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

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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.
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## Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ALD</td>
<td>Anoxic Limestone Drain</td>
</tr>
<tr>
<td>AML</td>
<td>Abandoned Mine Lands</td>
</tr>
<tr>
<td>ARD</td>
<td>Acid Rock Drainage</td>
</tr>
<tr>
<td>BCR</td>
<td>Biochemical Reactor</td>
</tr>
<tr>
<td>BOD</td>
<td>Biological Oxygen Demand</td>
</tr>
<tr>
<td>Clu-In</td>
<td>Contaminated Site Clean-up Information</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeter</td>
</tr>
<tr>
<td>DAS</td>
<td>Dispersed Alkaline Substrate</td>
</tr>
<tr>
<td>DL</td>
<td>Detection Limit</td>
</tr>
<tr>
<td>FRTR</td>
<td>Federal Remediation Technologies Roundtable</td>
</tr>
<tr>
<td>HDS</td>
<td>High-density Sludge</td>
</tr>
<tr>
<td>ITRC</td>
<td>Interstate Technology and Regulatory Council</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>LD</td>
<td>Limestone-dosed</td>
</tr>
<tr>
<td>LF</td>
<td>Limestone-free</td>
</tr>
<tr>
<td>L/min</td>
<td>Liters per minute</td>
</tr>
<tr>
<td>m²</td>
<td>Square meter</td>
</tr>
<tr>
<td>mg/L</td>
<td>Milligrams per liter</td>
</tr>
<tr>
<td>MIW</td>
<td>Mining-influenced Water</td>
</tr>
<tr>
<td>NA</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>ND</td>
<td>Not Detected</td>
</tr>
<tr>
<td>NFOL</td>
<td>Natural Iron (Fe)-Oxidizing Lagoon</td>
</tr>
<tr>
<td>NS</td>
<td>Not Stated</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation and Maintenance</td>
</tr>
<tr>
<td>PRB</td>
<td>Permeable Reactive Barrier</td>
</tr>
<tr>
<td>RAPS</td>
<td>Reducing and Alkalinity Producing System</td>
</tr>
<tr>
<td>RL</td>
<td>Reporting Limit</td>
</tr>
<tr>
<td>SME</td>
<td>Silica Microencapsulation</td>
</tr>
<tr>
<td>SRB</td>
<td>Sulfate-reducing Bacteria</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>SRBR</td>
<td>Sulfate-reducing Bioreactor</td>
</tr>
<tr>
<td>TCLP</td>
<td>Toxicity Characteristic Leaching Procedure</td>
</tr>
<tr>
<td>VFP</td>
<td>Vertical Flow Pond</td>
</tr>
<tr>
<td>WTP</td>
<td>Water Treatment Plant</td>
</tr>
<tr>
<td>μg/l</td>
<td>Micrograms per liter</td>
</tr>
<tr>
<td>μm</td>
<td>Micrometer</td>
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</table>
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 (m²) |
| 1 square meters (m²) | = | 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 (ft³/s, or cfs) |
| 1 cubic foot per second (ft³/s, or cfs) | = | 1.699 | liters per minute (L/min) |
| 1 liter per minute (L/min) | = | 1.6667 × 10⁻⁵ | cubic meters per second (m³/s) |
| 1 cubic meter per second (m³/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 (m³/s) | = | 15,850 | gallons per minute (gal/min, or gpm) |
| 1 gallons per minute (gal/min, or gpm) | = | 6.309 × 10⁻⁵ | cubic meter per second (m³/s) |

#### Length

| 1 foot (ft) | = | 0.3048 | meters (m) |
| 1 meter (m) | = | 3.28084 | feet (ft) |

#### Volume

| 1 cubic meter (m³) | = | 264.171928 | gallons (gal) |
| 1 gallon (gal) | = | 0.00378541 | cubic meter (m³) |
| 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), or 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

Biochemical Reactors

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.

\[
CH_3COOH + SO_4^{2-} \leftrightarrow 2HCO_3^- + H_2S \\
H_2S(aq) \leftrightarrow HS^- + H^+, pK_a \approx 7 \\
HS^- + Me^{2+} \leftrightarrow MeS + H^+, where Me^{2+} = any divalent metal
\]

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

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>BCR Type</th>
<th>System Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calliope Mine, Butte, Montana</td>
<td>Anaerobic, solid substrate</td>
<td>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; pretreatment units contained additional organic matter and limestone.</td>
<td>Pilot scale (technology demonstration)</td>
<td>Wilmoth, 2002*</td>
<td>Report</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bless et al., 2008</td>
<td>Journal paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nordwick et al., 2006</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Site Name and Location</td>
<td>BCR Type</td>
<td>System Description</td>
<td>Study Type</td>
<td>Reference</td>
<td>Reference Type</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------</td>
<td>------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Confidential Mine, Montana</td>
<td>Anaerobic, solid substrate</td>
<td>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.</td>
<td>Pilot scale (technology demonstration)</td>
<td>Blumenstein and Gusek, 2009*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Cwm Rheidol Mine, Wales, UK</td>
<td>Anaerobic, solid substrate</td>
<td>Vertical-flow bioreactor contained shells, wood chips, compost and anaerobic digested sludge.</td>
<td>Pilot scale</td>
<td>Jarvis et al., 2014*</td>
<td>Report</td>
</tr>
<tr>
<td>Force Crag, Cumbria, UK</td>
<td>Anaerobic, solid substrate</td>
<td>Parallel vertical-flow ponds contained compost, woodchips and dried activated sewage sludge, followed by an aerobic wetland.</td>
<td>Full scale</td>
<td>Jarvis et al., 2015*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Keno Hill, Yukon, Canada</td>
<td>Anaerobic, liquid substrate</td>
<td>Liquid BCR filled with adit water supplemented with sucrose, methanol and dried milk solids; continuous methanol once established.</td>
<td>Pilot scale</td>
<td>Harrington et al., 2015*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Leviathan Mine</td>
<td></td>
<td>System consisted of a pretreatment</td>
<td>Full scale</td>
<td>Doshi, 2006</td>
<td>Report</td>
</tr>
</tbody>
</table>
## Table 3-1: Bioreactor Case Study Sites

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>BCR Type</th>
<th>System Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpine County, California</td>
<td>Anaerobic, liquid</td>
<td>pond (using 25 percent sodium hydroxide and ethanol), two BCRs in series, two</td>
<td>Pilot scale (technology demonstration)</td>
<td>U.S. EPA, 2006a*</td>
<td>Report</td>
</tr>
<tr>
<td></td>
<td>substrate</td>
<td>continuous flow-settling ponds, and an aeration channel; BCRs were lined with high-density polyethylene, river rock and manure.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lilly Orphan Boy Mine</td>
<td>Anaerobic, solid</td>
<td>In-situ BCR built within the mine shaft and containing 70 percent cow manure, 20 percent decomposed wood chips and 10 percent alfalfa straw.</td>
<td>Pilot scale</td>
<td>Bless et al., 2008*</td>
<td>Journal paper</td>
</tr>
<tr>
<td>Elliston, Montana</td>
<td>substrate</td>
<td></td>
<td></td>
<td>Doshi, 2006</td>
<td>Report</td>
</tr>
<tr>
<td>Nenthead Cumbria, United</td>
<td>Anaerobic, solid</td>
<td>Vertical flow bioreactor containing compost, wood chips and activated digested sludge.</td>
<td>Pilot scale</td>
<td>Jarvis et al., 2014*</td>
<td>Report</td>
</tr>
<tr>
<td>Kingdom</td>
<td>substrate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Mine Crested Butte,</td>
<td>Anaerobic, solid</td>
<td>System comprised a BCR followed by aerobic polishing cells; BCR contained hay, wood chips, limestone and cow manure.</td>
<td>Pilot scale</td>
<td>Gallagher et al., 2012*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Colorado</td>
<td>substrate</td>
<td></td>
<td></td>
<td>Reisman et al., 2009*</td>
<td>Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Butler et al., 2011</td>
<td>Journal paper</td>
</tr>
</tbody>
</table>
Table 3-1: Bioreactor Case Study Sites

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>BCR Type</th>
<th>System Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surething Mine</td>
<td>Anaerobic and aerobic, solid substrates</td>
<td>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.</td>
<td>Pilot scale (technology demonstration)</td>
<td>Nordwick and Bless, 2008*</td>
<td>Report</td>
</tr>
</tbody>
</table>

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
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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>14.1 mg/L</td>
<td>0.0453 mg/L</td>
<td>Calliope (BCR III)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1.25 mg/L</td>
<td>0.01 mg/L</td>
<td>Surething (Reactor 1)</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.385 mg/L</td>
<td>0.005 mg/L</td>
<td>Surething (Reactor 1)</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Copper</td>
<td>4.25 mg/L</td>
<td>&lt;0.003 mg/L</td>
<td>Surething (Reactor 1)</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Iron</td>
<td>89.8 mg/L</td>
<td>0.7 mg/L</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Lead</td>
<td>6 mg/L</td>
<td>&lt;0.008 mg/L</td>
<td>Standard</td>
<td>Reisman et al., 2009</td>
</tr>
<tr>
<td>Manganese</td>
<td>65 mg/L</td>
<td>20 mg/L</td>
<td>Surething (Reactor 1)</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Nitrate</td>
<td>7.9 mg/L</td>
<td>ND</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.025 mg/L</td>
<td>ND</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Sulfate</td>
<td>900 mg/L</td>
<td>450 mg/L</td>
<td>Surething (Reactor 1)</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Thallium</td>
<td>1.6 mg/L</td>
<td>&lt;0.001 mg/L</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Zinc</td>
<td>39 mg/L</td>
<td>&lt;0.007 mg/L</td>
<td>Surething (Reactor 1)</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>pH</td>
<td>3.29 mg/L</td>
<td>7.56 mg/L</td>
<td>Calliope (BCR III)</td>
<td>Wilmoth, 2002</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.011 mg/L</td>
<td>0.0094 mg/L</td>
<td>Calliope (BCR III)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.0051 mg/L</td>
<td>&lt;0.005 mg/L</td>
<td>Calliope (BCR III)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0051 mg/L</td>
<td>0.0056 mg/L</td>
<td>Calliope (BCR III)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Copper</td>
<td>0.003 mg/L</td>
<td>0.0013 mg/L</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Iron</td>
<td>0.008 mg/L</td>
<td>0.031 mg/L</td>
<td>Calliope (BCR III)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Lead</td>
<td>0.011 mg/L</td>
<td>0.0009 mg/L</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.69 mg/L</td>
<td>0.076 mg/L</td>
<td>Calliope (BCR III)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Nitrate</td>
<td>2.9 mg/L</td>
<td>0.1 mg/L</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.01 mg/L</td>
<td>ND</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
</tbody>
</table>
Table 3-3: Minimum Influent and Corresponding Effluent Concentrations

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfate</td>
<td>40 mg/L</td>
<td>106 mg/L</td>
<td>Surething (Reactor 1)</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Thallium</td>
<td>0.25 mg/L</td>
<td>&lt;0.001 mg/L</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.7 mg/L</td>
<td>0.2 mg/L</td>
<td>Nenthead</td>
<td>Jarvis et al., 2014</td>
</tr>
<tr>
<td>pH</td>
<td>8.0</td>
<td>7.2</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>9.7</td>
<td>&lt;0.02</td>
<td>Lilly/Orphan Boy&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1.07&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.075</td>
<td>Lilly/Orphan Boy&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.33</td>
<td>&lt;0.005</td>
<td>Lilly/Orphan Boy&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>Copper</td>
<td>0.4078</td>
<td>0.0546</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Iron</td>
<td>27.7</td>
<td>11.25</td>
<td>Lilly/Orphan Boy&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>Lead&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.54</td>
<td>0.01</td>
<td>Standard</td>
<td>Reisman et al., 2009</td>
</tr>
<tr>
<td>Manganese</td>
<td>10.99</td>
<td>10.53</td>
<td>Standard</td>
<td>Reisman et al., 2009</td>
</tr>
<tr>
<td>Nitrate&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.1</td>
<td>0.08</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Selenium&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.013</td>
<td>0.001</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Sulfate</td>
<td>281</td>
<td>119</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Thallium&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.25</td>
<td>0.007</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Zinc</td>
<td>26.46</td>
<td>0.55</td>
<td>Standard</td>
<td>Reisman et al., 2009</td>
</tr>
<tr>
<td>pH</td>
<td>3.0</td>
<td>7.2</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008</td>
</tr>
</tbody>
</table>

Notes:
- <sup>a</sup> = 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
- <sup>b</sup> = Lead was monitored only at the Standard Mine
- <sup>c</sup> = Nitrate, selenium and thallium were monitored only at the Confidential Mine site
Table 3-5: Minimum Average Influent Concentration Treated

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1.2229</td>
<td>0.0616</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.075&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Lilly/Orphan Boy&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0112</td>
<td>&lt;0.005</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Copper</td>
<td>0.26</td>
<td>&lt;0.0038</td>
<td>Standard</td>
<td>Reisman et al., 2009</td>
</tr>
<tr>
<td>Iron</td>
<td>0.4556</td>
<td>0.4143</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Lead</td>
<td>0.54</td>
<td>0.01</td>
<td>Standard</td>
<td>Reisman et al., 2009</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.4581</td>
<td>1.0073</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Nitrate&lt;sup&gt;c&lt;/sup&gt;</td>
<td>5.1</td>
<td>0.08</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Selenium&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.013</td>
<td>0.001</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Sulfate</td>
<td>0.1029</td>
<td>0.1039</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Thallium&lt;sup&gt;c&lt;/sup&gt;</td>
<td>1.25</td>
<td>0.007</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Zinc</td>
<td>2.8406</td>
<td>0.7944</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>pH</td>
<td>6.05</td>
<td>7.16</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.0616</td>
<td>1.2229</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.075</td>
<td>1.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Lilly/Orphan Boy&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>Cadmium</td>
<td>&lt;0.005</td>
<td>0.0112</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0546</td>
<td>0.4078</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Iron</td>
<td>11.25</td>
<td>27.7</td>
<td>Lilly/Orphan Boy&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Bless et al., 2008</td>
</tr>
</tbody>
</table>
### Table 3-6: Maximum Average Effluent Concentration Attained

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

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>&lt;0.02</td>
<td>9.7</td>
<td>Lilly/Orphan Boy(^a)</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.075</td>
<td>1.07(^b)</td>
<td>Lilly/Orphan Boy(^a)</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.00019</td>
<td>0.095(^c)</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0014</td>
<td>0.1(^c)</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Iron</td>
<td>0.4143</td>
<td>0.4556</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Lead</td>
<td>0.00215</td>
<td>0.134(^c)</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.0073</td>
<td>1.4581</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Nitrate(^d)</td>
<td>0.08</td>
<td>5.1</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Selenium(^d)</td>
<td>0.001</td>
<td>0.013</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Sulfate</td>
<td>0.1039</td>
<td>0.1029</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
</tbody>
</table>

Concentrations reported as dissolved in mg/L; pH reported in standard units
Table 3-7: Minimum Average Effluent Concentration Attained

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thallium่อ</td>
<td>0.007</td>
<td>1.25</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.032</td>
<td>26.1</td>
<td>Lilly/Orphan Boyा</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>pH</td>
<td>7.2</td>
<td>3.0</td>
<td>Lilly/Orphan Boyｂ</td>
<td>Bless et al, 2008</td>
</tr>
</tbody>
</table>

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 CuS, 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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum(^a)</td>
<td>99.73%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Arsenic(^a)</td>
<td>86.89%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Cadmium</td>
<td>99.80%</td>
<td>Standard(^d)</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Copper</td>
<td>99.37%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Iron</td>
<td>97.94%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Lead(^a)</td>
<td>98.40%</td>
<td>Standard(^d)</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Manganese(^a)</td>
<td>98.05%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Nitrate(^f)</td>
<td>&gt;99%</td>
<td>Confidential(^g)</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Selenium(^f)</td>
<td>&gt;99%</td>
<td>Confidential(^g)</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Sulfate</td>
<td>57.20%</td>
<td>Standard(^d)</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Thallium(^f)</td>
<td>99.97%</td>
<td>Confidential(^h)</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Zinc</td>
<td>100.00%</td>
<td>Cwm Rheidol(^d)</td>
<td>Jarvis et al., 2014</td>
</tr>
</tbody>
</table>

**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 nondetect results, EPA used ½ the detection limit for calculations

**Table 3-9: Minimum Removal Efficiencies**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum(^a)</td>
<td>-650.00%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Arsenic(^a)</td>
<td>-95.38%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Cadmium</td>
<td>-9.80%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Copper</td>
<td>-189.59%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Iron</td>
<td>-14275.00%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Lead(^d)</td>
<td>98.10%</td>
<td>Standard(^e)</td>
<td>Reisman et al., 2009</td>
</tr>
</tbody>
</table>
Table 3-9: Minimum Removal Efficiencies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese(^a)</td>
<td>-108.22%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Nitrate(^f)</td>
<td>96.55%</td>
<td>Confidential(^e,g)</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Selenium(^f)</td>
<td>&gt;99%</td>
<td>Confidential(^e,h)</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-68.63%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Thallium(^f)</td>
<td>99.8%</td>
<td>Confidential(^e,g)</td>
<td>Blumenstein and Gusek, 2009</td>
</tr>
<tr>
<td>Zinc</td>
<td>-11.97%</td>
<td>Calliope – BCR III(^b,c)</td>
<td>Wilmoth, 2002</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Operational Flow Rate</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>All rates are in liters per minute (L/min)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3-10: Flow Rate – Anaerobic, Solid Substrate

<table>
<thead>
<tr>
<th>Operational Flow Rate</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8(^a)</td>
<td>Calliope</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>3.8 – 19.3(^b)</td>
<td>Confidential</td>
<td>Blumenstein and Gusek, 2009 (Figure 6, text)</td>
</tr>
<tr>
<td>1.9 – 4.5</td>
<td>Cwm Rheidol</td>
<td>Jarvis et al., 2014</td>
</tr>
<tr>
<td>1.1</td>
<td>Nenthead</td>
<td>Jarvis et al., 2014</td>
</tr>
<tr>
<td>7.6</td>
<td>Lilly Orphan Boy</td>
<td>Bless et al., 2008</td>
</tr>
<tr>
<td>3.8</td>
<td>Standard</td>
<td>Gallager et al., 2012</td>
</tr>
<tr>
<td>&lt; 7.6(^c)</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>All concentrations reported in mg/L; pH reported in standard units</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum&lt;sup&gt;a&lt;/sup&gt;</td>
<td>36.3</td>
<td>28.3</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.0059</td>
<td>0.005</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.00042</td>
<td>&lt; 0.00023</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.0147</td>
<td>0.0139</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.653</td>
<td>0.0676</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron&lt;sup&gt;a&lt;/sup&gt;</td>
<td>87</td>
<td>77.7</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.0059</td>
<td>0.0055</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.475</td>
<td>0.37</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.0114</td>
<td>0.0116</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Sulfate&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1520</td>
<td>1480</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.714</td>
<td>0.125</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>pH</td>
<td>3.6</td>
<td>4.7</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>

**Notes:**
- a = Total
- b = Dissolved

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrations reported in mg/L and as dissolved, except sulfate (total); pH reported in standard units</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.104</td>
<td>0.108</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.0028</td>
<td>&lt;0.0023</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.00021</td>
<td>0.00041</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.0118</td>
<td>0.012</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0057</td>
<td>0.0061</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron</td>
<td>0.266</td>
<td>0.247</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.0117</td>
<td>0.0102</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0042</td>
<td>0.0040</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.0075</td>
<td>0.0114</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Sulfate</td>
<td>1160</td>
<td>1090</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.0063</td>
<td>0.0104</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>pH</td>
<td>7.2</td>
<td>7.3</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>
Table 3-13: Maximum Influent and Corresponding Effluent Concentrations – Keno Hill

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>0.07</td>
<td>0.008</td>
<td>Keno Hilla</td>
<td>Harrington et al., 2015</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0016</td>
<td>&lt;0.0001</td>
<td>Keno Hilla</td>
<td>Harrington et al., 2015</td>
</tr>
<tr>
<td>Manganese</td>
<td>19</td>
<td>20</td>
<td>Keno Hilla</td>
<td>Harrington et al., 2015</td>
</tr>
<tr>
<td>Zinc</td>
<td>6.2</td>
<td>0.01</td>
<td>Keno Hilla</td>
<td>Harrington et al., 2015</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>0.018</td>
<td>0.001</td>
<td>Keno Hilla</td>
<td>Harrington et al., 2015</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0011</td>
<td>&lt;0.0001</td>
<td>Keno Hilla</td>
<td>Harrington et al., 2015</td>
</tr>
<tr>
<td>Manganese</td>
<td>15</td>
<td>16</td>
<td>Keno Hilla</td>
<td>Harrington et al., 2015</td>
</tr>
<tr>
<td>Zinc</td>
<td>4.8</td>
<td>0.055</td>
<td>Keno Hilla</td>
<td>Harrington et al., 2015</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Removal Efficiency</th>
<th>Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum&lt;sup&gt;a&lt;/sup&gt;</td>
<td>66.80%</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium&lt;sup&gt;a&lt;/sup&gt;</td>
<td>45.20%</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.90%</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper&lt;sup&gt;b&lt;/sup&gt;</td>
<td>99.10%</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron&lt;sup&gt;b&lt;/sup&gt;</td>
<td>94.60%</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.00%</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel&lt;sup&gt;b&lt;/sup&gt;</td>
<td>83.90%</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium&lt;sup&gt;b&lt;/sup&gt;</td>
<td>23.90%</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Sulfate&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.50%</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc&lt;sup&gt;a&lt;/sup&gt;</td>
<td>95.20%</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>

**Notes:**

<sup>a</sup> = Total
<sup>b</sup> = 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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.00%</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>0.00%</td>
<td>Recirculation and Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium&lt;sup&gt;a,b&lt;/sup&gt;</td>
<td>0.00%</td>
<td>Recirculation and Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-6.50%</td>
<td>Recirculation and Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.90%</td>
<td>Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead&lt;sup&gt;b&lt;/sup&gt;</td>
<td>-9.30%</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel&lt;sup&gt;b&lt;/sup&gt;</td>
<td>12.80</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.00%</td>
<td>Recirculation and Gravity</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Sulfate&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.50%</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-6.60%</td>
<td>Recirculation</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>
Table 3-16: Minimum Removal Efficiencies – Leviathan

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Mode</th>
<th>Source</th>
</tr>
</thead>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
</table>

All results reported as total  
Antimony  
Arsenic  
Nickel  
Zinc

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). 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 m³ (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).

