendment applications and during the period between applications (post-treatment).

Table 8-5: Constituent Concentration Ranges Pre- and Post-Treatment – Platoro Mine Pool

Constituent	Pre-treatment Concentration Range	Post-Treatment (between applications) Concentration Range	Treatment Period	Source	Notes
Concentrations reported as dissolved in mg/L					
Arsenic	2 – 51	<1 – 38	8/00 – 8/06[a]	Harrington et al., 2015	Figure 3
	<1 – 38	<1 – 4	8/06 – 8/07	Harrington et al., 2015	Figure 3
	<1 – 4	<1 – 2	8/07 – 8/08	Harrington et al., 2015	Figure 3
	<1 – 2	1 – 2	8/08 – 8/09	Harrington et al., 2015	Figure 3
	1 – 2	<1 – 2	8/09 – 8/10[b]	Harrington et al., 2015	Figure 3
	<1 – 2	2.5 – 11	8/10 – 8/11[b]	Harrington et al., 2015	Figure 3
	2.5 – 11	1 – 5	8/11 – 8/12	Harrington et al., 2015	Figure 3
	1 – 5	<1 – 1	8/12[b]	Harrington et al., 2015	Figure 3
Sulfate	1,400 – 2,900	1,000 – 2,700	8/00 – 8/06[a]	Harrington et al., 2015	Figure 3
	1,000 – 2,700	1,400 – 2,200	8/06 – 8/07	Harrington et al., 2015	Figure 3
	1,400 – 2,200	1,400 – 2,000	8/07 – 8/08	Harrington et al., 2015	Figure 3

Table 8-5: Constituent Concentration Ranges Pre- and Post-Treatment – Platoro Mine Pool

Constituent	Pre-treatment Concentration Range	Post-Treatment (between applications) Concentration Range	Treatment Period	Source	Notes
	1,400 – 2,000	820 – 1,800	8/08 – 8/09	Harrington et al., 2015	Figure 3
	820 – 1,800	1,490 – 2,050	8/09 – 8/10[b]	Harrington et al., 2015	Figure 3
	1,490 – 2,050	800 –2,250	8/10 – 8/11[b]	Harrington et al., 2015	Figure 3
	800 – 2,250	180 – 400	8/11 – 8/12	Harrington et al., 2015	Figure 3
	180 – 400	<1[c]	8/12[b]	Harrington et al., 2015	Figure 3
Zinc	7.5 – 20	<1 – 13	8/00 – 8/06[a]	Harrington et al., 2015	Figure 3
	<1 – 13	1 – 2.5	8/06 – 8/07	Harrington et al., 2015	Figure 3
	1 – 2.5	1 – 1	8/07 – 8/08	Harrington et al., 2015	Figure 3
	1 – 1	<1 – 3	8/08 – 8/09	Harrington et al., 2015	Figure 3
	<1 – 3	<1– 1	8/09 – 8/10[b]	Harrington et al., 2015	Figure 3
	<1 – 1	1 – 3	8/10 – 8/11[b]	Harrington et al., 2015	Figure 3
	1 – 3	<1 – 2	8/11 – 8/12	Harrington et al., 2015	Figure 3
	<1 – 2	<1	8/12[b]	Harrington et al., 2015	Figure 3

Notes:
Date range = 2000 – 2012
a = One injection event occurred during this period in 2000
b = Treatment consisted of WTP sludge and soluble organic carbon
c = Only one sampling date following application

As shown by differences between the pre- and during treatment ranges in Tables 8-5, in-situ treatment to stimulate biological activity can decrease zinc concentrations over time in the mine pool water. Table 8-5 shows arsenic, sulfate and zinc concentrations remained below initial pre-treatment concentrations in the mine pool water, although the sulfate concentration was decreased more slowly over time. Results suggest that consistent and continued in-situ treatment is necessary to sustain decreased concentrations of constituents.

8.5.2 Average Pre-Treatment and Post-Treatment Concentrations

Average pre- and post-treatment concentrations were not provided in the references and were not calculated from sources by EPA.

8.5.3 Removal Efficiency

Table 8-6 presents average removal efficiencies observed in the single case study.

Table 8-6: Average Removal Efficiencies

Constituent	Average Removal Efficiency	Mine	Source	Notes
All concentrations reported as dissolved				
Arsenic	97%	Platoro	Harrington et al., 2015	Based on the time period of injections from 2006 to 2012
Zinc	93%	Platoro	Harrington et al., 2015	Based on the time period of injections from 2006 to 2012
Notes: Arsenic and zinc removal efficiencies stated in text of source				

As shown in Table 8-6, in-situ treatment of a mine pool can achieve an average removal efficiency of greater than 90 percent for dissolved arsenic and zinc.

8.5.4 Flow Rates

Flow rates were not provided in the case study evaluated.

8.6 Costs

Costs were not stated specifically for either of the case studies of in-situ treatment of mine pools and pit lakes; however, Poling et al. (2003) project that material costs for fertilizer, costs associated with distribution of the fertilizer across the pit lake's surface (1,735,000 m^2), and routine monitoring would be less than $100,000 per year.

8.7 Lessons Learned

- Use of fertilizer with too high a nitrogen to phosphorus ratio (9:1) causes phosphorus-limited growth and leaves some nitrogen unutilized (Poling et al., 2003). Residual nitrogen requires reduction prior to sulfate reduction; therefore, unutilized nitrogen would slow sulfate-reduction processes that are sequestering metals as metal sulfides. The revised ratio of nitrogen to phosphorus, 6:1, leaves no nitrogen unutilized (Poling et al., 2003).
- At Island Copper, settling of organic matter containing adsorbed constituents through shallow to deeper depths of a stratified pit lake is essential for success of biochemical in-situ treatment (Poling et al., 2003).
- Blending denser carbon sources with alkaline ferric oxyhydroxide sludge allows targeting of deeper zones of mine pools than would be otherwise accessible when pumping up and amending mine water before returning the water through a second pipe (Harrington et al., 2015).

8.8 References

8.8.1 Case Study References

Fisher, T.S.R and Lawrence, G.A. 2006. Treatment of Acid Rock Drainage in a Meromictic Mine Pit Lake. *Journal of Environmental Engineering*, **32**(4):515-526.

Harrington, J., Harrington, J., Lancaster, E., Gault, A., and Woloshyn, K. 2015. "Bioreactor and In Situ Mine Pool Treatment Options for Cold Climate Mine Closure at Keno Hill, YT." In proceedings from the 10th International Conference on Acid Rock Drainage and IMWA Annual Conference, *Agreeing on solutions for more sustainable mine water management*, Gecamin, Santiago, Chile, 2015. pp. 1-10. https://www.imwa.info/imwaconferencesandcongresses/proceedings/293-proceedings-2015.html

Poling, G.W., Pelletier, C.A., Muggli, D., Wen, M., Gerits, J., Hanks, C., and Black, K. 2003. "Field Studies of Semi-Passive Biogeochemical Treatment of Acid Rock Drainage at the Island Copper Mine Pit Lake." In proceedings from the 6th International Conference on Acid Rock Drainage (ICARD 2003), Queensland, Australia, July 12-18. pp. 549-558.

8.8.2 General In Situ Treatment of Mine Pools and Pit Lakes References

Interstate Technology and Regulatory Council (ITRC) Mining Waste Treatment Technology Selection Web. 2010. *In Situ Treatment of Mine Pools and Pit Lakes, Minnesota*. Washington, D.C.. www.itrcweb.org

McCullough, C.D. 2008. Approaches to remediation of acid mine drainage water in pit lakes. *International Journal of Mining, Reclamation and Environment*, **22**(2): 105-119.

9 Permeable Reactive Barriers

A permeable reactive barrier (PRB) is a subsurface in-situ zone consisting of a water permeable material to treat constituents of concern in groundwater passing through it (Interstate Technology and Regulatory Council [ITRC], 2011). PRBs are used in treating both organic and inorganic contaminants in groundwater. Various materials are used individually or in combination in PRBs, including zero valent iron, organic carbon, apatite, mulch, zeolites, red mud (waste material from bauxite ore processing) and compost (ITRC, 2011; Benner at al., 2002; Conca and Wright, 2006 and Wright and Conca, 2006). Mechanisms for treatment within a PRB can be physical, chemical, biological or a combination. Chemical mechanisms include adsorption, ion exchange, oxidation-reduction or precipitation (Wright and Conca, 2006). Microbial communities can be stimulated by addition of organic carbon and nutrients to biodegrade organic contaminants (ITRC, 2011) or facilitate conversion of inorganic constituents to immobile precipitates (Conca and Wright, 2006; Wright and Conca, 2006), such as through the formation of metal sulfides.

9.1 Case Studies Evaluated

This chapter provides an evaluation of case studies in which a PRB was a primary component of mining-influenced water (MIW) treatment. The case studies were selected based on the screening criteria presented in see Section 1.1.1. The case studies examined include full-scale installations of PRBs at two mining sites: one in the United States and one in Canada. Table 9-1 summarizes site names and locations, treatment design information and references for each of the case studies. The chapter provides considerations for constraints, treatability of contaminants, capability, technological and site-specific requirements, and lessons learned for PRBs from evaluation of case study results.

Table 9-1: PRB Case Study Sites

Site Name and Location	Type and Treatment Material	Description	Study Type	Reference	Reference Type
Nickel Rim Mine Ontario, Canada	Biological (stimulation of sulfate reducing bacteria) and chemical (precipitation of iron sulfides). Treatment material is 20% (by volume) municipal compost, 20% leaf mulch, 9%	PRB is 20 meters wide and 3.5 meters deep and is installed in alluvium and keys into bedrock at base and sides. The reactive layer is 4 meters thick between two layers of 1-meter thick sand. Treatment of groundwater plume originating from a tailings impoundment and	Full scale	Benner et al., 2002*	Journal paper
				Benner et al., 1999* Doshi, 2006	Report

Table 9-1: PRB Case Study Sites

Site Name and Location	Type and Treatment Material	Description	Study Type	Reference	Reference Type
	woodchips, 50% gravel and 1% limestone.	infiltrated acidic surface water.			
Success Mine and Mill Northern Idaho, United States	Biological (stimulation of sulfate-reducing bacteria) and chemical (precipitation of metal sulfides). Treatment material is a biogenically-precipitated apatite material from fish bones.	PRB consists of a 442 meters (450-feet) pressure grouted wall keyed into bedrock that directed groundwater into a 4.1 x 4.6 x 15.2 meters (13.5 by 15 by 50 feet) long vault with two cells containing the treatment material. Treatment of groundwater plume originating from tailings pile.	Full scale	Wright and Conca, 2006*	Conference paper
				Conca and Wright, 2006*	Journal Paper
				McCloskey et al., 2006	Conference paper
				Doshi, 2006	Report
Notes: * Primary source(s) of data for evaluation in this chapter					

9.2 Constraints

Small variations in hydraulic conductivity will decrease residence time, which will decrease performance in PRBs that are limited by reaction rates (Benner, 2002). Accurate prediction of contaminant removal rates depends on adequately accounting for changes in groundwater in systems where reactions are microbially mediated (Benner, 2002). There is potential for odors to emanate from a PRB (McCloskey et al, 2006), which may need to be controlled if the PRB is located near a populated area.

9.3 Treatable Contaminants

PRBs can treat aluminum, cadmium, copper, iron, lead, nickel, sulfate and zinc.

9.4 Capability

Only two case studies were identified that met the screening criteria (Section 1.1.1); therefore, the limited data restricts the ability to determine the general capability for PRBs in treating mining-influenced groundwater. In the sections below, influent concentration refers to the concentration of a constituent in the groundwater entering the PRB and effluent concentration refers to the concentration of a constituent in the groundwater after passing through the PRB.

9.4.1 Ranges of Applicability

Concentrations of metals tend to be inversely related to the pH, with higher concentrations associated with a lower pH and lower concentrations associated with a higher pH. Table 9-2 lists maximum (minimum pH) and minimum (maximum pH) influent concentrations of cadmium, lead and zinc and their corresponding effluent concentrations from PRB treatment at the Success Mine and Mill. Table 9-3 lists maximum and minimum upgradient groundwater concentrations of iron and sulfate and their corresponding minimum concentrations both from within the PRB and downgradient from the PRB at the Nickel Rim Mine.

Table 9-2: Maximum and Minimum Influent and Corresponding Effluent Concentrations – Success Mine and Mill

Constituent	Maximum Influent Concentration	Corresponding Effluent Concentration	Minimum Influent Concentration	Corresponding Effluent Concentration	Source
Concentrations reported as dissolved in mg/L; pH reported in standard units					
Cadmium	0.809	<0.002	0.318	<0.002	Conca and Wright, 2006; Wright and Conca, 2006
Lead	1.45	<0.005	0.497	<0.005	Conca and Wright, 2006; Wright and Conca, 2006
Zinc	146.9	0.059	44.7	0.027	Conca and Wright, 2006; Wright and Conca, 2006
pH	4.2	7.1	5.5	6.9	Conca and Wright, 2006; Wright and Conca, 2006
Notes: < = Not detected above noted laboratory method detection limit Data extracted from Table 1 (reported averages of two cells sampled between 03/23/01 and 6/9/04) in Wright and Conca, 2006, and converted to mg/L					

Table 9-3: Maximum and Minimum Upgradient Concentrations and Corresponding Minimum Concentrations Within the PRB and Corresponding Concentration Downgradient of the PRB – Nickel Rim Mine

Constituent	Maximum Up-Gradient Conc.	Minimum Conc. Within PRB	Down-Gradient Conc.	Minimum Up-Gradient Conc.	Minimum Conc. Within PRB	Down-Gradient Conc.	Source
Concentrations reported as dissolved in mg/L							
Iron	670[a]	140[a]	357[a]	419[c]	17[c]	39[c]	Benner et al, 2002
Sulfate	3,408[a]	865[a]	2,420[a]	2,594[b]	1,537[b]	1,824[b]	Benner et al, 2002

Notes:
Data extracted from Figure 9, which presented vertically-averaged concentrations (4 wells in nest) collected biannually between 11/95 and 10/98; converted from millimoles per liter
a = 10/98 sampling event
b = 5/98 sampling event
c = 6/96 sampling event

As shown in Tables 9-2 and 9-3, PRBs designed to stimulate biological sulfate reduction and subsequent precipitation of metal sulfides can decrease concentrations of cadmium, iron, lead, sulfate and zinc as well as increase pH from slightly acidic to near neutral. Table 9-2 shows decreases in both maximum and minimum concentrations of cadmium and lead to below their detection limits. Zinc concentration also decreases following exposure to a PRB, with resulting concentration in effluent less than 0.1 mg/L (Table 9-2) when treating influent concentrations up to four orders of magnitude higher. Table 9-3 shows iron concentration can be reduced by up to an order of magnitude; sulfate concentration also is decreased but is on the same order of magnitude in both upgradient and downgradient groundwater. Although there are no corresponding data for alkalinity, Benner et al. (2002) noted that alkalinity increases as sulfate and iron concentrations decrease.

Table 9-3 also shows that the concentrations of iron and sulfate are lower within the PRB than they are downgradient of the PRB, which was explained by Benner et al. (2002) as possibly being due to a combination of heterogenous flow through the PRB and sampling that is biased toward a volume average. The case study at the Success Mine and Mill did not present data from within the PRB and no other studies examined met the screening criteria for this report; therefore, it is not known if the phenomenon observed by Benner et al. (2002) occurs at other sites having PRB treatment of groundwater.

9.4.2 Average Influent and Effluent Concentrations

Tables 9-4 and 9-5 present average influent and effluent concentrations for constituents assessed in the Success Mine and Mill case study and ranges in upgradient concentrations and averages in concentrations of constituents within the PRB at the Nickel Rim Mine.

Table 9-4: Average Influent and Effluent Concentrations – Success Mine and Mill

Constituent	Average Influent Concentration	Average Effluent Concentration	Source	Notes
Concentrations reported as dissolved in mg/L; pH in standard units				
Cadmium	0.521	0.0016	Conca and Wright, 2006; Wright and Conca, 2006	03/23/01 – 06/09/04
Lead	1.074	0.0062	Conca and Wright, 2006; Wright and Conca, 2006	03/23/01 – 06/09/04
Zinc	75.97	0.144	Conca and Wright, 2006; Wright and Conca, 2006	03/23/01 – 06/09/04
pH	4.69	6.69	Conca and Wright, 2006; Wright and Conca, 2006	03/23/01 – 06/09/04
Notes: Averages calculated by EPA from temporal data in Table 1 in Wright and Conca, 2006 and converted to mg/L; EPA used ½ the detection limit for values reported as below the detection limit to enable calculations				

Table 9-5: Average Upgradient and Within PRB Groundwater Concentrations – Nickel Rim Mine

Constituent	Upgradient Concentration Range[a]	Average Concentration Within PRB[b]	Source
Concentrations reported as dissolved in mg/L; pH in standard units			
Iron	250 – 1,350	80	Benner et al., 1999; Doshi, 2006
Nickel	0.12 – 30	<0.1	Benner et al., 1999; Doshi, 2006
Sulfate	2,500 – 5,200	840	Benner et al., 1999; Doshi, 2006
Alkalinity	< 1 – 60	2,300	Benner et al., 1999; Doshi, 2006
pH	2.8 – 5.9	6.7	Benner et al., 1999; Doshi, 2006
Notes: a = Stated in Table 9 of Doshi, 2006 as “depth-integrated concentrations at Nickel Rim PRB, 1995-1997”; however, it is not clear in Benner et al., 1999 (Doshi’s cited reference) if these ranges are maximum and minimum averages over the four nested wells for these three years or if they are a range over depth for a single year. Examination of Figure 3 in Benner et al., 1999 suggests that these are ranges over the four nested wells for only the 1996 sampling date. b = The PRB comprised sand and organic zones; these data are from the organic zone. It is not clear whether these data (stated in the text of Benner et al., 1999 as vertically-averaged (four nested wells) within the PRB and reported in Table 9 of Doshi, 2006) are averages of four sampling dates			

Table 9-5: Average Upgradient and Within PRB Groundwater Concentrations – Nickel Rim Mine

Constituent	Upgradient Concentration Range[a]	Average Concentration Within PRB[b]	Source
Concentrations reported as dissolved in mg/L; pH in standard units			
(Benner et al., 1999: September 1995, June and September 1996, July 1997), or if they represent a single sampling date. Examination of Figure 3 in Benner et al., 1999 suggests that these are averages of vertically-averaged data from three sampling locations within the organic zone for the single September 1996 sampling date.			

On average, concentrations of cadmium and lead can be decreased to low µg/l concentrations in groundwater treated by PRBs designed to stimulate sulfate reduction and subsequent precipitation of metal sulfides (Table 9-4). Although not directly comparable (numerically), average effluent concentrations of cadmium can be decreased by two orders of magnitude and lead can be decreased by three orders of magnitude, similar to values observed in the comparison of corresponding influent and effluent (Section 9.4.1). Unlike the corresponding influent and effluent concentrations, on average, zinc concentration is decreased by two orders of magnitude (Table 9-4) versus three or four (Section 9.4.1).

On average, nickel concentration can be decreased to below 100 mg/L. Average sulfate concentration within the PRB is an order of magnitude less than the upgradient concentration range. Coupled with the decreased average concentrations of iron and nickel, this suggests the loss of sulfate is due to microbial sulfate reduction and subsequent precipitation of the metals (Table 9-5). Alkalinity increased from sulfate reduction (Benner et al., 2002).

9.4.3 Removal Efficiencies

Table 9-6 presents the average, maximum and minimum removal efficiencies over time (March 2001 through June 2004) for the PRB at the Success Mine and Mill site.

Table 9-6: Removal Efficiencies – Success Mine and Mill

Constituent	Average Removal Efficiency	Maximum Removal Efficiency	Minimum Removal Efficiency	Source
All concentrations reported as dissolved				
Cadmium	99.64%	99.92%	98.06%	Conca and Wright, 2006; Wright and Conca, 2006
Lead	99.48%	99.96%	95.36%	Conca and Wright, 2006; Wright and Conca, 2006
Zinc	99.76%	100.00%	98.46%	Conca and Wright, 2006; Wright and Conca, 2006
Notes: EPA calculated removal efficiency from data provided in Table 1 of the source and used ½ the detection limit in calculations for data reported as below detection				

At the Success Mine and Mill site, average and maximum removal efficiencies for cadmium, lead and zinc were above 99 percent (Table 9-6). The lowest removal efficiency was 95 percent for lead, whereas the minimum removal efficiencies for cadmium and zinc were about the same at about 98 percent.

Doshi (2006) reported the iron removal efficiency as 68 to 95 percent, based on the range in iron concentration in the upgradient zone compared to the average concentration within the organic zone of the PRB (Benner et al., 1999). Benner et al. (2002) reported decreasing rates of sulfate and iron removal occurring 38 months after installation of the PRB; however, the authors did not provide removal efficiencies.

9.4.4 Flow Rates

An average velocity of 16 meters per year (Nickel Rim, Doshi, 2006) and an average flow of 19 liters per minute (L/min) (Success Mine, Adams et al., 2006) were treated by the two PRBs. On average, groundwater had a residence time within the PRBs ranging from 1 day (Success Mine, Adams et al., 2006) to 90 days (Nickel Rim, Benner et al., 2002). Residence time ranged from 60 days at the center of the PRB to 165 days at the top and bottom areas of the PRB at Nickel Rim (Benner et al., 2002). Future case study comparisons may provide additional information on the typical flows or velocities of groundwater treatable by a PRB.

9.5 Costs

At Success Mine, the cost of the PRB construction was approximately $500,000, including $35,000 for 100 tons of the apatite medium (Adams et al., 2006). At Nickel Rim, the PRB construction cost was $30,000, including design, construction, materials and the reactive media (U.S. EPA, 2002; RTDF, 2000).

9.6 Lessons Learned

- Treatment media may become plugged or channeling may occur, which can reduce PRB performance (Adams et al., 2006; Conca and Wright, 2006; Wright and Conca, 2006). The reduction in hydraulic conductivity from plugging may require replacing material (Conca and Wright, 2006; Wright and Conca, 2006) or air injections can be used to temporarily address the issue (Adams et al., 2006; Doshi, 2006), or some other means of disaggregation.
- Plastic packing rings (Success Mine and Mill, Doshi, 2006) or other types of large-diameter aggregate materials can be added to a media mixture to restore flow.
- Homogeneity and performance of PRBs can be improved by increasing the gravel fraction of the media, choosing a different particle size distribution, or selecting a more reactive organic carbon material, but costs of these enhancements should be weighed against the costs for replacing the PRB more often or installing a thicker PRB (Benner et al., 2002).
- PRB design (e.g., size, hydraulic residence time) should account for site-specific, seasonal temperature fluctuations that can lead to decreased treatment rates during cold periods. At the Nickel Rime site, residence times greater than a year would eliminate temperature influences on effluent concentrations (Benner et al, 2002).

9.7 References

9.7.1 Case Study References

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Wright, J. and Conca, J. 2006. “Remediation of Groundwater Contaminated with Zn, Pb and Cd Using a Permeable Reactive Barrier with Apatite II. Paper presented at the 7th International Conference on Acid Rock Drainage, St. Louis, MO, March 26-30, 2006. pp. 2514-2527.

9.7.2 General Capping References

Interstate Technology and Regulatory Council (ITRC). 2011. “Permeable Reactive Barrier: Technology Update.” https://www.itrcweb.org/Guidance/GetDocument?documentID=69.