---

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.
Biochemical Reactors

- 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


3.9.2 General BCR References


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>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Type</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kristineberg Mine, Northern Sweden</td>
<td>Composite cover consisting of till (protective layer) and sewage sludge (sealing layer)</td>
<td>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.</td>
<td>Pilot scale</td>
<td>Nason et al., 2013*</td>
<td>Journal paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nason, 2013</td>
<td>Conference proceedings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nason et al., 2010</td>
<td>Conference proceedings</td>
</tr>
</tbody>
</table>
### Table 4-1: Caps and Covers Case Study Sites

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Type</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savage River Mine, Tasmania, Australia</td>
<td>Watershed top cover and alkaline (calcite-chlorite schist) side cover</td>
<td>To control acid rock drainage (ARD), a combined watershedding and calcite-chlorite schist cover was placed over a historic dump (B-dump).</td>
<td>Full scale</td>
<td>Li et al., 2012*</td>
<td>Conference proceedings</td>
</tr>
<tr>
<td>Dunka Mine, Northeastern Minnesota</td>
<td>Several covers consisting of screened soil, compacted soil and/or flexible membrane liner</td>
<td>Five waste rock stockpiles were covered.</td>
<td>Full scale</td>
<td>Eger and Eger, 2005*</td>
<td>Conference proceedings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger et al., 1998</td>
<td>Conference proceedings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger et al., 1996</td>
<td>Conference proceedings</td>
</tr>
</tbody>
</table>

**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**

Ranges of applicability differ 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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Pre-Capping (or Uncapped Control) Concentration Range</th>
<th>Post-Capping Concentration Range</th>
<th>Media</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>ND – 0.03</td>
<td>ND</td>
<td>Leachate</td>
<td>Nason et al., 2013</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0005 – 0.04</td>
<td>ND – 0.001</td>
<td>Leachate</td>
<td>Nason et al., 2013</td>
</tr>
<tr>
<td>Iron</td>
<td>ND – 0.022</td>
<td>ND – 0.005</td>
<td>Leachate</td>
<td>Nason et al., 2013</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0001 – 0.00065</td>
<td>0.0001 – 0.00055</td>
<td>Leachate</td>
<td>Nason et al., 2013</td>
</tr>
<tr>
<td>Sulfur</td>
<td>410 – 700</td>
<td>15 – 220</td>
<td>Leachate</td>
<td>Nason et al., 2013</td>
</tr>
<tr>
<td>Zinc</td>
<td>2.5 – 40</td>
<td>ND</td>
<td>Leachate</td>
<td>Nason et al., 2013</td>
</tr>
<tr>
<td>pH</td>
<td>6.2 – 7.6</td>
<td>6.8 – 8.2</td>
<td>Leachate</td>
<td>Nason et al., 2013</td>
</tr>
</tbody>
</table>

**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>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Pre-Capping Leachate Concentration</th>
<th>Average Post-Capping Leachate Concentration Range</th>
<th>Stockpile/Wetland</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.036</td>
<td>0.009(a)</td>
<td>8018 and 8031/W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.068</td>
<td>0.02 – 0.03</td>
<td>8018 and 8031/W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>3.98</td>
<td>0.74 – 0.76</td>
<td>8018 and 8031/W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.052</td>
<td>0.019 – 0.021</td>
<td>8018 and 8031/W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH</td>
<td>7</td>
<td>7</td>
<td>8031/W2D/3D</td>
<td>Eger and Eger, 2005</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Pre-Capping Leachate Concentration</th>
<th>Average Post-Capping Leachate Concentration</th>
<th>Stockpile/Wetland</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.02</td>
<td>0.02</td>
<td>8031/W2D/3D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.05</td>
<td>0.05</td>
<td>8031/W2D/3D</td>
<td>Eger and Eger, 2005</td>
</tr>
</tbody>
</table>
### Table 4-4: Minimum Average Pre-Capping Leachate and Post-Capping Leachate Concentrations (1996-1998) – Dunka Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Pre-Capping Leachate Concentration</th>
<th>Average Post-Capping Leachate Concentration</th>
<th>Stockpile/Wetland</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>1.9</td>
<td>1.9</td>
<td>8031/W2D/3D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.05</td>
<td>0.05</td>
<td>8031/W2D/3D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH</td>
<td>7.07</td>
<td>7.26 – 7.3</td>
<td>8018 and 8031/W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
</tbody>
</table>

Concentrations reported in mg/L, total or dissolved not specified; pH reported in standard units

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

<table>
<thead>
<tr>
<th></th>
<th>Under Alkaline Cover</th>
<th>No Cover</th>
<th>Pre-Cover</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Percentage of Total Sulfur (%)</td>
<td>1.9</td>
<td>0.9</td>
<td>3.2a</td>
<td>Li et al., 2012</td>
</tr>
<tr>
<td>MPA (Sulfur)</td>
<td>57.1</td>
<td>27.2</td>
<td>97.2</td>
<td>Li et al., 2012</td>
</tr>
<tr>
<td>Decrease in Percentage of Total Sulfur between 2005 and 2010 (%)</td>
<td>41</td>
<td>72</td>
<td></td>
<td>Li et al., 2012</td>
</tr>
</tbody>
</table>

Notes:
- Table reproduced from Table 5 in source
- MPA = maximum potential acidity expressed as kg H₂SO₄/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) H₂SO₄/t) than the un-capped waste rock (27.2 kg H₂SO₄/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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Percentage Reduction</th>
<th>Minimum Percentage Reduction</th>
<th>Mine</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>&gt;99.00%</td>
<td>&gt;99.00%</td>
<td>Kristineberg&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Table B-1</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>&gt;99.00%</td>
<td>97.5%</td>
<td>Kristineberg&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Table B-1</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>&gt;99.00%</td>
<td>77.27%</td>
<td>Kristineberg&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Table B-1</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>84.62%</td>
<td>0.00%</td>
<td>Kristineberg&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Table B-1</td>
</tr>
<tr>
<td>Sulfur</td>
<td>Dissolved</td>
<td>97.86%</td>
<td>46.34%</td>
<td>Kristineberg&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Table B-1</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>&gt;99.00%</td>
<td>&gt;99.00%</td>
<td>Kristineberg&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Table B-1</td>
</tr>
<tr>
<td>Cobalt</td>
<td>NS</td>
<td>75.00%</td>
<td>75.00%&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Dunka&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Table B-2 (Wetland W1D)</td>
</tr>
<tr>
<td>Copper</td>
<td>NS</td>
<td>70.59%</td>
<td>55.88%</td>
<td>Dunka&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Table B-2 (Wetland W1D)</td>
</tr>
<tr>
<td>Nickel</td>
<td>NS</td>
<td>81.41%</td>
<td>80.90%</td>
<td>Dunka&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Table B-2 (Wetland W1D)</td>
</tr>
<tr>
<td>Zinc</td>
<td>NS</td>
<td>63.46%</td>
<td>59.62%</td>
<td>Dunka&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Table B-2 (Wetland W1D)</td>
</tr>
</tbody>
</table>

**Notes:**
NA = Pre-reclamation concentrations were not detected
NS = Not stated
<sup>a</sup> = 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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Percentage Reduction</th>
<th>Minimum Percentage Reduction</th>
<th>Mine</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Average Flow</th>
<th>Stockpile</th>
<th>Pre- or Post-Capping Date Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>All rates are in L/min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>W2D/3D</td>
<td>Pre-capping (1992-1994)</td>
</tr>
<tr>
<td>125</td>
<td>W1D</td>
<td>Pre-capping (1992-1994)</td>
</tr>
<tr>
<td>45</td>
<td>W2D/3D</td>
<td>Post-capping (1996-1998)</td>
</tr>
<tr>
<td>57</td>
<td>W1D</td>
<td>Post-capping (1996-1998)</td>
</tr>
<tr>
<td>45</td>
<td>W2D/3D</td>
<td>Post-capping (1999-2004)</td>
</tr>
<tr>
<td>38</td>
<td>W1D</td>
<td>Post-capping (1999-2004)</td>
</tr>
</tbody>
</table>

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**


4.7.2 General Capping References

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 (CaCO₃), lime (CaO), hydrated (or slaked) lime (Ca(OH)₂), sodium hydroxide (NaOH), and soda ash (Na₂CO₃). 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™ (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

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Type</th>
<th>System Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leviathan Mine, Alpine County, California</td>
<td>Active lime treatment</td>
<td>Two modes employed: single-stage and dual-stage mode (1st stage for arsenic removal and 2nd stage for removing remaining constituents)</td>
<td>Pilot scale</td>
<td>U.S. EPA, 2006a*</td>
<td>Report</td>
</tr>
<tr>
<td>Britannia Mine, Vancouver, British Columbia</td>
<td>Active lime treatment</td>
<td>High-density sludge (HDS)</td>
<td>Full scale</td>
<td>Madsen et al., 2012*</td>
<td>Conference proceedings</td>
</tr>
<tr>
<td>Monte Romero Mine Southwestern Spain</td>
<td>Passive limestone DAS</td>
<td>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</td>
<td>Pilot scale</td>
<td>Macías et al., 2012a*</td>
<td>Journal paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Macias et al., 2012b</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rötting et al., 2008a</td>
</tr>
<tr>
<td>Elizabeth Mine, Strafford, Vermont</td>
<td>Active lime treatment in Rotating Cylinder Treatment System™ (RCTS)</td>
<td>An RCTS™ system followed by a sedimentation basin</td>
<td>Full scale</td>
<td>Butler and Hathaway, 2020*</td>
<td>Report</td>
</tr>
</tbody>
</table>

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
Neutralization and Chemical Precipitation

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 (CaSO₄•2H₂O) 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>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>486 mg/L</td>
<td>1.09 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>4.05 mg/L</td>
<td>0.0101 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0683 mg/L</td>
<td>0.0007 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>1.24 mg/L</td>
<td>0.0024 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>2.99 mg/L</td>
<td>0.0101 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron</td>
<td>1,710 mg/L</td>
<td>23.6 mg/L</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0122 mg/L</td>
<td>&lt;0.0014 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel</td>
<td>8.77 mg/L</td>
<td>0.0389 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.0323 mg/L</td>
<td>&lt;0.0018 mg/L</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.81 mg/L</td>
<td>0.0307 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>pH</td>
<td>4.63</td>
<td>8.65 mg/L</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>98.6 mg/L</td>
<td>0.575 mg/L</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1.33 mg/L</td>
<td>0.0096 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0132 mg/L</td>
<td>&lt;0.00021 mg/L</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.266 mg/L</td>
<td>0.0116 mg/L</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>0.434 mg/L</td>
<td>&lt;0.0019 mg/L</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>
Table 5-3: Minimum Influent and Corresponding Effluent Concentrations – Active Treatment

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>50 mg/L</td>
<td>4 mg/L</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0017 mg/L</td>
<td>0.0044 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel</td>
<td>2.41 mg/L</td>
<td>0.0688 mg/L</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.0046 mg/L</td>
<td>0.0037 mg/L</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.49 mg/L</td>
<td>0.0031 mg/L</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>pH</td>
<td>6.87</td>
<td>9.6</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020</td>
</tr>
</tbody>
</table>

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

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

**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

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

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>4.2</td>
<td>9.2(^a)</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1.118</td>
<td>381</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.00859</td>
<td>2.239</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.002</td>
<td>0.087</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.0057</td>
<td>0.877</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>0.02</td>
<td>13.9</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Iron</td>
<td>12.28 ± 12.74</td>
<td>199.15 ± 64.75</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Lead</td>
<td>0.002</td>
<td>0.0082</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.4</td>
<td>3.94/4.1(^a)</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.0468</td>
<td>2.56</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.00378</td>
<td>0.0088</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.04</td>
<td>14.8</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>pH</td>
<td>9.2(^b)</td>
<td>3.7 – 4.2(^b)</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
</tbody>
</table>

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
Neutralization and Chemical Precipitation

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.4</td>
<td>19.3</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.0063</td>
<td>3.236</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium</td>
<td>ND</td>
<td>0.0261</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.00304</td>
<td>0.341</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>0.00307</td>
<td>0.502</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron</td>
<td>&lt;0.01</td>
<td>0.95</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Lead</td>
<td>0.00156</td>
<td>0.0071</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.1</td>
<td>4.33</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.0342</td>
<td>7.024</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.00214</td>
<td>0.0271</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.00561</td>
<td>0.538</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>pH</td>
<td>9.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.7 – 4.2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Britannia</td>
<td>Madsen et al., 2012</td>
</tr>
</tbody>
</table>

Concentrations reported as dissolved in mg/L; pH reported in standard units

**Notes:**
- ND = Not detected, detection limit not reported
- <sup>a</sup> = 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
Neutralization and Chemical Precipitation

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Removal Efficiency</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>All constituents reported as dissolved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>99.9%</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>99.9%</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium</td>
<td>99.7%</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>99.9%</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>100.0%</td>
<td>Britannia a</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Iron</td>
<td>100.0%</td>
<td>Leviathan/Single-stage and Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead</td>
<td>89.8%</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Manganese</td>
<td>97.7%</td>
<td>Britannia a</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Nickel</td>
<td>99.9%</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>94.4%</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>99.9%</td>
<td>Britannia a</td>
<td>Madsen et al., 2012</td>
</tr>
</tbody>
</table>

Notes:

a = EPA calculated removal efficiencies from the average influent and effluent concentrations for each year (2006 to 2010)
Neutralization and Chemical Precipitation

Table 5-9: Minimum Removal Efficiencies – Active Treatment

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Mine/Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>All constituents reported as dissolved</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>96.90%</td>
<td>Britanniaa</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Arsenic</td>
<td>99.20%</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium</td>
<td>97.50%</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>93.80%</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>99%</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron</td>
<td>93.40%</td>
<td>Britanniaa</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Lead</td>
<td>48.30%</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Manganese</td>
<td>89.80%</td>
<td>Britanniaa</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Nickel</td>
<td>95.70%</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>91%</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>97.40%</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Maximum Influent Flow Rate</th>
<th>Minimum Influent Flow Rate</th>
<th>Average Influent Flow Rate</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>All rates are in liters per minute (L/min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>246</td>
<td>212</td>
<td>223</td>
<td>Leviathan/Single-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>662</td>
<td>587</td>
<td>640</td>
<td>Leviathan/Dual-stage</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>193.19</td>
<td>100.64</td>
<td>140.34 ± 16.83</td>
<td>Elizabeth Mine (2009)</td>
<td>Butler and Hathaway, 2020</td>
</tr>
<tr>
<td>166.13</td>
<td>92.81</td>
<td>122.67 ± 20.67</td>
<td>Elizabeth Mine (2010)</td>
<td>Butler and Hathaway, 2020</td>
</tr>
<tr>
<td>218</td>
<td>34</td>
<td>100.00 ± 27.33</td>
<td>Elizabeth Mine (2011)</td>
<td>Butler and Hathaway, 2020</td>
</tr>
<tr>
<td>102.23</td>
<td>59.25</td>
<td>85.34 ± 13.17</td>
<td>Elizabeth Mine (2012)</td>
<td>Butler and Hathaway, 2020</td>
</tr>
</tbody>
</table>
Table 5-10: Flow Rate – Active Treatment

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

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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>33.6 mg/L</td>
<td>0.254 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.545 mg/L</td>
<td>0.0129 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.0235 mg/L</td>
<td>0.0038 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0163 mg/L</td>
<td>0.0061 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron</td>
<td>460 mg/L</td>
<td>0.0172 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0063 mg/L</td>
<td>0.0026 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.69 mg/L</td>
<td>0.0472 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.007 mg/L</td>
<td>&lt;0.0025 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.369 mg/L</td>
<td>0.019 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>pH</td>
<td>4.59</td>
<td>7.92</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>

**Notes:**
- < = Not detected above laboratory method detection limit shown

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>30.9 mg/L</td>
<td>0.185 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.485 mg/L</td>
<td>0.0038 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.0162 mg/L</td>
<td>0.0014 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0092 mg/L</td>
<td>0.0031 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron</td>
<td>360 mg/L</td>
<td>0.0881 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0027 mg/L</td>
<td>&lt;0.0012 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.57 mg/L</td>
<td>0.0201 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.0022 mg/L</td>
<td>0.0036 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.35 mg/L</td>
<td>0.0062 mg/L</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>pH</td>
<td>4.59</td>
<td>7.92</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine / Mode</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrations reported as dissolved in mg/L; pH reported in standard units</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>31.988</td>
<td>0.251</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.519</td>
<td>0.00584</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Cadmium</td>
<td>ND</td>
<td>0.00038</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.0193</td>
<td>0.00225</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0135</td>
<td>0.00546</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron</td>
<td>391.25</td>
<td>0.148</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0051</td>
<td>0.00166</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.631</td>
<td>0.0226</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.0033</td>
<td>0.00324</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.356</td>
<td>0.0142</td>
<td>Leviathan/Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Removal Efficiency</th>
<th>Minimum Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>99.5%</td>
<td>98%</td>
<td>Leviathan Mine / Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Arsenic</td>
<td>99.5%</td>
<td>97.6%</td>
<td>Leviathan Mine / Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Chromium</td>
<td>92.3%</td>
<td>83.1%</td>
<td>Leviathan Mine / Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>74.5%</td>
<td>27.7%</td>
<td>Leviathan Mine / Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Iron</td>
<td>100%</td>
<td>99.9%</td>
<td>Leviathan Mine / Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Lead</td>
<td>78.9%</td>
<td>37.7%</td>
<td>Leviathan Mine / Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Nickel</td>
<td>99.1%</td>
<td>97.2%</td>
<td>Leviathan Mine / Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>98.2%</td>
<td>90.6%</td>
<td>Leviathan Mine / Alkaline Lagoon</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>

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.
Neutralization and Chemical Precipitation