10 Treatment Trains

A treatment train is a set of multiple technologies used in series to treat mining-influenced water (MIW). Treatment trains can include technologies that are active, passive, semi-passive, or any combination. MIW can contain a wide variety of inorganic constituents needing treatment, some of which are treated best with technologies employing oxic mechanisms (e.g., aerobic wetlands, oxic limestone drains) and some that are treated more effectively by anoxic mechanisms (e.g., biochemical reactors (BCRs), anaerobic wetlands, anoxic limestone drains). Therefore, to treat all constituents of concern, multiple treatment technologies (single or multi-step) are used in a treatment train. Some treatment systems require a secondary step but are still considered a single treatment system. For example, aerobic treatment is required for the effluent from an anaerobic treatment to increase oxygen content, remove biochemical oxygen demand (BOD) and remove any residual gases produced by the anaerobic microbial processes before the water can be released into a receiving water body. Settling ponds are an integral part of treatment trains when the treatment includes processes that create precipitates (e.g., iron oxyhydroxides) that need to be removed from the water prior to being released to the environment. In these examples, the aerobic treatment or settling pond are not themselves considered add-on treatment technologies forming a treatment train.

10.1 Case Studies Evaluated

This chapter provides an evaluation of case studies in which treatment trains were used to treat MIW. The case studies evaluated were based on the screening criteria presented in the Section 1.1.1 and include field pilot-scale and full-scale deployments at multiple mine sites in North America and Europe (Table 10-1). This chapter includes full system treatment influent and effluent, rather than influent and effluent for each successive technology within the treatment train; case studies that provided influent and effluent for individual steps within a treatment train were discussed in previous technology-specific chapters.

Nine of the treatment trains examined incorporated passive anaerobic BCRs with pre- and/or post-treatment. In seven of these treatment trains, all components were passive. For the other two, one treatment train consisted of three distinct systems included an active limestone-dosed (LD)[2] pre-treatment component, a limestone-free (LF) component, and an anoxic limestone drain (ALD) later converted to a LD system (Wheal Jane Mine, Table 10-2), and the other included gravity-fed addition of sodium hydroxide and ethanol prior to a settling pond (Leviathan, Table 10-2). Three of the treatment trains included passive aerobic or anaerobic wetlands with additional treatments, such as limestone filters or capping and one included neutralization and chemical precipitation via the use of a dispersed alkaline substrate (DAS) in a system similar to an anoxic limestone drain or reducing and alkalinity-producing system (RAPS), followed by post-treatment oxidation and settling. This chapter provides considerations for constraints, treatability of contaminants, capability, technological and site-specific requirements, costs, and lessons learned for treatment trains from evaluation of these case studies.

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[2] All references cited for the Wheal Jane case study indicated lime-dosed and lime-free, but it was indicated in Whitehead and Prior (2005) that the pre-treatment was “lime dosing (calcium carbonate) to pH 5 (LD)”, rather than lime (calcium oxide or hydroxide); therefore, this report refers to these as limestone-dosed and limestone-free.

Table 10-1: Treatment Train Case Study Sites

Site Name and Location	Technologies	Description	Study Type	Reference	Reference Type
Calliope Mine Butte, Montana	Passive anaerobic BCRs with passive pre-treatment	Two horizontal flow BCRs: one below ground with pre-treatment (BCR II) and one above ground with pre-treatment (BCR IV); each unit contained organic matter (cow manure and straw) and cobbles; pre-treatment units contained additional organic matter and limestone.	Pilot scale	Wilmoth, 2002*	Report
				Bless et al., 2008	Journal paper
				Nordwick et al., 2006	Conference paper
Confidential Mine, Montana	Passive anaerobic solid substrate BCR followed by a passive aerobic polishing cell and aeration cell	The BCR substrate consisted of wood chips, hay, limestone, animal manure and crushed basalt. The aerobic polishing cell was a series of vegetated ponds with a large surface area.	Pilot scale (technology demonstration)	Blumenstein and Gusek, 2009*	Conference paper
Copper Basin Mining District, Copper Hill, Tennessee	Passive anaerobic wetlands followed by passive aerobic wetlands and limestone rock filter	8,094 m^2 (2-acre) anaerobic wetland constructed with a geosynthetic clay liner overlain with lime-enriched soil, crushed limestone, hay, mushroom compost and planted with cattails. After four years, two aerobic cells and an aerobic limestone rock filter were added.	Pilot scale	Federal Remediation Technologies Roundtable (FRTR), 2007	FRTR case study summary (online document)
				U.S. EPA, 2006b	Report
				Faulkner and Miller, 2002*	Conference paper

Table 10-1: Treatment Train Case Study Sites

Site Name and Location	Technologies	Description	Study Type	Reference	Reference Type
Dunka Mine, Babbitt, Minnesota	Passive aerobic wetlands with passive pre- and/or post-treatment limestone	Five unconnected surface flow wetland treatment systems, each with pre- and/or post-treatment with limestone. Each system included a series of soil berms, covered in local peat and peat screenings, built to control water levels and maximize contact between the drainage and the substrate.	Full scale	Eger and Eger, 2005*	Conference paper
				Eger et al., 1996	Conference Paper
				Eger et al., 1998	Conference paper
				ITRC, 2010*	Report
				Eger and Beatty, 2013	Journal paper
Force Crag Cumbria, United Kingdom	Passive anaerobic BCR, solid substrate and aerobic wetland	Parallel vertical-flow ponds containing compost, woodchips and dried activated sewage sludge, followed by an aerobic wetland.	Full scale	Jarvis et al., 2015*	Conference paper
Golden Sunlight Mine Whitehall, Montana	Settling pond and passive anaerobic BCR	Two-step process using a settling pond followed by a BCR, which contained crushed limestone and manure; water was recirculated through the system.	Pilot scale	Bless et al., 2008*	Journal paper
Leviathan Mine Alpine County, California	Semi-passive chemical addition, pre-treatment pond, passive anaerobic BCRs, settling ponds and	System consisted of a pre-treatment pond (preceded by gravity fed addition of 25 percent sodium hydroxide and ethanol), two BCRs in series, two	Full scale	Doshi, 2006	Report
				U.S. EPA, 2006a*	Report

Table 10-1: Treatment Train Case Study Sites

Site Name and Location	Technologies	Description	Study Type	Reference	Reference Type
	aeration channel	continuous flow-settling ponds, and an aeration channel; BCRs were lined with high-density polyethylene, river rock and manure. From November 2003 to mid-May 2004, the system operated in gravity flow mode; from mid-May 2004 through 2005, the system operated in recirculating mode.			
Monte Romero Mine Southwestern Spain	Passive natural Fe-oxidizing lagoon (NFOL) followed by passive limestone-DAS system	NFOL, followed by a limestone-DAS tank, two aeration structures and settling ponds, a second limestone-DAS tank followed by two more aeration structures and settling ponds, and then to a MgO-DAS tank. DAS tanks filled with coarse pine wood chips mixed with limestone sand.	Pilot scale	Macías et al., 2012a*	Journal paper
				Macías et al., 2012b	Journal paper
				Rötting et al., 2008	Journal paper
Standard Mine Crested Butte, Colorado	Passive anaerobic BCR with passive aerobic polishing cells	System comprised a BCR followed by aerobic polishing cells; BCR contained hay, wood chips, limestone and cow manure.	Pilot scale	Gallagher et al., 2012*	Conference paper
				Reisman et al., 2009*	Conference paper
				Butler et al., 2011	Journal paper
			Pilot scale		Report

Table 10-1: Treatment Train Case Study Sites

Site Name and Location	Technologies	Description	Study Type	Reference	Reference Type
Surething Mine Helena, Montana	Passive anaerobic BCRs, limestone drain and passive aerobic BCR	System comprised an anaerobic BCR followed by an anoxic limestone drain, followed by another anaerobic BCR, followed by an aerobic BCR containing manganese-oxidizing bacteria.		Nordwick and Bless, 2008*	
Tar Creek Superfund Site Oklahoma, Kansas, Missouri	Passive system including oxidation pond, aerobic wetlands, passive anaerobic BCRs, aeration ponds, limestone bed and wetland	Oxidation pond followed by parallel treatment trains consisting of surface flow wetlands/ponds, vertical flow BCRs, re-aeration ponds, and horizontal-flow limestone beds. Effluent from the parallel trains are recombined in a polishing wetland/pond prior to final discharge.	Full scale		
				Nairn et al., 2009	Conference paper
				Nairn et al., 2010a*	Conference paper
				Nairn et al., 2010b	Conference paper
				Nairn et al., 2011*	Conference paper
Valzinco Mine Spotsylvania County, Virginia	Capping, passive limestone drains and constructed wetlands	Reclamation occurred between 2001 and 2002 and included the removal and isolation of tailings in a covered pit, installation of several limestone drains leading from the pit and a series of ponds and wetlands.	Full scale	Seal et al, 2008*	Conference paper
				Sobeck et al, 2008	Conference paper

Table 10-1: Treatment Train Case Study Sites

Site Name and Location	Technologies	Description	Study Type	Reference	Reference Type
Wheal Jane Mine Cornwall, United Kingdom	Active limestone[a] pre-treatment at two configurations, passive aerobic wetland, passive anaerobic BCR and aerobic rock filter	Three multi-cell treatment systems that utilized one of three pre-treatment methods to raise pH: limestone[a] dosing to pH 5.0 with calcium carbonate (LD), an anoxic limestone drain (ALD, modified to a LD[a] system June 2000), or a limestone[a]-free system without pre-treatment (LF). Pre-treated drainage passed to aerobic reed bed wetlands for iron and arsenic removal. Next, water flowed through an anaerobic cell (BCR) for sulfate reduction and metals removal. The final stage was an aerobic rock filter, designed to promote manganese removal. The underground, lined BCR contained a mixture of 95% softwood sawdust, 5% hay, and a small quantity of cow manure.	Pilot scale	Whitehead et al., 2005*	Journal paper
				Whitehead and Prior, 2005	Journal paper
				Johnson and Hallberg, 2005*	Journal paper

Notes:
* Primary source(s) of data for evaluation in this chapter

Table 10-1: Treatment Train Case Study Sites

Site Name and Location	Technologies	Description	Study Type	Reference	Reference Type
a = Whitehead and Prior (2005) specified that "lime dosing" was by using limestone rather than lime. All the references for this case study site used the term "lime" when meaning limestone; this chapter uses the term "limestone".					

The treatment train at the Confidential Mine site is evaluated only qualitatively in this chapter because the case study evaluated did not document successful treatment of constituents of concern with one component of the treatment train – the aerobic polishing cell (Blumenstein and Gusek, 2009). The case study did document successful treatment of thallium, selenium and nitrate with the BCR component of the treatment train; this component of the case study is evaluated quantitatively in the BCRs chapter (Section 3). BCR effluent water reported secondary constituents of concern – arsenic, iron and manganese – that were not successfully treated with the aerobic polishing cell. The crushed basalt in the BCR substrate was the suspected source of the unanticipated arsenic in the effluent; the basalt was not characterized prior to its use in the BCR. The BCR effluent also had elevated levels of BOD as compared to the influent, resulting from decomposition of the organic matter. Blumenstein and Gusek (2009) noted that treatment of the secondary constituents of concern did not occur because BOD concentrations did not decrease to levels below 30 to 50 mg/L before reaching the aerobic polishing cell.

10.2 Constraints

A primary constraint associated with treatment trains is the need for enough land area and suitable topography to accommodate the treatment technologies. An additional constraint is the need to determine the most effective combination and sequence of treatment technologies to treat MIW having multiple constituents of concern, a process which may evolve over time (U.S. EPA, 2006a). Technologies within the treatment train may have specific constraints; see Sections 3, 4, 5 and 7 for discussion on constraints associated with BCRs, capping, neutralization and chemical precipitation, and constructed wetlands, respectively.

10.3 Treatable Contaminants (All Configurations)

Treatment trains are capable of treating aluminum, arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, selenium, silicon, sulfate and zinc and raising pH (Wilmoth, 2002; Bless et al, 2008; Doshi, 2006; U.S. EPA, 2006a; Macías et al., 2012a; Gallagher et al., 2012; Nordwick and Bless, 2008; Nairn et al., 2010a; Nairn et al., 2011; U.S. EPA, 2006a; Eger and Eger, 2005; Seal et al., 2008; Jarvis et al., 2015; Whitehead et al., 2005; Johnson and Hallberg, 2005).

Treatment trains that incorporate an anaerobic BCR coupled with pre- and/or post-treatment with an aerobic treatment technology (surface wetlands, ponds or lagoons) and/or active or passive limestone treatment are able to raise pH and treat aluminum, arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, selenium, sulfate and zinc (Wilmoth, 2002; Bless et al, 2008; Doshi, 2006; U.S. EPA, 2006a; Gallagher et al., 2012; Nordwick and Bless, 2008; Nairn et al., 2010a; Nairn et al., 2011; Jarvis et al., 2015; Whitehead et al., 2005; Johnson and Hallberg, 2005).

Treatment trains that incorporate passive aerobic or anaerobic constructed wetlands with capping and/or passive pre- and/or post-treatment with limestone are able to raise pH and treat aluminum, cadmium, cobalt, copper, iron, lead, manganese, nickel, sulfate and zinc (U.S. EPA, 2006a; Eger and Eger, 2005; Seal et al., 2008). Passive treatment using limestone, such as the dispersed alkaline precipitation system, can treat aluminum, arsenic, copper, iron, lead, and silicon (Macías et al., 2012a).

10.4 Capability - Treatment Trains (All Configurations)

The capabilities of the three sub-categories of treatment trains are presented in sections below: passive anaerobic BCR with active or passive pre-treatment and/or passive post-treatment (Section 10.5); passive constructed wetlands (aerobic and/or aerobic) with passive pre- and/or post-treatment (Section 10.6); and alkaline precipitation with pre- and/or post-treatment (Section 10.7). Overall, treatment trains can attain very low constituent concentrations, often below laboratory detection limits. Treatment trains that incorporate an anaerobic BCR with passive pre- and/or post-treatment are capable of treating influent concentrations less than 1 mg/L (cadmium, cobalt, chromium, nickel and selenium; Tables 10-2 and 10-4) to over 80 mg/L (copper, iron, magnesium, manganese, sulfate, zinc; Table 10-2 and 10-4). Treatment trains that incorporate anaerobic BCRs with passive pre- and/or post-treatment are capable of decreasing influent concentrations of aluminum (1,740 mg/L), copper (81.4 mg/L) and lead (1.07 mg/L) by three or more orders of magnitude and can treat influent concentrations of iron (198 mg/L), manganese (117 mg/L) and zinc (39.5 mg/L) by up to three orders of magnitude (Table 10-2). The treatment train that incorporated an active limestone pre-treatment treated higher concentrations, on average, of aluminum (about 50 mg/L) and zinc (>80 mg/L), as compared to the treatment trains not having limestone addition. The treatment train that incorporated a semi-passive sodium hydroxide and ethanol pre-treatment treated higher concentrations, on average, of chromium (about 0.01 mg/L) and copper (about 0.8 mg/L), as compared to the treatment trains not having chemical additions (Table 10-4).

Treatment trains incorporating passive constructed wetlands with capping and/or passive pre- and/or post-treatment are able to increase pH and decrease influent concentrations of aluminum (1.4 mg/L), cadmium (0.088 mg/L), copper (2.2 mg/L), iron (69.7 mg/L), lead (1.3 mg/L), manganese (2.1 mg/L), nickel (0.037 mg/L), sulfate (1,400 mg/L)and zinc (27 mg/L) by an order of magnitude or more, as indicated in Table 10-11 and Table 10-12.

On average, alkaline precipitation with pre- and/or post-treatment can decrease high concentrations (>100 mg/L) of aluminum and iron to below detection limits. Lower concentrations of arsenic and lead (<1 mg/L) and copper (5 mg/L) also can be decreased below detection limits in a treatment train incorporating alkaline precipitation with pre- and/or post-treatment.

10.5 Capability - Anaerobic BCR with Pre- and/or Post-Treatment

10.5.1 Ranges of Applicability

Concentrations of metals tend to be inversely related to the pH, with higher concentrations associated with a lower pH and lower concentrations associated with a higher pH. Tables 10-2 and 10-3, respectively, show the ranges of applicability – the maximum influent concentration (minimum pH) treated and corresponding effluent concentration attained, and the minimum influent concentration (maximum pH) treated and corresponding effluent concentration attained. The tables include sites with passive pre-treatment and sites with active pre-treatment; data were not available for Tar Creek. The ranges were determined by comparing values in Appendix E, Tables E-1, E-2, E-3, E-4, E-5, E-6, E-7, and E-8. For each constituent, the minimum influent concentrations in the Appendix E tables are the lowest concentrations reported that exceeded a case study's reported detection limit (DL).

Table 10-2: Maximum Influent and Corresponding Effluent Concentrations

Constituent	Maximum Influent Concentration	Corresponding Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Aluminum[a]	1,740	0.126	Golden Sunlight	Bless, 2008
Arsenic[a]	1.25	<0.01	Surething	Nordwick and Bless, 2008
Cadmium[a]	0.385	0.005	Surething	Nordwick and Bless, 2008
Chromium[b]	0.0198	0.0132	Leviathan	U.S. EPA, 2006a
Copper[a]	81.4	0.001	Golden Sunlight	Bless, 2008
Iron[a]	198	2.62	Golden Sunlight	Bless, 2008
Lead[a]	1.07	0.001	Standard	Gallagher et al., 2012
Manganese[a]	117	67.8	Golden Sunlight	Bless, 2008
Nickel[a]	0.531	0.0189	Leviathan	U.S. EPA, 2006a
Selenium[b]	0.0199	0.0108	Leviathan	U.S. EPA, 2006a
Sulfate[b]	1,510	1,160	Leviathan	U.S. EPA, 2006a
Zinc[a]	39.5	0.011	Golden Sunlight	Bless, 2008
pH	2.5	6.9	Surething	Nordwick and Bless, 2008
Notes: Seven case studies provided influent and corresponding effluent data: Calliope (Table E-1), Force Crag (Table E-2), Golden Sunlight (Table E-3), Leviathan (Table E-4), Standard (Table E-5), Surething (Table E-6 and Table E-7), and Wheal Jane (Table E-8) Chromium, nickel and selenium reported only for Leviathan Mine a = dissolved b = total				

Table 10-3: Minimum Influent and Corresponding Effluent Concentrations

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Aluminum[a]	2.4	0.0542	Calliope – BCR IV	Wilmoth, 2002
Arsenic[b]	0.0028	0.0024	Leviathan; Gravity mode	U.S. EPA, 2006a

Table 10-3: Minimum Influent and Corresponding Effluent Concentrations

Constituent	Minimum Influent Concentration	Corresponding Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Cadmium[b]	0.0004	<0.00023	Leviathan; Gravity mode	U.S. EPA, 2006a
Chromium[a]	0.0164	0.008	Leviathan; Gravity mode	U.S. EPA, 2006a
Copper[b]	0.011	0.0022	Standard	Gallagher et al., 2012
Iron[a]	0.524	0.417	Calliope – BCR IV	Wilmoth, 2002
Lead[a]	0.0049	0.0029	Leviathan; Gravity Mode	U.S. EPA, 2006a
Manganese[a]	0.69	0.6	Calliope – BCR II	Wilmoth, 2002
Nickel[a]	0.478	0.0715	Leviathan; Gravity Mode	U.S. EPA, 2006a
Selenium[b]	0.0096	0.0087	Leviathan; Gravity Mode	U.S. EPA, 2006a
Sulfate[c]	260	200	Wheal Jane; LF system	Johnson and Hallberg, 2005
Zinc[a]	0.692	0.0147	Leviathan; Gravity Mode	U.S. EPA, 2006a
pH	7.52	7.21	Calliope – BCR II	Wilmoth, 2002

Notes:
Seven case studies provided influent and corresponding effluent data: Calliope (Table E-1), Force Crag (Table E-2), Golden Sunlight (Table E-3), Leviathan (Table E-4), Standard (Table E-5), Surething (Table E-6 and Table E-70), and Wheal Jane (Table E-8)
Chromium, nickel and selenium reported only for Leviathan Mine
a = total
b = dissolved
c = total or dissolved not specified
LF = Limestone-free system without pre-treatment

Table 10-2 shows that treatment trains that incorporate anaerobic BCRs with pre- and/or post-treatment technologies are able to decrease concentrations of many constituents by a minimum of about one order of magnitude when starting with concentrations exceeding 0.5 mg/L; influent concentrations of aluminum (1,740 mg/L), copper (81.4 mg/L) and lead (1.07 mg/L) decreased by three or more orders of magnitude and influent concentrations of iron (198 mg/L), manganese (117 mg/L) and zinc (39.5 mg/L) decreased by up to three orders of magnitude. Arsenic and cadmium influent concentrations (1.25 mg/L and 0.385 mg/L) can be decreased by two orders of magnitude with treatment.

Table 10-2 shows that a treatment train that incorporates anaerobic BCRs with semi-passive chemical precipitation can decrease influent concentrations of chromium and selenium less than 0.02 mg/L at the single evaluated site. Each constituent was treated only to slightly lower concentrations on the same order of magnitude (Table 10-2). The treatment train with semi-passive chemical precipitation was also able to decrease nickel by one order of magnitude with a starting concentration of approximately 0.5 mg/L.

Table 10-3 shows that treatment trains that incorporate anaerobic BCRs with pre- and/or post-treatment technologies are able to treat chromium, copper and nickel concentrations by more than one order of magnitude and arsenic, cadmium, iron, lead, manganese, selenium and zinc by less than an order of magnitude when concentrations are <1 mg/L. Treatment also occurs for aluminum when beginning with an approximate concentration of 2 mg/L. A treatment train system that incorporates anaerobic BCRs with pre- and/or post-treatment can also reduce cadmium influent (0.0004 mg/L) to below the detection limit and was able to increase pH (Table 10-3).

The treatment train that incorporated the active limestone pre-treatment for two configurations (the LD and ALD system after June 2000) reported data for a single sampling event; however, the highest influent concentrations were lower than those in the other treatment trains and the lowest influent concentrations were higher than those observed in the other treatment trains, so are not represented in Tables 10-2 or 10-3. See Table E-8 in Appendix E for the range of applicability for the systems that included an active limestone pre-treatment component (Johnson and Hallberg, 2005).

The treatment train that incorporated the semi-passive chemical pre-treatment reported treatment for higher influent concentrations for chromium (0.0198 mg/L), nickel (0.531 mg/L) and sulfate (1,510 mg/L) and lower influent concentrations for arsenic (0.0028 mg/L), cadmium (0.0004 mg/L), chromium (0.0164 mg/L), lead (0.0049 mg/L), nickel (0.478 mg/L) and zinc (0.692 mg/L) as compared to treatment trains not having chemical additions (Tables 10-2 and 10-3).

10.5.2 Average Influent and Effluent Concentrations

Tables 10-4 and 10-5 present the highest and lowest average influent concentrations treated for each constituent, respectively. Tables 10-6 and 10-7 list the highest and lowest average effluent concentrations attained for each constituent, respectively. These values were determined by comparing values in Appendix E, Tables E-9, E-10, E-11, E-12, and E-13 derived from studies that reported this information. It is important to note that average influent concentrations do not correspond directly with the average effluent concentrations.