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>100</td>
<td>10</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Aluminum</td>
<td>10</td>
<td>&lt;0.2</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Arsenic</td>
<td>97</td>
<td>&lt;0.002</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Arsenic</td>
<td>&lt;0.002</td>
<td>&lt;0.002</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Calcium</td>
<td>252</td>
<td>181</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Calcium</td>
<td>790</td>
<td>850</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Copper</td>
<td>5</td>
<td>&lt;0.005</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Copper</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Iron</td>
<td>171</td>
<td>15</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Iron</td>
<td>5</td>
<td>&lt;0.2</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Lead</td>
<td>182</td>
<td>&lt;0.001</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Lead</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>263</td>
<td>279</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Magnesium</td>
<td>316</td>
<td>386</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Manganese</td>
<td>18</td>
<td>19</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Manganese</td>
<td>18</td>
<td>19</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Potassium</td>
<td>3</td>
<td>4</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Potassium</td>
<td>7</td>
<td>7</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Silicon</td>
<td>18</td>
<td>19</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Silicon</td>
<td>38</td>
<td>19</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Sulfate</td>
<td>3440</td>
<td>3590</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Sulfate</td>
<td>3870</td>
<td>3770</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>Zinc</td>
<td>443</td>
<td>436</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>Zinc</td>
<td>430</td>
<td>414</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
<tr>
<td>pH</td>
<td>2.7</td>
<td>6.1</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 1</td>
</tr>
<tr>
<td>pH</td>
<td>6</td>
<td>6.6</td>
<td>Monte Romero</td>
<td>Macías et al., 2012a</td>
<td>Tank 2</td>
</tr>
</tbody>
</table>

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

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


5.9.2 General Neutralization Chemical Precipitation Treatment References

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

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Type</th>
<th>System Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gilt Edge Mine, South Dakota</td>
<td>Envirobond (Metals Treatment Technologies, MT2)*</td>
<td>Applied as a liquid spray onto waste rock in two above-ground treatment cells; used phosphate stabilization chemistry</td>
<td>Pilot scale</td>
<td>Trudnowski, 2004* Nordwick et al., 2006</td>
<td>Report</td>
</tr>
</tbody>
</table>
Table 6-1: Chemical Stabilization Case Study Site

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Type</th>
<th>System Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium Permanganate Passivation Technology (University of Nevada-Reno)</td>
<td>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</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silica Microencapsulation (SME) Technology (Klean Earth Environmental Company, KEECO)</td>
<td>Applied as a liquid spray onto waste rock in two above-ground treatment cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime</td>
<td>Waste rock was mixed with calcium oxide ex situ and placed into three above-ground treatment cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Concentration Range – Untreated Cells&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Concentration Range – Treated Cells&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Technology</th>
<th>Source</th>
<th>Notes (location within source)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>198.545 – 2,796.667</td>
<td>0.22 – 0.422</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Table 4-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.005 – 0.264</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.011 – 0.326</td>
<td>Potassium Permanganate Passivation</td>
<td>Trudnowski, 2004</td>
<td>Table 6-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.401 – 398.0</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Table 7-2</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1.4223 – 123.8027</td>
<td>0.0238 – 0.0481&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.4950 – 50.20</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0059&lt;sup&gt;c&lt;/sup&gt; – 2.6148&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Potassium Permanganate Passivation</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0056&lt;sup&gt;c&lt;/sup&gt; – 0.04979&lt;sup&gt;d&lt;/sup&gt;</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td>Iron</td>
<td>535.110 – 21,204.900</td>
<td>0.008 – 0.397</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Table 4-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.008 – 0.145</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.017 – 0.739</td>
<td>Potassium Permanganate Passivation</td>
<td>Trudnowski, 2004</td>
<td>Table 6-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.178 – 528.0</td>
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<td>Trudnowski, 2004</td>
<td>Table 7-3</td>
</tr>
<tr>
<td>Sulfate</td>
<td>1,106 – 72,667</td>
<td>204 – 1,403</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Table 4-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8,150 – 26,700</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,490 – 8,350</td>
<td>Potassium Permanganate Passivation</td>
<td>Trudnowski, 2004</td>
<td>Table 6-4&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,834 – 7,100</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Table 7-4</td>
</tr>
<tr>
<td>Zinc</td>
<td>11.45 – 71.93</td>
<td>0.0045&lt;sup&gt;c&lt;/sup&gt; – 0.0437&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
</tbody>
</table>

Concentrations reported as dissolved in mg/L; pH reported in standard units.
Table 6-2: Average Leachate Concentration Ranges from Treated and Untreated Cells of Waste Rock – All Treatment Types

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Concentration Range – Untreated Cells&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Concentration Range – Treated Cells&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Technology</th>
<th>Source</th>
<th>Notes (location within source)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0028&lt;sup&gt;c&lt;/sup&gt; – 0.4720&lt;sup&gt;c&lt;/sup&gt;</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0211&lt;sup&gt;c&lt;/sup&gt; – 0.1645</td>
<td>Potassium Permanganate Passivation</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.3555&lt;sup&gt;c&lt;/sup&gt; – 21.5333</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>pH&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2.49 – 4.52</td>
<td>6.85 – 12.09</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Appendix B</td>
</tr>
<tr>
<td></td>
<td>6.78 – 7.95</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Appendix B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.15 – 8.55</td>
<td>Potassium Permanganate Passivation</td>
<td>Trudnowski, 2004</td>
<td>Appendix B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.71 – 6.86</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Appendix B</td>
<td></td>
</tr>
</tbody>
</table>

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

Concentrations reported as dissolved in mg/L; pH reported in standard units
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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Concentration from Untreated Cells</th>
<th>Average Concentration from Treated Cells</th>
<th>Technology</th>
<th>Source</th>
<th>Notes (location within source)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>687.800</td>
<td>0.1691</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Table 4-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.135</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.107</td>
<td>Potassium Permanganate</td>
<td>Trudnowski, 2004</td>
<td>Table 6-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>192.497</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Table 7-2</td>
</tr>
<tr>
<td>Arsenicc</td>
<td>26.6829</td>
<td>0.0287</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36.8332</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2489</td>
<td>Potassium Permanganate</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.6265</td>
<td>SMEd</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td>Iron</td>
<td>4,237.946</td>
<td>0.0792</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Table 4-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.075</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.151</td>
<td>Potassium Permanganate</td>
<td>Trudnowski, 2004</td>
<td>Table 6-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>763.211</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Table 7-3</td>
</tr>
<tr>
<td>Sulfate</td>
<td>22,406</td>
<td>444.3</td>
<td>Lime^d</td>
<td>Trudnowski, 2004</td>
<td>Table 4-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18,425</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,443</td>
<td>Potassium Permanganate</td>
<td>Trudnowski, 2004</td>
<td>Table 6-4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6,026</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Table 7-4</td>
</tr>
<tr>
<td>Zincc</td>
<td>36.3993</td>
<td>0.0329</td>
<td>Lime^d</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1398</td>
<td>MT2 Envirobond^d</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0609</td>
<td>Potassium Permanganate</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.4349</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td>pH^a</td>
<td>3.52</td>
<td>10.56</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Appendix B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.39</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Appendix B</td>
</tr>
</tbody>
</table>

Concentrations reported as dissolved in mg/L; pH reported in standard units.

---

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Concentration from Untreated Cells\textsuperscript{a}</th>
<th>Average Concentration from Treated Cells\textsuperscript{b}</th>
<th>Technology</th>
<th>Source</th>
<th>Notes (location within source)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentrations reported as dissolved in mg/L; pH reported in standard units</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.18</td>
<td>Potassium Permanganate Passivation</td>
<td>Trudnowski, 2004</td>
<td>Appendix B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.32</td>
<td>SME</td>
<td>Trudnowski, 2004</td>
<td>Appendix B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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
- \textsuperscript{a} The study included three control cells
- \textsuperscript{b} Lime treatment included three cells, while the other three treatments included two treatment cells
- \textsuperscript{c} Values calculated from all data provided by the source, including for sampling dates having results reported as estimated or below the reporting limit
- \textsuperscript{d} Majority of data provided by the source was indicated as estimated or below the reporting limit
- \textsuperscript{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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Percent Reduction</th>
<th>Minimum Percent Reduction</th>
<th>Maximum Percent Reduction</th>
<th>Technology</th>
<th>Source</th>
<th>Notes (location within source)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All constituents reported as dissolved</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>99.96%</td>
<td>99.80%</td>
<td>99.99%</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Table 4-2</td>
</tr>
<tr>
<td>Arsenic</td>
<td>99.89%</td>
<td>97.19%</td>
<td>99.98%</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td>Iron</td>
<td>100.00%</td>
<td>99.99%</td>
<td>100.00%</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Table 4-3</td>
</tr>
<tr>
<td>Sulfate</td>
<td>95.32%</td>
<td>74.14%</td>
<td>99.52%</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Table 4-4</td>
</tr>
<tr>
<td>Zinc</td>
<td>99.91%</td>
<td>99.72%</td>
<td>99.99%</td>
<td>Lime</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td>Aluminum</td>
<td>99.98%</td>
<td>99.91%</td>
<td>100.00%</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-2</td>
</tr>
<tr>
<td>Arsenic</td>
<td>-38.04%</td>
<td>-2,032.45%</td>
<td>93.14%</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
<tr>
<td>Iron</td>
<td>99.99%</td>
<td>99.95%</td>
<td>100.00%</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-3</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-275.04%</td>
<td>-2,313.89%</td>
<td>88.37%</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Table 5-4</td>
</tr>
<tr>
<td>Zinc</td>
<td>99.62%</td>
<td>97.99%</td>
<td>99.99%</td>
<td>MT2 Envirobond</td>
<td>Trudnowski, 2004</td>
<td>Appendix A</td>
</tr>
</tbody>
</table>
Table 6-4: Percent Reduction – All Treatment Types

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

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


6.7.2 General Chemical Stabilization References

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

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Wetland Type</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Basin Mining District, Copper Hill, Tennessee</td>
<td>Anaerobic followed by aerobic</td>
<td>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.</td>
<td>Pilot scale</td>
<td>Federal Remediation Technologies Roundtable (FRTR), 2007 FRTR Case Study summary (online document)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U.S. EPA, 2006b Report Faulkner and Miller, 2002 (anaerobic only)* Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger and Eger, 2005* Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger et al., 1996 Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger et al., 1998 Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ITRC, 2010* Report</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger and Beatty, 2013 Journal paper</td>
</tr>
<tr>
<td>Dunka Mine, Babbitt, Minnesota</td>
<td>Aerobic</td>
<td>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.</td>
<td>Full scale</td>
<td>Eger and Eger, 2005* Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger et al., 1996 Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger et al., 1998 Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ITRC, 2010* Report</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eger and Beatty, 2013 Journal paper</td>
</tr>
</tbody>
</table>

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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.351</td>
<td>0.073</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Copper</td>
<td>0.311</td>
<td>0.008</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Iron</td>
<td>1.07</td>
<td>0.353</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.52</td>
<td>1.64</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.094</td>
<td>0.045</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Sulfate</td>
<td>142</td>
<td>128</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>pH</td>
<td>4.2</td>
<td>7.1</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>All results</td>
<td></td>
<td></td>
<td>all results reported as total except</td>
</tr>
<tr>
<td>Aluminum</td>
<td>96.9%</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Copper</td>
<td>97.4%</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Copper(^b)</td>
<td>94.2%</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Iron</td>
<td>67.0%</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Manganese</td>
<td>-7.9%</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Zinc</td>
<td>95.9%</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
<tr>
<td>Sulfate</td>
<td>9.9%</td>
<td>Copper Basin</td>
<td>Faulkner and Miller, 2002</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent Conc.</th>
<th>Corresponding Effluent Conc.</th>
<th>Minimum Influent Conc.</th>
<th>Corresponding Effluent Conc.</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>8</td>
<td>0.006</td>
<td>0.15</td>
<td>0.04</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.036</td>
<td>0.008</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>0.068</td>
<td>0.008/0.010</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>Nickel</td>
<td>3.98</td>
<td>0.36/0.700</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.052</td>
<td>0.013</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>pH</td>
<td>7.07</td>
<td>7.18</td>
<td>Dunka – W1D Expanded</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.009</td>
<td>0.001</td>
<td>Dunka – W1D; Dunka – W1D Expanded</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.02</td>
<td>0.002</td>
<td>Dunka – W1D; Dunka – W1D Expanded</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.74</td>
<td>0.19/0.18</td>
<td>Dunka – W1D; Dunka – W1D Expanded</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.017</td>
<td>0.011</td>
<td>Dunka – W1D Expanded</td>
<td>ITRC, 2010</td>
</tr>
<tr>
<td>pH</td>
<td>7.30</td>
<td>7.48</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
</tbody>
</table>

Notes:
a = Dunka – W1D and Dunka – W1D Expanded had identical concentrations reported for some sampling periods

### Table 7-7: Maximum Average Effluent Concentration Attained

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.008</td>
<td>0.036</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>0.010</td>
<td>0.068</td>
<td>Dunka – W1D</td>
<td>ITRC, 2010</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.700</td>
<td>3.98</td>
<td>Dunka – W1D</td>
<td>ITRC, 2010</td>
</tr>
</tbody>
</table>
Table 7-7: Maximum Average Effluent Concentration Attained

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>0.013</td>
<td>0.052</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>pH</td>
<td>7.18</td>
<td>7.07</td>
<td>Dunka – W1D Expanded</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Effluent Concentration</th>
<th>Average Influent Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.001</td>
<td>0.009/0.023</td>
<td>Dunka – W1D and W1D Expanded</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>0.002</td>
<td>0.02</td>
<td>Dunka – W1D and W1D Expanded</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.099</td>
<td>0.76</td>
<td>Dunka – W1D Expanded</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.006</td>
<td>0.019/0.021</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>pH</td>
<td>7.48</td>
<td>7.30</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Removal Efficiency</th>
<th>Mine – Wetland</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total or dissolved not stated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>95.7%</td>
<td>Dunka – W1D Expanded</td>
<td>ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>91.5%</td>
<td>Dunka – W1D Expanded</td>
<td>ITRC, 2010</td>
</tr>
<tr>
<td>Nickel</td>
<td>91%</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>75%</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
</tbody>
</table>

**Notes:**  
a = Average removal efficiencies calculated by EPA

#### Table 7-10: Minimum Average Removal Efficiencies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Removal Efficiency</th>
<th>Mine – Wetland</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total or dissolved not stated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>77.8%</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005; ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>83.3%</td>
<td>Dunka – W1D Expanded</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>74.3%</td>
<td>Dunka – W1D</td>
<td>Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>35.3%</td>
<td>Dunka – W1D Expanded</td>
<td>ITRC, 2010</td>
</tr>
</tbody>
</table>

**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**

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

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 (m²) to $28/m² (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


7.8.2 General Constructed Wetlands References


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

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Type</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Island Copper Mine</td>
<td>Pit Lake</td>
<td>Seawater and freshwater capping (stratification); liquid fertilizer, applied across the</td>
<td>Full scale</td>
<td>Poling et al., 2003*</td>
<td>Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fisher and Lawrence, 2006*</td>
<td>Journal paper</td>
</tr>
</tbody>
</table>
Table 8-1: In Situ Mine Pools and Pit Lakes Case Study Sites

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

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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Pre-treatment Concentration Range</th>
<th>During Treatment Concentration Range</th>
<th>Post-treatment (between applications) Concentration Range</th>
<th>Treatment Event</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>0.004&lt;sup&gt;a&lt;/sup&gt; – 0.0051&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0 – 0.006</td>
<td>NA</td>
<td>2001 – 2002</td>
<td>Poling et al., 2003, Figure 8</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0065 – 0.055</td>
<td>0.0055 – 0.014</td>
<td>0.006 – 0.011</td>
<td>1997</td>
<td>Fisher and Lawrence, 2006, Figure 7</td>
</tr>
<tr>
<td></td>
<td>0.006 – 0.011</td>
<td>0.007 – 0.0135</td>
<td>0.0045 – 0.008</td>
<td>1998</td>
<td>Fisher and Lawrence, 2006, Figure 7</td>
</tr>
<tr>
<td></td>
<td>0.0045 – 0.008</td>
<td>0.002 – 0.006</td>
<td>0.005 – 0.013</td>
<td>1999</td>
<td>Fisher and Lawrence, 2006, Figure 7</td>
</tr>
<tr>
<td></td>
<td>0.005 – 0.013</td>
<td>0.001 – 0.010</td>
<td>0.003&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2000</td>
<td>Fisher and Lawrence, 2006, Figure 7</td>
</tr>
<tr>
<td></td>
<td>0.003&lt;sup&gt;a&lt;/sup&gt; – 0.008</td>
<td>0.001 – 0.006</td>
<td>NA</td>
<td>2001 – 2002</td>
<td>Poling et al., 2003, Figure 7</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.3 – 0.6</td>
<td>0.01 – 0.59</td>
<td>0.01 – 0.25</td>
<td>1997</td>
<td>Fisher and Lawrence, 2006, Figure 7</td>
</tr>
<tr>
<td></td>
<td>0.01 – 0.025</td>
<td>0.01 – 0.42</td>
<td>0.15 – 0.38</td>
<td>1998</td>
<td>Fisher and Lawrence, 2006, Figure 7</td>
</tr>
<tr>
<td></td>
<td>0.15 – 0.38</td>
<td>0.01 – 0.18</td>
<td>0.17 – 0.24</td>
<td>1999</td>
<td>Fisher and Lawrence, 2006, Figure 7</td>
</tr>
<tr>
<td></td>
<td>0.17 – 0.24</td>
<td>0.08 – 0.22</td>
<td>0.20&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2000</td>
<td>Fisher and Lawrence, 2006, Figure 7</td>
</tr>
<tr>
<td></td>
<td>0.41&lt;sup&gt;a&lt;/sup&gt; – 0.51&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0 – 0.2</td>
<td>NA</td>
<td>2001 – 2002</td>
<td>Poling et al., 2003, Figure 6</td>
</tr>
</tbody>
</table>

**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**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>All constituents reported as dissolved</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadmium</td>
<td>&gt;90%</td>
<td>Island Copper</td>
<td>Poling et al., 2003</td>
<td>Based on the results of the 18-month study</td>
</tr>
<tr>
<td>Copper</td>
<td>&gt;90%</td>
<td>Island Copper</td>
<td>Poling et al., 2003</td>
<td>Based on the results of the 18-month study</td>
</tr>
<tr>
<td>Zinc</td>
<td>&gt;90%</td>
<td>Island Copper</td>
<td>Poling et al., 2003</td>
<td>Based on the results of the 18-month study</td>
</tr>
</tbody>
</table>

*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**

<table>
<thead>
<tr>
<th>Average Flow</th>
<th>Notes</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>All rates are in liters per minute (L/min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.7</td>
<td>Annual Daily Average (North Injection System)</td>
<td>Fisher and Lawrence, 2006</td>
</tr>
<tr>
<td>8.8</td>
<td>Annual Daily Average (South Injection System)</td>
<td>Fisher and Lawrence, 2006</td>
</tr>
</tbody>
</table>
Table 8-4: Average Flow Rate

<table>
<thead>
<tr>
<th>Average Flow</th>
<th>Notes</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>143</td>
<td>Peak Daily Flow (North Injection System)</td>
<td>Fisher and Lawrence, 2006</td>
</tr>
<tr>
<td>137</td>
<td>Peak Daily Flow (South Injection System)</td>
<td>Fisher and Lawrence, 2006</td>
</tr>
</tbody>
</table>

The average yearly ARD inflow to the pit lake was 4,321,600 million cubic meters \((7,190 + 4,650) \times 365\). 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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Pre-treatment Concentration Range</th>
<th>Post-Treatment (between applications) Concentration Range</th>
<th>Treatment Period</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>2 – 51</td>
<td>&lt;1 – 38</td>
<td>8/00 – 8/06⁴</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>&lt;1 – 38</td>
<td>&lt;1 – 4</td>
<td>8/06 – 8/07</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>&lt;1 – 4</td>
<td>&lt;1 – 2</td>
<td>8/07 – 8/08</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>&lt;1 – 2</td>
<td>1 – 2</td>
<td>8/08 – 8/09</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>1 – 2</td>
<td>&lt;1 – 2</td>
<td>8/09 – 8/10⁵</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>&lt;1 – 2</td>
<td>2.5 – 11</td>
<td>8/10 – 8/11⁵</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>2.5 – 11</td>
<td>1 – 5</td>
<td>8/11 – 8/12</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>1 – 5</td>
<td>&lt;1 – 1</td>
<td>8/12⁵</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td>Sulfate</td>
<td>1,400 – 2,900</td>
<td>1,000 – 2,700</td>
<td>8/00 – 8/06⁴</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>1,000 – 2,700</td>
<td>1,400 – 2,200</td>
<td>8/06 – 8/07</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>1,400 – 2,200</td>
<td>1,400 – 2,000</td>
<td>8/07 – 8/08</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
</tbody>
</table>

Concentrations reported as dissolved in mg/L
Table 8-5: Constituent Concentration Ranges Pre- and Post-Treatment – Platoro Mine Pool

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Pre-treatment Concentration Range</th>
<th>Post-Treatment (between applications) Concentration Range</th>
<th>Treatment Period</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,400 – 2,000</td>
<td>820 – 1,800</td>
<td>8/08 – 8/09</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
<td></td>
</tr>
<tr>
<td>820 – 1,800</td>
<td>1,490 – 2,050</td>
<td>8/09 – 8/10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
<td></td>
</tr>
<tr>
<td>1,490 – 2,050</td>
<td>800 – 2,250</td>
<td>8/10 – 8/11&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
<td></td>
</tr>
<tr>
<td>800 – 2,250</td>
<td>180 – 400</td>
<td>8/11 – 8/12</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
<td></td>
</tr>
<tr>
<td>180 – 400</td>
<td>&lt;1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>8/12&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>7.5 – 20</td>
<td>&lt;1 – 13</td>
<td>8/00 – 8/06&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>&lt;1 – 13</td>
<td>1 – 2.5</td>
<td>8/06 – 8/07</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>1 – 2.5</td>
<td>1 – 1</td>
<td>8/07 – 8/08</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>1 – 1</td>
<td>&lt;1 – 3</td>
<td>8/08 – 8/09</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>&lt;1 – 3</td>
<td>&lt;1 – 1</td>
<td>8/09 – 8/10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>&lt;1 – 1</td>
<td>1 – 3</td>
<td>8/10 – 8/11&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>1 – 3</td>
<td>&lt;1 – 2</td>
<td>8/11 – 8/12</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
<tr>
<td></td>
<td>&lt;1 – 2</td>
<td>&lt;1</td>
<td>8/12&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Harrington et al., 2015</td>
<td>Figure 3</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>All concentrations reported as dissolved</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td>97%</td>
<td>Platoro</td>
<td>Harrington et al., 2015</td>
<td>Based on the time period of injections from 2006 to 2012</td>
</tr>
<tr>
<td>Zinc</td>
<td>93%</td>
<td>Platoro</td>
<td>Harrington et al., 2015</td>
<td>Based on the time period of injections from 2006 to 2012</td>
</tr>
</tbody>
</table>

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 m²), 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


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


www.itrcweb.org

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 et 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

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Type and Treatment Material</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel Rim Mine, Ontario, Canada</td>
<td>Biological (stimulation of sulfate reducing bacteria) and chemical (precipitation of iron sulfides). Treatment material is 20% (by volume) municipal compost, 20% leaf mulch, 9%</td>
<td>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</td>
<td>Full scale</td>
<td>Benner et al., 2002*</td>
<td>Journal paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Benner et al., 1999*</td>
<td>Report</td>
</tr>
</tbody>
</table>
Table 9-1: PRB Case Study Sites

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Type and Treatment Material</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success Mine and Mill Northern Idaho, United States</td>
<td>woodchips, 50% gravel and 1% limestone.</td>
<td>infiltrated acidic surface water.</td>
<td>Full scale</td>
<td>Wright and Conca, 2006*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Success Mine and Mill Northern Idaho, United States</td>
<td>Biological (stimulation of sulfate-reducing bacteria) and chemical (precipitation of metal sulfides). Treatment material is a biogenically-precipitatedapatite material from fish bones.</td>
<td>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.</td>
<td>Full scale</td>
<td>Conca and Wright, 2006*</td>
<td>Journal Paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>McCloskey et al., 2006</td>
<td>Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Doshi, 2006</td>
<td>Report</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>0.809</td>
<td>&lt;0.002</td>
<td>0.318</td>
<td>&lt;0.002</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
</tr>
<tr>
<td>Lead</td>
<td>1.45</td>
<td>&lt;0.005</td>
<td>0.497</td>
<td>&lt;0.005</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
</tr>
<tr>
<td>Zinc</td>
<td>146.9</td>
<td>0.059</td>
<td>44.7</td>
<td>0.027</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
</tr>
<tr>
<td>pH</td>
<td>4.2</td>
<td>7.1</td>
<td>5.5</td>
<td>6.9</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>670&lt;sup&gt;a&lt;/sup&gt;</td>
<td>140&lt;sup&gt;a&lt;/sup&gt;</td>
<td>357&lt;sup&gt;a&lt;/sup&gt;</td>
<td>419&lt;sup&gt;c&lt;/sup&gt;</td>
<td>17&lt;sup&gt;c&lt;/sup&gt;</td>
<td>39&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Benner et al, 2002</td>
</tr>
<tr>
<td>Sulfate</td>
<td>3,408&lt;sup&gt;a&lt;/sup&gt;</td>
<td>865&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2,420&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2,594&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1,537&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1,824&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Benner et al, 2002</td>
</tr>
</tbody>
</table>

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
<sup>a</sup> = 10/98 sampling event
<sup>b</sup> = 5/98 sampling event
<sup>c</sup> = 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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>0.521</td>
<td>0.0016</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
<td>03/23/01 – 06/09/04</td>
</tr>
<tr>
<td>Lead</td>
<td>1.074</td>
<td>0.0062</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
<td>03/23/01 – 06/09/04</td>
</tr>
<tr>
<td>Zinc</td>
<td>75.97</td>
<td>0.144</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
<td>03/23/01 – 06/09/04</td>
</tr>
<tr>
<td>pH</td>
<td>4.69</td>
<td>6.69</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
<td>03/23/01 – 06/09/04</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Upgradient Concentration Range(^a)</th>
<th>Average Concentration Within PRB(^b)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>250 – 1,350</td>
<td>80</td>
<td>Benner et al., 1999; Doshi, 2006</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.12 – 30</td>
<td>&lt;0.1</td>
<td>Benner et al., 1999; Doshi, 2006</td>
</tr>
<tr>
<td>Sulfate</td>
<td>2,500 – 5,200</td>
<td>840</td>
<td>Benner et al., 1999; Doshi, 2006</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>&lt; 1 – 60</td>
<td>2,300</td>
<td>Benner et al., 1999; Doshi, 2006</td>
</tr>
<tr>
<td>pH</td>
<td>2.8 – 5.9</td>
<td>6.7</td>
<td>Benner et al., 1999; Doshi, 2006</td>
</tr>
</tbody>
</table>

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.
Permeable Reactive Barriers

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Upgradient Concentration Range(^a)</th>
<th>Average Concentration Within PRB(^b)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrations reported as dissolved in mg/L; pH in standard units</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(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.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum Removal Efficiency</th>
<th>Minimum Removal Efficiency</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>All concentrations reported as dissolved</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadmium</td>
<td>99.64%</td>
<td>99.92%</td>
<td>98.06%</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
</tr>
<tr>
<td>Lead</td>
<td>99.48%</td>
<td>99.96%</td>
<td>95.36%</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
</tr>
<tr>
<td>Zinc</td>
<td>99.76%</td>
<td>100.00%</td>
<td>98.46%</td>
<td>Conca and Wright, 2006; Wright and Conca, 2006</td>
</tr>
</tbody>
</table>

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


9.7.2 General Capping References

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)\textsuperscript{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.

\textsuperscript{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>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Technologies</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calliope Mine Butte, Montana</td>
<td>Passive anaerobic BCRs with passive pre-treatment</td>
<td>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.</td>
<td>Pilot scale</td>
<td>Wilmoth, 2002*</td>
<td>Report</td>
</tr>
<tr>
<td>Confidential Mine, Montana</td>
<td>Passive anaerobic solid substrate BCR followed by a passive aerobic polishing cell and aeration cell</td>
<td>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.</td>
<td>Pilot scale (technology demonstration)</td>
<td>Blumenstein and Gusek, 2009*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Copper Basin Mining District, Copper Hill, Tennessee</td>
<td>Passive anaerobic wetlands followed by passive aerobic wetlands and limestone rock filter</td>
<td>8,094 m² (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.</td>
<td>Pilot scale</td>
<td>Federal Remediation Technologies Roundtable (FRTR), 2007</td>
<td>FRTR case study summary (online document)</td>
</tr>
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<td></td>
<td></td>
<td></td>
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<td>U.S. EPA, 2006b</td>
<td>Report</td>
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<td>Faulkner and Miller, 2002*</td>
<td>Conference paper</td>
</tr>
</tbody>
</table>
### Table 10-1: Treatment Train Case Study Sites

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Technologies</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dunka Mine, Babbitt, Minnesota</td>
<td>Passive aerobic wetlands with passive pre- and/or post-treatment limestone</td>
<td>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.</td>
<td>Full scale</td>
<td>Eger and Eger, 2005*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Force Crag, Cumbria, United Kingdom</td>
<td>Passive anaerobic BCR, solid substrate and aerobic wetland</td>
<td>Parallel vertical-flow ponds containing compost, woodchips and dried activated sewage sludge, followed by an aerobic wetland.</td>
<td>Full scale</td>
<td>Jarvis et al., 2015*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Golden Sunlight Mine, Whitehall, Montana</td>
<td>Settling pond and passive anaerobic BCR</td>
<td>Two-step process using a settling pond followed by a BCR, which contained crushed limestone and manure; water was recirculated through the system.</td>
<td>Pilot scale</td>
<td>Bless et al., 2008*</td>
<td>Journal paper</td>
</tr>
<tr>
<td>Leviathan Mine, Alpine County, California</td>
<td>Semi-passive chemical addition, pre-treatment pond, passive anaerobic BCRs, settling ponds and</td>
<td>System consisted of a pre-treatment pond (preceded by gravity fed addition of 25 percent sodium hydroxide and ethanol), two BCRs in series, two</td>
<td>Full scale</td>
<td>Doshi, 2006</td>
<td>Report</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U.S. EPA, 2006a*</td>
<td>Report</td>
</tr>
<tr>
<td>Site Name and Location</td>
<td>Technologies</td>
<td>Description</td>
<td>Study Type</td>
<td>Reference</td>
<td>Reference Type</td>
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<tr>
<td>Monte Romero Mine, Southwestern Spain</td>
<td>Passive natural Fe-oxidizing lagoon (NFOL) followed by passive limestone-DAS system</td>
<td>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.</td>
<td>Pilot scale</td>
<td>Macías et al., 2012a*</td>
<td>Journal paper</td>
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<td></td>
<td></td>
<td>Macías et al., 2012b</td>
<td>Journal paper</td>
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<td></td>
<td></td>
<td>Rötting et al., 2008</td>
<td>Journal paper</td>
</tr>
<tr>
<td>Standard Mine, Crested Butte, Colorado</td>
<td>Passive anaerobic BCR with passive aerobic polishing cells</td>
<td>System comprised a BCR followed by aerobic polishing cells; BCR contained hay, wood chips, limestone and cow manure.</td>
<td>Pilot scale</td>
<td>Gallagher et al., 2012*</td>
<td>Conference paper</td>
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<td></td>
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<td></td>
<td>Reisman et al., 2009*</td>
<td>Conference paper</td>
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<td></td>
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<td></td>
<td>Butler et al., 2011</td>
<td>Journal paper</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Report</td>
</tr>
<tr>
<td>Site Name and Location</td>
<td>Technologies</td>
<td>Description</td>
<td>Study Type</td>
<td>Reference</td>
<td>Reference Type</td>
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<tr>
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</tr>
<tr>
<td>Surething Mine Helena, Montana</td>
<td>Passive anaerobic BCRs, limestone drain and passive aerobic BCR</td>
<td>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.</td>
<td>Full scale</td>
<td>Nordwick and Bless, 2008*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Tar Creek Superfund Site Oklahoma, Kansas, Missouri</td>
<td>Passive system including oxidation pond, aerobic wetlands, passive anaerobic BCRs, aeration ponds, limestone bed and wetland</td>
<td>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.</td>
<td>Full scale</td>
<td>Nairn et al., 2009</td>
<td>Conference paper</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Nairn et al., 2010a*</td>
<td>Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nairn et al., 2010b</td>
<td>Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nairn et al., 2011*</td>
<td>Conference paper</td>
</tr>
<tr>
<td>Valzinco Mine Spotsylvania County, Virginia</td>
<td>Capping, passive limestone drains and constructed wetlands</td>
<td>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.</td>
<td>Full scale</td>
<td>Seal et al, 2008*</td>
<td>Conference paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sobeck et al, 2008</td>
<td>Conference paper</td>
</tr>
</tbody>
</table>
Table 10-1: Treatment Train Case Study Sites

<table>
<thead>
<tr>
<th>Site Name and Location</th>
<th>Technologies</th>
<th>Description</th>
<th>Study Type</th>
<th>Reference</th>
<th>Reference Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheal Jane Mine, Cornwall, United Kingdom</td>
<td>Active limestone* pre-treatment at two configurations, passive aerobic wetland, passive anaerobic BCR and aerobic rock filter</td>
<td>Three multi-cell treatment systems that utilized one of three pre-treatment methods to raise pH: limestone* dosing to pH 5.0 with calcium carbonate (LD), an anoxic limestone drain (ALD, modified to a LD* system June 2000), or a limestone *-free system without pre-treatment (LF). Pretreated 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.</td>
<td>Pilot scale</td>
<td>Whitehead et al., 2005*</td>
<td>Journal paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Whitehead and Prior, 2005</td>
<td>Journal paper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Johnson and Hallberg, 2005*</td>
<td>Journal paper</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1,740</td>
<td>0.126</td>
<td>Golden Sunlight</td>
<td>Bless, 2008</td>
</tr>
<tr>
<td>Arsenic</td>
<td>1.25</td>
<td>&lt;0.01</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.385</td>
<td>0.005</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.0198</td>
<td>0.0132</td>
<td>Leviathan</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper</td>
<td>81.4</td>
<td>0.001</td>
<td>Golden Sunlight</td>
<td>Bless, 2008</td>
</tr>
<tr>
<td>Iron</td>
<td>198</td>
<td>2.62</td>
<td>Golden Sunlight</td>
<td>Bless, 2008</td>
</tr>
<tr>
<td>Lead</td>
<td>1.07</td>
<td>0.001</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
</tr>
<tr>
<td>Manganese</td>
<td>117</td>
<td>67.8</td>
<td>Golden Sunlight</td>
<td>Bless, 2008</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.531</td>
<td>0.0189</td>
<td>Leviathan</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.0199</td>
<td>0.0108</td>
<td>Leviathan</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Sulfate</td>
<td>1,510</td>
<td>1,160</td>
<td>Leviathan</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Zinc</td>
<td>39.5</td>
<td>0.011</td>
<td>Golden Sunlight</td>
<td>Bless, 2008</td>
</tr>
<tr>
<td>pH</td>
<td>2.5</td>
<td>6.9</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
</tbody>
</table>

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.

\(a = \text{dissolved} \)  
\(b = \text{total} \)

Table 10-3: Minimum Influent and Corresponding Effluent Concentrations

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.4</td>
<td>0.0542</td>
<td>Calliope – BCR IV</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.0028</td>
<td>0.0024</td>
<td>Leviathan; Gravity mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>
Table 10-3: Minimum Influent and Corresponding Effluent Concentrations

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Influent Concentration</th>
<th>Corresponding Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>0.0004</td>
<td>&lt;0.00023</td>
<td>Leviathan; Gravity mode</td>
<td>U.S. EPA, 2006a</td>
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<tr>
<td>Chromium</td>
<td>0.0164</td>
<td>0.008</td>
<td>Leviathan; Gravity mode</td>
<td>U.S. EPA, 2006a</td>
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<tr>
<td>Copper</td>
<td>0.011</td>
<td>0.0022</td>
<td>Standard</td>
<td>Gallagher et al., 2012</td>
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<tr>
<td>Iron</td>
<td>0.524</td>
<td>0.417</td>
<td>Calliope – BCR IV</td>
<td>Wilmoth, 2002</td>
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<tr>
<td>Lead</td>
<td>0.0049</td>
<td>0.0029</td>
<td>Leviathan; Gravity Mode</td>
<td>U.S. EPA, 2006a</td>
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<tr>
<td>Manganese</td>
<td>0.69</td>
<td>0.6</td>
<td>Calliope – BCR II</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.478</td>
<td>0.0715</td>
<td>Leviathan; Gravity Mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.0096</td>
<td>0.0087</td>
<td>Leviathan; Gravity Mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Sulfate</td>
<td>260</td>
<td>200</td>
<td>Wheal Jane; LF system</td>
<td>Johnson and Hallberg, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.692</td>
<td>0.0147</td>
<td>Leviathan; Gravity Mode</td>
<td>U.S. EPA, 2006a</td>
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<tr>
<td>pH</td>
<td>7.52</td>
<td>7.21</td>
<td>Calliope – BCR II</td>
<td>Wilmoth, 2002</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>48.6</td>
<td>3.3</td>
<td>Wheal Jane; ALD system</td>
<td>Whitehead et al., 2005</td>
</tr>
<tr>
<td>Arsenic</td>
<td>2.7</td>
<td>0.0</td>
<td>Wheal Jane; LD, ALD and LF systems</td>
<td>Whitehead et al., 2005</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.1</td>
<td>0.0</td>
<td>Wheal Jane; LD, ALD and LF systems</td>
<td>Whitehead et al., 2005</td>
</tr>
</tbody>
</table>
Table 10-4: Maximum Average Influent Concentration Treated

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

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

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

Concentrations reported in mg/L; pH reported in standard units
Table 10-6: Maximum Average Effluent Concentration Attained

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

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

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

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum*</td>
<td>99.99%</td>
<td>Golden Sunlight</td>
<td>Bless, 2008</td>
</tr>
</tbody>
</table>
### Table 10-8: Maximum Removal Efficiencies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic(^a)</td>
<td>&gt;92.13%</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Cadmium(^a)</td>
<td>&gt;99.96%</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Chromium(^a)</td>
<td>84.8%</td>
<td>Leviathan – Recirculation mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper(^a)</td>
<td>99.99%</td>
<td>Golden Sunlight</td>
<td>Bress, 2008</td>
</tr>
<tr>
<td>Iron(^a)</td>
<td>&gt;99.91%</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Lead(^a)</td>
<td>97.35%</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Manganese(^a)</td>
<td>99.86%</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Nickel(^b)</td>
<td>98.8%</td>
<td>Tar Creek</td>
<td>Nairn et al., 2010b</td>
</tr>
<tr>
<td>Selenium(^b)</td>
<td>57.4%</td>
<td>Leviathan – Gravity mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Sulfate(^b)</td>
<td>37.29%</td>
<td>Calliope – BCR IV</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Zinc(^a)</td>
<td>&gt;99.97%</td>
<td>Surething</td>
<td>Nordwick and Bless, 2008</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum(^a)</td>
<td>-430.81%</td>
<td>Calliope – BCR II</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Arsenic(^a)</td>
<td>-839.29%</td>
<td>Calliope – BCR IV</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Cadmium(^a)</td>
<td>8.11%</td>
<td>Calliope – BCR IV</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Chromium(^b)</td>
<td>21.2%</td>
<td>Leviathan – Recirc. mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Copper(^a)</td>
<td>-233.33%</td>
<td>Calliope – BCR II</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Iron(^a)</td>
<td>-10192.68%</td>
<td>Calliope – BCR II</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Lead(^a)</td>
<td>9.7%</td>
<td>Leviathan – Recirc. mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Manganese(^a)</td>
<td>-185.71%</td>
<td>Calliope – BCR II</td>
<td>Wilmoth, 2002</td>
</tr>
<tr>
<td>Nickel(^b)</td>
<td>71.0%</td>
<td>Leviathan – Recirc. mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
<tr>
<td>Selenium(^b)</td>
<td>9.4%</td>
<td>Leviathan – Gravity mode</td>
<td>U.S. EPA, 2006a</td>
</tr>
</tbody>
</table>
Table 10-9: Minimum Removal Efficiencies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfate a</td>
<td>-167.21%</td>
<td>Calliope – BCR IV</td>
<td>Wilmuth, 2002</td>
</tr>
<tr>
<td>Zinc a</td>
<td>25.48%</td>
<td>Calliope – BCR II</td>
<td>Wilmuth, 2002</td>
</tr>
</tbody>
</table>

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.