Table 10-4: Maximum Average Influent Concentration Treated

Constituent	Maximum Average Influent Concentration	Average Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Aluminum[a]	48.6	3.3	Wheal Jane; ALD system	Whitehead et al., 2005
Arsenic[a]	2.7	0.0	Wheal Jane; LD, ALD and LF systems	Whitehead et al., 2005
Cadmium[a]	0.1	0.0	Wheal Jane; LD, ALD and LF systems	Whitehead et al., 2005

Table 10-4: Maximum Average Influent Concentration Treated

Constituent	Maximum Average Influent Concentration	Average Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Chromium[a]	0.0122	0.0078	Leviathan; Gravity mode	U.S. EPA, 2006a
Cobalt[b]	0.066 ± 0.008	0.007 ± 0.0004	Tar Creek	Nairn et al., 2011
Copper[a]	0.795	0.0046	Leviathan; Recirculation mode	U.S. EPA, 2006a
Iron[b]	177 ± 2.33	0.57 ± 0.207	Tar Creek	Nairn et al., 2011
Lead[a]	0.134	0.0038	Standard	Gallagher et al., 2012
Magnesium[b]	200 ± 2.53	198 ± 7.49	Tar Creek	Nairn et al., 2011
Manganese[a]	21.4	12.2	Wheal Jane; ALD system	Whitehead et al., 2005
Nickel[b]	0.945 ± 0.015	0.035 ± 0.007	Tar Creek	Nairn et al., 2011
Selenium[a]	0.0139	0.0112	Leviathan; Gravity mode	U.S. EPA, 2006a
Sulfate[b]	2,239 ± 26	2,047 ± 72	Tar Creek	Nairn et al., 2011
Zinc[a]	82.0	4.9	Wheal Jane; ALD system	Whitehead et al., 2005
pH	3.9	6.6	Wheal Jane; ALD system	Whitehead et al., 2005

Notes:

Five case studies provided average influent and effluent data: Calliope (Table E-9), Leviathan (Table E-10), Standard (Table E-11); Tar Creek (Table E-12) and Wheal Jane (Table E-13)

Whitehead et al., 2005 only reported one decimal place in Tables 1, 2 and 3

Cobalt and magnesium reported only for Tar Creek

Selenium reported only for Leviathan

a = dissolved

b = total

LD = Limestone-dosed pre-treatment

ALD = Anoxic limestone drain, modified to limestone-dosed system in June 2000 (Whitehead et al., 2005)

LF = Limestone-free system without pre-treatment

Table 10-5: Minimum Average Influent Concentration Treated

Constituent	Minimum Average Influent Concentration	Average Effluent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Aluminum[a]	0.094 ± 0.009	0.071 ± 0.030	Tar Creek	Nairn et al., 2011
Arsenic[b]	0.0074	0.0065	Leviathan; Recirculation mode	U.S. EPA, 2006a
Cadmium[b]	0.00060	<0.00020	Leviathan; Recirculation mode	U.S. EPA, 2006a
Chromium[b]	0.0111	0.0064	Leviathan; Recirculation mode	U.S. EPA, 2006a
Cobalt[a]	0.066 ± 0.008	0.007 ± 0.0004	Tar Creek	Nairn et al., 2011
Copper[b]	0.1	0.0028	Standard	Gallagher et al., 2012
Iron[a]	11.2	0.54	Standard	Gallagher et al., 2012
Lead[b]	0.0042	0.0025	Leviathan; Recirculation mode	U.S. EPA, 2006a
Magnesium[a]	200 ± 2.53	198 ± 7.49	Tar Creek	Nairn et al., 2011
Manganese[a]	1.4	0.96	Calliope	Wilmoth, 2002
Nickel[b]	0.487	0.0655	Leviathan; Gravity mode	U.S. EPA, 2006a
Selenium[b]	0.0115	0.0085	Leviathan; Recirculation mode	U.S. EPA, 2006a
Sulfate[b]	281	122	Standard	Gallagher et al., 2012
Zinc[b]	0.715	0.0158	Leviathan; Gravity mode	U.S. EPA, 2006a
pH	6.05	7.49	Calliope – BCR II	Wilmoth, 2002

Notes:
Five case studies provided average influent and effluent data: Calliope (Table E-9), Leviathan (Table E-10), Standard (Table E-11); Tar Creek (Table E-12) and Wheal Jane (Table E-13)
Whitehead et al., 2005 only reported one decimal place in Tables 1, 2 and 3
Cobalt and magnesium reported only for Tar Creek
Selenium reported only for Leviathan
a = total
b = dissolved
LD = Limestone-dosed pre-treatment
ALD = Anoxic limestone drain, modified to limestone-dosed system in June 2000 (Whitehead et al., 2005)
LF = Limestone-free system without pre-treatment

Table 10-6: Maximum Average Effluent Concentration Attained

Constituent	Maximum Average Effluent Concentration	Average Influent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Aluminum[a]	3.3	48.6	Wheal Jane; ALD system	Whitehead et al., 2005
Arsenic[b]	0.007	0.5634	Calliope	Wilmoth, 2002
Cadmium[b]	0.0039	0.0103	Calliope	Wilmoth, 2002
Chromium[a]	0.0078	0.0122	Leviathan; Gravity mode	U.S. EPA, 2006a
Cobalt[b]	0.007 ± 0.0004	0.066 ± 0.008	Tar Creek	Nairn et al., 2011
Copper[a]	0.1	0.4	Wheal Jane; LF and LD systems	Whitehead et al., 2005
Iron[a]	13.2	143.6	Wheal Jane; LD system	Whitehead et al., 2005
Lead[a]	0.0038	0.134	Standard	Gallagher et al., 2012
Magnesium[b]	198 ± 7.49	200 ± 2.53	Tar Creek	Nairn et al., 2011
Manganese[a]	12.2	21.4	Wheal Jane; ALD system	Whitehead et al., 2005
Nickel[a]	0.0697	0.529	Leviathan; Recirculation mode	U.S. EPA, 2006a
Selenium[a]	0.0112	0.0139	Leviathan; Gravity mode	U.S. EPA, 2006a
Sulfate[b]	2,047 ± 72	2,239 ± 26	Tar Creek	Nairn et al., 2011
Zinc[a]	51.3	82	Wheal Jane; LF system	Whitehead et al., 2005
pH	6.6	3.9	Wheal Jane; ALD system	Whitehead et al., 2005

Notes:
Five case studies provided average influent and effluent data: Calliope (Table E-9), Leviathan (Table E-10), Standard (Table E-11); Tar Creek (Table E-12) and Wheal Jane (Table E-13)
Whitehead et al., 2005 only reported one decimal place in Tables 1, 2 and 3
Cobalt and magnesium reported only for Tar Creek
Selenium reported only for Leviathan
a = dissolved
b = total
LD = Limestone-dosed pre-treatment
ALD = Anoxic limestone drain, modified to a limestone-dosed system June 2000 (Whitehead et al., 2005)
LF = Limestone-free system without pre-treatment

Table 10-7: Minimum Average Effluent Concentration Attained

Constituent	Minimum Average Effluent Concentration	Average Influent Concentration	Mine	Source
Concentrations reported in mg/L; pH reported in standard units				
Aluminum[a]	0.0372	1.2229	Calliope – BCR IV	Wilmoth, 2002
Arsenic[b]	0.0	2.7	Wheal Jane; LF, ALD and LD systems	Whitehead et al., 2005
Cadmium[b]	0.0	0.1	Wheal Jane; LF, ALD and LD systems	Whitehead et al., 2005
Chromium[b]	0.0064	0.0111	Leviathan; Recirculation mode	U.S. EPA, 2006a
Cobalt[a]	0.007 ± 0.0004	0.066 ± 0.008	Tar Creek	Nairn et al., 2011
Copper[b]	0.0	0.4	Wheal Jane; ALD system	Whitehead et al., 2005
Iron[a]	0.57 ± 0.207	177 ± 2.33	Tar Creek	Nairn et al., 2011
Lead[b]	0.0025	0.0042	Leviathan; Recirculation mode	U.S. EPA, 2006a
Magnesium[a]	198 ± 7.49	200 ± 2.53	Tar Creek	Nairn et al., 2011
Manganese[a]	0.786067	1.4581	Calliope – BCR II	Wilmoth, 2002
Nickel[a]	0.035 ± 0.007	0.945 ± 0.015	Tar Creek	Nairn et al., 2011
Selenium[b]	0.0085	0.0115	Leviathan; Recirculation mode	U.S. EPA, 2006a
Sulfate[b]	122	281	Standard	Gallagher et al., 2012
Zinc[b]	0.0089	0.776	Leviathan; Recirculation mode	U.S. EPA, 2006a
pH	7.74	5.84	Calliope – BCR IV	Wilmoth, 2002

Notes:
Five case studies provided average influent and effluent data: Calliope (Table E-9), Leviathan (Table E-10), Standard (Table E-11); Tar Creek (Table E-12) and Wheal Jane (Table E-13)
Whitehead et al., 2005 only reported one decimal place in Tables 1, 2 and 3
Cobalt and magnesium reported only for Tar Creek
Selenium reported only for Leviathan
a = total
b = dissolved
LD = Limestone-dosed pre-treatment
ALD = Anoxic limestone drain, modified to a limestone-dosed system June 2000 (Whitehead et al., 2005)
LF = Limestone-free system without pre-treatment

The treatment train that incorporated an active limestone pre-treatment (Wheal Jane) for a portion of the treatment period (ALD system was converted to LD after June 2000) was capable of treating higher concentrations, on average, of aluminum (about 50 mg/L) and zinc (>80 mg/L) and raising pH from 3.9 to 6.6 (Table 10-4). In contrast, the LD system in the treatment train did not treat aluminum, on average (Table E-13). The lowest influent concentrations were not observed in the single case study evaluated with limestone pre-treatment (LD system and ALD system after June 2000), which generally exhibited higher average influent concentrations than at other sites that reported average influent and effluent (Table 10-5). Treatment of manganese occurred in the treatment train with active pre-treatment for a portion of the treatment period (ALD system) with maximum average influent and average effluent concentrations on the same order of magnitude (21.4 mg/L, influent to 12.2 mg/L, effluent). The maximum average effluent concentrations for aluminum (ALD; 3.3 mg/L), copper (LD; 0.1 mg/L), iron (LD; 13.2 mg/L), and manganese (ALD; 12.2 mg/L) were observed in the single case study evaluated that incorporated active limestone pre-treatment (Table 10-6). Table 10-7 shows that at the single case study evaluated that incorporated anaerobic BCRs with limestone pre-treatment decreased concentrations of arsenic, cadmium, and copper concentrations to 0.0, although the data were reported to only one decimal place (Whitehead et al., 2005). It should also be noted that the same influent and effluent concentrations of arsenic, cadmium and copper were reported for all three configurations, one of which (Wheal Jane limestone-free configuration) did not contain an active limestone pre-treatment component.

The treatment train that incorporates anaerobic BCRs with semi-passive chemical precipitation pre-treatment (Leviathan) is capable of treating influent concentrations of chromium (0.0111 - 0.0122 mg/L), copper (0.795 mg/L), nickel (0.487 mg/L), selenium (0.0115 - 0.0139 mg/L) and zinc (0.715 mg/L) by at least one order of magnitude. Influent concentrations of arsenic (0.0074 mg/L), lead (0.0042 mg/L) and cadmium (0.00060 mg/L) were treated but effluent concentrations were within the same order of magnitude (Table 10-4 and 10-5).

Treatment trains that incorporate anaerobic BCRs and pre- and/or post-treatment technologies are capable of treating by more than one order of magnitude the highest average influent concentrations of chromium, cobalt, copper, iron, lead and nickel and the lowest average influent concentrations of cadmium, chromium, cobalt, copper, iron, nickel, selenium and zinc (Table 10-4 and 10-5). Tables 10-4 and 10-5 also show that, on average, there is treatment of less than an order of magnitude of arsenic at <0.01 mg/L and manganese at 1.4 mg/L with average effluent concentrations for arsenic and manganese. The highest reported average effluent concentrations for treatment trains with anaerobic BCRs and passive pre- and/or post-treatment were below 0.01 mg/L for arsenic, cadmium, cobalt and lead and below 0.1 mg/L for nickel and selenium (Table 10-6). The lowest average effluent concentrations were below 0.01 mg/L for chromium, cobalt, lead, selenium and zinc and below 1.0 mg/L for aluminum, iron and manganese (Table 10-7). Regardless of the type of pre- and/or post-treatment technologies used in the treatment trains having BCRs as a primary treatment, all treatment trains were able to increase pH of the water treated.

10.5.3 Removal Efficiency

The maximum and minimum removal efficiencies in Tables 10-8 and 10-9, respectively, were determined by comparing values in Appendix E, Tables E-14, E-15, E-16, E-17, E-18, E-19, E-20, E-21 and E-22. The comparison was done on the same sample type – total or dissolved.

Table 10-8: Maximum Removal Efficiencies

Constituent	Maximum Removal Efficiency	Mine	Source
Aluminum[a]	99.99%	Golden Sunlight	Bless, 2008

Table 10-8: Maximum Removal Efficiencies

Constituent	Maximum Removal Efficiency	Mine	Source
Arsenic[a]	>92.13%	Surething	Nordwick and Bless, 2008
Cadmium[a]	>99.96%	Surething	Nordwick and Bless, 2008
Chromium[a]	84.8%	Leviathan – Recirculation mode	U.S. EPA, 2006a
Copper[a]	99.99%	Golden Sunlight	Bless, 2008
Iron[a]	>99.91%	Surething	Nordwick and Bless, 2008
Lead[a]	97.35%	Surething	Nordwick and Bless, 2008
Manganese[a]	99.86%	Surething	Nordwick and Bless, 2008
Nickel[b]	98.8%	Tar Creek	Nairn et al., 2010b
Selenium[b]	57.4%	Leviathan – Gravity mode	U.S. EPA, 2006a
Sulfate[b]	37.29%	Calliope – BCR IV	Wilmoth, 2002
Zinc[a]	>99.97%	Surething	Nordwick and Bless, 2008

Notes:
Nine case studies provided removal efficiencies or influent and effluent data from which EPA calculated removal efficiencies: Calliope (Table E-14), Golden Sunlight (Table E-15), Leviathan (Tables E-16 and E-17), Standard (Table E-18), Surething (Table E-19), Tar Creek (Table E-20), and Wheal Jane (Tables E-21 and E-22)
Chromium and selenium only reported for Leviathan
Maximum removal efficiencies are the higher percentage of average and maximum removal efficiencies provided in Appendix E, Tables E-3, E-9, E-11, E-13, E-18, E-21, E-23, E-26 and E-28
a = dissolved
b = total

Table 10-9: Minimum Removal Efficiencies

Constituent	Minimum Removal Efficiency	Mine	Source
Aluminum[a]	-430.81%	Calliope – BCR II	Wilmoth, 2002
Arsenic[a]	-839.29%	Calliope – BCR IV	Wilmoth, 2002
Cadmium[a]	8.11%	Calliope – BCR IV	Wilmoth, 2002
Chromium[b]	21.2%	Leviathan – Recirc. mode	U.S. EPA, 2006a
Copper[a]	-233.33%	Calliope – BCR II	Wilmoth, 2002
Iron[a]	-10192.68%	Calliope – BCR II	Wilmoth, 2002
Lead[a]	9.7%	Leviathan – Recirc. mode	U.S. EPA, 2006a
Manganese[a]	-185.71%	Calliope – BCR II	Wilmoth, 2002
Nickel[b]	71.0%	Leviathan – Recirc. mode	U.S. EPA, 2006a
Selenium[b]	9.4%	Leviathan – Gravity mode	U.S. EPA, 2006a

Table 10-9: Minimum Removal Efficiencies

Constituent	Minimum Removal Efficiency	Mine	Source
Sulfate[a]	-167.21%	Calliope – BCR IV	Wilmoth, 2002
Zinc[a]	25.48%	Calliope – BCR II	Wilmoth, 2002
Notes: Nine case studies provided removal efficiencies or influent and effluent data from which EPA calculated removal efficiencies: Calliope (Table E-14), Golden Sunlight (Table E-15), Leviathan (Tables E-16 and E-17), Standard (Table E-18), Surething (Table E-19), Tar Creek (Table E-20) and Wheal Jane (Tables E-21 and E-22) Chromium and selenium only reported for Leviathan Minimum removal efficiencies are the lower percentage of average and minimum removal efficiencies provided in Appendix E, Tables E-14, E-15, E-16, E-17, E-18, E-19, E-20, E-21 and E-22 a = total b = dissolved LF = Limestone-free system without pre-treatment			

Table 10-8 shows that treatment trains that incorporate anaerobic BCRs and pre- and/or post-treatment can attain greater than 98 percent removal efficiency for aluminum, cadmium, copper, iron, manganese, nickel and zinc. Treatment trains that incorporate anaerobic BCRs and pre- and/or post-treatment can also attain removal efficiencies of approximately 92 percent, 85 percent, 97 percent, 57 percent and 37 percent, for arsenic, chromium, lead, selenium and sulfate, respectively.

As shown by comparing data in Tables 10-8 and 10-9, removal efficiencies from treatment trains that incorporate anaerobic BCRs and pre- and/or post-treatment span a wide range for most constituents. When comparing constituents where this information was available from more than one case study, the widest range (~10,293 percent) occurs for iron, while the smallest range (~28 percent) occurs for nickel.

The negative removal efficiencies for multiple constituents in Table 10-9 were from a single case study in which EPA calculated the sampling date specific removal efficiencies from the corresponding influent and effluent data provided in the study (Wilmoth, 2002). Some sampling dates had concentrations of aluminum, arsenic, copper, iron, manganese and sulfate in the effluent samples that were higher than the corresponding influent samples used for calculating removal efficiencies. Removal efficiencies for a treatment train that incorporates anaerobic BCR and semi-passive chemical precipitation range from 21.2 percent to 84.8 percent for chromium and 9.4 percent to 57.4 percent for selenium.

10.5.4 Flow Rates

Flow rates for treatment trains that incorporate anaerobic BCRs and active or passive pre- and/or post-treatment are provided in Table 10-10. In the absence of operational flow rates and where available, design flow rates were included.

Table 10-10: Influent Flow Rates

Mine	Flow Rate (L/min)	Source	Notes
Passive Pre-treatment and Passive Post-Treatment			
Calliope	3.8 with four months at 7.6	Wilmoth, 2002	Operational flow rate

Table 10-10: Influent Flow Rates

Mine	Flow Rate (L/min)	Source	Notes
Passive Pre-treatment and Passive Post-Treatment			
Force Crag	360	Jarvis et al., 2015	Design flow rate; influent flow rate 510 – 1,464 L/min; average flow rate 888 L/min
Golden Sunlight	11.4	Bless, 2008	Design flow rate; BCR operated at 7.6 L/min
Leviathan	31.8 (gravity-flow mode) 34.2 (recirculation mode)	Doshi, 2006	Reported for 2003-2005
Standard	3.8	Gallagher et al., 2012	Design flow rate
Surething	7.6	Doshi, 2006	Design flow rate; actual discharge reached peaks of 38 L/min
Tar Creek	1,000	Nairn et al, 2010a	Design flow rate
Active Pre-treatment and Passive Post-Treatment			
Wheal Jane	12 – 24	Whitehead et al., 2005	Operational flow rate range

Flow rates for treatment trains incorporating anaerobic BCRs with passive pre- and/or post-treatment range from 3.8 to 1,000 liters per minute (L/min). Flow rates for the treatment train consisting of an anaerobic BCR with an active pre-treatment component ranged from 12 to 24 L/min.

10.6 Capability - Constructed Wetlands with Capping and/or Pre- or Post-Treatment

10.6.1 Ranges of Applicability

No case studies were examined where an influent or pre-treatment concentration provided for any constituent corresponded directly to an effluent or post-treatment concentration. Only two examined case studies provided non-averaged pre-treatment and post-treatment data and those data are included in this section to address range of applicability.

Table 10-11 shows the range in concentrations of constituents in stream water below the Valzinco site prior to reclamation, which included capping of mining wastes, and the concentrations of those constituents in the stream water six years after completion of reclamation (Seal et al., 2008) from data in Appendix E, Table E-23. Table 10-12 shows the maximum pre-treatment and maximum post-treatment concentrations observed over 2004-2006 for constituents at Copper Basin (U.S. EPA, 2006a) from data in Appendix E, Table E-24.

Table 10-11: Pre-Treatment Concentration Range and Post-Treatment Concentration in Stream Water Downstream from Valzinco

Constituent	Pre-Treatment Concentration Range	Post-Treatment Concentration
Concentrations reported in mg/l as dissolved; pH reported in standard units		
Aluminum	0.60 – 19.5	0.051
Cadmium	0.0032 – 0.088	0.00091
Copper	0.049 – 2.2	0.0097
Iron	5.0 – 69.7	1.01
Lead	0.170 – 1.3	0.0016
Manganese	0.410 – 2.1	1.12
Nickel	0.002 – 0.037	0.0023
Sulfate	27 – 1,400	38.0
Zinc	1.9 – 27	1.32
pH	2.6 – 4.0	5.1
Notes: Data from Table 1 in Seal et al., 2008; pre-reclamation and post-reclamation samples collected at the same location; pre-reclamation data collected 1998 – 2001; post-reclamation data collected June 2007		

Table 10-12: Maximum Pre-Treatment and Post-Treatment Concentrations for the Copper Basin Site

Constituent	Maximum Pre-Treatment Concentration	Maximum Post-Treatment Concentration
Concentrations reported in mg/l as total, except manganese is reported as dissolved; pH reported in standard units; acidity reported in mg/l as $CaCO_3$		
Aluminum	1.423	0.055
Copper	0.197	0.017
Iron	0.211	0.133
Manganese	1.148	0.294
Sulfate	110	104
Zinc	0.640	0.197
pH	4.28	7.16
Net acidity	37	< 1
Notes: Data from Table 1 of U.S. EPA, 2006 represents the maximum values observed between 2004 and 2006.		

Treatment trains incorporating passive constructed wetlands with capping and/or passive pre- or post-treatment are able to increase pH and decrease concentrations of aluminum, cadmium, copper, iron, lead, manganese, nickel, sulfate and zinc by an order of magnitude or more, as indicated in Table 10-11 and Table 10-12. At lower pre-treatment concentrations of nickel, sulfate, and zinc, however, post-treatment concentrations are similar or on the same order of magnitude.

The treatment train at Copper Basin was able to achieve a maximum pH of 7.16 over the 3 years of study and decrease acidity to less than 1 mg/l as $CaCO_3$, whereas the pH of effluent from the treatment train at Valzinco was somewhat acidic (pH 5.1) after 6 years of treatment. The difference in observed achievable pH may be due to the differences in treatment duration or perhaps to the differences in concentrations of constituents contributing to pH, where maximum pre-treatment constituent concentrations at Valzinco were higher (see Tables 10-11 and 10-12).

10.6.2 Average Pre- and Post-Treatment Concentrations

Average concentrations were reported for four independent wetland treatment trains in a single case study site (Dunka Mine). Note, an additional wetland was operated at the Dunka Mine site but was independent of other components and is captured in the Constructed Wetlands chapter, Section 7. Tables 10-13 and 10-14 list the highest and lowest average pre-treatment concentrations for each constituent, respectively. Tables 10-15 and 10-16 list the highest and lowest average post-treatment concentrations attained for each constituent, respectively. Values in Tables 10-13 through 10-16 were determined from Table E-25 in Appendix E. It is important to note that the average pre-treatment concentrations do not correspond directly with the average post-treatment concentrations.