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 (Wilmuth, 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

<table>
<thead>
<tr>
<th>Mine</th>
<th>Flow Rate (L/min)</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calliope</td>
<td>3.8 with four months at 7.6</td>
<td>Wilmuth, 2002</td>
<td>Operational flow rate</td>
</tr>
</tbody>
</table>
Table 10-10: Influent Flow Rates

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

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Pre-Treatment Concentration Range</th>
<th>Post-Treatment Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrations reported in mg/l as dissolved; pH reported in standard units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.60 – 19.5</td>
<td>0.051</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0032 – 0.088</td>
<td>0.00091</td>
</tr>
<tr>
<td>Copper</td>
<td>0.049 – 2.2</td>
<td>0.0097</td>
</tr>
<tr>
<td>Iron</td>
<td>5.0 – 69.7</td>
<td>1.01</td>
</tr>
<tr>
<td>Lead</td>
<td>0.170 – 1.3</td>
<td>0.0016</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.410 – 2.1</td>
<td>1.12</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.002 – 0.037</td>
<td>0.0023</td>
</tr>
<tr>
<td>Sulfate</td>
<td>27 – 1,400</td>
<td>38.0</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.9 – 27</td>
<td>1.32</td>
</tr>
<tr>
<td>pH</td>
<td>2.6 – 4.0</td>
<td>5.1</td>
</tr>
</tbody>
</table>

*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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Pre-Treatment Concentration</th>
<th>Maximum Post-Treatment Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrations reported in mg/l as total, except manganese is reported as dissolved; pH reported in standard units; acidity reported in mg/l as CaCO₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.423</td>
<td>0.055</td>
</tr>
<tr>
<td>Copper</td>
<td>0.197</td>
<td>0.017</td>
</tr>
<tr>
<td>Iron</td>
<td>0.211</td>
<td>0.133</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.148</td>
<td>0.294</td>
</tr>
<tr>
<td>Sulfate</td>
<td>110</td>
<td>104</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.640</td>
<td>0.197</td>
</tr>
<tr>
<td>pH</td>
<td>4.28</td>
<td>7.16</td>
</tr>
<tr>
<td>Net acidity</td>
<td>37</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

*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 CaCO₃, 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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Pre-Treatment Concentration</th>
<th>Average Post-Treatment Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.13</td>
<td>0.04</td>
<td>Dunka – Seep 1</td>
<td>Eger and Eger, 2005</td>
<td>1995 – 1997</td>
</tr>
<tr>
<td>Copper</td>
<td>0.37</td>
<td>0.11</td>
<td>Dunka – Seep X</td>
<td>Eger and Eger, 2005</td>
<td>1999 – 2004</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.928</td>
<td>0.385</td>
<td>Dunka – Seep 1</td>
<td>Eger and Eger, 2005</td>
<td>1995 – 1997</td>
</tr>
</tbody>
</table>

Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units
Table 10-14: Minimum Average Pre-Treatment Concentration Treated

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Pre-Treatment Concentration</th>
<th>Average Post-Treatment Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.015</td>
<td>0.006</td>
<td>Dunka – EM8</td>
<td>ITRC, 2010a</td>
<td>Jan. to Sept. 1998</td>
</tr>
<tr>
<td>Copper</td>
<td>0.026</td>
<td>0.009</td>
<td>Dunka – EM8</td>
<td>Eger and Eger, 2005</td>
<td>1999 – 2004</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.5</td>
<td>0.61</td>
<td>Dunka – Seep X</td>
<td>Eger and Eger, 2005</td>
<td>1995 – 1997</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.05</td>
<td>0.008; &lt;0.001; 0.006</td>
<td>Dunka – W2D/3D</td>
<td>Eger and Eger, 2005</td>
<td>Minimum average influent corresponds to effluent for 1992 – 1994; 1996 – 1998; and 1999 – 2004</td>
</tr>
<tr>
<td>pH</td>
<td>7.41</td>
<td>7.3</td>
<td>Dunka – EM8</td>
<td>Eger and Eger, 2005</td>
<td>1999 – 2004</td>
</tr>
</tbody>
</table>

Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Post-Treatment Concentration</th>
<th>Average Pre-Treatment Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.04</td>
<td>0.13</td>
<td>Dunka – Seep 1</td>
<td>Eger and Eger, 2005</td>
<td>1995 –1997</td>
</tr>
<tr>
<td>Copper</td>
<td>0.11</td>
<td>0.37</td>
<td>Dunka – Seep X</td>
<td>Eger and Eger, 2005</td>
<td>1999 – 2004</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.385</td>
<td>0.928</td>
<td>Dunka – Seep 1</td>
<td>Eger and Eger, 2005</td>
<td>1999 – 2004</td>
</tr>
</tbody>
</table>

Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units
### Table 10-16: Minimum Average Post-Treatment Concentration Attained

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Post-Treatment Concentration</th>
<th>Average Pre-Treatment Concentration</th>
<th>Mine – Wetland</th>
<th>Source(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.002</td>
<td>0.02</td>
<td>Dunka – W2D/3D</td>
<td>ITRC, 2010a</td>
<td>1992 – 1997</td>
</tr>
<tr>
<td>Copper</td>
<td>&lt;0.001</td>
<td>0.05</td>
<td>Dunka – W2D/3D</td>
<td>Eger and Eger, 2005</td>
<td>1996 – 1998</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.036</td>
<td>1.9</td>
<td>Dunka – W2D/3D</td>
<td>Eger and Eger, 2005</td>
<td>1999 – 2004</td>
</tr>
<tr>
<td>Zinc</td>
<td>&lt;0.001</td>
<td>0.05</td>
<td>Dunka – W2D/3D</td>
<td>Eger and Eger, 2005</td>
<td>1996 – 1998</td>
</tr>
<tr>
<td>pH</td>
<td>7.4</td>
<td>7</td>
<td>Dunka – W2D/3D</td>
<td>Eger and Eger, 2005</td>
<td>1999 – 2004</td>
</tr>
</tbody>
</table>

Concentrations reported in mg/L, total or dissolved not stated; pH reported in standard units.

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Removal Efficiency</th>
<th>Mine - Wetland</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
</table>
Table 10-17: Maximum Average Removal Efficiencies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Average Removal Efficiency</th>
<th>Mine - Wetland</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>98%</td>
<td>Dunka – W2D/3D</td>
<td>Eger and Eger, 2005</td>
<td>Calculated based on averages presented for 1999 – 2004</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Average Removal Efficiency</th>
<th>Mine - Wetland</th>
<th>Source</th>
<th>Notes, Notes: Calculated based on averages presented for 1999 – 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>60%</td>
<td>Dunka – EM8</td>
<td>ITRC, 2010a</td>
<td>Calculated based on averages presented for Jan. to Sept. 1998</td>
</tr>
<tr>
<td>Copper</td>
<td>62%</td>
<td>Dunka – EM8</td>
<td>ITRC, 2010a</td>
<td>Calculated based on averages presented for Jan. to Sept. 1998</td>
</tr>
<tr>
<td>Nickel</td>
<td>33%</td>
<td>Dunka – EM8</td>
<td>Eger and Eger, 2005</td>
<td>Calculated based on averages presented for 1999 – 2004</td>
</tr>
<tr>
<td>Zinc</td>
<td>36%</td>
<td>Dunka – Seep X</td>
<td>Eger and Eger, 2005</td>
<td>Calculated based on averages presented for 1999 – 2004</td>
</tr>
</tbody>
</table>

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 (CaCO₃) 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 CaCO₃ from the mine shaft water having 1,800 mg/l net acidity as CaCO₃.

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td></td>
<td></td>
</tr>
<tr>
<td>concentrations reported as total in mg/L; pH reported in standard units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>100</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.507</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>Calcium</td>
<td>250</td>
<td>850</td>
</tr>
<tr>
<td>Copper</td>
<td>5</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Iron</td>
<td>275</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Lead</td>
<td>0.174</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Magnesium</td>
<td>255</td>
<td>386</td>
</tr>
<tr>
<td>Manganese</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Potassium</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Silicon</td>
<td>37</td>
<td>11</td>
</tr>
<tr>
<td>Sulfate</td>
<td>3,430</td>
<td>3,770</td>
</tr>
<tr>
<td>Zinc</td>
<td>440</td>
<td>414</td>
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<tr>
<td>pH</td>
<td>3</td>
<td>6.6</td>
</tr>
<tr>
<td>Eh</td>
<td>508</td>
<td>341</td>
</tr>
</tbody>
</table>
Table 10-19: Average Influent and Effluent Concentrations – Monte Romero Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent Concentration</th>
<th>Average Effluent Concentration</th>
</tr>
</thead>
</table>

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


Appendix A: Biochemical Reactors Data Tables

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
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<tr>
<td><strong>Solid substrate</strong></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Sulfate</td>
<td>NS</td>
<td>195</td>
<td>150</td>
<td>114</td>
<td>117</td>
<td>Cwm Rheidol&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Jarvis et al., 2014 (Figure 42)</td>
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<tr>
<td>Zinc</td>
<td>Total</td>
<td>15.5</td>
<td>2.5</td>
<td>9</td>
<td>4.1</td>
<td>Cwm Rheidol&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>15.5</td>
<td>&lt;0.01</td>
<td>9</td>
<td>4</td>
<td>Cwm Rheidol&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Jarvis et al., 2014 (Figure 37)</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>3.5</td>
<td>7.5</td>
<td>4.8</td>
<td>7.25</td>
<td>Cwm Rheidol&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Jarvis et al., 2014 (Figure 40)</td>
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<tr>
<td>Sulfate</td>
<td>Not specified</td>
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<td>145</td>
<td>92</td>
<td>85</td>
<td>Nenthead</td>
<td>Jarvis et al., 2014 (Figure 32)</td>
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<td>0.5</td>
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<td>0.25</td>
<td>1.7</td>
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<td>Jarvis et al., 2014 (Figure 30)</td>
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<tr>
<td>Cadmium</td>
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<td>0.2</td>
<td>0.00025</td>
<td>0.027</td>
<td>Not plotted</td>
<td>Standard</td>
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<tr>
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<td>0.003</td>
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<td>0.7</td>
<td>1&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Gallagher et al., 2012 (Figure 6)</td>
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</table>
### Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese</td>
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<td>13.2</td>
<td>10</td>
<td>5.4</td>
<td>7</td>
<td>Standard</td>
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<tr>
<td>Sulfate</td>
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<td>400</td>
<td>200</td>
<td>150</td>
<td>110</td>
<td>Standard</td>
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<tr>
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<td>32.1</td>
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<td>Standard</td>
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<td>19.3</td>
<td>Not provided</td>
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<td>Jarvis et al., 2015 (Text)</td>
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<td>0.04</td>
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<td>Jarvis et al., 2015 (Figure 2)</td>
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<td>0.22</td>
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<td>&lt;0.003</td>
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<td>40</td>
<td>106</td>
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<td>Nordwick and Bless, 2008 (Figure 4-14)</td>
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</table>
Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>39</td>
<td>&lt;0.007</td>
<td>4.5</td>
<td>&lt;0.007</td>
<td>Surething (Reactor 1)</td>
<td>Nordwick and Bless, 2008 (Figure 4-4)</td>
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<tr>
<td>Cadmium</td>
<td>Total</td>
<td>0.17</td>
<td>&lt;0.0024</td>
<td>0.11</td>
<td>&lt;0.0024</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Figure 7)</td>
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<tr>
<td>Cadmium</td>
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<td>&lt;0.0024</td>
<td>0.11</td>
<td>&lt;0.0024</td>
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<td>Standard</td>
<td>Reisman et al., 2009 (Figure 8)</td>
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<td>0.17</td>
<td>15</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Figure 9)</td>
</tr>
<tr>
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<td>Dissolved</td>
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<td>0.17</td>
<td>0.08</td>
<td>4.5</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Figure 9)</td>
</tr>
<tr>
<td>Lead</td>
<td>Total</td>
<td>6</td>
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<td>0.016</td>
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<td>Reisman et al., 2009 (Figure 10)</td>
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<td>10</td>
<td>6</td>
<td>7.5</td>
<td>Standard</td>
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<tr>
<td>Manganese</td>
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<td>12.71</td>
<td>10.5</td>
<td>5.34</td>
<td>8</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Figure 11)</td>
</tr>
</tbody>
</table>
# Appendix A: Biochemical Reactors Data Tables

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Total</td>
<td>30.9</td>
<td>0.8</td>
<td>21(^e)</td>
<td>0.9</td>
<td>Standard(^d)</td>
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<tr>
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<td>Dissolved</td>
<td>30.9</td>
<td>0.4</td>
<td>21</td>
<td>1.5</td>
<td>Standard(^d)</td>
<td>Reisman et al., 2009 (Figure 12)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Total</td>
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<td>0.0453</td>
<td>0.011</td>
<td>0.0094</td>
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<td>Wilmoth, 2002 (Table 5-6)</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Total</td>
<td>0.0109</td>
<td>0.0035</td>
<td>0.0051</td>
<td>&lt;0.005</td>
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<td>Wilmoth, 2002</td>
</tr>
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<td>Total</td>
<td>0.0419</td>
<td>0.0048</td>
<td>0.0051</td>
<td>0.0056</td>
<td>Calliope (BCR III)(^f)</td>
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<td>Copper</td>
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<td>3.05</td>
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<td>Wilmoth, 2002</td>
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<td>Total</td>
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<td>0.149</td>
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<td>Calliope (BCR III)(^f)</td>
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<td>Sulfate</td>
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<tr>
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<td>6.79</td>
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<td>NS</td>
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<td>ND</td>
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<td>Blumenstein and Gusek, 2009 (Figure 9)</td>
</tr>
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<td>Selenium</td>
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<td>ND</td>
<td>0.01</td>
<td>ND</td>
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<td>&lt;0.001</td>
<td>Confidential Mine(^b)</td>
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<td>pH</td>
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<td>6.8</td>
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<td>7.2</td>
<td>Confidential Mine(^g)</td>
<td>Blumenstein and Gusek, 2009 (Figure 2)</td>
</tr>
</tbody>
</table>
### Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>Total</td>
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<td>0.008</td>
<td>0.018</td>
<td>0.001</td>
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<tr>
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<td>0.0011</td>
<td>&lt;0.0001</td>
<td>Keno Hill</td>
<td>Harrington et al., 2015 (Figure 2)</td>
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<td>Total</td>
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<td>20</td>
<td>15</td>
<td>16</td>
<td>Keno Hill</td>
<td>Harrington et al., 2015 (Figure 2)</td>
</tr>
<tr>
<td>Zinc</td>
<td>Total</td>
<td>6.2</td>
<td>0.01</td>
<td>4.8</td>
<td>0.55</td>
<td>Keno Hill</td>
<td>Harrington et al., 2015 (Figure 2)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>34.2</td>
<td>26.1</td>
<td>26.1</td>
<td>22.2</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Total</td>
<td>36.3</td>
<td>28.3</td>
<td>28.3</td>
<td>22.7</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>0.155</td>
<td>0.104</td>
<td>0.104</td>
<td>0.108</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Total</td>
<td>1.170</td>
<td>0.389</td>
<td>0.389</td>
<td>0.334</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>0.003</td>
<td>&lt;0.0023</td>
<td>0.0028</td>
<td>&lt;0.0023</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Total</td>
<td>&lt;0.0023</td>
<td>0.0034</td>
<td>&lt;0.0022</td>
<td>&lt;0.0023</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>0.0059</td>
<td>0.005</td>
<td>0.0044</td>
<td>0.0059</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
</tbody>
</table>
Appendix A: Biochemical Reactors Data Tables

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>Total</td>
<td>&lt;0.0021</td>
<td>&lt;0.0021</td>
<td>&lt;0.0021</td>
<td>0.0026</td>
<td>Leviathan – recirculation mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>&lt;0.00023</td>
<td>&lt;0.00023</td>
<td>&lt;0.0023</td>
<td>0.0023</td>
<td>Leviathan – gravity mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Total</td>
<td>0.00042</td>
<td>&lt;0.00023</td>
<td>&lt;0.00023</td>
<td>0.00023</td>
<td>Leviathan – gravity mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.00035</td>
<td>0.00021</td>
<td>0.00021</td>
<td>0.00041</td>
<td>Leviathan – recirculation mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Total</td>
<td>0.00023</td>
<td>&lt;0.00016</td>
<td>&lt;0.00016</td>
<td>0.0026</td>
<td>Leviathan – recirculation mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.0139</td>
<td>0.0133</td>
<td>0.0133</td>
<td>0.0143</td>
<td>Leviathan – gravity mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Chromium</td>
<td>Total</td>
<td>0.0147</td>
<td>0.0139</td>
<td>0.0139</td>
<td>0.0128</td>
<td>Leviathan – gravity mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.0122</td>
<td>0.0118</td>
<td>0.0118</td>
<td>0.012</td>
<td>Leviathan – recirculation mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Chromium</td>
<td>Total</td>
<td>0.012</td>
<td>0.012</td>
<td>0.012</td>
<td>0.0117</td>
<td>Leviathan – recirculation mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.614</td>
<td>0.0057</td>
<td>0.0057</td>
<td>0.0061</td>
<td>Leviathan – gravity mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Copper</td>
<td>Total</td>
<td>0.653</td>
<td>0.0676</td>
<td>0.0676</td>
<td>0.0537</td>
<td>Leviathan – gravity mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.0083</td>
<td>0.0071</td>
<td>0.0071</td>
<td>0.0076</td>
<td>Leviathan – recirculation mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
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<tr>
<td>Copper</td>
<td>Total</td>
<td>0.0243</td>
<td>0.0107</td>
<td>0.0107</td>
<td>0.0114</td>
<td>Leviathan – recirculation mode(^1)</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
</tbody>
</table>
Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>73.1</td>
<td>71.7</td>
<td>71.1</td>
<td>63.7</td>
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<td>U.S. EPA, 2006a (Table 2-13)</td>
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<tr>
<td>Iron</td>
<td>Total</td>
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<td>77.7</td>
<td>77.7</td>
<td>63.7</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>0.266</td>
<td>0.247</td>
<td>0.266</td>
<td>0.247</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
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<tr>
<td>Iron</td>
<td>Total</td>
<td>7.93</td>
<td>3.14</td>
<td>3.14</td>
<td>2.69</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.0058</td>
<td>0.0058</td>
<td>0.0058</td>
<td>0.005</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Lead</td>
<td>Total</td>
<td>0.0059</td>
<td>0.0055</td>
<td>0.0055</td>
<td>0.0044</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0040</td>
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<td>U.S. EPA, 2006a (Table 2-15)</td>
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<tr>
<td>Lead</td>
<td>Total</td>
<td>0.0047</td>
<td>0.0038</td>
<td>0.0043</td>
<td>0.0047</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>0.449</td>
<td>0.35</td>
<td>0.350</td>
<td>0.300</td>
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<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Nickel</td>
<td>Total</td>
<td>0.475</td>
<td>0.37</td>
<td>0.37</td>
<td>0.30</td>
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<td>U.S. EPA, 2006a (Table 2-17)</td>
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<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>0.0726</td>
<td>0.0117</td>
<td>0.0117</td>
<td>0.0102</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Nickel</td>
<td>Total</td>
<td>0.0734</td>
<td>0.0334</td>
<td>0.0334</td>
<td>0.0286</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Selenium</td>
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<td>0.0108</td>
<td>0.0108</td>
<td>0.0106</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
</tbody>
</table>
## Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selenium</td>
<td>Total</td>
<td>0.014</td>
<td>0.0124</td>
<td>0.0124</td>
<td>0.0099</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
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<tr>
<td>Selenium</td>
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<td>0.0114</td>
<td>0.0116</td>
<td>0.0075</td>
<td>0.0114</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
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<tr>
<td>Selenium</td>
<td>Total</td>
<td>0.0124</td>
<td>0.0103</td>
<td>0.0103</td>
<td>0.0089</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
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<tr>
<td>Sulfate</td>
<td>Total</td>
<td>1520</td>
<td>1480</td>
<td>1480</td>
<td>1310</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-9)</td>
</tr>
<tr>
<td>Sulfate</td>
<td>Total</td>
<td>1190</td>
<td>1160</td>
<td>1160</td>
<td>1090</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-11)</td>
</tr>
<tr>
<td>Sulfide</td>
<td>Dissolved</td>
<td>37</td>
<td>38</td>
<td>0</td>
<td>37</td>
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<td>U.S. EPA, 2006a (Table 2-9)</td>
</tr>
<tr>
<td>Sulfide</td>
<td>Dissolved</td>
<td>27</td>
<td>50</td>
<td>0</td>
<td>27</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-11)</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>0.661</td>
<td>0.032</td>
<td>0.032</td>
<td>0.0288</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Zinc</td>
<td>Total</td>
<td>0.714</td>
<td>0.125</td>
<td>0.125</td>
<td>0.0927</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>0.0172</td>
<td>0.0063</td>
<td>0.0063</td>
<td>0.0104</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Zinc</td>
<td>Total</td>
<td>0.028</td>
<td>0.0137</td>
<td>0.0137</td>
<td>0.0146</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>3.6</td>
<td>4.7</td>
<td>4.7</td>
<td>4.8</td>
<td>Leviathan – gravity mode</td>
<td>U.S. EPA, 2006a (Table 2-9)</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>7.2</td>
<td>7.2</td>
<td>7.2</td>
<td>7.3</td>
<td>Leviathan – recirculation mode</td>
<td>U.S. EPA, 2006a (Table 2-11)</td>
</tr>
</tbody>
</table>
### Table A-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
</table>
| 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