Table 10-13: Maximum Average Pre-Treatment Concentration Treated

Constituent	Maximum Average Pre-Treatment Concentration	Average Post-Treatment Concentration	Mine – Wetland	Source(s)	Notes
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units					
Cobalt	0.13	0.04	Dunka – Seep 1	Eger and Eger, 2005	1995 – 1997
Copper	0.37	0.11	Dunka – Seep X	Eger and Eger, 2005	1999 – 2004
Nickel	6.64	3.27	Dunka – Seep 1	Eger and Eger, 2005	1995 – 1997
Zinc	0.928	0.385	Dunka – Seep 1	Eger and Eger, 2005	1995 – 1997
pH	6.94	7.23	Dunka – Seep 1	Eger and Eger, 2005	1995 – 1997

Table 10-14: Minimum Average Pre-Treatment Concentration Treated

Constituent	Minimum Average Pre-Treatment Concentration	Average Post-Treatment Concentration	Mine – Wetland	Source(s)	Notes
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units					
Cobalt	0.015	0.006	Dunka – EM8	ITRC, 2010a	Jan. to Sept. 1998
Copper	0.026	0.009	Dunka – EM8	Eger and Eger, 2005	1999 – 2004
Nickel	1.5	0.61	Dunka – Seep X	Eger and Eger, 2005	1995 – 1997
Zinc	0.05	0.008; <0.001; 0.006	Dunka – W2D/3D	Eger and Eger, 2005	Minimum average influent corresponds to effluent for 1992 – 1994; 1996 – 1998; and 1999 – 2004
pH	7.41	7.3	Dunka – EM8	Eger and Eger, 2005	1999 – 2004

Table 10-15: Maximum Average Post-Treatment Concentration Attained

Constituent	Maximum Average Post-Treatment Concentration	Average Pre-Treatment Concentration	Mine – Wetland	Source(s)	Notes
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units					
Cobalt	0.04	0.13	Dunka – Seep 1	Eger and Eger, 2005	1995 –1997
Copper	0.11	0.37	Dunka – Seep X	Eger and Eger, 2005	1999 – 2004
Nickel	3.27	6.64	Dunka – Seep 1	Eger and Eger, 2005	1995 – 1997
Zinc	0.385	0.928	Dunka – Seep 1	Eger and Eger, 2005	1999 – 2004
pH	7	7	Dunka – W2D/3D	Eger and Eger, 2005	1992 – 1994, 1996 – 1998, 1992 – 1997

Table 10-16: Minimum Average Post-Treatment Concentration Attained

Constituent	Minimum Average Post-Treatment Concentration	Average Pre-Treatment Concentration	Mine – Wetland	Source(s)	Notes
Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units					
Cobalt	0.002	0.02	Dunka – W2D/3D	ITRC, 2010a	1992 – 1997
Copper	<0.001	0.05	Dunka – W2D/3D	Eger and Eger, 2005	1996 – 1998
Nickel	0.036	1.9	Dunka – W2D/3D	Eger and Eger, 2005	1999 – 2004
Zinc	<0.001	0.05	Dunka – W2D/3D	Eger and Eger, 2005	1996 – 1998
pH	7.4	7	Dunka – W2D/3D	Eger and Eger, 2005	1999 – 2004

Tables 10-13 through 10-16 suggest that, on average, cobalt, copper and zinc concentrations of less than 1 mg/L, and nickel concentrations ranging from 1.5 to 6.6 mg/L, are able to be decreased by treatment trains incorporating wetland treatment. Generally, the average post-treatment concentrations are at least one order of magnitude lower than the average pre-treatment concentrations for each constituent. Wetland treatment can achieve average post-treatment concentrations of below detection limits for copper and zinc. Influent to the wetland treatment trains in the single case study had average pH values of near neutral, and these were maintained in the effluent.

10.6.3 Removal Efficiency

Removal efficiencies were reported for four independent wetland treatment trains at a single case study (Dunka). Tables 10-17 and 10-18 present the maximum and minimum average removal efficiencies, respectively, extracted from average removal efficiencies presented in Appendix E, Table E-26 for the four wetlands.

Table 10-17: Maximum Average Removal Efficiencies

Constituent	Maximum Average Removal Efficiency	Mine - Wetland	Source	Notes
Total or dissolved not stated				
Cobalt	90%	Dunka – W2D/3D	Eger and Eger, 2005	Calculated based on averages presented for 1992 – 1994 and 1992 – 1997
Copper	99%	Dunka – W2D/3D	Eger and Eger, 2005	Calculated based on averages presented for 1996 – 1998

Table 10-17: Maximum Average Removal Efficiencies

Constituent	Maximum Average Removal Efficiency	Mine - Wetland	Source	Notes
Nickel	98%	Dunka – W2D/3D	Eger and Eger, 2005	Calculated based on averages presented for 1999 – 2004
Zinc	99%	Dunka – W2D/3D	Eger and Eger, 2005	Calculated based on averages presented for 1996 – 1998
Notes: One case study – Dunka – provided average influent and effluent data for four separate wetland treatment trains: Seep 1, Seep X, W2D/3D, EM8				

Table 10-18: Minimum Average Removal Efficiencies

Constituent	Minimum Average Removal Efficiency	Mine - Wetland	Source	Notes
Total or dissolved not stated				
Cobalt	60%	Dunka – EM8	ITRC, 2010a	Calculated based on averages presented for Jan. to Sept. 1998
Copper	62%	Dunka – EM8	ITRC, 2010a	Calculated based on averages presented for Jan. to Sept. 1998
Nickel	33%	Dunka – EM8	Eger and Eger, 2005	Calculated based on averages presented for 1999 – 2004
Zinc	36%	Dunka – Seep X	Eger and Eger, 2005	Calculated based on averages presented for 1999 – 2004
Notes: One case study – Dunka – provided average influent and effluent data for four separate wetland treatment trains: Seep 1, Seep X, W2D/3D, EM8				

Table 10-17 shows that treatment trains that incorporate constructed wetlands with pre- or post-treatment can attain 98 percent or greater removal efficiency for copper, nickel and zinc and 90 percent for cobalt. The minimum average removal efficiencies range from 33 percent (nickel) to 62 percent (copper). Eger and Eger, 2005 indicated that wetland treatment train W2D/3D was built with sufficient area to treat the original flow, whereas the available area for wetland treatment train EM8 was too small and Seep X, while properly sized, had a smaller effective treatment area that was smaller than the total size of the system.

10.6.4 Flow Rates

Average influent flow treatable with passive treatment trains that incorporate constructed wetlands with pre- and post-treatment ranges between 20 L/min and 400 L/min at Dunka (Eger and Eger, 2005; ITRC, 2010 – Dunka) to 342 L/min to 4,200 L/min at Valzinco (Seal et al., 2008) (Appendix E, Table E-27). Future case study comparisons may provide additional information on the flow capabilities of the passive treatment trains that incorporate constructed wetlands as a primary component of treatment.

10.7 Capability – Alkaline Precipitation with Pre- and/or Post-Treatment

10.7.1 Ranges of Applicability

No non-averaged corresponding influent and effluent concentrations of constituents treated were presented in the single case study evaluated; therefore, the range of applicability cannot be determined.

10.7.2 Average Pre- and Post-Treatment Concentrations

Average concentrations were reported for the alkaline precipitation with pre- and post-treatment at a single case study (Monte Romero Mine) (Table 10-19 and E-28). On average, alkaline precipitation with pre- and post-treatment is able to decrease high concentrations (>100 mg/L) of aluminum and iron to below detection limits. Lower concentrations of arsenic and lead (<1 mg/L) and copper (5 mg/L) also were decreased to below detection limits. Manganese, magnesium, calcium, potassium and sulfate increased, on average. Increases in concentrations of calcium and magnesium are expected in effluent from these types of treatment systems from dissolution of the limestone ($CaCO_3$) that also typically has magnesium salts associated with it. Although not stated in the study, potassium may have originated from the pine wood shavings. The pre-existing iron terraces, cascades, and lagoon (NFOL) and two DAS treatment tanks were able to increase pH, on average, to 6.6 (Table 10-19) and to remove 1,350 mg/l of net acidity as $CaCO_3$ from the mine shaft water having 1,800 mg/l net acidity as $CaCO_3$.

Table 10-19: Average Influent and Effluent Concentrations – Monte Romero Mine

Constituent	Average Influent Concentration	Average Effluent Concentration
All concentrations reported as total in mg/L; pH reported in standard units		
Aluminum	100	<0.2
Arsenic	0.507	<0.002
Calcium	250	850
Copper	5	<0.005
Iron	275	<0.2
Lead	0.174	<0.001
Magnesium	255	386
Manganese	18	19
Potassium	5	7
Silicon	37	11
Sulfate	3,430	3,770
Zinc	440	414
pH	3	6.6
Eh	508	341

Table 10-19: Average Influent and Effluent Concentrations – Monte Romero Mine

Constituent	Average Influent Concentration	Average Effluent Concentration
Notes: Source: Macías et al., 2012a Influent represents untreated water in the "Shaft" samples Effluent is the overall system effluent, represented by "T2 Out" samples Influent and effluent averages from Table 1 and represent monitoring from April to September 2008		

10.7.3 Removal Efficiency

Removal efficiencies were reported in the single case study (Table E-29 in Appendix E). Treatment trains that incorporate alkaline precipitation with pre- and post-treatment can attain 99 percent or greater removal efficiency for aluminum, arsenic, copper, iron and lead and approximately 70 percent removal efficiency for silicon. The removal efficiency for zinc is much lower, at about 6 percent (Table E-29 in Appendix E). Based on the single study, alkaline precipitation with pre- and post-treatment was not able to remove manganese or sulfate. As seen with the average effluent concentrations, negative removal efficiencies for calcium, magnesium, and potassium indicate dissolution of the limestone or originate from other substrate materials as the water is treated.

10.7.4 Flow Rates

The single case study of a treatment train incorporating alkaline precipitation with pre- and post-treatment reported an influent flow rate of 90 L/min with an operational flow rate in the post-treatment lagoon of 1 L/min (Table E-27 in Appendix E).

10.8 Costs

Construction of treatment train systems range from $75,000 to about $1.7 million (Eger et al., 1998; U.S. EPA, 2006a; Nairn et al., 2009; ITRC, 2010; Doshi, 2006). Operation and maintenance (O&M) of these systems are approximately $100,000 per year (Doshi, 2006).

- Construction of treatment trains with wetlands as the primary component range from $75,000 to $1 million (Eger et al., 1998; ITRC, 2010; U.S. EPA, 2006a). O&M costs were not available.
- Construction of treatment trains with BCRs range from $836,600 to $1.7 million (U.S. EPA, 2006a; Nairn et al., 2009; Doshi, 2006). O&M costs for these systems are approximately $100,000 per year (Doshi, 2006). Costs were not provided for the treatment trains with BCR and active limestone pre-treatment.

Construction or O&M costs were not provided for treatment trains with alkaline precipitation.

10.9 Lessons Learned

- Microbially-mediated processes in passive treatment systems operate more effectively when the acidity of the influent water is decreased through use of a settling pond (Bless et al., 2008) or bioreactors are given time to develop stable and healthy populations before being exposed to the water to be treated (Doshi, 2006).

- Although concentrations of constituents may be decreased by passive treatment trains, concentrations attained may remain above chronic or acute aquatic toxicity criteria (Seal et al., 2008).
- The collection and treatment of rainwater within treatment train consisting of aerobic cells and a compost bioreactor should be avoided (Doshi, 2006).
- Passive treatment trains using anaerobic BCRs should include technologies such as rock filters, ponds or aerobic wetlands to remove manganese, bacteria and sulfide, and to restore dissolved oxygen prior to discharge (Butler et al., 2011; Doshi, 2006).

10.10 References

10.10.1 Case Study References

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Appendix A: Biochemical Reactors Data Tables

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Solid substrate							
Sulfate	NS	195	150	114	117	Cwm Rheidol[a]	Jarvis et al., 2014 (Figure 42)
Zinc	Total	15.5	2.5	9	4.1	Cwm Rheidol[a]	Jarvis et al., 2014 (Figure 37)
Zinc	Dissolved	15.5	<0.01	9	4	Cwm Rheidol[a]	Jarvis et al., 2014 (Figure 37)
pH	NA	3.5	7.5	4.8	7.25	Cwm Rheidol[a]	Jarvis et al., 2014 (Figure 40)
Sulfate	Not specified	165	145	92	85	Nenthead	Jarvis et al., 2014 (Figure 32)
Zinc	Total	4.5	0.5	1.7	0.5	Nenthead	Jarvis et al., 2014 (Figure 30)
Zinc	Dissolved	4.5	0.25	1.7	0.2	Nenthead	Jarvis et al., 2014 (Figure 30)
Cadmium	Dissolved	0.2	0.00025	0.027	Not plotted	Standard	Gallagher et al., 2012 (Figure 3)
Copper	Dissolved	0.99	0.002	0.003	0.0013	Standard	Gallagher et al., 2012 (Figure 4)
Iron	Total	89.8	0.7	1[b]	0.025	Standard	Gallagher et al., 2012 (Figure 5)
Lead	Dissolved	2.07	0.0011	0.011	0.0009	Standard	Gallagher et al., 2012 (Figure 6)

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Manganese	Dissolved	13.2	10	5.4	7	Standard	Gallagher et al., 2012 (Figure 7)
Sulfate	NA	400	200	150	110	Standard	Gallagher et al., 2012 (Figure 9)
Zinc	Dissolved	32.1	0.01	14.9	0.006	Standard	Gallagher et al., 2012 (Figure 8)
Sulfate	Dissolved	38.2	Not provided	19.3	Not provided	Force Crag, VP1 and VP2	Jarvis et al., 2015 (Text)
Zinc	Total	4.5	0.02	2.2	0.04	Force Crag, VFP1	Jarvis et al., 2015 (Figure 2)
Zinc	Total	4.5	0.22	2.2	0.06	Force Crag, VFP2	Jarvis et al., 2015 (Figure 2)
Arsenic	Dissolved	1.25	0.01	0.125	0.01	Surething (Reactor 1)[c]	Nordwick and Bless, 2008 (Figure 4-6)
Cadmium	Dissolved	0.385	0.005	0.040	0.0001	Surething (Reactor 1)[c]	Nordwick and Bless, 2008 (Figure 4-3)
Copper	Dissolved	4.25	<0.003	0.500	<0.003	Surething (Reactor 1)[c]	Nordwick and Bless, 2008 (Figure 4-2)
Iron	Dissolved	51	0.014	12.5	10.625	Surething (Reactor 1)[c]	Nordwick and Bless, 2008 (Figure 4-5)
Manganese	Dissolved	65	20	4.55	6.36	Surething (Reactor 1)[c]	Nordwick and Bless, 2008 (Figure 4-7)
Sulfate	Dissolved	900	450	40	106	Surething (Reactor 1)[c]	Nordwick and Bless, 2008 (Figure 4-14)

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Zinc	Dissolved	39	<0.007	4.5	<0.007	Surething (Reactor 1)[c]	Nordwick and Bless, 2008 (Figure 4-4)
Cadmium	Total	0.17	<0.0024	0.11	<0.0024	Standard[d]	Reisman et al., 2009 (Figure 7)
Cadmium	Dissolved	0.17	<0.0024	0.11	<0.0024	Standard[d]	Reisman et al., 2009 (Figure 7)
Copper	Total	1.03	0.0055	0.13	<0.0038	Standard[d]	Reisman et al., 2009 (Figure 8)
Copper	Dissolved	1.01	<0.0038	0.080	0.005	Standard[d]	Reisman et al., 2009 (Figure 8)
Iron	Total	21	0.21	0.17	15	Standard[d]	Reisman et al., 2009 (Figure 9)
Iron	Dissolved	8	0.17	0.08	4.5	Standard[d]	Reisman et al., 2009 (Figure 9)
Lead	Total	6	<0.008	0.23	0.016	Standard[d]	Reisman et al., 2009 (Figure 10)
Lead	Dissolved	2.50	<0.008	0.02	0.008	Standard[d]	Reisman et al., 2009 (Figure 10)
Manganese	Total	14	10	6	7.5	Standard[d]	Reisman et al., 2009 (Figure 11)
Manganese	Dissolved	12.71	10.5	5.34	8	Standard[d]	Reisman et al., 2009 (Figure 11)

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Zinc	Total	30.9	0.8	21[e]	0.9	Standard[d]	Reisman et al., 2009 (Figure 12)
Zinc	Dissolved	30.9	0.4	21	1.5	Standard[d]	Reisman et al., 2009 (Figure 12)
Aluminum	Total	14.1	0.0453	0.011	0.0094	Calliope (BCR III)[f]	Wilmoth, 2002 (Table 5-6)
Arsenic	Total	0.0109	0.0035	0.0051	<0.005	Calliope (BCR III)[f]	Wilmoth, 2002
Cadmium	Total	0.0419	0.0048	0.0051	0.0056	Calliope (BCR III)[f]	(Table 5-6)
Copper	Total	3.05	0.0434	0.0072	0.0195	Calliope (BCR III)[f]	Wilmoth, 2002
Iron	Total	7.22	0.149	0.008	0.031	Calliope (BCR III)[f]	(Table 5-6)
Manganese	Total	3.77	2.10	0.69	0.076	Calliope (BCR III)[f]	Wilmoth, 2002
Sulfate	Total	229	223	60.6	60	Calliope (BCR III)[f]	Wilmoth, 2002 (Table 5-4)
Zinc	Total	11.1	0.459	0.99	0.790	Calliope (BCR III)[f]	Wilmoth, 2002 (Table 5-6)
pH	NA	3.29	7.56	7.52	6.79	Calliope (BCR III)[f]	Wilmoth, 2002 (Table 5-2)
Nitrate	NS	7.9	ND	2.9	0.1	Confidential Mine[g]	Blumenstein and Gusek, 2009 (Figure 9)
Selenium	NS	0.025	ND	0.01	ND	Confidential Mine[g]	Blumenstein and Gusek, 2009 (Figure 8)
Thallium	NS	1.6	<0.001	0.25	<0.001	Confidential Mine[g, h]	Blumenstein and Gusek, 2009 (Figure 7)
pH	NA	7.0	6.8	8.0	7.2	Confidential Mine[g]	Blumenstein and Gusek, 2009 (Figure 2)

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Liquid Substrate							
Arsenic	Total	0.07	0.008	0.018	0.001	Keno Hill[i]	Harrington et al., 2015 (Figure 2)
Cadmium	Total	0.0016	<0.0001	0.0011	<0.0001	Keno Hill[i]	Harrington et al., 2015 (Figure 2)
Manganese	Total	19	20	15	16	Keno Hill[i]	Harrington et al., 2015 (Figure 2)
Zinc	Total	6.2	0.01	4.8	0.55	Keno Hill[i]	Harrington et al., 2015 (Figure 2)
Aluminum	Dissolved	34.2	26.1	26.1	22.2	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Aluminum	Total	36.3	28.3	28.3	22.7	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Aluminum	Dissolved	0.155	0.104	0.104	0.108	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Aluminum	Total	1.170	0.389	0.389	0.334	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
Arsenic	Dissolved	0.003	<0.0023	0.0028	<0.0023	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Arsenic	Total	<0.0023	0.0034	<0.0022	<0.0023	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Arsenic	Dissolved	0.0059	0.005	0.0044	0.0059	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Arsenic	Total	<0.0021	<0.0021	<0.0021	0.0026	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
Cadmium	Dissolved	<0.00023	<0.00023	<0.0023	<0.0023	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Cadmium	Total	0.00042	<0.00023	<0.00023	<0.00023	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Cadmium	Dissolved	0.00035	0.00021	0.00021	0.00041	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Cadmium	Total	0.00023	<0.00016	<0.00016	0.0026	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
Chromium	Dissolved	0.0139	0.0133	0.0133	0.0143	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Chromium	Total	0.0147	0.0139	0.0139	0.0128	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Chromium	Dissolved	0.0122	0.0118	0.0118	0.012	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Chromium	Total	0.012	0.012	0.012	0.0117	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
Copper	Dissolved	0.614	0.0057	0.0057	0.0061	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Copper	Total	0.653	0.0676	0.0676	0.0537	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Copper	Dissolved	0.0083	0.0071	0.0071	0.0076	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Copper	Total	0.0243	0.0107	0.0107	0.0114	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Iron	Dissolved	73.1	71.7	71.1	63.7	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Iron	Total	87.0	77.7	77.7	63.7	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Iron	Dissolved	0.266	0.247	0.266	0.247	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Iron	Total	7.93	3.14	3.14	2.69	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
Lead	Dissolved	0.0058	0.0058	0.0058	0.005	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Lead	Total	0.0059	0.0055	0.0055	0.0044	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Lead	Dissolved	0.0042	0.0042	0.0042	0.0040	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Lead	Total	0.0047	0.0038	0.0043	0.0047	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
Nickel	Dissolved	0.449	0.35	0.350	0.300	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Nickel	Total	0.475	0.37	0.37	0.30	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Nickel	Dissolved	0.0726	0.0117	0.0117	0.0102	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Nickel	Total	0.0734	0.0334	0.0334	0.0286	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
Selenium	Dissolved	0.0142	0.0108	0.0108	0.0106	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Selenium	Total	0.014	0.0124	0.0124	0.0099	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Selenium	Dissolved	0.0114	0.0116	0.0075	0.0114	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Selenium	Total	0.0124	0.0103	0.0103	0.0089	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
Sulfate	Total	1520	1480	1480	1310	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-9)
Sulfate	Total	1190	1160	1160	1090	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-11)
Sulfide	Dissolved	37	38	0	37	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-9)
Sulfide	Dissolved	27	50	0	27	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-11)
Zinc	Dissolved	0.661	0.032	0.032	0.0288	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-13)
Zinc	Total	0.714	0.125	0.125	0.0927	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-17)
Zinc	Dissolved	0.0172	0.0063	0.0063	0.0104	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-15)
Zinc	Total	0.028	0.0137	0.0137	0.0146	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-18)
pH	NA	3.6	4.7	4.7	4.8	Leviathan – gravity mode[j]	U.S. EPA, 2006a (Table 2-9)
pH	NA	7.2	7.2	7.2	7.3	Leviathan – recirculation mode[j]	U.S. EPA, 2006a (Table 2-11)

Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source

Notes:

All analytical results reported in mg/L

pH results reported in standard units

NA = not applicable

NS = not specified

ND = Assumed not detected based on figures referenced; detection limits unknown

a = Cwm Rheidol data used were from post-May 2011, which were deemed most representative of the capabilities of the BCR due to initial increasing zinc concentrations

b = The minimum influent concentration reported was 0.89 mg/L; however, the corresponding effluent concentration was higher than this. Therefore, the data were considered anomalous and the next lowest influent concentration and its corresponding effluent concentration were chosen

c = Influent to Reactor 1 is labeled “feed” in the referenced figures and the effluent for Reactor 1 is labeled “SP1” in the referenced figures

d = Data used were from after the start-up period, which is shown in the figures as September 2007; influent concentrations were verified in text if available

e = The minimum influent concentration reported was 0.1 mg/L for total zinc, but this concentration was lower than the dissolved concentration and considered anomalous. The next lowest influent concentration and its corresponding effluent concentration were chosen.

f = BCR III was the only BCR without pre-treatment

g = Data used were from post-December 2007, after the two-month flushing maturation period

h = Excludes thallium data from BCR overload event, shown on Figure 7

i = Keno Hill data used were from post-August 2009, which corresponds to the start of sulfate-reducing conditions in the BCR; data were approximated from figures

j = Leviathan gravity flow configuration data March 24, 2004; recirculation flow configuration data August 19, 2004. Maximum and minimum influent concentrations for Leviathan determined by comparison of the two BCRs within each of the operating modes

Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Solid Substrate						
Aluminum	Dissolved	9.7	<0.02	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was reported in the source as average of “several samples” taken from September 1993 until August 1994
Arsenic	Dissolved	1.07	0.075	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was reported in the source as average of “several samples” taken from September 1993 until August 1994
Cadmium	Dissolved	0.33	<0.005	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was reported in the source as average of “several samples” taken from September 1993 until August 1994
Copper	Dissolved	0.32	0.012[a]	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was reported in the source as average of “several samples” taken from September 1993 until August 1994
Iron	Dissolved	27.7	11.25	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was

Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
						reported in the source as average of "several samples" taken from September 1993 until August 1994
Manganese	Dissolved	6.2	2.05	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was reported in the source as average of "several samples" taken from September 1993 until August 1994
Sulfate	Dissolved	277	136.5	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was reported in the source as average of "several samples" taken from September 1993 until August 1994
Zinc	Dissolved	26.1	0.032[a]	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was reported in the source as average of "several samples" taken from September 1993 until August 1994
pH	Dissolved	3.0	7.2	Lilly/Orphan Boy	Bless et al., 2008 (Table 1)	EPA calculated average effluent based on March and May 2001 sampling events of treated tunnel water; the average influent was reported in the source as average of "several samples" taken from September 1993 until August 1994. Average for pH is average of the pH values provided in source.

Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Cadmium	Dissolved	0.14	<0.002	Standard	Reisman et al., 2009 (Table 1)	September 2007 – September 2008
Cadmium	Dissolved	0.095[b]	0.00019	Standard	Gallagher et al., 2012 (Text)	August 2008 – November 2011
Copper	Dissolved	0.26	<0.0038	Standard	Reisman et al., 2009 (Table 1)	September 2007 – September 2008
Copper	Dissolved	0.10[b]	0.0014	Standard	Gallagher et al., 2012 (Text)	August 2008 – November 2011
Iron	Total	5.23	2.01	Standard	Reisman et al., 2009 (Table 1)	September 2007 – September 2008
Iron	Total	11.2[b]	0.56	Standard	Gallagher et al., 2012 (Text)	August 2008 – November 2011
Lead	Dissolved	0.54	0.01	Standard	Reisman et al., 2009 (Table 1)	September 2007 – September 2008
Lead	Dissolved	0.134[b]	0.00215	Standard	Gallagher et al., 2012 (Text)	August 2008 – November 2011
Manganese	Dissolved	10.99	10.53	Standard	Reisman et al., 2009 (Table 1)	September 2007 – September 2008
Sulfate	Dissolved	281	119	Standard	Gallagher et al., 2012 (Text)	August 2008 – November 2011
Sulfide	Dissolved	<0.5	12.5	Standard	Gallagher et al., 2012 (Text)	August 2008 – November 2011
Zinc	Dissolved	26.46	0.55	Standard	Reisman et al., 2009 (Table 1)	September 2007 – September 2008
Zinc	Dissolved	18.25[b]	0.073	Standard	Gallagher et al., 2012 (Text)	August 2008 – November 2011

Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Aluminum	Dissolved	1.2229	0.0616	Calliope	Wilmoth, 2002[c] (Table 5-6)	BCR III effluent
Arsenic	Dissolved	<0.005	<0.005	Calliope	Wilmoth, 2002[c] (Table 5-6)	BCR III effluent
Cadmium	Dissolved	0.0112	<0.005	Calliope	Wilmoth, 2002[c] (Table 5-6)	BCR III effluent
Copper	Dissolved	0.4078	0.0546	Calliope	Wilmoth, 2002[c] (Table 5-6)	BCR III effluent
Iron	Dissolved	0.4556	0.4143	Calliope	Wilmoth, 2002[c] (Table 5-6)	BCR III effluent
Manganese	Dissolved	1.4581	1.0073	Calliope	Wilmoth, 2002[c] (Table 5-6)	BCR III effluent
Sulfate	Dissolved	0.1029	0.1039	Calliope	Wilmoth, 2002[c] (Table 5-4)	BCR III effluent
Zinc	Dissolved	2.8406	0.7944	Calliope	Wilmoth, 2002[c] (Table 5-6)	BCR III effluent
pH	NA	6.05	7.16	Calliope	Wilmoth, 2002[c] (Table 5-1)	BCR III effluent
Sulfate	Dissolved	30.4	10.1	Force Crag	Jarvis et al., 2015 (Text)	VFP1
Sulfate	Dissolved	30.4	8.1	Force Crag	Jarvis et al., 2015 (Text)	VFP2
Nitrate	NS	5.1	0.08	Confidential Mine	Blumenstein and Gusek, 2009 (Text)	Over 14 months of operation
Selenium	NS	0.013	0.001	Confidential Mine	Blumenstein and Gusek, 2009 (Text)	Over 14 months of operation
Thallium	NS	1.25	0.007	Confidential Mine	Blumenstein and Gusek, 2009 (Text)	Over 14 months of operation; average effluent influenced by two upset events
Liquid Substrate (Not available)						
Notes: All analytical results reported in mg/L						

Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<tr><th>Constituent</th><th>Water Sample</th><th>Average Influent</th><th>Average Effluent</th><th>Mine</th><th>Source</th><th>Notes</th></tr>
<tr><td colspan="7">pH results reported in standard units
NA = not applicable
NS = not specified
a = ½ detection limit (DL) was used for samples reported as <DL to enable calculation
b = EPA calculated from average effluent and percent removal provided: 100* (avg in – avg out)/avg in = % removal
c = EPA calculated average influent and effluent from data reported in Table 5-4 and 5-6; ½ the DL was used for samples reported as <DL to enable calculation of averages. Average pH is average of pH values.</td></tr>
</table>

Table A-3: Removal Efficiencies – All Applicable Sites

Constituent	Average Removal Efficiency	Maximum	Minimum	Mine	Source
Solid Substrate					
Total Zinc	68.00%[a]	85%	37%	Nenthead	Jarvis et al., 2014 (Figure 34; Text)
Dissolved Zinc	84%[a]	95%	68%	Nenthead	Jarvis et al., 2014 (Figure 26; Text)
Total Zinc[b]	63%	85%	50%	Cwm Rheidol	Jarvis et al., 2014 (Figure 38)
Dissolved Zinc[b]	76%	100%	50%	Cwm Rheidol	Jarvis et al., 2014 (Figure 39)
Dissolved Cadmium	99.8%	NA	NA	Standard	Gallagher et al., 2012 (Text)
Dissolved Copper	98.6%	NA	NA	Standard	Gallagher et al., 2012 (Text)
Total Iron	95%	NA	NA	Standard	Gallagher et al., 2012 (Text)
Dissolved Lead	98.4%	NA	NA	Standard	Gallagher et al., 2012 (Text)
Sulfate[c]	57.2%	NA	NA	Standard	Gallagher et al., 2012 (Text)
Dissolved Zinc	99.6%	NA	NA	Standard	Gallagher et al., 2012 (Text)
Total Zinc	98.70%	NA	NA	Force Crag, VFP1	Jarvis et al., 2015 (Text)
Total Zinc	94.10%	NA	NA	Force Crag, VFP2	Jarvis et al., 2015 (Text)
Total Zinc	96.80%	NA	NA	Force Crag, overall system	Jarvis et al., 2015 (Text)
Cadmium[c]	98.50%	NA	NA	Standard	Reisman et al., 2009 (Text)
Copper[c]	98.60%	NA	NA	Standard	Reisman et al., 2009 (Text)
Iron[c]	65.00%	NA	NA	Standard	Reisman et al., 2009 (Text)

Table A-3: Removal Efficiencies – All Applicable Sites

Constituent	Average Removal Efficiency	Maximum	Minimum	Mine	Source
Lead[c]	98.10%	NA	NA	Standard	Reisman et al., 2009 (Text)
Zinc[c]	97.90%	NA	NA	Standard	Reisman et al., 2009 (Text)
Total Aluminum	-6.17%	99.73%	-650.00%	Calliope – BCR III[d]	Wilmoth, 2002 (Table 5-6)
Total Arsenic	28.31%	86.89%	-95.38%	Calliope – BCR III[d]	Wilmoth, 2002 (Table 5-6)
Total Cadmium	76.34%	95.97%	-9.80%	Calliope – BCR III[d]	Wilmoth, 2002 (Table 5-6)
Total Copper	44.07%	99.37%	-189.59%	Calliope – BCR III[d]	Wilmoth, 2002 (Table 5-6)
Total Iron	-801.74%	97.94%	-14275.00%	Calliope – BCR III[d]	Wilmoth, 2002 (Table 5-6)
Total Manganese	30.86%	98.05%	-108.22%	Calliope – BCR III[d]	Wilmoth, 2002 (Table 5-6)
Total Sulfate	-2.09%	32.20%	-68.63%	Calliope – BCR III[e]	Wilmoth, 2002 (Table 5-4)
Total Zinc	58.24%	99.21%	-11.97%	Calliope – BCR III[d]	Wilmoth, 2002 (Table 5-6)
Nitrate[c]	98.43%[f]	>99%[g]	96.55%[f]	Confidential Mine	Blumenstein and Gusek, 2009 (Figure 9)
Selenium[c]	>99%[a]	>99%[g]	>99%[g]	Confidential Mine	Blumenstein and Gusek, 2009 (Text, Figure 8)
Thallium[c]	>99%[a]	99.97%[f]	99.8%[f]	Confidential Mine	Blumenstein and Gusek, 2009 (Text, Figure 7)
Liquid Substrate					
Total Aluminum	NA	22%	19.8%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Aluminum	NA	23.7%	14.9%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)

Table A-3: Removal Efficiencies – All Applicable Sites

Constituent	Average Removal Efficiency	Maximum	Minimum	Mine	Source
Total Aluminum	NA	66.8%	14.1%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Aluminum	NA	32.9%	0%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Arsenic	NA	NC (influent < DL)	NC (influent < DL)	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Arsenic	NA	NC (influent < DL)	NC (influent < DL)	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)
Total Arsenic	NA	NC (influent < DL)	NC (influent < DL)	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Arsenic	NA	NC (influent < DL)	NC (influent < DL)	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Cadmium	NA	45.2%	0%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Cadmium	NA	NC (influent < DL)	NC (influent < DL)	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)
Total Cadmium	NA	NC (influent < DL)	NC (influent < DL)	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Cadmium	NA	40.0%	0%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Chromium	NA	7.9%	5.4%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Chromium	NA	4.3%	0%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)
Total Chromium	NA	2.5%	0%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Chromium	NA	0%	0%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Copper	NA	89.7%	20.6%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Copper	NA	99.1%	0%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)

Table A-3: Removal Efficiencies – All Applicable Sites

Constituent	Average Removal Efficiency	Maximum	Minimum	Mine	Source
Total Copper	NA	56%	-6.5%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Copper	NA	14.5%	0%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Iron	NA	18%	10.7%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Iron	NA	11.2%	1.9%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)
Total Iron	NA	60.4%	14.3%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Iron	NA	94.6%	7.1%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Lead	NA	20%	6.8%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Lead	NA	0%	0%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)
Total Lead	NA	19.2%	-9.3%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Lead	NA	0%	0%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Nickel	NA	18.9%	22.1%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Nickel	NA	22.1%	14.3%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)
Total Nickel	NA	54.5%	14.4%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Nickel	NA	83.9%	12.8%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Selenium	NA	20.2%	11.4%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Selenium	NA	23.9%	0%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)

Table A-3: Removal Efficiencies – All Applicable Sites

Constituent	Average Removal Efficiency	Maximum	Minimum	Mine	Source
Total Selenium	NA	16.9%	13.6%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Selenium	NA	0%	0%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Sulfate	NA	11.5%	2.6%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-9)
Total Sulfate	NA	6.0%	2.5%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-11)
Total Zinc	NA	82.5%	25.8%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-17)
Dissolved Zinc	NA	95.2%	10%	Leviathan – gravity flow mode[h,i]	U.S. EPA, 2006a (Table 2-13)
Total Zinc	NA	51.1%	-6.6%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-18)
Dissolved Zinc	NA	63.4%	0%	Leviathan – recirculation mode[h,i]	U.S. EPA, 2006a (Table 2-15)
Total Antimony	80.00%	NA	NA	Keno Hill[j]	Harrington et al., 2015 (Text)
Total Arsenic	80.00%	NA	NA	Keno Hill[j]	Harrington et al., 2015 (Text)
Total Nickel	80.00%	NA	NA	Keno Hill[j]	Harrington et al., 2015 (Text)
Total Zinc	99.00%	NA	NA	Keno Hill[j]	Harrington et al., 2015 (Text)

Notes:
DL = Detection limit
NA = Not available
NC = Not calculated
a = Average removal efficiency provided in text
b = Cwm Rheidol data used were from post-May 2011, which we deemed most representative of the capabilities of the BCR due to initial increasing zinc concentrations; data were approximated from figures
c = Total or dissolved not specified

Table A-3: Removal Efficiencies – All Applicable Sites

<table>
<tr><th>Constituent</th><th>Average Removal Efficiency</th><th>Maximum</th><th>Minimum</th><th>Mine</th><th>Source</th></tr>
<tr><td colspan="6">d = EPA calculated sampling date specific removal efficiencies from the corresponding influent and effluent data provided in Table 5-6. Maximum and minimum removal efficiencies were chosen from calculated individual removal efficiencies. The average removal efficiency for each constituent was calculated from the individually calculated removal efficiencies.
e = EPA calculated sampling date specific removal efficiencies from the corresponding influent and effluent data provided in Table 5-4. Maximum and minimum removal efficiencies were chosen from calculated individual removal efficiencies. The average removal efficiency for each constituent was calculated from the individually calculated removal efficiencies.
f = EPA calculated average removal efficiency from the average influent and effluent data provided in the text of Blumenstein and Gusek, 2009. Maximum and minimum removal efficiencies were calculated from data provided in referenced figures.
g = Assumed to be greater than 99 percent based on corresponding effluent data assumed to be at or below detection limits based on referenced figure
h = Leviathan gravity flow configuration data March 24, 2004; recirculation flow configuration data August 19, 2004
i = Minimum removal efficiencies mostly due to low concentrations into the 2nd BCR
j = Keno Hill data used were from post-August 2009, which corresponds to the start of sulfate-reducing conditions in the BCR</td></tr>
</table>

Appendix B: Caps and Covers Data Tables

Table B-1: Kristineberg Mine – Maximum and Minimum Leachate Concentrations from Capped and Uncapped Tailings

Constituent	Maximum Leachate Concentration from Uncapped Cell	Maximum Leachate Concentration from Capped Cell	Minimum Leachate Concentration from Uncapped Cell	Minimum Leachate Concentration from Capped Cell	Source	Notes
Cadmium	0.03	ND	ND	ND	Nason et al., 2013 (Figure 7)	Data extracted from Figure 7; range 2005 to 2010[a]
Copper	0.04	0.001	0.0005	ND	Nason et al., 2013 (Figure 7)	Data extracted from Figure 7; range 2005 to 2010[a]
Iron	0.022	0.005	ND	ND	Nason et al., 2013 (Figure 7)	Data extracted from Figure 7; range 2005 to 2010[a]
Lead	0.00065	0.00055	0.0001	0.0001	Nason et al., 2013 (Figure 7)	Data extracted from Figure 7; range 2005 to 2010[a]
Sulfur	700	220	410	15	Nason et al., 2013 (Figure 7)	Data extracted from Figure 7; range 2005 to 2010[a]
Zinc	40	ND	2.5	ND	Nason et al., 2013 (Figure 7)	Data extracted from Figure 7; range 2005 to 2010[a]
pH	6.2	6.8	7.6	8.2	Nason et al., 2013 (Figure 7)	Data extracted from Figure 7; range 2005 to 2010[a]

Notes:

All analytical results reported as dissolved mg/L

pH results reported in standard units

ND = Assumed not detected based on Figure 7; detection limits unknown

a = Source noted that a flush of metals was observed in 2003 and subsided within a year. Values were extracted from 2005 to 2010 to be representative of typical conditions

Table B-2: Dunka Mine – Average Pre-Capping and Post-Capping Concentrations

Wetland	Stockpile	Parameter	Water Sample	Pre-Capping, Average Concentration (1992 – 1994)[a]	Post-Capping, Average Concentration (1996 – 1998)[b]	Post-Capping, Average Concentration (1999 – 2004)[c]	Source	Notes
W1D	8018 and 8031	Cobalt	NS	0.036	0.009	NR	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W1D and are average values for period of record.
W1D	8018 and 8031	Copper	NS	0.068	0.03	0.02	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W1D and are average values for period of record.
W1D	8018 and 8031	Nickel	NS	3.98	0.74	0.76	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W1D and are average values for period of record.
W1D	8018 and 8031	Zinc	NS	0.052	0.021	0.019	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W1D and are average values for the period of record.
W1D	8018 and 8031	pH	NA	7.07	7.3	7.26	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W1D and are average of pH values for period of record.
W2D/3D	8031	Cobalt	NS	0.02	0.02	--[d]	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W2D/3D and are average values for the period of record.
W2D/3D	8031	Copper	NS	0.05	0.05	--[d]	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W2D/3D and are average values for the period of record.

Table B-2: Dunka Mine – Average Pre-Capping and Post-Capping Concentrations

Wetland	Stockpile	Parameter	Water Sample	Pre-Capping, Average Concentration (1992 – 1994)[a]	Post-Capping, Average Concentration (1996 – 1998)[b]	Post-Capping, Average Concentration (1999 – 2004)[c]	Source	Notes
W2D/3D	8031	Nickel	NS	1.9	1.9	--[d]	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W2D/3D and are average values for the period of record.
W2D/3D	8031	Zinc	NS	0.05	0.05	--[d]	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W2D/3D and are average values for the period of record.
W2D/3D	8031	pH	NA	7	7	--[d]	Eger and Eger, 2005 (Table 1)	Values are influent to Wetland W2D/3D and are average of pH values for the period of record.

Notes:

All analytical results reported in mg/L
pH results reported in standard units
NS = Not specified
NR = Not reported
NA = Not applicable
a = Values are the input to the listed wetland from Table 1 of reference for 1992-1994
b = Values are the input to the listed wetland from Table 1 of reference for 1996-1998
c = Values are the input to the listed wetland from Table 1 of reference for 1999-2004
d = The source indicated that the 1999-to-2004 data for W2D/3D was estimated (values in source were identical to previous period). Therefore, it was not included in this assessment

Appendix C: Neutralization and Chemical Precipitation Data Tables

Table C-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Aluminum	Dissolved	119	0.584	98.6	0.575	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Arsenic	Dissolved	3.47	0.097	2.81	<0.0018	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Cadmium	Dissolved	0.0463	<0.00016	0.0132	<0.00021	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Chromium	Dissolved	0.629	0.0013	0.266	0.0116	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Copper	Dissolved	0.549	<0.0019	0.434	<0.0019	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Iron	Dissolved	545	0.0999	392	0.0057	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Lead	Dissolved	0.010	<0.0014	0.0023	<0.0009	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Nickel	Dissolved	2.76	0.0418	2.41	0.0688	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Selenium	Dissolved	0.0323	<0.0018	0.02	<0.0018	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)
Zinc	Dissolved	0.583	0.0026	0.49	0.0031	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-1)

Table C-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Aluminum	Dissolved	486	1.09	326	1.14	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Arsenic	Dissolved	4.05	0.0101	1.33	0.0096	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Cadmium	Dissolved	0.0683	0.0007	0.0479	0.0009	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Chromium	Dissolved	1.24	0.0024	0.729	0.0463	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Copper	Dissolved	2.99	0.0101	2.11	0.0102	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Iron	Dissolved	653	<0.0038	336	0.243	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Lead	Dissolved	0.0122	<0.0014	0.0017	0.0044	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Nickel	Dissolved	8.77	0.0389	5.98	0.0172	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Selenium	Dissolved	0.0145	0.004	0.0046	0.0037	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Zinc	Dissolved	1.81	0.0307	1.25	0.0097	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-2)
Aluminum	Dissolved	33.6	0.254	30.9	0.185	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
Arsenic	Dissolved	0.545	0.0129	0.485	0.0038	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
Cadmium	Dissolved	<0.0003	<0.0003 – 0.0007	<0.00029	<0.0003	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
Chromium	Dissolved	0.0235	0.0038	0.0162	0.0014	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)

Table C-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source
Copper	Dissolved	0.0163	0.0061	0.0092	0.0031	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
Iron	Dissolved	460	0.0172	360	0.0881	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
Lead	Dissolved	0.0063	0.0026	0.0027	<0.0012	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
Nickel	Dissolved	1.69	0.0472	1.57	0.0201	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
Selenium	Dissolved	0.007	<0.0025	0.0022[a]	0.0036	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
Zinc	Dissolved	0.369	0.019	0.350	0.0062	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-3)
pH	NA	4.59	7.92	4.59	7.92	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table 2-18)
Iron	Total	1,710	23.6	50	4	Elizabeth Mine	Butler and Hathaway, 2020 (Table 3)
pH	NA	4.63	8.65	6.87	9.6	Elizabeth Mine	Butler and Hathaway, 2020 (Appendices B and E)

Notes:
All analytical results reported in mg/L
NA – Not applicable

Table C-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Mine	Source

Dual-stage data come from 12 sampling dates in 2002 and 1 in 2003 and the single-stage data come from 7 sampling dates in 2003; and the semi-passive results are from 8 samples collected in 2002 except for pH; pH for semi-passive alkaline lagoon from Table 2-18 in U.S. EPA, 2006a

< = Not detected above laboratory method detection limit shown

[a] Value reported in reference, but below reference's stated DL

Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Aluminum	Dissolved	107.8	0.633	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Arsenic	Dissolved	3.236	0.0063	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Cadmium	Dissolved	0.0261	ND	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Chromium	Dissolved	0.341	0.00304	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Copper	Dissolved	0.502	0.00307	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Iron	Dissolved	456.428	0.176	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Lead	Dissolved	0.0071	0.00156	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Nickel	Dissolved	2.56	0.0468	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Selenium	Dissolved	0.0271	0.00214	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Zinc	Dissolved	0.538	0.00561	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table B-4)	
Aluminum	Dissolved	381	1.118	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Arsenic	Dissolved	2.239	0.00859	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Cadmium	Dissolved	0.054	0.00071	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Chromium	Dissolved	0.877	0.0057	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Copper	Dissolved	2.383	0.00805	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Iron	Dissolved	461.615	0.0449	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	

Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Lead	Dissolved	0.0082	0.002	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Nickel	Dissolved	7.024	0.0342	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Selenium	Dissolved	0.0088	0.00378	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Zinc	Dissolved	1.469	0.0193	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table B-5)	
Aluminum	Dissolved	31.988	0.251	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Arsenic	Dissolved	0.519	0.00584	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Cadmium	Dissolved	ND	0.00038	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Chromium	Dissolved	0.0193	0.00225	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Copper	Dissolved	0.0135	0.00546	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Iron	Dissolved	391.250	0.148	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Lead	Dissolved	0.0051	0.00166	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Nickel	Dissolved	1.631	0.0226	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	

Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Selenium	Dissolved	0.0033	0.00324	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Zinc	Dissolved	0.356	0.0142	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Table B-6)	
Iron	Total	850.57 ± 239.84	8.92 ± 20.41	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2009 Average
Iron	Total	858.45 ±189.55	0.52 ± 0.59	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2010 Average
Iron	Total	856.24 ± 126.83	1.98 ± 6.85	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2011 Average
Iron	Total	879.55 ± 181.09	0.37 ± 0.29	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2012 Average
Iron	Total	461.65 ± 74.47	0.24 ± 0.58	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2013 Average
Iron	Total	309.32 ± 51.68	0.35 ± 1.01	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2014 Average
Iron	Total	214.35 ± 96.21	1.61 ± 11.05	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2015 Average
Iron	Total	183.62 ± 53.93	10.46 ± 17.95	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2016 Average
Iron	Total	199.15 ± 64.75	12.28 ± 12.74	Elizabeth Mine	Butler and Hathaway, 2020 (Table 1)	2017 Average

Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Aluminum	Dissolved	21	0.5	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2006 Average[a,b]
Aluminum	Dissolved	19	0.5	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2007 Average[a,d]
Aluminum	Dissolved	16	0.5	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2008 Average[a,e]
Aluminum	Dissolved	19	0.4	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2009 Average[a,f]
Aluminum	Dissolved	19	0.5	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2010 Average[a,g]
Cadmium	Dissolved	0.09	0.002	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2006 Average[a,b]
Cadmium	Dissolved	0.097	0.001	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2007 Average[a,d]
Cadmium	Dissolved	0.085	0.001	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2008 Average[a,e]
Cadmium	Dissolved	0.087	0.001	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2009 Average[a,f]
Cadmium	Dissolved	0.087	0.001	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2010 Average[a,g]
Copper	Dissolved	17	0.01	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2006 Average[a,b]

Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Copper	Dissolved	16.8	0.01	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2007 Average[a,d]
Copper	Dissolved	13.9	0.02	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2008 Average[a,e]
Copper	Dissolved	15.8	<0.01	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2009 Average[a,f]
Copper	Dissolved	13.9	<0.01	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2010 Average[a,g]
Iron	Dissolved	1.7	0.01	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2006 Average[a,b]
Iron	Dissolved	0.75	0.05	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2007 Average[a,d]
Iron	Dissolved	0.7	0.01	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2008 Average[a,e]
Iron	Dissolved	0.75	0.01	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2009 Average[a,f]
Iron	Dissolved	0.95	<0.01	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2010 Average[a,g]
Manganese	Dissolved	4.8	0.3	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2006 Average[a,b]
Manganese	Dissolved	4.3	0.1	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2007 Average[a,d]

Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
Manganese	Dissolved	3.5	0.3	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2008 Average[a,e]
Manganese	Dissolved	4.1	0.4	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2009 Average[a,f]
Manganese	Dissolved	3.9	0.4	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2010 Average[a,g]
Zinc	Dissolved	20	0.02	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2006 Average[a,b]
Zinc	Dissolved	19.7	0.03	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2007 Average[a,d]
Zinc	Dissolved	14.8	0.04	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2008 Average[a,e]
Zinc	Dissolved	17.7	0.03	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2009 Average[a,f]
Zinc	Dissolved	18.7	0.03	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2010 Average[a,g]
pH	NA	4.0	9.2[c]	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2006 Average[a,b]
pH	NA	3.7	9.2	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2007 Average[a,d]
pH	NA	3.8	9.2	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2008 Average[a,e]

Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Mine	Source	Notes
pH	NA	4.1	9.2	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2009 Average[a,f]
pH	NA	4.2	9.2	Britannia Mine	Madsen et al., 2012 (Tables 2 and 7)	2010 Average[a,g]

Notes:

All analytical results reported in mg/L

pH results reported in standard units

NA – Not applicable

ND – Not detected

Leviathan data calculated from data in Appendix B in U.S. EPA, 2006a. Dual-stage data come from 12 sampling dates in 2002 and 1 in 2003 and the single-stage data comes from 7 sampling dates in 2003; and the semi-passive results are from 8 samples collected in 2002.

Data from Butler and Hathaway, 2020, include average concentrations and standard deviations

a = Average influent concentration (C3) calculated from average mine workings concentrations (C1) and volume (V1) and average groundwater concentrations (C2) and volume (V2) via this equation: $(V1C1 + V2C2)/(V1+V2) = C3$.

b = 2006 combined influent volume = 3,923,000,000 liters

c = Madsen et al., 2012 (page 10): "WTP discharge water pH is consistently 9.2"

d = 2007 combined influent volume = 5,256,400,000 L

e = 2008 combined influent volume = 3,836,200,000 L

f = 2009 combined influent volume = 3,370,700,000 L

g = 2010 combined influent volume = 4,424,400,000 L

Non-detect values were adjusted to ½ the detection limit for calculations

Table C-3: Average Mass Treated and Average Mass Removed per Year – Britannia Mine

Constituent	Water Sample	Average Mass Treated[a]	Average Mass Removed[b]	Mine	Source	Year
Aluminum	Dissolved	83,005	81,043	Britannia Mine	Madsen et al., 2012	2006[c]
Aluminum	Dissolved	100,589	97,960	Britannia Mine	Madsen et al., 2012	2007[d]
Aluminum	Dissolved	61,677	59,759	Britannia Mine	Madsen et al., 2012	2008[e]
Aluminum	Dissolved	65,060	63,712	Britannia Mine	Madsen et al., 2012	2009[f]
Aluminum	Dissolved	85,399	83,187	Britannia Mine	Madsen et al., 2012	2010[g]
Cadmium	Dissolved	354	346	Britannia Mine	Madsen et al., 2012	2006[c]
Cadmium	Dissolved	508	503	Britannia Mine	Madsen et al., 2012	2007[d]
Cadmium	Dissolved	326	323	Britannia Mine	Madsen et al., 2012	2008[e]
Cadmium	Dissolved	293	289	Britannia Mine	Madsen et al., 2012	2009[f]
Cadmium	Dissolved	384	380	Britannia Mine	Madsen et al., 2012	2010[g]
Copper	Dissolved	65,862	65,823	Britannia Mine	Madsen et al., 2012	2006[c]
Copper	Dissolved	88,319	88,267	Britannia Mine	Madsen et al., 2012	2007[d]
Copper	Dissolved	53,179	53,102	Britannia Mine	Madsen et al., 2012	2008[e]
Copper	Dissolved	53,199	53,182	Britannia Mine	Madsen et al., 2012	2009[f]
Copper	Dissolved	61,329	61,307	Britannia Mine	Madsen et al., 2012	2010[g]
Iron	Dissolved	6,623	6,584	Britannia Mine	Madsen et al., 2012	2006[c]

Table C-3: Average Mass Treated and Average Mass Removed per Year – Britannia Mine

Constituent	Water Sample	Average Mass Treated[a]	Average Mass Removed[b]	Mine	Source	Year
Iron	Dissolved	3,963	3,700	Britannia Mine	Madsen et al., 2012	2007[d]
Iron	Dissolved	2,532	2,494	Britannia Mine	Madsen et al., 2012	2008[e]
Iron	Dissolved	2,513	2,480	Britannia Mine	Madsen et al., 2012	2009[f]
Iron	Dissolved	4,220	4,198	Britannia Mine	Madsen et al., 2012	2010[g]
Manganese	Dissolved	18,870	17,694	Britannia Mine	Madsen et al., 2012	2006[c]
Manganese	Dissolved	22,770	22,244	Britannia Mine	Madsen et al., 2012	2007[d]
Manganese	Dissolved	13,248	12,097	Britannia Mine	Madsen et al., 2012	2008[e]
Manganese	Dissolved	13,882	12,534	Britannia Mine	Madsen et al., 2012	2009[f]
Manganese	Dissolved	17,430	15,660	Britannia Mine	Madsen et al., 2012	2010[g]
Zinc	Dissolved	77,320	77,242	Britannia Mine	Madsen et al., 2012	2006[c]
Zinc	Dissolved	103,706	103,548	Britannia Mine	Madsen et al., 2012	2007[d]
Zinc	Dissolved	56,844	56,690	Britannia Mine	Madsen et al., 2012	2008[e]
Zinc	Dissolved	59,727	59,626	Britannia Mine	Madsen et al., 2012	2009[f]
Zinc	Dissolved	82,850	82,718	Britannia Mine	Madsen et al., 2012	2010[g]

Notes:

Results reported in kilograms (kg)

a = Average mass (M) calculated from average mine workings concentrations (C1) and yearly volume (V1) and average groundwater concentrations (C2) and yearly groundwater volume (V2) via this equation: (V1C1 + V2C2) = M

Table C-3: Average Mass Treated and Average Mass Removed per Year – Britannia Mine

Constituent	Water Sample	Average Mass Treated[a]	Average Mass Removed[b]	Mine	Source	Year

b = Average mass removed (M2) calculated from average mass (M) and average effluent concentrations (C4) and combined influent volume (V3) via this equation: M – (C4V3) = M2
c = 2006 combined influent volume = 3,923,000,000 L
d = 2007 combined influent volume = 5,256,400,000 L
e = 2008 combined influent volume = 3,836,200,000 L
f = 2009 combined influent volume = 3,370,700,000 L
g = 2010 combined influent volume = 4,424,400,000 L
Non-detect values were adjusted to ½ the detection limit for calculations

Table C-4: Removal Efficiencies – All Applicable Sites

Constituent	Average Removal Efficiency	Maximum	Minimum	Mine	Source
Aluminum	99.5%	99.8%	99%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Arsenic	99.8%	99.9%	99.7%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Cadmium	99.1%	99.7%	98.4%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Chromium	99.0%	99.8%	95.6%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Copper	99.4%	99.7%	99%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Iron	100.0%	100%	99.9%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Lead	74.6%	89.8%	48.3%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Nickel	97.9%	99.3%	95.7%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Selenium	93.1%	94.4%	91%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Zinc	98.9%	99.6%	97.7%	Leviathan Mine, Active, Single-stage	U.S. EPA, 2006a (Table 1-2)
Aluminum	99.7%	99.9%	99.2%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)
Arsenic	99.6%	99.8%	99.2%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)
Cadmium	98.7%	99.4%	97.5%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)
Chromium	99.3%	99.9%	93.8%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)
Copper	99.7%	99.8%	99.4%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)
Iron	100%	100%	99.9%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)

Table C-4: Removal Efficiencies – All Applicable Sites

Constituent	Average Removal Efficiency	Maximum	Minimum	Mine	Source
Lead	78.3%	86.7%	69.2%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)
Nickel	99.5%	99.9%	99.2%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)
Zinc	98.7%	99.4%	97.4%	Leviathan Mine, Active, Dual-stage	U.S. EPA, 2006a (Table 1-1)
Aluminum	99.2%	99.5%	98%	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Tables 1-3 and 2-4)
Arsenic	98.9%	99.5%	97.6%	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Tables 1-3 and 2-4)
Chromium	88.5%	92.3%	83.1%	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Tables 1-3 and 2-4)
Copper	58.3%	74.5%	27.7%	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Tables 1-3 and 2-4)
Iron	100%	100%	99.9%	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Tables 1-3 and 2-4)
Lead	66.4%	78.9%	37.7%	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Tables 1-3 and 2-4)
Nickel	98.6%	99.1%	97.2%	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Tables 1-3 and 2-4)
Zinc	96.0%	98.2%	90.6%	Leviathan Mine, Semi-Passive, Alkaline Lagoon	U.S. EPA, 2006a (Tables 1-3 and 2-4)
Iron	98.43%	99.96%	93.83%	Elizabeth Mine[b]	Butler and Hathaway, 2020
Aluminum	97.5%	97.9%	96.9%	Britannia Mine[c]	Madsen et al., 2012
Cadmium	98.7%	99.0%	97.8%	Britannia Mine[c]	Madsen et al., 2012
Copper	99.9%	100.0%	99.9%	Britannia Mine[c]	Madsen et al., 2012
Iron	97.9%	99.5%	93.4%	Britannia Mine[c]	Madsen et al., 2012
Manganese	92.6%	97.7%	89.8%	Britannia Mine[c]	Madsen et al., 2012
Zinc	99.8%	99.9%	99.7%	Britannia Mine[c]	Madsen et al., 2012
Notes:					

Table C-4: Removal Efficiencies – All Applicable Sites

<table>
<tr><th>Constituent</th><th>Average Removal Efficiency</th><th>Maximum</th><th>Minimum</th><th>Mine</th><th>Source</th></tr>
<tr><td colspan="6">For Leviathan Mine, Dual-stage data come from 12 sampling dates in 2002 and 1 in 2003 and the Single-stage comes from 7 sampling dates in 2003; and the semi-passive results are from 8 samples collected in 2002
a = EPA calculated the average removal efficiencies across 2006-2010 by determining the average removal efficiencies for each year and then averaging those values
b = EPA calculated maximum and minimum removal efficiencies from yearly average influent and effluent concentrations from 2009 to 2017
c = EPA calculated maximum and minimum removal efficiencies from yearly average influent and effluent concentrations from 2006 to 2010
Non-detect values were adjusted to ½ the detection limit in calculation</td></tr>
</table>

Appendix D: Constructed Wetlands Data Tables

Table D-1: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Timeframe	Mine – Wetland	Source	Notes
			Aerobic				
Cobalt	NS	0.036	0.008	1992 to 1994	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Cobalt	NS	0.036	0.008	1992 to 1997	Dunka Mine – W1D	ITRC, 2010	Table 2-2
Cobalt	NS	0.009	0.001	1996 to 1998	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Copper	NS	0.068	0.008	1992 to 1994	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Copper	NS	0.068	0.010	1992 to 1997	Dunka Mine – W1D	ITRC, 2010	Table 2-2
Copper	NS	0.03	0.003	1996 to 1998	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Copper	NS	0.02	0.002	1999 to 2004	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Nickel	NS	3.98	0.36	1992 to 1994	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Nickel	NS	3.98	0.700	1992 to 1997	Dunka Mine – W1D	ITRC, 2010	Table 2-2
Nickel	NS	0.74	0.19	1996 to 1998	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Nickel	NS	0.76	0.1	1999 to 2004	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
pH	NA	7.07	7.18	1992 to 1994	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
pH	NA	7.07	7.18	1992 to 1997	Dunka Mine – W1D	ITRC, 2010	Table 2-2
pH	NA	7.30	7.48	1996 to 1998	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1

Table D-1: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Timeframe	Mine – Wetland	Source	Notes
pH	NA	7.26	7.34	1999 to 2004	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Zinc	NS	0.052	0.013	1992 to 1994	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Zinc	NS	0.052	0.013	1992 to 1997	Dunka Mine – W1D	ITRC, 2010	Table 2-2
Zinc	NS	0.021	0.006	1996 to 1998	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Zinc	NS	0.019	0.006	1999 to 2004	Dunka Mine – W1D[a]	Eger and Eger, 2005	Table 1
Cobalt	NS	0.023	0.001	1995 to 1997	Dunka Mine – W1D Expanded	ITRC, 2010	Table 2-2
Cobalt	NS	0.009	0.001	1996 to 1999	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
Copper	NS	0.059	0.005	1995 to 1997	Dunka Mine – W1D Expanded	ITRC, 2010	Table 2-2
Copper	NS	0.03	0.005	1996 to 1999	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
Copper	NS	0.02	0.002	1999 to 2004	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
Nickel	NS	1.200	0.180	1995 to 1997	Dunka Mine – W1D Expanded	ITRC, 2010	Table 2-2
Nickel	NS	0.74	0.18	1996 to 1999	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
Nickel	NS	0.76	0.099	1999 to 2004	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
pH	NA	7.1	7.38	1995 to 1997	Dunka Mine – W1D Expanded	ITRC, 2010	Table 2-2
pH	NA	7.3	7.38	1996 to 1999	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
pH	NA	7.26	7.37	1999 to 2004	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1

Table D-1: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Timeframe	Mine – Wetland	Source	Notes
Zinc	NS	0.017	0.011	1995 to 1997	Dunka Mine – W1D Expanded	ITRC, 2010	Table 2-2
Zinc	NS	0.0216	0.011	1996 to 1999	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
Zinc	NS	0.019	0.011	1999 to 2004	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
pH	NA	7.1	7.38	1995 to 1997	Dunka Mine – W1D Expanded	ITRC, 2010	Table 2-2
pH	NA	7.3	7.38	1996 to 1999	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
pH	NA	7.26	7.37	1999 to 2004	Dunka Mine – W1D Expanded	Eger and Eger, 2005	Table 1
Anaerobic							
Aluminum	Total	2.351	0.073	9/8/99 to 1/1/2002	Copper Basin Mining District	Faulkner and Miller, 2002	Table 4
Copper	Total	0.43	<0.025	10/1998 to 3/1999	Copper Basin Mining District	Faulkner and Miller, 2002	Table 4
Copper	Total	0.311	0.008	9/8/99 to 1/1/2002	Copper Basin Mining District	Faulkner and Miller, 2002	Table 4
Iron	Total	1.07	0.353	9/8/99 to 1/1/2002	Copper Basin Mining District	Faulkner and Miller, 2002	Table 4
Manganese	Total	1.52	1.64	9/8/99 to 1/1/2002	Copper Basin Mining District	Faulkner and Miller, 2002	Table 4
Sulfate	NA	142	128	9/8/99 to 1/1/2002	Copper Basin Mining District	Faulkner and Miller, 2002	Table 4

Table D-1: Average Influent and Effluent Concentrations – All Applicable Case Studies

Constituent	Water Sample	Average Influent	Average Effluent	Timeframe	Mine – Wetland	Source	Notes
Zinc	Total	1.094	0.045	9/8/99 to 1/1/2002	Copper Basin Mining District	Faulkner and Miller, 2002	Table 4
pH	NA	4.2	7.1	9/8/99 to 1/1/2002	Copper Basin Mining District[b]	Faulkner and Miller, 2002	Table 4

Notes:
All analytical results reported in mg/L
pH results reported in standard units
NS = Not specified
NA = Not applicable
a = Figure 4 in Eger and Eger, 2005, shows inputs of "base metal input" and "base metal seep" in several locations downstream of the wetland W1D influent monitoring station (WS-005); actual concentrations of influent to W1D may be higher than concentrations reported in the reference
b = Base flow from McPherson Branch only

Table D-2: Removal Efficiencies – All Applicable Sites

Constituent	Water Sample	Average Removal Efficiency	Mine – Wetland	Source	Notes
Aerobic					
Cobalt	NS	77.8%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1992 to 1994
Cobalt	NS	77.8%	Dunka Mine – W1D	ITRC, 2010 (Table 2-2)	Calculated by EPA based on averages presented for 1992 to 1997
Cobalt	NS	88.9%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1996 to 1998
Copper	NS	88.2%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1992 to 1994
Copper	NS	85.3%	Dunka Mine – W1D	ITRC, 2010 (Table 2-2)	Calculated by EPA based on averages presented for 1992 to 1997
Copper	NS	90.0%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1996 to 1998
Copper	NS	90.0%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1999 to 2004
Nickel	NS	91.0%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1992 to 1994
Nickel	NS	82.4%	Dunka Mine – W1D	ITRC, 2010 (Table 2-2)	Calculated by EPA based on averages presented for 1992 to 1997
Nickel	NS	74.3%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1996 to 1998
Nickel	NS	86.8%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1999 to 2004
Zinc	NS	75.0%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1992 to 1994
Zinc	NS	75.0%	Dunka Mine – W1D	ITRC, 2010 (Table 2-2)	Calculated by EPA based on averages presented for 1992 to 1997
Zinc	NS	71.4%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1996 to 1998
Zinc	NS	68.4%	Dunka Mine – W1D	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1999 to 2004
Cobalt	NS	95.7%	Dunka Mine – W1D Expanded	ITRC, 2010 (Table 2-2)	Calculated by EPA based on averages presented for 1995 to 1997

Table D-2: Removal Efficiencies – All Applicable Sites

Constituent	Water Sample	Average Removal Efficiency	Mine – Wetland	Source	Notes
Cobalt	NS	88.9%	Dunka Mine – W1D Expanded	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1996 to 1999
Copper	NS	91.5%	Dunka Mine – W1D Expanded	ITRC, 2010 (Table 2-2)	Calculated based on averages presented for 1995 to 1997
Copper	NS	83.3%	Dunka Mine – W1D Expanded	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1996 to 1999
Copper	NS	90.0%	Dunka Mine – W1D Expanded	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1999 to 2004
Nickel	NS	85.0%	Dunka Mine – W1D Expanded	ITRC, 2010 (Table 2-2)	Calculated by EPA based on averages presented for 1995 to 1997
Nickel	NS	75.7%	Dunka Mine – W1D Expanded	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1996 to 1999
Nickel	NS	87.0%	Dunka Mine – W1D Expanded	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1999 to 2004
Zinc	NS	35.3%	Dunka Mine – W1D Expanded	ITRC, 2010 (Table 2-2)	Calculated by EPA based on averages presented for 1995 to 1997
Zinc	NS	49.1%	Dunka Mine – W1D Expanded	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1996 to 1999
Zinc	NS	42.1%	Dunka Mine – W1D Expanded	Eger and Eger, 2005 (Table 1)	Calculated by EPA based on averages presented for 1999 to 2004
Anaerobic					
Aluminum	Total	96.9%	Copper Basin Mining District	Faulkner and Miller, 2002 (Table 4)	Calculated by EPA based on averages presented for 9/8/99 to 1/1/2002
Copper	Total	97.4%	Copper Basin Mining District	Faulkner and Miller, 2002 (Table 4)	Calculated by EPA based on averages presented for 9/8/99 to 1/1/2002
Copper	Total	94.2%	Copper Basin Mining District	Faulkner and Miller, 2002 (Table 4)	Calculated by EPA based on averages presented for 10/1998-3/1999; assumed average effluent of 0.025 mg/L[a]
Iron	Total	67.0%	Copper Basin Mining District	Faulkner and Miller, 2002 (Table 4)	Calculated by EPA based on averages presented for 9/8/99 to 1/1/2002
Manganese	Total	-7.9%	Copper Basin Mining District	Faulkner and Miller, 2002 (Table 4)	Calculated by EPA based on averages presented for 9/8/99 to 1/1/2002

Table D-2: Removal Efficiencies – All Applicable Sites

Constituent	Water Sample	Average Removal Efficiency	Mine – Wetland	Source	Notes
Sulfate	NS	9.9%	Copper Basin Mining District	Faulkner and Miller, 2002 (Table 4)	Calculated by EPA based on averages presented for 9/8/99 to 1/1/2002
Zinc	Total	95.9%	Copper Basin Mining District	Faulkner and Miller, 2002 (Table 4)	Calculated by EPA based on averages presented for 9/8/99 to 1/1/2002

Notes:

NS – Not specified

a = Reference stated, “average influent copper concentration was reduced from 0.43 mg/L to less than 0.025 mg/L in the effluent”; therefore, 0.025 mg/L was used to enable calculation