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>9.7</td>
<td>&lt;0.02</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>1.07</td>
<td>0.075</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.33</td>
<td>&lt;0.005</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.32</td>
<td>0.012²</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>27.7</td>
<td>11.25</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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</td>
</tr>
</tbody>
</table>
## Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>Manganese</td>
<td>Dissolved</td>
<td>6.2</td>
<td>2.05</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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.</td>
</tr>
<tr>
<td>Sulfate</td>
<td>Dissolved</td>
<td>277</td>
<td>136.5</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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.</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>26.1</td>
<td>0.032&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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.</td>
</tr>
<tr>
<td>pH</td>
<td>Dissolved</td>
<td>3.0</td>
<td>7.2</td>
<td>Lilly/Orphan Boy</td>
<td>Bless et al., 2008 (Table 1)</td>
<td>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.</td>
</tr>
</tbody>
</table>

<sup>a</sup> : Notes
### Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.14</td>
<td>&lt;0.002</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Table 1)</td>
<td>September 2007 – September 2008</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.095&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.00019</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
<td>August 2008 – November 2011</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.26</td>
<td>&lt;0.0038</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Table 1)</td>
<td>September 2007 – September 2008</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.0014</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
<td>August 2008 – November 2011</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>5.23</td>
<td>2.01</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Table 1)</td>
<td>September 2007 – September 2008</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>11.2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.56</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
<td>August 2008 – November 2011</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.54</td>
<td>0.01</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Table 1)</td>
<td>September 2007 – September 2008</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.134&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.00215</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
<td>August 2008 – November 2011</td>
</tr>
<tr>
<td>Manganese</td>
<td>Dissolved</td>
<td>10.99</td>
<td>10.53</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Table 1)</td>
<td>September 2007 – September 2008</td>
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<td>Sulfate</td>
<td>Dissolved</td>
<td>281</td>
<td>119</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
<td>August 2008 – November 2011</td>
</tr>
<tr>
<td>Sulfide</td>
<td>Dissolved</td>
<td>&lt;0.5</td>
<td>12.5</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
<td>August 2008 – November 2011</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>26.46</td>
<td>0.55</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Table 1)</td>
<td>September 2007 – September 2008</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>18.25&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.073</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
<td>August 2008 – November 2011</td>
</tr>
</tbody>
</table>
### Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>1.2229</td>
<td>0.0616</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-6)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-6)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.0112</td>
<td>&lt;0.005</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-6)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.4078</td>
<td>0.0546</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-6)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>0.4556</td>
<td>0.4143</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-6)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>Manganese</td>
<td>Dissolved</td>
<td>1.4581</td>
<td>1.0073</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-6)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>Sulfate</td>
<td>Dissolved</td>
<td>0.1029</td>
<td>0.1039</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-4)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>2.8406</td>
<td>0.7944</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-6)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>6.05</td>
<td>7.16</td>
<td>Calliope</td>
<td>Wilmuth, 2002c (Table 5-1)</td>
<td>BCR III effluent</td>
</tr>
<tr>
<td>Sulfate</td>
<td>Dissolved</td>
<td>30.4</td>
<td>10.1</td>
<td>Force Crag</td>
<td>Jarvis et al., 2015 (Text)</td>
<td>VFP1</td>
</tr>
<tr>
<td>Sulfate</td>
<td>Dissolved</td>
<td>30.4</td>
<td>8.1</td>
<td>Force Crag</td>
<td>Jarvis et al., 2015 (Text)</td>
<td>VFP2</td>
</tr>
<tr>
<td>Nitrate</td>
<td>NS</td>
<td>5.1</td>
<td>0.08</td>
<td>Confidential Mine</td>
<td>Blumenstein and Gusek, 2009 (Text)</td>
<td>Over 14 months of operation</td>
</tr>
<tr>
<td>Selenium</td>
<td>NS</td>
<td>0.013</td>
<td>0.001</td>
<td>Confidential Mine</td>
<td>Blumenstein and Gusek, 2009 (Text)</td>
<td>Over 14 months of operation</td>
</tr>
<tr>
<td>Thallium</td>
<td>NS</td>
<td>1.25</td>
<td>0.007</td>
<td>Confidential Mine</td>
<td>Blumenstein and Gusek, 2009 (Text)</td>
<td>Over 14 months of operation; average effluent influenced by two upset events</td>
</tr>
</tbody>
</table>

**Liquid Substrate (Not available)**

**Notes:**
- All analytical results reported in mg/L

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A-13
Table A-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
</thead>
</table>
| 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.
### Appendix A: Biochemical Reactors Data Tables

#### Table A-3: Removal Efficiencies – All Applicable Sites

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solid Substrate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Zinc</td>
<td>68.00%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>85%</td>
<td>37%</td>
<td>Nenthead</td>
<td>Jarvis et al., 2014 (Figure 34; Text)</td>
</tr>
<tr>
<td>Dissolved Zinc</td>
<td>84%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>95%</td>
<td>68%</td>
<td>Nenthead</td>
<td>Jarvis et al., 2014 (Figure 26; Text)</td>
</tr>
<tr>
<td>Total Zinc&lt;sup&gt;b&lt;/sup&gt;</td>
<td>63%</td>
<td>85%</td>
<td>50%</td>
<td>Cwm Rheidol</td>
<td>Jarvis et al., 2014 (Figure 38)</td>
</tr>
<tr>
<td>Dissolved Zinc&lt;sup&gt;b&lt;/sup&gt;</td>
<td>76%</td>
<td>100%</td>
<td>50%</td>
<td>Cwm Rheidol</td>
<td>Jarvis et al., 2014 (Figure 39)</td>
</tr>
<tr>
<td>Dissolved Cadmium</td>
<td>99.8%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
</tr>
<tr>
<td>Dissolved Copper</td>
<td>98.6%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
</tr>
<tr>
<td>Total Iron</td>
<td>95%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
</tr>
<tr>
<td>Dissolved Lead</td>
<td>98.4%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
</tr>
<tr>
<td>Sulfate&lt;sup&gt;c&lt;/sup&gt;</td>
<td>57.2%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
</tr>
<tr>
<td>Dissolved Zinc</td>
<td>99.6%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Gallagher et al., 2012 (Text)</td>
</tr>
<tr>
<td>Total Zinc</td>
<td>98.70%</td>
<td>NA</td>
<td>NA</td>
<td>Force Crag, VFP1</td>
<td>Jarvis et al., 2015 (Text)</td>
</tr>
<tr>
<td>Total Zinc</td>
<td>94.10%</td>
<td>NA</td>
<td>NA</td>
<td>Force Crag, VFP2</td>
<td>Jarvis et al., 2015 (Text)</td>
</tr>
<tr>
<td>Total Zinc</td>
<td>96.80%</td>
<td>NA</td>
<td>NA</td>
<td>Force Crag, overall system</td>
<td>Jarvis et al., 2015 (Text)</td>
</tr>
<tr>
<td>Cadmium&lt;sup&gt;c&lt;/sup&gt;</td>
<td>98.50%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Text)</td>
</tr>
<tr>
<td>Copper&lt;sup&gt;c&lt;/sup&gt;</td>
<td>98.60%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Text)</td>
</tr>
<tr>
<td>Iron&lt;sup&gt;c&lt;/sup&gt;</td>
<td>65.00%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Text)</td>
</tr>
</tbody>
</table>
### Table A-3: Removal Efficiencies – All Applicable Sites

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead&lt;sup&gt;c&lt;/sup&gt;</td>
<td>98.10%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Text)</td>
</tr>
<tr>
<td>Zinc&lt;sup&gt;c&lt;/sup&gt;</td>
<td>97.90%</td>
<td>NA</td>
<td>NA</td>
<td>Standard</td>
<td>Reisman et al., 2009 (Text)</td>
</tr>
<tr>
<td>Total Aluminum</td>
<td>-6.17%</td>
<td>99.73%</td>
<td>-650.00%</td>
<td>Calliope – BCR III&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Wilmoth, 2002 (Table 5-6)</td>
</tr>
<tr>
<td>Total Arsenic</td>
<td>28.31%</td>
<td>86.89%</td>
<td>-95.38%</td>
<td>Calliope – BCR III&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Wilmoth, 2002 (Table 5-6)</td>
</tr>
<tr>
<td>Total Cadmium</td>
<td>76.34%</td>
<td>95.97%</td>
<td>-9.80%</td>
<td>Calliope – BCR III&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Wilmoth, 2002 (Table 5-6)</td>
</tr>
<tr>
<td>Total Copper</td>
<td>44.07%</td>
<td>99.37%</td>
<td>-189.59%</td>
<td>Calliope – BCR III&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Wilmoth, 2002 (Table 5-6)</td>
</tr>
<tr>
<td>Total Iron</td>
<td>-801.74%</td>
<td>97.94%</td>
<td>-14275.00%</td>
<td>Calliope – BCR III&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Wilmoth, 2002 (Table 5-6)</td>
</tr>
<tr>
<td>Total Manganese</td>
<td>30.86%</td>
<td>98.05%</td>
<td>-108.22%</td>
<td>Calliope – BCR III&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Wilmoth, 2002 (Table 5-6)</td>
</tr>
<tr>
<td>Total Sulfate</td>
<td>-2.09%</td>
<td>32.20%</td>
<td>-68.63%</td>
<td>Calliope – BCR III&lt;sup&gt;e&lt;/sup&gt;</td>
<td>Wilmoth, 2002 (Table 5-4)</td>
</tr>
<tr>
<td>Total Zinc</td>
<td>58.24%</td>
<td>99.21%</td>
<td>-11.97%</td>
<td>Calliope – BCR III&lt;sup&gt;d&lt;/sup&gt;</td>
<td>Wilmoth, 2002 (Table 5-6)</td>
</tr>
<tr>
<td>Nitrate&lt;sup&gt;c&lt;/sup&gt;</td>
<td>98.43%&lt;sup&gt;f&lt;/sup&gt;</td>
<td>&gt;99%&lt;sup&gt;g&lt;/sup&gt;</td>
<td>96.55%&lt;sup&gt;f&lt;/sup&gt;</td>
<td>Confidential Mine</td>
<td>Blumenstein and Gusek, 2009 (Figure 9)</td>
</tr>
<tr>
<td>Selenium&lt;sup&gt;c&lt;/sup&gt;</td>
<td>&gt;99%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&gt;99%&lt;sup&gt;g&lt;/sup&gt;</td>
<td>&gt;99%&lt;sup&gt;g&lt;/sup&gt;</td>
<td>Confidential Mine</td>
<td>Blumenstein and Gusek, 2009 (Text, Figure 8)</td>
</tr>
<tr>
<td>Thallium&lt;sup&gt;c&lt;/sup&gt;</td>
<td>&gt;99%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>99.97%&lt;sup&gt;f&lt;/sup&gt;</td>
<td>99.8%&lt;sup&gt;f&lt;/sup&gt;</td>
<td>Confidential Mine</td>
<td>Blumenstein and Gusek, 2009 (Text, Figure 7)</td>
</tr>
</tbody>
</table>

**Liquid Substrate**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Aluminum</td>
<td>NA</td>
<td>22%</td>
<td>19.8%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Aluminum</td>
<td>NA</td>
<td>23.7%</td>
<td>14.9%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
</tbody>
</table>
## Table A-3: Removal Efficiencies – All Applicable Sites

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Aluminum</td>
<td>NA</td>
<td>66.8%</td>
<td>14.1%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Dissolved Aluminum</td>
<td>NA</td>
<td>32.9%</td>
<td>0%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Total Arsenic</td>
<td>NA</td>
<td>NC (influent &lt; DL)</td>
<td>NC (influent &lt; DL)</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Arsenic</td>
<td>NA</td>
<td>NC (influent &lt; DL)</td>
<td>NC (influent &lt; DL)</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Total Cadmium</td>
<td>NA</td>
<td>45.2%</td>
<td>0%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Cadmium</td>
<td>NA</td>
<td>NC (influent &lt; DL)</td>
<td>NC (influent &lt; DL)</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Total Chromium</td>
<td>NA</td>
<td>7.9%</td>
<td>5.4%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Chromium</td>
<td>NA</td>
<td>4.3%</td>
<td>0%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Total Chromium</td>
<td>NA</td>
<td>2.5%</td>
<td>0%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Dissolved Chromium</td>
<td>NA</td>
<td>0%</td>
<td>0%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Total Copper</td>
<td>NA</td>
<td>89.7%</td>
<td>20.6%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Copper</td>
<td>NA</td>
<td>99.1%</td>
<td>0%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
</tbody>
</table>
## Table A-3: Removal Efficiencies – All Applicable Sites

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Copper</td>
<td>NA</td>
<td>56%</td>
<td>-6.5%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Dissolved Copper</td>
<td>NA</td>
<td>14.5%</td>
<td>0%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Total Iron</td>
<td>NA</td>
<td>18%</td>
<td>10.7%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Iron</td>
<td>NA</td>
<td>11.2%</td>
<td>1.9%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Total Iron</td>
<td>NA</td>
<td>60.4%</td>
<td>14.3%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Dissolved Iron</td>
<td>NA</td>
<td>94.6%</td>
<td>7.1%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Total Lead</td>
<td>NA</td>
<td>20%</td>
<td>6.8%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Lead</td>
<td>NA</td>
<td>0%</td>
<td>0%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Total Lead</td>
<td>NA</td>
<td>19.2%</td>
<td>-9.3%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Dissolved Lead</td>
<td>NA</td>
<td>0%</td>
<td>0%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Total Nickel</td>
<td>NA</td>
<td>18.9%</td>
<td>22.1%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Nickel</td>
<td>NA</td>
<td>22.1%</td>
<td>14.3%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Total Nickel</td>
<td>NA</td>
<td>54.5%</td>
<td>14.4%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Dissolved Nickel</td>
<td>NA</td>
<td>83.9%</td>
<td>12.8%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Total Selenium</td>
<td>NA</td>
<td>20.2%</td>
<td>11.4%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Selenium</td>
<td>NA</td>
<td>23.9%</td>
<td>0%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
</tbody>
</table>
## Table A-3: Removal Efficiencies – All Applicable Sites

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Selenium</td>
<td>NA</td>
<td>16.9%</td>
<td>13.6%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Dissolved Selenium</td>
<td>NA</td>
<td>0%</td>
<td>0%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Total Sulfate</td>
<td>NA</td>
<td>11.5%</td>
<td>2.6%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-9)</td>
</tr>
<tr>
<td>Total Sulfate</td>
<td>NA</td>
<td>6.0%</td>
<td>2.5%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-11)</td>
</tr>
<tr>
<td>Total Zinc</td>
<td>NA</td>
<td>82.5%</td>
<td>25.8%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-17)</td>
</tr>
<tr>
<td>Dissolved Zinc</td>
<td>NA</td>
<td>95.2%</td>
<td>10%</td>
<td>Leviathan – gravity flow mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-13)</td>
</tr>
<tr>
<td>Total Zinc</td>
<td>NA</td>
<td>51.1%</td>
<td>-6.6%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-18)</td>
</tr>
<tr>
<td>Dissolved Zinc</td>
<td>NA</td>
<td>63.4%</td>
<td>0%</td>
<td>Leviathan – recirculation mode&lt;sup&gt;h,i&lt;/sup&gt;</td>
<td>U.S. EPA, 2006a (Table 2-15)</td>
</tr>
<tr>
<td>Total Antimony</td>
<td>80.00%</td>
<td>NA</td>
<td>NA</td>
<td>Keno Hill&lt;sup&gt;l&lt;/sup&gt;</td>
<td>Harrington et al., 2015 (Text)</td>
</tr>
<tr>
<td>Total Arsenic</td>
<td>80.00%</td>
<td>NA</td>
<td>NA</td>
<td>Keno Hill&lt;sup&gt;l&lt;/sup&gt;</td>
<td>Harrington et al., 2015 (Text)</td>
</tr>
<tr>
<td>Total Nickel</td>
<td>80.00%</td>
<td>NA</td>
<td>NA</td>
<td>Keno Hill&lt;sup&gt;l&lt;/sup&gt;</td>
<td>Harrington et al., 2015 (Text)</td>
</tr>
<tr>
<td>Total Zinc</td>
<td>99.00%</td>
<td>NA</td>
<td>NA</td>
<td>Keno Hill&lt;sup&gt;l&lt;/sup&gt;</td>
<td>Harrington et al., 2015 (Text)</td>
</tr>
</tbody>
</table>

**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>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>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.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>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.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>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.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>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</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h = Leviathan gravity flow configuration data March 24, 2004; recirculation flow configuration data August 19, 2004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i = Minimum removal efficiencies mostly due to low concentrations into the 2&lt;sup&gt;nd&lt;/sup&gt; BCR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>j = Keno Hill data used were from post-August 2009, which corresponds to the start of sulfate-reducing conditions in the BCR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Appendix B: Caps and Covers Data Tables

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Leachate Concentration from Uncapped Cell</th>
<th>Maximum Leachate Concentration from Capped Cell</th>
<th>Minimum Leachate Concentration from Uncapped Cell</th>
<th>Minimum Leachate Concentration from Capped Cell</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>0.03</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>Nason et al., 2013 (Figure 7)</td>
<td>Data extracted from Figure 7; range 2005 to 2010&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Copper</td>
<td>0.04</td>
<td>0.001</td>
<td>0.0005</td>
<td>ND</td>
<td>Nason et al., 2013 (Figure 7)</td>
<td>Data extracted from Figure 7; range 2005 to 2010&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Iron</td>
<td>0.022</td>
<td>0.005</td>
<td>ND</td>
<td>ND</td>
<td>Nason et al., 2013 (Figure 7)</td>
<td>Data extracted from Figure 7; range 2005 to 2010&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Lead</td>
<td>0.00065</td>
<td>0.00055</td>
<td>0.0001</td>
<td>0.0001</td>
<td>Nason et al., 2013 (Figure 7)</td>
<td>Data extracted from Figure 7; range 2005 to 2010&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sulfur</td>
<td>700</td>
<td>220</td>
<td>410</td>
<td>15</td>
<td>Nason et al., 2013 (Figure 7)</td>
<td>Data extracted from Figure 7; range 2005 to 2010&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Zinc</td>
<td>40</td>
<td>ND</td>
<td>2.5</td>
<td>ND</td>
<td>Nason et al., 2013 (Figure 7)</td>
<td>Data extracted from Figure 7; range 2005 to 2010&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>pH</td>
<td>6.2</td>
<td>6.8</td>
<td>7.6</td>
<td>8.2</td>
<td>Nason et al., 2013 (Figure 7)</td>
<td>Data extracted from Figure 7; range 2005 to 2010&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