Appendix E: Treatment Trains Data Tables

Table E-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – Calliope Mine

Constituent	Influent Flow[a]	Maximum Influent	Corresponding Effluent	Influent Flow[b]	Minimum Influent	Corresponding Effluent	Notes
Aluminum	3.85x10^{-5}	14.1	0.0138	6.16x10^{-5}	0.011	0.0165	BCR II effluent
Arsenic	5.53x10^{-5}	0.0109	0.0054	5.80x10^{-5}	0.0011	0.004	BCR II effluent
Cadmium	3.85x10^{-5}	0.0419	0.0048	5.57x10^{-5}	0.0028	0.0001	BCR II effluent
Copper	3.85x10^{-5}	3.05	0.0078	5.14x10^{-5}	0.0028	0.0237	BCR II effluent
Iron	3.85x10^{-5}	7.22	0.0975	5.57x10^{-5}	0.008	0.110	BCR II effluent
Manganese	3.85x10^{-5}	3.77	0.551	5.57x10^{-5}	0.690	0.600	BCR II effluent
Sulfate	3.85x10^{-5}	229	281	5.57x10^{-5}	60.6	8	BCR II effluent
Zinc	3.85x10^{-5}	11.1	0.249	5.57x10^{-5}	0.990	0.048	BCR II effluent
pH	5.14x10^{-5}	7.52	7.21	3.85x10^{-5}	3.29	8.29	BCR II effluent
Aluminum	5.03x10^{-5}	2.4	0.0542	1.07x10^{-4}	0.0173	0.0173	BCR IV effluent
Arsenic	3.39x10^{-5}	0.0067	0.0034	5.79x10^{-5} 6.23x10^{-5}	0.0011 0.0011	0.0041 0.0011	BCR IV effluent
Cadmium	3.07x10^{-5}	0.0179	0.0039	1.59x10^{-4}	0.0037	0.0034	BCR IV effluent
Copper	5.03x10^{-5}	0.884	0.103	8.06x10^{-5}	0.0442	0.0529	BCR IV effluent
Iron	5.03x10^{-5}	0.524	0.417	1.59x10^{-4} 1.29x10^{-4}	0.0155 0.0155	0.0671 0.124	BCR IV effluent
Manganese	3.07x10^{-5} 6.38x10^{-5}	1.95 1.95	1.07 1.48	1.07x10^{-4}	1.07	0.837	BCR IV effluent
Sulfate	5.43x10^{-5}	122	326	8.06x10^{-5}	69.8	84.7	BCR IV effluent
Zinc	3.07x10^{-5}	3.79	0.672	8.06x10^{-5}	1.42	0.383	BCR IV effluent

Table E-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – Calliope Mine

Constituent	Influent Flow[a]	Maximum Influent	Corresponding Effluent	Influent Flow[b]	Minimum Influent	Corresponding Effluent	Notes
pH	8.06×10^{-5}	7.08	7.57	5.03×10^{-5}	3.87	9.98	BCR IV effluent

Notes:

Source: Wilmoth, 2002 (Tables 5-1 and 5-2 (pH), 5-4 (sulfate) and 5-6 (all other constituents)

All analytical results reported in mg/l

All flow reported in cubic meters per second (converted from gallons per minute)

pH results reported in standard units

All constituent concentrations reported as total

a = Influent flow rate from same date as maximum influent concentration, as reported in Table 4-1a, Wilmoth, 2002

b = Influent flow rate from same date as minimum influent concentration, as reported in Table 4-1a, Wilmoth, 2002

c = Wilmoth, 2002 reported this value as an outlier

The aboveground BCR (IV) reports no flow (0) during winter months; the BCR was designed to be shut down for winter

Table E-2: Maximum and Minimum Influent and Corresponding Effluent Concentrations – Force Crag

Constituent	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Notes
Zinc	4.5	0.14	2.5	0.08	Figure 2

Notes:

Source: Jarvis et al., 2015

All analytical results in mg/L

All values reported as dissolved

Table E-3: Influent and Effluent Concentrations – Golden Sunlight Mine

Constituent	Influent	Effluent	Notes
Aluminum	1,740	0.126	Data originated from Table 4, collected March 12, 2003
Copper	81.4	0.001	Data originated from Table 4, collected March 12, 2003
Iron	198	2.62	Data originated from Table 4, collected March 12, 2003
Manganese	117	67.8	Data originated from Table 4, collected March 12, 2003
Zinc	39.5	0.011	Data originated from Table 4, collected March 12, 2003

Notes:
Source: Bless, 2008
All analytical results in mg/L
All constituent concentrations reported as dissolved

Table E-4: Influent and Effluent Concentrations – Leviathan Mine

Constituent	Water Sample	System Influent	Corresponding System Effluent	Mode	Notes
Aluminum	Dissolved	36.9	0.144	Gravity mode	Data extracted from Table 2-13
Aluminum	Total	36.4	0.468	Gravity mode	Data extracted from Table 2-17
Aluminum	Dissolved	40.4	0.105	Recirculation mode	Data extracted from Table 2-15
Aluminum	Total	40.4	0.120	Recirculation mode	Data extracted from Table 2-18
Arsenic	Dissolved	0.0028	0.0024	Gravity mode	Data extracted from Table 2-13
Arsenic	Total	0.0042	<0.0022	Gravity mode	Data extracted from Table 2-17
Arsenic	Dissolved	<0.0021	0.0147	Recirculation mode	Data extracted from Table 2-15

Table E-4: Influent and Effluent Concentrations – Leviathan Mine

Constituent	Water Sample	System Influent	Corresponding System Effluent	Mode	Notes
Arsenic	Total	<0.0021	0.0149	Recirculation mode	Data extracted from Table 2-18
Cadmium	Dissolved	0.0004	<0.00023	Gravity mode	Data extracted from Table 2-13
Cadmium	Total	0.00041	<0.00023	Gravity mode	Data extracted from Table 2-17
Cadmium	Dissolved	0.00094	<0.00016	Recirculation mode	Data extracted from Table 2-15
Cadmium	Total	0.0011	<0.00016	Recirculation mode	Data extracted from Table 2-18
Chromium	Dissolved	0.0172	0.0064	Gravity mode	Data extracted from Table 2-13
Chromium	Total	0.0164	0.008	Gravity mode	Data extracted from Table 2-17
Chromium	Dissolved	0.0193	0.0116	Recirculation mode	Data extracted from Table 2-15
Chromium	Total	0.0198	0.0132	Recirculation mode	Data extracted from Table 2-18
Copper	Dissolved	0.656	0.0056	Gravity mode	Data extracted from Table 2-13
Copper	Total	0.647	0.0078	Gravity mode	Data extracted from Table 2-17
Copper	Dissolved	0.766	0.0095	Recirculation mode	Data extracted from Table 2-15
Copper	Total	0.757	0.0079	Recirculation mode	Data extracted from Table 2-18
Iron	Dissolved	113	0.389	Gravity mode	Data extracted from Table 2-13
Iron	Total	113	1.66	Gravity mode	Data extracted from Table 2-17
Iron	Dissolved	99.5	0.269	Recirculation mode	Data extracted from Table 2-15
Iron	Total	99.1	0.532	Recirculation mode	Data extracted from Table 2-18

Table E-4: Influent and Effluent Concentrations – Leviathan Mine

Constituent	Water Sample	System Influent	Corresponding System Effluent	Mode	Notes
Lead	Dissolved	0.0053	0.0034	Gravity mode	Data extracted from Table 2-13
Lead	Total	0.0049	0.0029	Gravity mode	Data extracted from Table 2-17
Lead	Dissolved	0.0059	0.0031	Recirculation mode	Data extracted from Table 2-15
Lead	Total	0.0072	0.0065	Recirculation mode	Data extracted from Table 2-18
Nickel	Dissolved	0.481	0.0531	Gravity mode	Data extracted from Table 2-13
Nickel	Total	0.478	0.0715	Gravity mode	Data extracted from Table 2-17
Nickel	Dissolved	0.531	0.0189	Recirculation mode	Data extracted from Table 2-15
Nickel	Total	0.529	0.0224	Recirculation mode	Data extracted from Table 2-18
Selenium	Dissolved	0.0096	0.0087	Gravity mode	Data extracted from Table 2-13
Selenium	Total	0.0122	0.0052	Gravity mode	Data extracted from Table 2-17
Selenium	Dissolved	0.0144	0.0078	Recirculation mode	Data extracted from Table 2-15
Selenium	Total	0.0199	0.0108	Recirculation mode	Data extracted from Table 2-18
Sulfate	Total	1,510	1,160	Gravity mode	Data extracted from Table 2-9
Sulfate	Total	1,190	1,200	Recirculation mode	Data extracted from Table 2-11
Zinc	Dissolved	0.702	0.0103	Gravity mode	Data extracted from Table 2-13
Zinc	Total	0.692	0.0147	Gravity mode	Data extracted from Table 2-17
Zinc	Dissolved	0.755	0.0045	Recirculation mode	Data extracted from Table 2-15

Table E-4: Influent and Effluent Concentrations – Leviathan Mine

Constituent	Water Sample	System Influent	Corresponding System Effluent	Mode	Notes
Zinc	Total	0.757	0.0106	Recirculation mode	Data extracted from Table 2-18
pH	NA	3.1	7.7	Gravity mode	Data extracted from Table 2-9
pH	NA	7.2	7.6	Recirculation mode	Data extracted from Table 2-11

Notes:
Source: U.S. EPA, 2006a
All analytical results reported in mg/L
pH results reported in standard units
NA = not applicable
Leviathan gravity flow configuration data March 24, 2004; recirculation flow configuration data August 19, 2004

Table E-5: Maximum and Minimum Influent and Corresponding Effluent Concentrations – Standard Mine

Constituent	Maximum Influent	Corresponding APC Effluent	Minimum Influent	Corresponding APC Effluent	Notes
Cadmium	0.2	0.00006	0.085	0.00015	Data extracted from Figure 3
Copper	0.55	0.0015	0.011	0.0022	Data extracted from Figure 4
Iron	16	0.35	2	0.3	Data extracted from Figure 5
Lead	1.07	0.001	0.03	0.0007	Data extracted from Figure 6
Manganese	15	3	5.4	1	Data extracted from Figure 7
Zinc	30	0.033	14.9	1	Data extracted from Figure 8

Notes:
Source: Gallagher et al., 2012
All analytical results reported in mg/L
All constituent concentrations reported as dissolved except for iron, which was reported as total

Table E-5: Maximum and Minimum Influent and Corresponding Effluent Concentrations – Standard Mine

Constituent	Maximum Influent	Corresponding APC Effluent	Minimum Influent	Corresponding APC Effluent	Notes

Maximum and minimum influent selected from data points with corresponding APC effluent
APC = Aerobic Polishing Cell

Table E-6: Maximum and Minimum Influent and Corresponding Effluent Concentrations – Surething Mine

Constituent	Maximum Influent	Corresponding Effluent	Minimum Influent	Corresponding Effluent	Notes
Aluminum	29.5	<0.04	29.5	<0.04	Data from Table ES-1, one data point collected September 1, 2005
Arsenic	1.25	<0.01	0.125	0.02	Data extracted from Figure 4-6, date range 2001 through 2005
Cadmium	0.385	0.005	0.04	<0.00009	Data extracted from Figure 4-3, date range 2001 through 2005
Copper	4.25	<0.003	0.5	<0.003	Data extracted from Figure 4-2, date range 2001 through 2005
Iron	51	<0.014	12	<0.014	Data extracted from Figure 4-5, date range 2001 through 2005
Manganese	26	<0.040	24	0.1	Data extracted from Figure 4-7, date range from September through November2005, which reflects upgrades to the aerobic BCR
Sulfate	900	120	50	170	Data extracted from Figure 4-14, date range from 2001 through 2005
Zinc	39	<0.007	4.5	<0.007	Data extracted from Figure 4-4, date range from 2001 through 2005.
pH	2.5	6.9	2.5	6.9	Data from Table ES-1, one data point collected September 1, 2005

Notes:
Source: Nordwick and Bless, 2008
All analytical results reported in mg/L
pH results reported in standard units
All constituent concentrations reported as dissolved.
Detection limits inferred from Figure and the values provided in Table ES-1 in Nordwick and Bless, 2008.

Table E-7: Influent and Effluent Concentrations – Surething Mine

Constituent	Influent	Effluent
Aluminum	29.5	<0.04
Arsenic	0.127	<0.01
Cadmium	0.208	<0.00009
Copper	2.35	<0.003
Iron	15.0	<0.014
Lead	0.151	0.004
Manganese	26.7	0.037
Zinc	22.7	<0.007
Notes: Source: Nordwick and Bless, 2008; Data from Table 4-2; collected September 1, 2005 All analytical results reported in mg/L All constituent concentrations reported as dissolved		

Table E-8: Influent and Effluent Concentrations – Wheal Jane Mine

Constituent	Influent	Effluent	Treatment System	Notes
Iron	50	1	LD	Data extracted from Figure 4
Iron	67	<1	ALD	Data extracted from Figure 4
Iron	59	<1	LF	Data extracted from Figure 4
Zinc	31	11	LD	Data extracted from Figure 5
Zinc	33	14	ALD	Data extracted from Figure 5
Zinc	33	0.5	LF	Data extracted from Figure 5
Sulfate	238	333	LD	Data extracted from Figure 3
Sulfate	180	298	ALD	Data extracted from Figure 3
Sulfate	260	200	LF	Data extracted from Figure 3
ORP	360	730	LD	Data extracted from Figure 2
ORP	470	640	ALD	Data extracted from Figure 2
ORP	560	640	LF	Data extracted from Figure 2
pH	5.4	4.1	LD	Data extracted from Figure 2
pH	5	5	ALD	Data extracted from Figure 2

Table E-8: Influent and Effluent Concentrations – Wheal Jane Mine

Constituent	Influent	Effluent	Treatment System	Notes
pH	3.9	6.7	LF	Data extracted from Figure 2

Notes:
Source: Johnson and Hallberg, 2005, based sampling conducted on September 19, 2002
The ALD became nonoperational in June 2000, after which the system operated as a second limestone-dosed system.
All analytical results in mg/L; total or dissolved not specified
pH reported in standard units
LD = Limestone-dosed pre-treatment
ALD = Anoxic limestone drain
LF = Limestone-free system without pre-treatment
ORP = Oxidation-reduction potential
NA = not applicable
<1 = EPA could not determine concentration based on the data provided in the figure

Table E-9: Average Influent and Effluent Concentrations – Calliope Mine

Constituent	Average Influent	Average Effluent	Notes
Aluminum	1.2229	0.051703	BCR II effluent
Arsenic	<0.005	0.005894	BCR II effluent
Cadmium	0.01082	<0.005	BCR II effluent
Copper	0.4078	0.044064	BCR II effluent
Iron	0.4556	0.551436	BCR II effluent
Manganese	1.4581	0.786067	BCR II effluent
Sulfate	102.90	115.43	BCR II effluent
Zinc	2.8406	0.46329	BCR II effluent
pH	6.05	7.49	BCR II effluent
Aluminum	1.2229	0.0372	BCR IV effluent
Arsenic	0.5634	0.0070	BCR IV effluent
Cadmium	0.0103	0.0039	BCR IV effluent
Copper	0.2774	0.0347	BCR IV effluent

Table E-9: Average Influent and Effluent Concentrations – Calliope Mine

Constituent	Average Influent	Average Effluent	Notes
Iron	0.1556	0.4869	BCR IV effluent
Manganese	1.40	0.96	BCR IV effluent
Sulfate	97.5	111.9	BCR IV effluent
Zinc	2.54	0.36	BCR IV effluent
pH	5.84	7.74	BCR IV effluent

Notes:
Source: Wilmoth, 2002
All analytical results reported in mg/L
pH results reported in standard units
All constituent concentrations reported as total
EPA calculated average influent and effluent from constituent data reported in Table 5-2, 5-4 and 5-6 in Wilmoth, 2002

Table E-10: Average Influent and Effluent Concentrations – Leviathan Mine

Constituent	Average Influent	Average Effluent	Mode	Notes
Aluminum	37.467	0.103	Gravity mode	Data from Table 2-2, based on 6 sampling events
Aluminum	40.209	0.0527	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Arsenic	0.0021	0.0047	Gravity mode	Data from Table 2-2, based on 6 sampling events
Arsenic	0.0074	0.0065	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Cadmium	0.00061	<0.00021	Gravity mode	Data from Table 2-2, based on 6 sampling events
Cadmium	0.00060	<0.00020	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Chromium	0.0122	0.0078	Gravity mode	Data from Table 2-2, based on 6 sampling events

Table E-10: Average Influent and Effluent Concentrations – Leviathan Mine

Constituent	Average Influent	Average Effluent	Mode	Notes
Chromium	0.0111	0.0064	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Copper	0.691	0.0048	Gravity mode	Data from Table 2-2, based on 6 sampling events
Copper	0.795	0.0046	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Iron	117.167	4.885	Gravity mode	Data from Table 2-2, based on 6 sampling events
Iron	115.785	2.704	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Lead	0.0036	0.0047	Gravity mode	Data from Table 2-2, based on 6 sampling events
Lead	0.0042	0.0025	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Nickel	0.487	0.0655	Gravity mode	Data from Table 2-2, based on 6 sampling events
Nickel	0.529	0.0697	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Selenium	0.0139	0.0112	Gravity mode	Data from Table 2-2, based on 6 sampling events
Selenium	0.0115	0.0085	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Zinc	0.715	0.0158	Gravity mode	Data from Table 2-2, based on 6 sampling events
Zinc	0.776	0.0089	Recirculation mode	Data from Table 2-3, based on 7 sampling events

Notes:
Source: U.S. EPA, 2006a
All analytical results reported in mg/L
All constituent concentrations reported as dissolved.

Table E-11: Average Influent and Effluent Concentrations – Standard Mine

Constituent	Average Influent	Average APC Effluent	Notes
Cadmium	0.095	0.00063	Influent calculated from average BCR effluent and percent removal provided in text; average APC effluent data provided in text.
Copper	0.10	0.0028	Influent calculated from average BCR effluent and percent removal provided in text; average APC effluent data provided in text.
Iron	11.2	0.54	Influent calculated from average BCR effluent and percent removal provided in text; average APC effluent data provided in text.
Lead	0.134	0.0038	Influent calculated from average BCR effluent and percent removal provided in text; average APC effluent data provided in text.
Manganese	5.4-13.2[a]	4.1	Manganese removal increased as APC matured and became fully vegetated
Sulfate	281	122	Data from Table 4
Sulfide	<0.5	<0.5	Data from Table 4
Zinc	18.25	0.14	Influent calculated from average BCR effluent and percent removal provided in text; average APC effluent data provided in text.

Notes:
Source: Gallagher et al., 2012
All analytical results reported in mg/L
All constituent concentrations reported as dissolved except for iron, which was reported as total.
a = Average not provided, represents range reported in text
APC = Aerobic Polishing Cell
NA = Not applicable

Table E-12: Average Influent and Effluent Concentrations – Tar Creek

Constituent	Average Influent	Average Effluent
Aluminum	0.094 ± 0.009	0.071 ± 0.030
Arsenic	0.063 ± 0.002	ND
Calcium	742 ± 9.0	740 ± 22.3
Cadmium	0.016 ± 0.002	ND
Chromium	0.001 ± 0.0002	0.002 ± 0.0006
Cobalt	0.066 ± 0.008	0.007 ± 0.0004

Table E-12: Average Influent and Effluent Concentrations – Tar Creek

Constituent	Average Influent	Average Effluent
Copper	0.002 ± 0.0003	0.003 ± 0.0003
Iron	177 ± 2.33	0.57 ± 0.207
Lead	0.068 ± 0.003	ND
Lithium	0.366 ± 0.010	0.365 ± 0.018
Magnesium	200 ± 2.53	198 ± 7.49
Manganese	1.51 ± 0.016	1.38 ± 0.197
Nickel	0.945 ± 0.015	0.035 ± 0.007
Potassium	26.0 ± 0.286	31.1 ± 4.82
Sodium	94.9 ± 1.63	96.6 ± 4.23
Sulfate	2,239 ± 26	2,047 ± 72
Zinc	8.29 ± 0.078	0.096 ± 0.037
Notes: Source: Nairn et al., 2011 All analytical results reported in mg/L All constituent concentrations reported as total Data from Table 3, representing flow-weighted influent and final system effluent as mean +/- standard error ND = Not detected		

Table E-13: Average Influent and Effluent Concentrations – Wheal Jane Mine

Constituent	Average Influent	Average Effluent	Treatment System	Notes
Aluminum	48.6	55.8	LD	Influent and effluent data reported in Table 3
Aluminum	48.6	3.3	ALD	Influent and effluent data reported in Table 2
Aluminum	48.6	75.8	LF	Influent and effluent data reported in Table 1
Arsenic	2.7	0.0	LD	Influent and effluent data reported in Table 3
Arsenic	2.7	0.0	ALD	Influent and effluent data reported in Table 2
Arsenic	2.7	0.0	LF	Influent and effluent data reported in Table 1
Cadmium	0.1	0.0	LD	Influent and effluent data reported in Table 3
Cadmium	0.1	0.0	ALD	Influent and effluent data reported in Table 2
Cadmium	0.1	0.0	LF	Influent and effluent data reported in Table 1
Copper	0.4	0.1	LD	Influent and effluent data reported in Table 3

Table E-13: Average Influent and Effluent Concentrations – Wheal Jane Mine

Constituent	Average Influent	Average Effluent	Treatment System	Notes
Copper	0.4	0.0	ALD	Influent and effluent data reported in Table 2
Copper	0.4	0.1	LF	Influent and effluent data reported in Table 1
Iron	143.6	13.2	LD	Influent and effluent data reported in Table 3
Iron	143.6	2.2	ALD	Influent and effluent data reported in Table 2
Iron	143.6	12.7	LF	Influent and effluent data reported in Table 1
Manganese	21.4	24.8	LD	Influent and effluent data reported in Table 3
Manganese	21.4	12.2	ALD	Influent and effluent data reported in Table 2
Manganese	21.4	27.6	LF	Influent and effluent data reported in Table 1
Sulfate	1649.5	1591.2	LD	Influent and effluent data reported in Table 3
Sulfate	1649.5	1150.4	ALD	Influent and effluent data reported in Table 2
Sulfate	1649.5	1636.1	LF	Influent and effluent data reported in Table 1
Zinc	82.0	45.6	LD	Influent and effluent data reported in Table 3
Zinc	82.0	4.9	ALD	Influent and effluent data reported in Table 2
Zinc	82.0	51.3	LF	Influent and effluent data reported in Table 1
pH	3.8	3.0	LD	Influent and effluent data reported in Table 3
pH	3.9	6.6	ALD	Influent and effluent data reported in Table 2
pH	3.9	3.1	LF	Influent and effluent data reported in Table 1

Source: Whitehead et al., 2005

The authors did not provide the time period over which the averages were calculated, but it may have been over the same period for which the removal efficiencies were calculated (1999-2001) as reported in Whitehead et al., 2005

The ALD became nonoperational in June 2000, after which the system operated as a second limestone-dosed system

Whitehead et al., 2005 only reported one decimal place in Tables 1, 2 and 3

All analytical results reported in mg/L

All constituent concentrations reported as dissolved

pH results reported in standard units

LD = Limestone-dosed pre-treatment

ALD = Anoxic limestone drain

LF = Limestone-free system without pre-treatment

Table E-14: Removal Efficiencies – Calliope Mine

Constituent	Average Removal Efficiency	Maximum	Minimum	Notes
Aluminum	0.24%	99.90%	-430.81%	BCR II
Arsenic	18.93%	86.89%	-31.58%	BCR II
Cadmium	78.16%	95.97%	40.86%	BCR II
Copper	48.22%	99.76%	-233.33%	BCR II
Iron	-1446.83%	98.65%	-10192.68%	BCR II
Manganese	35.49%	98.46%	-185.71%	BCR II
Sulfate	4.62%	30.43%	-52.00%	BCR II
Zinc	77.62%	99.58%	25.48%	BCR II
Aluminum	43.61%	97.74%	-140.21%	BCR IV
Arsenic	-147.35%	62.90%	-839.29%	BCR IV
Cadmium	52.16%	84.85%	8.11%	BCR IV
Copper	79.66%	98.23%	-19.68%	BCR IV
Iron	-698.05%	20.42%	-2663.53%	BCR IV
Manganese	29.46%	98.81%	-6.72%	BCR IV
Sulfate	-12.78%	37.29%	-167.21%	BCR IV
Zinc	85.08%	96.84%	73.03%	BCR IV

Notes:

Source: Wilmoth, 2002

All analytical results reported in mg/L

pH results reported in standard units.