**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
- <sup>a</sup> = 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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W1D</td>
<td>8018 and 8031</td>
<td>Cobalt</td>
<td>NS</td>
<td>0.036</td>
<td>0.009</td>
<td>NR</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W1D and are average values for period of record.</td>
</tr>
<tr>
<td>W1D</td>
<td>8018 and 8031</td>
<td>Copper</td>
<td>NS</td>
<td>0.068</td>
<td>0.03</td>
<td>0.02</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W1D and are average values for period of record.</td>
</tr>
<tr>
<td>W1D</td>
<td>8018 and 8031</td>
<td>Nickel</td>
<td>NS</td>
<td>3.98</td>
<td>0.74</td>
<td>0.76</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W1D and are average values for period of record.</td>
</tr>
<tr>
<td>W1D</td>
<td>8018 and 8031</td>
<td>Zinc</td>
<td>NS</td>
<td>0.052</td>
<td>0.021</td>
<td>0.019</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W1D and are average values for the period of record.</td>
</tr>
<tr>
<td>W1D</td>
<td>8018 and 8031</td>
<td>pH</td>
<td>NA</td>
<td>7.07</td>
<td>7.3</td>
<td>7.26</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W1D and are average of pH values for period of record.</td>
</tr>
<tr>
<td>W2D/3D</td>
<td>8031</td>
<td>Cobalt</td>
<td>NS</td>
<td>0.02</td>
<td>0.02</td>
<td>–d</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W2D/3D and are average values for the period of record.</td>
</tr>
<tr>
<td>W2D/3D</td>
<td>8031</td>
<td>Copper</td>
<td>NS</td>
<td>0.05</td>
<td>0.05</td>
<td>–d</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W2D/3D and are average values for the period of record.</td>
</tr>
</tbody>
</table>
### Table B-2: Dunka Mine – Average Pre-Capping and Post-Capping Concentrations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W2D/3D</td>
<td>8031</td>
<td>Nickel</td>
<td>NS</td>
<td>1.9</td>
<td>1.9</td>
<td>--$^d$</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W2D/3D and are average values for the period of record.</td>
</tr>
<tr>
<td>W2D/3D</td>
<td>8031</td>
<td>Zinc</td>
<td>NS</td>
<td>0.05</td>
<td>0.05</td>
<td>--$^d$</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W2D/3D and are average values for the period of record.</td>
</tr>
<tr>
<td>W2D/3D</td>
<td>8031</td>
<td>pH</td>
<td>NA</td>
<td>7</td>
<td>7</td>
<td>--$^d$</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Values are influent to Wetland W2D/3D and are average of pH values for the period of record.</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>119</td>
<td>0.584</td>
<td>98.6</td>
<td>0.575</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>3.47</td>
<td>0.097</td>
<td>2.81</td>
<td>&lt;0.0018</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.0463</td>
<td>&lt;0.00016</td>
<td>0.0132</td>
<td>&lt;0.00021</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.629</td>
<td>0.0013</td>
<td>0.266</td>
<td>0.0116</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.549</td>
<td>&lt;0.0019</td>
<td>0.434</td>
<td>&lt;0.0019</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>545</td>
<td>0.0999</td>
<td>392</td>
<td>0.0057</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.010</td>
<td>&lt;0.0014</td>
<td>0.0023</td>
<td>&lt;0.0009</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>2.76</td>
<td>0.0418</td>
<td>2.41</td>
<td>0.0688</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Selenium</td>
<td>Dissolved</td>
<td>0.0323</td>
<td>&lt;0.0018</td>
<td>0.02</td>
<td>&lt;0.0018</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>0.583</td>
<td>0.0026</td>
<td>0.49</td>
<td>0.0031</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-1)</td>
</tr>
</tbody>
</table>
Table C-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>486</td>
<td>1.09</td>
<td>326</td>
<td>1.14</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>4.05</td>
<td>0.0101</td>
<td>1.33</td>
<td>0.0096</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.0683</td>
<td>0.0007</td>
<td>0.0479</td>
<td>0.0009</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>1.24</td>
<td>0.0024</td>
<td>0.729</td>
<td>0.0463</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>2.99</td>
<td>0.0101</td>
<td>2.11</td>
<td>0.0102</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>653</td>
<td>&lt;0.0038</td>
<td>336</td>
<td>0.243</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.0122</td>
<td>&lt;0.0014</td>
<td>0.0017</td>
<td>0.0044</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
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<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>8.77</td>
<td>0.0389</td>
<td>5.98</td>
<td>0.0172</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Selenium</td>
<td>Dissolved</td>
<td>0.0145</td>
<td>0.004</td>
<td>0.0046</td>
<td>0.0037</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>1.81</td>
<td>0.0307</td>
<td>1.25</td>
<td>0.0097</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-2)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>33.6</td>
<td>0.254</td>
<td>30.9</td>
<td>0.185</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-3)</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>0.545</td>
<td>0.0129</td>
<td>0.485</td>
<td>0.0038</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-3)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>&lt;0.0003</td>
<td>&lt;0.0003 – 0.0007</td>
<td>&lt;0.00029</td>
<td>&lt;0.0003</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-3)</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.0235</td>
<td>0.0038</td>
<td>0.0162</td>
<td>0.0014</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-3)</td>
</tr>
</tbody>
</table>
### Table C-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – All Applicable Case Studies

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

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Mine</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual-stage</td>
<td>sample</td>
<td>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</td>
<td>&lt;= Not detected above laboratory method detection limit shown</td>
<td>a Value reported in reference, but below reference’s stated DL</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Value reported in reference, but below reference’s stated DL.
### Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>107.8</td>
<td>0.633</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
<td></td>
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<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>3.236</td>
<td>0.0063</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
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<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.0261</td>
<td>ND</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
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</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.341</td>
<td>0.00304</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.502</td>
<td>0.00307</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
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<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>456.428</td>
<td>0.176</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
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<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.0071</td>
<td>0.00156</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>2.56</td>
<td>0.0468</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
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<tr>
<td>Selenium</td>
<td>Dissolved</td>
<td>0.0271</td>
<td>0.00214</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
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<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>0.538</td>
<td>0.00561</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
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<tr>
<td>Aluminum</td>
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<td>381</td>
<td>1.118</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table B-4)</td>
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<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>2.239</td>
<td>0.00859</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
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<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.054</td>
<td>0.00071</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
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<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.877</td>
<td>0.0057</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
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<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>2.383</td>
<td>0.00805</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
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<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>461.615</td>
<td>0.0449</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
<td></td>
</tr>
</tbody>
</table>
# Appendix C: Neutralization and Chemical Precipitation Data Tables

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

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.0082</td>
<td>0.002</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>7.024</td>
<td>0.0342</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
<td></td>
</tr>
<tr>
<td>Selenium</td>
<td>Dissolved</td>
<td>0.0088</td>
<td>0.00378</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
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<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>1.469</td>
<td>0.0193</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table B-5)</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>31.988</td>
<td>0.251</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>0.519</td>
<td>0.00584</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
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<td>Cadmium</td>
<td>Dissolved</td>
<td>ND</td>
<td>0.00038</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
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<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.0193</td>
<td>0.00225</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
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<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.0135</td>
<td>0.00546</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
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<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>391.250</td>
<td>0.148</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
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<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>0.0051</td>
<td>0.00166</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
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<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>1.631</td>
<td>0.0226</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
<td></td>
</tr>
</tbody>
</table>
Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>Selenium</td>
<td>Dissolved</td>
<td>0.0033</td>
<td>0.00324</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
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</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>0.356</td>
<td>0.0142</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Table B-6)</td>
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<tr>
<td>Iron</td>
<td>Total</td>
<td>850.57 ± 239.84</td>
<td>8.92 ± 20.41</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2009 Average</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>858.45 ±189.55</td>
<td>0.52 ± 0.59</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2010 Average</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>856.24 ± 126.83</td>
<td>1.98 ± 6.85</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2011 Average</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>879.55 ± 181.09</td>
<td>0.37 ± 0.29</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2012 Average</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>461.65 ± 74.47</td>
<td>0.24 ± 0.58</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2013 Average</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>309.32 ± 51.68</td>
<td>0.35 ± 1.01</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2014 Average</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>214.35 ± 96.21</td>
<td>1.61 ± 11.05</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2015 Average</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>183.62 ± 53.93</td>
<td>10.46 ± 17.95</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2016 Average</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>199.15 ± 64.75</td>
<td>12.28 ± 12.74</td>
<td>Elizabeth Mine</td>
<td>Butler and Hathaway, 2020 (Table 1)</td>
<td>2017 Average</td>
</tr>
</tbody>
</table>
### Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>21</td>
<td>0.5</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2006 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>19</td>
<td>0.5</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2007 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>Aluminum</td>
<td>Dissolved</td>
<td>16</td>
<td>0.5</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2008 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>19</td>
<td>0.4</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2009 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>19</td>
<td>0.5</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2010 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.09</td>
<td>0.002</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2006 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.097</td>
<td>0.001</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2007 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;d&lt;/sup&gt;</td>
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<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.085</td>
<td>0.001</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2008 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;e&lt;/sup&gt;</td>
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<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.087</td>
<td>0.001</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2009 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;f&lt;/sup&gt;</td>
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<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.087</td>
<td>0.001</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2010 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;g&lt;/sup&gt;</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>17</td>
<td>0.01</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2006 Average&lt;sup&gt;a&lt;/sup&gt;,&lt;sup&gt;b&lt;/sup&gt;</td>
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### Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
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<tbody>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>16.8</td>
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<td>2007 Average&lt;sup&gt;a,d&lt;/sup&gt;</td>
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<td>Dissolved</td>
<td>13.9</td>
<td>0.02</td>
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<td>2008 Average&lt;sup&gt;a,e&lt;/sup&gt;</td>
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<td>Dissolved</td>
<td>15.8</td>
<td>&lt;0.01</td>
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<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2009 Average&lt;sup&gt;a,f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>13.9</td>
<td>&lt;0.01</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2010 Average&lt;sup&gt;a,g&lt;/sup&gt;</td>
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<tr>
<td>Iron</td>
<td>Dissolved</td>
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<td>0.01</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2006 Average&lt;sup&gt;a,b&lt;/sup&gt;</td>
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<td>0.01</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2008 Average&lt;sup&gt;a,e&lt;/sup&gt;</td>
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<td>Iron</td>
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<td>0.01</td>
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<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2009 Average&lt;sup&gt;a,f&lt;/sup&gt;</td>
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<tr>
<td>Iron</td>
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<td>&lt;0.01</td>
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<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2010 Average&lt;sup&gt;a,g&lt;/sup&gt;</td>
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<td>Manganese</td>
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<td>4.8</td>
<td>0.3</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2006 Average&lt;sup&gt;a,b&lt;/sup&gt;</td>
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<td>0.1</td>
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<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2007 Average&lt;sup&gt;a,d&lt;/sup&gt;</td>
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Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

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<thead>
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<th>Constituent</th>
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<th>Average Influent</th>
<th>Average Effluent</th>
<th>Mine</th>
<th>Source</th>
<th>Notes</th>
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<td>Manganese</td>
<td>Dissolved</td>
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<td>0.3</td>
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<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2008 Average&lt;sup&gt;a,e&lt;/sup&gt;</td>
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<td>Dissolved</td>
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<td>0.4</td>
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<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2009 Average&lt;sup&gt;a,f&lt;/sup&gt;</td>
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<td>Manganese</td>
<td>Dissolved</td>
<td>3.9</td>
<td>0.4</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2010 Average&lt;sup&gt;a,g&lt;/sup&gt;</td>
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<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2006 Average&lt;sup&gt;a,b&lt;/sup&gt;</td>
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<td>0.03</td>
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<td>2007 Average&lt;sup&gt;a,d&lt;/sup&gt;</td>
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<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2008 Average&lt;sup&gt;a,e&lt;/sup&gt;</td>
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<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>17.7</td>
<td>0.03</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2009 Average&lt;sup&gt;a,f&lt;/sup&gt;</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>18.7</td>
<td>0.03</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2010 Average&lt;sup&gt;a,g&lt;/sup&gt;</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>4.0</td>
<td>9.2&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2006 Average&lt;sup&gt;a,b&lt;/sup&gt;</td>
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<tr>
<td>pH</td>
<td>NA</td>
<td>3.7</td>
<td>9.2</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2007 Average&lt;sup&gt;a,d&lt;/sup&gt;</td>
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<tr>
<td>pH</td>
<td>NA</td>
<td>3.8</td>
<td>9.2</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2008 Average&lt;sup&gt;a,e&lt;/sup&gt;</td>
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</table>
Table C-2: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<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>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>NA</td>
<td>4.1</td>
<td>9.2</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2009 Average&lt;sup&gt;a,f&lt;/sup&gt;</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>4.2</td>
<td>9.2</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012 (Tables 2 and 7)</td>
<td>2010 Average&lt;sup&gt;a,g&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

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
<sup>a</sup> = 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.
<sup>b</sup> = 2006 combined influent volume = 3,923,000,000 liters
<sup>c</sup> = Madsen et al., 2012 (page 10): "WTP discharge water pH is consistently 9.2"
<sup>d</sup> = 2007 combined influent volume = 5,256,400,000 L
<sup>e</sup> = 2008 combined influent volume = 3,836,200,000 L
<sup>f</sup> = 2009 combined influent volume = 3,370,700,000 L
<sup>g</sup> = 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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Average Mass Treated*</th>
<th>Average Mass Removed*</th>
<th>Mine</th>
<th>Source</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>83,005</td>
<td>81,043</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2006&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>100,589</td>
<td>97,960</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2007&lt;sup&gt;d&lt;/sup&gt;</td>
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<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>61,677</td>
<td>59,759</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2008&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>65,060</td>
<td>63,712</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2009&lt;sup&gt;f&lt;/sup&gt;</td>
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<td>Dissolved</td>
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<td>83,187</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2010&lt;sup&gt;g&lt;/sup&gt;</td>
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<td>Cadmium</td>
<td>Dissolved</td>
<td>354</td>
<td>346</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2006&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
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<td>508</td>
<td>503</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2007&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>Madsen et al., 2012</td>
<td>2008&lt;sup&gt;e&lt;/sup&gt;</td>
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<td>289</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2009&lt;sup&gt;f&lt;/sup&gt;</td>
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<td>Cadmium</td>
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<td>380</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2010&lt;sup&gt;g&lt;/sup&gt;</td>
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<td>Copper</td>
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<td>65,823</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2006&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>Copper</td>
<td>Dissolved</td>
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<td>88,267</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2007&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>Copper</td>
<td>Dissolved</td>
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<td>53,102</td>
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<td>Madsen et al., 2012</td>
<td>2008&lt;sup&gt;e&lt;/sup&gt;</td>
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<td>53,182</td>
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<td>Madsen et al., 2012</td>
<td>2009&lt;sup&gt;f&lt;/sup&gt;</td>
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<td>61,307</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2010&lt;sup&gt;g&lt;/sup&gt;</td>
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<td>Iron</td>
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<td>6,584</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2006&lt;sup&gt;c&lt;/sup&gt;</td>
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### Table C-3: Average Mass Treated and Average Mass Removed per Year – Britannia Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Average Mass Treated(^a)</th>
<th>Average Mass Removed(^b)</th>
<th>Mine</th>
<th>Source</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
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<td>3,963</td>
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<td>Madsen et al., 2012</td>
<td>2007(^d)</td>
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<td>Iron</td>
<td>Dissolved</td>
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<td>2,494</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2008(^e)</td>
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<td>Iron</td>
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<td>2,513</td>
<td>2,480</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2009(^f)</td>
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<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>4,220</td>
<td>4,198</td>
<td>Britannia Mine</td>
<td>Madsen et al., 2012</td>
<td>2010(^g)</td>
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<td>Manganese</td>
<td>Dissolved</td>
<td>18,870</td>
<td>17,694</td>
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<td>Madsen et al., 2012</td>
<td>2006(^c)</td>
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<td>Manganese</td>
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<td>22,244</td>
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<td>Madsen et al., 2012</td>
<td>2007(^d)</td>
</tr>
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<td>Manganese</td>
<td>Dissolved</td>
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<td>Madsen et al., 2012</td>
<td>2008(^e)</td>
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<td>Madsen et al., 2012</td>
<td>2009(^f)</td>
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<td>Madsen et al., 2012</td>
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<td>Madsen et al., 2012</td>
<td>2006(^c)</td>
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<td>Madsen et al., 2012</td>
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<td>Dissolved</td>
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<td>59,626</td>
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<td>82,718</td>
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<td>Madsen et al., 2012</td>
<td>2010(^g)</td>
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**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Average Mass Treated*</th>
<th>Average Mass Removed*</th>
<th>Mine</th>
<th>Source</th>
<th>Year</th>
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<tbody>
<tr>
<td>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</td>
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<td>c = 2006 combined influent volume = 3,923,000,000 L</td>
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<tr>
<td>d = 2007 combined influent volume = 5,256,400,000 L</td>
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<tr>
<td>e = 2008 combined influent volume = 3,836,200,000 L</td>
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<tr>
<td>f = 2009 combined influent volume = 3,370,700,000 L</td>
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<tr>
<td>g = 2010 combined influent volume = 4,424,400,000 L</td>
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<td>Non-detect values were adjusted to ½ the detection limit for calculations</td>
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Appendix C: Neutralization and Chemical Precipitation Data Tables

**Table C-4: Removal Efficiencies – All Applicable Sites**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
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<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
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<tr>
<td>Aluminum</td>
<td>99.5%</td>
<td>99.8%</td>
<td>99%</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table 1-2)</td>
</tr>
<tr>
<td>Arsenic</td>
<td>99.8%</td>
<td>99.9%</td>
<td>99.7%</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table 1-2)</td>
</tr>
<tr>
<td>Cadmium</td>
<td>99.1%</td>
<td>99.7%</td>
<td>98.4%</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table 1-2)</td>
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<tr>
<td>Chromium</td>
<td>99.0%</td>
<td>99.8%</td>
<td>95.6%</td>
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<td>U.S. EPA, 2006a (Table 1-2)</td>
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<tr>
<td>Copper</td>
<td>99.4%</td>
<td>99.7%</td>
<td>99%</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table 1-2)</td>
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<tr>
<td>Iron</td>
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<td>100%</td>
<td>99.9%</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table 1-2)</td>
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<td>Lead</td>
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<td>89.8%</td>
<td>48.3%</td>
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<td>99.3%</td>
<td>95.7%</td>
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<td>U.S. EPA, 2006a (Table 1-2)</td>
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<td>Selenium</td>
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<td>99.6%</td>
<td>97.7%</td>
<td>Leviathan Mine, Active, Single-stage</td>
<td>U.S. EPA, 2006a (Table 1-2)</td>
</tr>
<tr>
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<td>99.9%</td>
<td>99.2%</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table 1-1)</td>
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<td>99.8%</td>
<td>99.2%</td>
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<td>U.S. EPA, 2006a (Table 1-1)</td>
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<td>Copper</td>
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<td>99.8%</td>
<td>99.4%</td>
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<td>U.S. EPA, 2006a (Table 1-1)</td>
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<td>100%</td>
<td>99.9%</td>
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<td>U.S. EPA, 2006a (Table 1-1)</td>
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Table C-4: Removal Efficiencies – All Applicable Sites

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<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
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<td>86.7%</td>
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<td>U.S. EPA, 2006a (Table 1-1)</td>
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<td>99.5%</td>
<td>99.9%</td>
<td>99.2%</td>
<td>Leviathan Mine, Active, Dual-stage</td>
<td>U.S. EPA, 2006a (Table 1-1)</td>
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<td>Zinc</td>
<td>98.7%</td>
<td>99.4%</td>
<td>97.4%</td>
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<td>U.S. EPA, 2006a (Table 1-1)</td>
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<td>Aluminum</td>
<td>99.2%</td>
<td>99.5%</td>
<td>98%</td>
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<td>U.S. EPA, 2006a (Tables 1-3 and 2-4)</td>
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<td>98.9%</td>
<td>99.5%</td>
<td>97.6%</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Tables 1-3 and 2-4)</td>
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<tr>
<td>Chromium</td>
<td>88.5%</td>
<td>92.3%</td>
<td>83.1%</td>
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<td>Copper</td>
<td>58.3%</td>
<td>74.5%</td>
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<td>Iron</td>
<td>100%</td>
<td>100%</td>
<td>99.9%</td>
<td>Leviathan Mine, Semi-Passive, Alkaline Lagoon</td>
<td>U.S. EPA, 2006a (Tables 1-3 and 2-4)</td>
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<tr>
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<td>78.9%</td>
<td>37.7%</td>
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<td>Nickel</td>
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<td>99.1%</td>
<td>97.2%</td>
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<td>U.S. EPA, 2006a (Tables 1-3 and 2-4)</td>
</tr>
<tr>
<td>Zinc</td>
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<td>98.2%</td>
<td>90.6%</td>
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<td>U.S. EPA, 2006a (Tables 1-3 and 2-4)</td>
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<tr>
<td>Iron</td>
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<td>99.96%</td>
<td>93.83%</td>
<td>Elizabeth Mineb</td>
<td>Butler and Hathaway, 2020</td>
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<tr>
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<td>97.9%</td>
<td>96.9%</td>
<td>Britannia Minec</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Cadmium</td>
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<td>99.0%</td>
<td>97.8%</td>
<td>Britannia Minec</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Copper</td>
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<td>100.0%</td>
<td>99.9%</td>
<td>Britannia Minec</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Iron</td>
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<td>99.5%</td>
<td>93.4%</td>
<td>Britannia Minec</td>
<td>Madsen et al., 2012</td>
</tr>
<tr>
<td>Manganese</td>
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<td>97.7%</td>
<td>89.8%</td>
<td>Britannia Minec</td>
<td>Madsen et al., 2012</td>
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<tr>
<td>Zinc</td>
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<td>99.9%</td>
<td>99.7%</td>
<td>Britannia Minec</td>
<td>Madsen et al., 2012</td>
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Notes:
### Table C-4: Removal Efficiencies – All Applicable Sites