All constituent concentrations reported as total

EPA calculated removal efficiencies calculated for each sampling date from constituent data provided in Table 5-6 in Wilmoth, 2002. The average removal efficiency for each metal was obtained from the individual calculated removal efficiencies for each sampling date.

Table E-15: Removal Efficiencies – Golden Sunlight Mine

Constituent	Removal Efficiency	Notes
Aluminum	99.99%	Data originated from Table 4, collected March 12, 2003
Copper	99.99%	Data originated from Table 4, collected March 12, 2003

Table E-15: Removal Efficiencies – Golden Sunlight Mine

Constituent	Removal Efficiency	Notes
Iron	98.68%	Data originated from Table 4, collected March 12, 2003
Manganese	42.05%	Data originated from Table 4, collected March 12, 2003
Zinc	99.97%	Data originated from Table 4, collected March 12, 2003
Notes: Source: Bless, 2008 EPA calculated average removal efficiencies from influent and effluent presented in Table E-8 All analytical results in mg/L All constituent concentrations reported as dissolved		

Table E-16: Removal Efficiencies – Leviathan Mine

Constituent	Water Sample	Removal Efficiency[a]	Mode	Notes
Aluminum	Dissolved	99.6%	Gravity mode	Data extracted from Table 2-13
Aluminum	Total	98.7%	Gravity mode	Data extracted from Table 2-17
Aluminum	Dissolved	99.7%	Recirculation mode	Data extracted from Table 2-15
Aluminum	Total	99.7%	Recirculation mode	Data extracted from Table 2-18
Arsenic	Dissolved	14.3%	Gravity mode	Data extracted from Table 2-13
Arsenic	Total	47.6%	Gravity mode	Data extracted from Table 2-17
Arsenic	Dissolved	-600%	Recirculation mode	Data extracted from Table 2-15
Arsenic	Total	-548%	Recirculation mode	Data extracted from Table 2-18
Cadmium	Dissolved	42.5%	Gravity mode	Data extracted from Table 2-13
Cadmium	Total	43.9%	Gravity mode	Data extracted from Table 2-17
Cadmium	Dissolved	83.0%	Recirculation mode	Data extracted from Table 2-15
Cadmium	Total	85.5%	Recirculation mode	Data extracted from Table 2-18
Chromium	Dissolved	62.8%	Gravity mode	Data extracted from Table 2-13
Chromium	Total	51.2%	Gravity mode	Data extracted from Table 2-17
Chromium	Dissolved	39.9%	Recirculation mode	Data extracted from Table 2-15
Chromium	Total	33.3%	Recirculation mode	Data extracted from Table 2-18
Copper	Dissolved	99.1%	Gravity mode	Data extracted from Table 2-13
Copper	Total	98.8%	Gravity mode	Data extracted from Table 2-17
Copper	Dissolved	98.8%	Recirculation mode	Data extracted from Table 2-15

Table E-16: Removal Efficiencies – Leviathan Mine

Constituent	Water Sample	Removal Efficiency[a]	Mode	Notes
Copper	Total	99%	Recirculation mode	Data extracted from Table 2-18
Iron	Dissolved	99.7%	Gravity mode	Data extracted from Table 2-13
Iron	Total	98.5%	Gravity mode	Data extracted from Table 2-17
Iron	Dissolved	99.7%	Recirculation mode	Data extracted from Table 2-15
Iron	Total	99.5%	Recirculation mode	Data extracted from Table 2-18
Lead	Dissolved	35.8%	Gravity mode	Data extracted from Table 2-13
Lead	Total	40.8%	Gravity mode	Data extracted from Table 2-17
Lead	Dissolved	47.5%	Recirculation mode	Data extracted from Table 2-15
Lead	Total	9.7%	Recirculation mode	Data extracted from Table 2-18
Nickel	Dissolved	89%	Gravity mode	Data extracted from Table 2-13
Nickel	Total	85%	Gravity mode	Data extracted from Table 2-17
Nickel	Dissolved	96.4%	Recirculation mode	Data extracted from Table 2-15
Nickel	Total	95.8%	Recirculation mode	Data extracted from Table 2-18
Selenium	Dissolved	9.4%	Gravity mode	Data extracted from Table 2-13
Selenium	Total	57.4%	Gravity mode	Data extracted from Table 2-17
Selenium	Dissolved	45.8%	Recirculation mode	Data extracted from Table 2-15
Selenium	Total	45.7%	Recirculation mode	Data extracted from Table 2-18
Sulfate	Total	23.18%[b]	Gravity mode	Data extracted from Table 2-9
Sulfate	Total	26.38%[b]	Recirculation mode	Data extracted from Table 2-11
Zinc	Dissolved	98.5%	Gravity mode	Data extracted from Table 2-13
Zinc	Total	97.9%	Gravity mode	Data extracted from Table 2-17
Zinc	Dissolved	99.4%	Recirculation mode	Data extracted from Table 2-15
Zinc	Total	98.6%	Recirculation mode	Data extracted from Table 2-18

Notes:

Source: U.S. EPA, 2006a

Leviathan gravity flow configuration data March 24, 2004; recirculation flow configuration data August 19, 2004.

a = Removal efficiency provided by source unless otherwise noted

b = EPA calculated removal efficiency based on influent and effluent concentrations presented in Table E-10

Table E-17: Minimum, Maximum and Average Removal Efficiencies – Leviathan Mine

Constituent	Minimum Removal Efficiency	Maximum Removal Efficiency	Average Removal Efficiency	Mode	Notes
Aluminum	99.5%	99.9%	99.7%	Gravity mode	Data from Table 2-2, based on 6 sampling events
Aluminum	99.7%	99.9%	99.9%	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Arsenic	NC	NC	NC	Gravity mode	Data from Table 2-2, based on 6 sampling events
Arsenic	NC	NC	NC	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Cadmium	42.5%	79%	65.3%	Gravity mode	Data from Table 2-2, based on 6 sampling events
Cadmium	NC	NC	NC	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Chromium	NC	NC	NC	Gravity mode	Data from Table 2-2, based on 6 sampling events
Chromium	21.2%	84.8%	42.5%	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Copper	99.1%	99.7%	99.3%	Gravity mode	Data from Table 2-2, based on 6 sampling events
Copper	98.8%	99.8%	99.4%	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Iron	65.6%	99.9%	95.8%	Gravity mode	Data from Table 2-2, based on 6 sampling events
Iron	92.8%	99.7%	97.7%	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Lead	NC	NC	NC	Gravity mode	Data from Table 2-2, based on 6 sampling events
Lead	22.0%	57.1%	41.3%	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Nickel	72.1%	92.6%	86.6%	Gravity mode	Data from Table 2-2, based on 6 sampling events
Nickel	71.0%	96.4%	86.8%	Recirculation mode	Data from Table 2-3, based on 7 sampling events

Table E-17: Minimum, Maximum and Average Removal Efficiencies – Leviathan Mine

Constituent	Minimum Removal Efficiency	Maximum Removal Efficiency	Average Removal Efficiency	Mode	Notes
Selenium	NC	NC	NC	Gravity mode	Data from Table 2-2, based on 6 sampling events
Selenium	NC	NC	NC	Recirculation mode	Data from Table 2-3, based on 7 sampling events
Zinc	95.9%	98.6%	97.8%	Gravity mode	Data from Table 2-2, based on 6 sampling events
Zinc	97.7%	99.8%	98.9%	Recirculation mode	Data from Table 2-3, based on 7 sampling events

Notes:
Source: U.S. EPA, 2006a
NC = Not calculated because influent and effluent concentrations are not statistically different
All constituents reported as dissolved

Table E-18: Average Removal Efficiencies – Standard Mine

Constituent	Average Removal Efficiency	Notes
Cadmium	99.34%	Removal efficiency calculated from average influent and average APC effluent.
Copper	97.2%	Removal efficiency calculated from average influent and average APC effluent.
Iron	95.18%	Removal efficiency calculated from average influent and average APC effluent.
Lead	97.16%	Removal efficiency calculated from average influent and average APC effluent.
Manganese	42.2% (2009) 87.7% (2010)	Removal efficiencies provided in text.
Sulfate	56.58%	Data from Table 4
Zinc	99.23%	Removal efficiency calculated from average influent and average APC effluent.

Table E-18: Average Removal Efficiencies – Standard Mine

Constituent	Average Removal Efficiency	Notes

Notes:
Source: Gallagher et al., 2012
APC = Aerobic Polishing Cell
All constituent concentrations reported as dissolved except for iron, which was reported as total

Table E-19: Removal Efficiencies - Surething Mine

Constituent	Removal Efficiency
Aluminum	>99.86%
Arsenic	>92.13%
Cadmium	>99.96%
Copper	>99.87%
Iron	>99.91%
Lead	97.35%
Manganese	99.86%
Zinc	>99.97%

Notes:
Source: Nordwick and Bless, 2008
EPA calculated removal efficiencies based on data presented in Table 4-2 in Nordwick and Bless, 2008 and reported in Table E-20.

Table E-20: Average Removal Efficiencies – Tar Creek

Constituent	Average Removal Efficiency
Iron	99.7%
Nickel	98.8%
Zinc	96.3%

Notes:

Table E-20: Average Removal Efficiencies – Tar Creek

Constituent	Average Removal Efficiency

Notes:
Source: Nairn et al., 2010b
Removal efficiencies reported in text of Nairn et al., 2010b

Table E-21: Removal Efficiencies – Wheal Jane Mine

Constituent	Removal Efficiency	Treatment System
Iron	98%	LD
Iron	>99%	ALD
Iron	>98%	LF
Zinc	65%	LD
Zinc	58%	ALD
Zinc	98%	LF
Sulfate	-40%	LD
Sulfate	-66%	ALD
Sulfate	23%	LF

Notes:
Source: Johnson and Hallberg, 2005, based sampling conducted on September 19, 2002
The ALD became nonoperational in June 2000, after which the system operated as a second limestone-dosed system
EPA calculated removal efficiency from influent and effluent concentrations in Johnson and Hallberg, 2005
Total or dissolved not specified
LD = Limestone-dosed pre-treatment
ALD = Anoxic limestone drain
LF = Limestone-free system without pre-treatment
ORP = Oxidation-reduction potential

Table E-22: Median Removal Efficiencies – Wheal Jane Mine

Constituent	Median Removal Efficiency	Treatment System
Aluminum	65%	LD
Aluminum	90%	ALD
Aluminum	35%	LF
Cadmium	78%	LD
Cadmium	98%	ALD
Cadmium	53%	LF
Copper	73%	LD
Copper	95%	ALD
Copper	42%	LF
Manganese	54%	LD
Manganese	60%	ALD
Manganese	45%	LF
Zinc	66%	LD
Zinc	73%	ALD
Zinc	47%	LF

Notes:
Source: Whitehead et al., 2005, Table 4
The authors indicated that median removal efficiencies were based on data collected from 1999-2001.
The ALD became nonoperational in June 2000, after which the system operated as a second limestone-dosed system.
Median removal efficiencies were not provided for arsenic or iron
All constituent concentrations reported as dissolved
LD = Limestone-dosed pre-treatment
ALD = Anoxic limestone drain
LF = Limestone-free system without pre-treatment

Table E-23: Pre- and Post-Reclamation Concentrations – Valzinco Mine

Constituent	Pre-Reclamation Concentration		Post-Reclamation Concentration
	Range	Mean	
Aluminum	0.6 – 19.5	3.1	0.051
Cadmium	0.0032 -0.088	0.0152	0.00091
Copper	0.049 – 2.2	0.3116	0.0097
Iron	5.0 – 69.7	17.7	1.01
Lead	0.170 – 1.3	0.349	0.0016
Manganese	0.410 – 2.1	0.779	1.12
Nickel	0.002 – 0.037	0.0085	0.0023
Sulfate	27.0 – 1,400	204	38.0
Zinc	1.9 – 27.0	5.75	1.32
Hardness	10.0 – 62.0	21.2	29.0
pH	2.6 – 4.0	3.4	5.1

Notes:
Source: Seal et al., 2008
All analytical results in mg/L
All constituent concentrations reported as dissolved
pH results reported in standard units
Hardness reported as mg/L $CaCO_3$
Data from Table 1. Pre-reclamation and post-reclamation collected at same sample location: pre-reclamation data collected 1998-2001; post-reclamation data collected June 2007

Table E-24: Influent and Effluent Concentrations – Copper Basin Mining District

Constituent	Maximum Influent	Maximum Effluent	Notes
Aluminum	1.423	0.055	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006
Copper	0.197	0.017	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006

Table E-24: Influent and Effluent Concentrations – Copper Basin Mining District

Constituent	Maximum Influent	Maximum Effluent	Notes
Iron	0.211	0.133	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006
Manganese	1.148	0.294	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006
Sulfate	110	104	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006
Zinc	0.640	0.197	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006
Acidity	37	<1	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006
Alkalinity	<1	45	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006
Hardness	97	142	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006
pH	4.28	7.16	Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006

Notes:
Source: U.S. EPA, 2006b
All analytical results in mg/L
All constituent concentrations reported as total except for manganese, which was reported as dissolved
pH results reported in standard units
NA = not applicable

Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

Constituent[a]	Average Influent	Average Effluent	Timeframe	Notes
Cobalt	0.015	0.006	Jan. to Sept. 1998	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
Copper	0.026	0.009	1999 to 2004	EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005

Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

Constituent[a]	Average Influent	Average Effluent	Timeframe	Notes
Copper	0.029	0.011	Jan. to Sept. 1998	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
Nickel	2.08	1.4	1999 to 2004	EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005
Nickel	1.600	0.902	Jan. to Sept. 1998	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
Zinc	0.052	0.032	1999 to 2004	EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005
Zinc	0.059	0.033	Jan. to Sept. 1998	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
pH	7.41	7.3	1999 to 2004	EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005
pH	7.20	7.01	Jan. to Sept. 1998	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
Cobalt	0.13	0.04	1995 to 1997	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Copper	0.15	0.05	1995 to 1997	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Copper	0.325	0.043	1999 to 2004	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Nickel	5.39	1.85	1995 to 1997	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Nickel	6.64	3.27	1999 to 2004	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Zinc	0.65	0.29	1995 to 1997	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Zinc	0.928	0.385	1999 to 2004	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
pH	6.94	7.23	1995 to 1997	Seep 1 aerobic wetland with post-treatment limestone bed– Eger and Eger, 2005

Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

Constituent[a]	Average Influent	Average Effluent	Timeframe	Notes
pH	7.28	7.34	1999 to 2004	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Cobalt	0.08	0.02	1995 to 1997	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Copper	0.33	0.08	1995 to 1997	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Copper	0.37	0.11	1999 to 2004	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Nickel	1.5	0.61	1995 to 1997	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Nickel	1.82	1.09	1999 to 2004	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Zinc	0.48	0.21	1995 to 1997	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Zinc	0.58	0.37	1999 to 2004	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
pH	7.03	7.13	1995 to 1997	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
pH	7.38	7.35	1999 to 2004	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Cobalt	0.02	0.002	1992 to 1994	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Cobalt	0.02	0.002	1992 to 1997	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010
Cobalt	0.02	NR	1996 to 1998	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Cobalt[b]	0.02	NR	1999 to 2004	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Copper	0.05	0.004	1992 to 1994	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005

Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

Constituent[a]	Average Influent	Average Effluent	Timeframe	Notes
Copper	0.05	0.004	1992 to 1997	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010
Copper	0.05	<0.001	1996 to 1998	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Copper[b]	0.05	0.002	1999 to 2004	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Nickel	1.90	0.08	1992 to 1994	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Nickel	1.90	0.080	1992 to 1997	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010
Nickel	1.90	0.06	1996 to 1998	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Nickel[b]	1.90	0.036	1999 to 2004	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Zinc	0.05	0.008	1992 to 1994	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Zinc	0.05	0.008	1992 to 1997	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010
Zinc	0.05	<0.001	1996 to 1998	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Zinc[b]	0.05	0.006	1999 to 2004	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
pH	7.0	7.0	1992 to 1994	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
pH	7.0	7.0	1992 to 1997	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010
pH	7.0	7.0	1996 to 1998	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
pH[b]	7.0	7.4	1999 to 2004	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005

Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

Constituent[a]	Average Influent	Average Effluent	Timeframe	Notes
Notes: Sources: Eger and Eger, 2005 and ITRC, 2010 All analytical results reported in mg/L pH reported in standard units a = total or dissolved not specified b = reported values noted as being estimates NR = not reported				

Table E-26: Average Removal Efficiencies – Dunka Mine

Constituent[a]	Timeframe	Average Removal Efficiency	Notes
Cobalt	Jan. to Sept. 1998	60%	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
Copper	1999 to 2004	65%	EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005
Copper	Jan. to Sept. 1998	62%	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
Nickel	1999 to 2004	33%	EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005
Nickel[b]	Jan. to Sept. 1998	44%	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
Zinc	1999 to 2004	38%	EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005
Zinc	Jan. to Sept. 1998	44%	EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010
Cobalt	1995 to 1997	69%	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005

Table E-26: Average Removal Efficiencies – Dunka Mine

Constituent[a]	Timeframe	Average Removal Efficiency	Notes
Copper	1995 to 1997	67%	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Copper	1999 to 2004	87%	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Nickel	1995 to 1997	66%	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Nickel	1999 to 2004	51%	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Zinc	1995 to 1997	55%	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Zinc	1999 to 2004	59%	Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005
Cobalt	1995 to 1997	75%	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Copper	1995 to 1997	76%	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Copper	1999 to 2004	70%	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Nickel	1995 to 1997	59%	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Nickel	1999 to 2004	40%	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Zinc	1995 to 1997	56%	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Zinc	1999 to 2004	36%	Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005
Cobalt	1992 to 1994	90%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Cobalt	1992 to 1997	90%	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010

Table E-26: Average Removal Efficiencies – Dunka Mine

Constituent[a]	Timeframe	Average Removal Efficiency	Notes
Copper	1992 to 1994	92%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Copper	1992 to 1997	92%	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010
Copper	1996 to 1998	99%[c]	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Copper	1999 to 2004	96%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Nickel	1992 to 1994	96%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Nickel	1992 to 1997	96%	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010
Nickel	1996 to 1998	97%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Nickel[b]	1999 to 2004	98%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Zinc	1992 to 1994	84%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Zinc	1992 to 1997	84%	W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010
Zinc	1996 to 1998	99%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005
Zinc	1999 to 2004	88%	W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005

Notes:

Sources: Eger and Eger, 2005 and ITRC, 2010

EPA calculated average removal efficiencies from average influent and effluent values presented in Table E-5 for each timeframe

a = Total or dissolved not specified, unless noted otherwise

b = Total

d = ½ the average detection limit used to calculate average removal efficiency

Table E-27: Flow Rates – All Treatment Train Mine Sites

Site	Flow Rate (L/min)	Source	Notes
Calliope	3.8 with four months at 7.6	Wilmoth, 2002	Operational flow rate
Copper Basin	1,102	U.S. EPA, 2006b	Average flow rate
Dunka	310	ITRC, 2010	Average flow rate; Jan. to Sept. 1998; EM8 aerobic wetland with limestone beds incorporated into the wetland
	400	Eger and Eger, 2005	Average flow rate; 1995 to 1997; EM8 aerobic wetland with limestone beds incorporated into the wetland
	20	Eger and Eger, 2005	Average flow rate; 1995 to 1997; Seep 1 aerobic wetland with post-treatment limestone bed
	27	Eger and Eger, 2005	Average flow rate; 1999 to 2004; Seep 1 aerobic wetland with post-treatment limestone bed
	100	Eger and Eger, 2005	Average flow rate; 1995 to 1997; Seep X aerobic wetland with pre- and post-treatment limestone beds
	103	Eger and Eger, 2005	Average flow rate; 1999 to 2004; Seep X aerobic wetland with pre- and post-treatment limestone beds

Table E-27: Flow Rates – All Treatment Train Mine Sites

Site	Flow Rate (L/min)	Source	Notes
	75	Eger and Eger, 2005	Average flow rate; 1992 to 1994; W2D/3D aerobic wetland with post-treatment limestone beds
	75	Eger and Eger, 2005	Average flow rate; 1992 to 1997; W2D/3D aerobic wetland with post-treatment limestone beds
	45	Eger and Eger, 2005	Average flow rate; 1996 to 1998; W2D/3D aerobic wetland with post-treatment limestone beds
	45	Eger and Eger, 2005	Average flow rate; 1999 to 2004; W2D/3D aerobic wetland with post-treatment limestone beds
Force Crag	510 – 1,464	Jarvis et al., 2015	Influent flow rate range; 2011-2014
	888	Jarvis et al., 2015	Average flow rate; 2011-2014
	360	Jarvis et al., 2015	Design flow rate
Golden Sunlight	11.4	Bless et al., 2008	Design flow rate; BCR operated at 7.6 L/min
Leviathan	31.8 (gravity-flow mode) 34.2 (recirculation mode)	Doshi, 2006	Reported for 2003-2005
Monte Romero	1	Macías et al., 2012a	Operational flow rate in NFOL
	90	Macías et al., 2012a	Influent flow rate
Standard	3.8	Gallagher et al., 2012	Design flow rate

Table E-27: Flow Rates – All Treatment Train Mine Sites

Site	Flow Rate (L/min)	Source	Notes
Surething	7.6	Doshi, 2006	Design flow rate; actual discharge reached peaks of 38 L/min
Tar Creek	1,000	Nairn et al., 2010a	Design flow rate
Valzinco	342 – 4,200	Seal et al., 2008	Flow rate range at sample location VLZN-3
Wheal Jane	12-24	Whitehead et al., 2005	Operational flow rate range
Notes: Wilmoth, 2002 reported flow data associated with influent and effluent samples results at Calliope Mine; these flows are shown in Table E-1			

Table E-28: Average Influent and Effluent Concentrations – Monte Romero Mine

Constituent	Average Influent	Average Effluent
Aluminum	100	<0.2
Arsenic	0.507	<0.002
Calcium	250	850
Copper	5	<0.005
Iron	275	<0.2
Lead	0.174	<0.001
Magnesium	255	386
Manganese	18	19
Potassium	5	7
Silicon	37	11
Sulfate	3,430	3,770
Zinc	440	414
Eh	508	341
pH	3	6.6

Table E-28: Average Influent and Effluent Concentrations – Monte Romero Mine

Constituent	Average Influent	Average Effluent

Notes:
Source: Macías et al., 2012a
All analytical results in mg/L
All constituent concentrations reported as total
pH results reported in standard units.
Influent represents untreated water in the "Shaft" samples
Effluent is the overall system effluent, represented by "T2 Out" samples
Influent and effluent averages from Table 1 and represent monitoring from April to September 2008

Table E-29: Average Removal Efficiencies – Monte Romero Mine

Constituent	Average Removal Efficiency
Aluminum	99.90%
Arsenic	100.00%
Calcium	-240.00%
Copper	99.95%
Iron	99.96%
Lead	100.00%
Magnesium	-51.37%
Manganese	-5.56%
Potassium	-40.00%
Silicon	70.27%
Sulfate	-9.91%
Zinc	5.91%

Notes:
Source: Macías et al., 2012a
EPA calculated average removal efficiencies based on influent and effluent concentration averages provided in Table E-14