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mine</th>
<th>Source</th>
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</thead>
</table>
| 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 |
### Appendix D: Constructed Wetlands Data Tables

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Mine – Wetland</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerobic</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>NS</td>
<td>0.036</td>
<td>0.008</td>
<td>1992 to 1994</td>
<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
<td>Table 1</td>
</tr>
<tr>
<td>Cobalt</td>
<td>NS</td>
<td>0.036</td>
<td>0.008</td>
<td>1992 to 1997</td>
<td>Dunka Mine – W1D</td>
<td>ITRC, 2010</td>
<td>Table 2-2</td>
</tr>
<tr>
<td>Cobalt</td>
<td>NS</td>
<td>0.009</td>
<td>0.001</td>
<td>1996 to 1998</td>
<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
<td>Table 1</td>
</tr>
<tr>
<td>Copper</td>
<td>NS</td>
<td>0.068</td>
<td>0.008</td>
<td>1992 to 1994</td>
<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
<td>Table 1</td>
</tr>
<tr>
<td>Copper</td>
<td>NS</td>
<td>0.068</td>
<td>0.010</td>
<td>1992 to 1997</td>
<td>Dunka Mine – W1D</td>
<td>ITRC, 2010</td>
<td>Table 2-2</td>
</tr>
<tr>
<td>Copper</td>
<td>NS</td>
<td>0.03</td>
<td>0.003</td>
<td>1996 to 1998</td>
<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
<td>Table 1</td>
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<tr>
<td>Copper</td>
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<td>0.02</td>
<td>0.002</td>
<td>1999 to 2004</td>
<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
<td>Table 1</td>
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<tr>
<td>Nickel</td>
<td>NS</td>
<td>3.98</td>
<td>0.36</td>
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<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
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<td>Nickel</td>
<td>NS</td>
<td>0.74</td>
<td>0.19</td>
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<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
<td>Table 1</td>
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<td>Nickel</td>
<td>NS</td>
<td>0.76</td>
<td>0.1</td>
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<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
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</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>7.07</td>
<td>7.18</td>
<td>1992 to 1994</td>
<td>Dunka Mine – W1D&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Eger and Eger, 2005</td>
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</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>7.07</td>
<td>7.18</td>
<td>1992 to 1997</td>
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<td>Table 1</td>
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Table D-1: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Mine – Wetland</th>
<th>Source</th>
<th>Notes</th>
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<td>pH</td>
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<td>7.34</td>
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### Table D-1: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
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<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Mine – Wetland</th>
<th>Source</th>
<th>Notes</th>
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<td>0.011</td>
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<td>0.011</td>
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<td>Eger and Eger, 2005</td>
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**Anaerobic**

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<th>Constituent</th>
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<th>Average Effluent</th>
<th>Timeframe</th>
<th>Mine – Wetland</th>
<th>Source</th>
<th>Notes</th>
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<tr>
<td>Aluminum</td>
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<td>0.073</td>
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<td>Copper Basin Mining District</td>
<td>Faulkner and Miller, 2002</td>
<td>Table 4</td>
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<tr>
<td>Copper</td>
<td>Total</td>
<td>0.43</td>
<td>&lt;0.025</td>
<td>10/1998 to 3/1999</td>
<td>Copper Basin Mining District</td>
<td>Faulkner and Miller, 2002</td>
<td>Table 4</td>
</tr>
<tr>
<td>Copper</td>
<td>Total</td>
<td>0.311</td>
<td>0.008</td>
<td>9/8/99 to 1/1/2002</td>
<td>Copper Basin Mining District</td>
<td>Faulkner and Miller, 2002</td>
<td>Table 4</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>1.07</td>
<td>0.353</td>
<td>9/8/99 to 1/1/2002</td>
<td>Copper Basin Mining District</td>
<td>Faulkner and Miller, 2002</td>
<td>Table 4</td>
</tr>
<tr>
<td>Manganese</td>
<td>Total</td>
<td>1.52</td>
<td>1.64</td>
<td>9/8/99 to 1/1/2002</td>
<td>Copper Basin Mining District</td>
<td>Faulkner and Miller, 2002</td>
<td>Table 4</td>
</tr>
<tr>
<td>Sulfate</td>
<td>NA</td>
<td>142</td>
<td>128</td>
<td>9/8/99 to 1/1/2002</td>
<td>Copper Basin Mining District</td>
<td>Faulkner and Miller, 2002</td>
<td>Table 4</td>
</tr>
</tbody>
</table>
Table D-1: Average Influent and Effluent Concentrations – All Applicable Case Studies

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Mine – Wetland</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Total</td>
<td>1.094</td>
<td>0.045</td>
<td>9/8/99 to 1/1/2002</td>
<td>Copper Basin Mining District</td>
<td>Faulkner and Miller, 2002</td>
<td>Table 4</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>4.2</td>
<td>7.1</td>
<td>9/8/99 to 1/1/2002</td>
<td>Copper Basin Mining Districtb</td>
<td>Faulkner and Miller, 2002</td>
<td>Table 4</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Average Removal Efficiency</th>
<th>Mine – Wetland</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>NS</td>
<td>77.8%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1992 to 1994</td>
</tr>
<tr>
<td>Cobalt</td>
<td>NS</td>
<td>77.8%</td>
<td>Dunka Mine – W1D</td>
<td>ITRC, 2010 (Table 2-2)</td>
<td>Calculated by EPA based on averages presented for 1992 to 1997</td>
</tr>
<tr>
<td>Cobalt</td>
<td>NS</td>
<td>88.9%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1996 to 1998</td>
</tr>
<tr>
<td>Copper</td>
<td>NS</td>
<td>88.2%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1992 to 1994</td>
</tr>
<tr>
<td>Copper</td>
<td>NS</td>
<td>85.3%</td>
<td>Dunka Mine – W1D</td>
<td>ITRC, 2010 (Table 2-2)</td>
<td>Calculated by EPA based on averages presented for 1992 to 1997</td>
</tr>
<tr>
<td>Copper</td>
<td>NS</td>
<td>90.0%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1996 to 1998</td>
</tr>
<tr>
<td>Copper</td>
<td>NS</td>
<td>90.0%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1999 to 2004</td>
</tr>
<tr>
<td>Nickel</td>
<td>NS</td>
<td>91.0%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1992 to 1994</td>
</tr>
<tr>
<td>Nickel</td>
<td>NS</td>
<td>82.4%</td>
<td>Dunka Mine – W1D</td>
<td>ITRC, 2010 (Table 2-2)</td>
<td>Calculated by EPA based on averages presented for 1992 to 1997</td>
</tr>
<tr>
<td>Nickel</td>
<td>NS</td>
<td>74.3%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1996 to 1998</td>
</tr>
<tr>
<td>Nickel</td>
<td>NS</td>
<td>86.8%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1999 to 2004</td>
</tr>
<tr>
<td>Zinc</td>
<td>NS</td>
<td>75.0%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1992 to 1994</td>
</tr>
<tr>
<td>Zinc</td>
<td>NS</td>
<td>75.0%</td>
<td>Dunka Mine – W1D</td>
<td>ITRC, 2010 (Table 2-2)</td>
<td>Calculated by EPA based on averages presented for 1992 to 1997</td>
</tr>
<tr>
<td>Zinc</td>
<td>NS</td>
<td>71.4%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1996 to 1998</td>
</tr>
<tr>
<td>Zinc</td>
<td>NS</td>
<td>68.4%</td>
<td>Dunka Mine – W1D</td>
<td>Eger and Eger, 2005 (Table 1)</td>
<td>Calculated by EPA based on averages presented for 1999 to 2004</td>
</tr>
<tr>
<td>Cobalt</td>
<td>NS</td>
<td>95.7%</td>
<td>Dunka Mine – W1D Expanded</td>
<td>ITRC, 2010 (Table 2-2)</td>
<td>Calculated by EPA based on averages presented for 1995 to 1997</td>
</tr>
</tbody>
</table>
### Table D-2: Removal Efficiencies – All Applicable Sites

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

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

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Influent Flow&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Influent Flow&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>3.85x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>14.1</td>
<td>0.0138</td>
<td>6.16x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.011</td>
<td>0.0165</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Arsenic</td>
<td>5.53x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0109</td>
<td>0.0054</td>
<td>5.80x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0011</td>
<td>0.004</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Cadmium</td>
<td>3.85x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0419</td>
<td>0.0048</td>
<td>5.57x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0028</td>
<td>0.0001</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Copper</td>
<td>3.85x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>3.05</td>
<td>0.0078</td>
<td>5.14x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0028</td>
<td>0.0237</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Iron</td>
<td>3.85x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>7.22</td>
<td>0.0975</td>
<td>5.57x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.008</td>
<td>0.110</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Manganese</td>
<td>3.85x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>3.77</td>
<td>0.551</td>
<td>5.57x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.690</td>
<td>0.600</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Sulfate</td>
<td>3.85x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>229</td>
<td>281</td>
<td>5.57x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>60.6</td>
<td>8</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Zinc</td>
<td>3.85x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>11.1</td>
<td>0.249</td>
<td>5.57x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.990</td>
<td>0.048</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>pH</td>
<td>5.14x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>7.52</td>
<td>7.21</td>
<td>3.85x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>3.29</td>
<td>8.29</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5.03x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>2.4</td>
<td>0.0542</td>
<td>1.07x10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>0.0173</td>
<td>0.0173</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Arsenic</td>
<td>3.39x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0067</td>
<td>0.0034</td>
<td>5.79x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0011</td>
<td>0.0041</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Cadmium</td>
<td>3.07x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0179</td>
<td>0.0039</td>
<td>1.59x10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>0.0037</td>
<td>0.0034</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Copper</td>
<td>5.03x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.884</td>
<td>0.103</td>
<td>8.06x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.0442</td>
<td>0.0529</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Iron</td>
<td>5.03x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>0.524</td>
<td>0.417</td>
<td>1.59x10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>0.0155</td>
<td>0.0671</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Manganese</td>
<td>3.07x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>1.95</td>
<td>1.07</td>
<td>1.07x10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>1.07</td>
<td>0.837</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Sulfate</td>
<td>5.43x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>122</td>
<td>326</td>
<td>8.06x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>69.8</td>
<td>84.7</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Zinc</td>
<td>3.07x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>3.79</td>
<td>0.672</td>
<td>8.06x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>1.42</td>
<td>0.383</td>
<td>BCR IV effluent</td>
</tr>
</tbody>
</table>
### Table E-1: Maximum and Minimum Influent and Corresponding Effluent Concentrations – Calliope Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Influent Flow&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Influent Flow&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>8.06x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>7.08</td>
<td>7.57</td>
<td>5.03x10&lt;sup&gt;-5&lt;/sup&gt;</td>
<td>3.87</td>
<td>9.98</td>
<td>BCR IV effluent</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent</th>
<th>Corresponding Effluent</th>
<th>Minimum Influent</th>
<th>Corresponding Effluent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>4.5</td>
<td>0.14</td>
<td>2.5</td>
<td>0.08</td>
<td>Figure 2</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Influent</th>
<th>Effluent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1,740</td>
<td>0.126</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
<tr>
<td>Copper</td>
<td>81.4</td>
<td>0.001</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
<tr>
<td>Iron</td>
<td>198</td>
<td>2.62</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
<tr>
<td>Manganese</td>
<td>117</td>
<td>67.8</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
<tr>
<td>Zinc</td>
<td>39.5</td>
<td>0.011</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>System Influent</th>
<th>Corresponding System Effluent</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>36.9</td>
<td>0.144</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Total</td>
<td>36.4</td>
<td>0.468</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>40.4</td>
<td>0.105</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Total</td>
<td>40.4</td>
<td>0.120</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>0.0028</td>
<td>0.0024</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Total</td>
<td>0.0042</td>
<td>&lt;0.0022</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>&lt;0.0021</td>
<td>0.0147</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
</tbody>
</table>
### Table E-4: Influent and Effluent Concentrations – Leviathan Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>System Influent</th>
<th>Corresponding System Effluent</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>Total</td>
<td>&lt;0.0021</td>
<td>0.0149</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.0004</td>
<td>&lt;0.00023</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
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<tr>
<td>Cadmium</td>
<td>Total</td>
<td>0.00041</td>
<td>&lt;0.00023</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>0.00094</td>
<td>&lt;0.00016</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Total</td>
<td>0.0011</td>
<td>&lt;0.00016</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.0172</td>
<td>0.0064</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Chromium</td>
<td>Total</td>
<td>0.0164</td>
<td>0.008</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>0.0193</td>
<td>0.0116</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
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<tr>
<td>Chromium</td>
<td>Total</td>
<td>0.0198</td>
<td>0.0132</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
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<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.656</td>
<td>0.0056</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Copper</td>
<td>Total</td>
<td>0.647</td>
<td>0.0078</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>0.766</td>
<td>0.0095</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Copper</td>
<td>Total</td>
<td>0.757</td>
<td>0.0079</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>113</td>
<td>0.389</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>113</td>
<td>1.66</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>99.5</td>
<td>0.269</td>
<td>Recirculation mode</td>
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<tr>
<td>Iron</td>
<td>Total</td>
<td>99.1</td>
<td>0.532</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
</tbody>
</table>
Table E-4: Influent and Effluent Concentrations – Leviathan Mine

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

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>System Influent</th>
<th>Corresponding System Effluent</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Total</td>
<td>0.757</td>
<td>0.0106</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>3.1</td>
<td>7.7</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-9</td>
</tr>
<tr>
<td>pH</td>
<td>NA</td>
<td>7.2</td>
<td>7.6</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-11</td>
</tr>
</tbody>
</table>

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

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

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

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

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Influent</th>
<th>Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>29.5</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.127</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.208</td>
<td>&lt;0.00009</td>
</tr>
<tr>
<td>Copper</td>
<td>2.35</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>Iron</td>
<td>15.0</td>
<td>&lt;0.014</td>
</tr>
<tr>
<td>Lead</td>
<td>0.151</td>
<td>0.004</td>
</tr>
<tr>
<td>Manganese</td>
<td>26.7</td>
<td>0.037</td>
</tr>
<tr>
<td>Zinc</td>
<td>22.7</td>
<td>&lt;0.007</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Influent</th>
<th>Effluent</th>
<th>Treatment System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>50</td>
<td>1</td>
<td>LD</td>
<td>Data extracted from Figure 4</td>
</tr>
<tr>
<td>Iron</td>
<td>67</td>
<td>&lt;1</td>
<td>ALD</td>
<td>Data extracted from Figure 4</td>
</tr>
<tr>
<td>Iron</td>
<td>59</td>
<td>&lt;1</td>
<td>LF</td>
<td>Data extracted from Figure 4</td>
</tr>
<tr>
<td>Zinc</td>
<td>31</td>
<td>11</td>
<td>LD</td>
<td>Data extracted from Figure 5</td>
</tr>
<tr>
<td>Zinc</td>
<td>33</td>
<td>14</td>
<td>ALD</td>
<td>Data extracted from Figure 5</td>
</tr>
<tr>
<td>Zinc</td>
<td>33</td>
<td>0.5</td>
<td>LF</td>
<td>Data extracted from Figure 5</td>
</tr>
<tr>
<td>Sulfate</td>
<td>238</td>
<td>333</td>
<td>LD</td>
<td>Data extracted from Figure 3</td>
</tr>
<tr>
<td>Sulfate</td>
<td>180</td>
<td>298</td>
<td>ALD</td>
<td>Data extracted from Figure 3</td>
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<tr>
<td>Sulfate</td>
<td>260</td>
<td>200</td>
<td>LF</td>
<td>Data extracted from Figure 3</td>
</tr>
<tr>
<td>ORP</td>
<td>360</td>
<td>730</td>
<td>LD</td>
<td>Data extracted from Figure 2</td>
</tr>
<tr>
<td>ORP</td>
<td>470</td>
<td>640</td>
<td>ALD</td>
<td>Data extracted from Figure 2</td>
</tr>
<tr>
<td>ORP</td>
<td>560</td>
<td>640</td>
<td>LF</td>
<td>Data extracted from Figure 2</td>
</tr>
<tr>
<td>pH</td>
<td>5.4</td>
<td>4.1</td>
<td>LD</td>
<td>Data extracted from Figure 2</td>
</tr>
<tr>
<td>pH</td>
<td>5</td>
<td>5</td>
<td>ALD</td>
<td>Data extracted from Figure 2</td>
</tr>
</tbody>
</table>
### Table E-8: Influent and Effluent Concentrations – Wheal Jane Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Influent</th>
<th>Effluent</th>
<th>Treatment System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>3.9</td>
<td>6.7</td>
<td>LF</td>
<td>Data extracted from Figure 2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1.2229</td>
<td>0.051703</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Arsenic</td>
<td>&lt;0.005</td>
<td>0.005894</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.01082</td>
<td>&lt;0.005</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Copper</td>
<td>0.4078</td>
<td>0.044064</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Iron</td>
<td>0.4556</td>
<td>0.551436</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.4581</td>
<td>0.786067</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Sulfate</td>
<td>102.90</td>
<td>115.43</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Zinc</td>
<td>2.8406</td>
<td>0.46329</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>pH</td>
<td>6.05</td>
<td>7.49</td>
<td>BCR II effluent</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.2229</td>
<td>0.0372</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.5634</td>
<td>0.0070</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0103</td>
<td>0.0039</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Copper</td>
<td>0.2774</td>
<td>0.0347</td>
<td>BCR IV effluent</td>
</tr>
</tbody>
</table>
### Table E-9: Average Influent and Effluent Concentrations – Calliope Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>0.1556</td>
<td>0.4869</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.40</td>
<td>0.96</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Sulfate</td>
<td>97.5</td>
<td>111.9</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>Zinc</td>
<td>2.54</td>
<td>0.36</td>
<td>BCR IV effluent</td>
</tr>
<tr>
<td>pH</td>
<td>5.84</td>
<td>7.74</td>
<td>BCR IV effluent</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>37.467</td>
<td>0.103</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Aluminum</td>
<td>40.209</td>
<td>0.0527</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.0021</td>
<td>0.0047</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.0074</td>
<td>0.0065</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.00061</td>
<td>&lt;0.00021</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.00060</td>
<td>&lt;0.00020</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.0122</td>
<td>0.0078</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
</tbody>
</table>
## Table E-10: Average Influent and Effluent Concentrations – Leviathan Mine

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

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

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

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.094 ± 0.009</td>
<td>0.071 ± 0.030</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.063 ± 0.002</td>
<td>ND</td>
</tr>
<tr>
<td>Calcium</td>
<td>742 ± 9.0</td>
<td>740 ± 22.3</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.016 ± 0.002</td>
<td>ND</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.001 ± 0.0002</td>
<td>0.002 ± 0.0006</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.066 ± 0.008</td>
<td>0.007 ± 0.0004</td>
</tr>
</tbody>
</table>
Table E-12: Average Influent and Effluent Concentrations – Tar Creek

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>0.002 ± 0.0003</td>
<td>0.003 ± 0.0003</td>
</tr>
<tr>
<td>Iron</td>
<td>177 ± 2.33</td>
<td>0.57 ± 0.207</td>
</tr>
<tr>
<td>Lead</td>
<td>0.068 ± 0.003</td>
<td>ND</td>
</tr>
<tr>
<td>Lithium</td>
<td>0.366 ± 0.010</td>
<td>0.365 ± 0.018</td>
</tr>
<tr>
<td>Magnesium</td>
<td>200 ± 2.53</td>
<td>198 ± 7.49</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.51 ± 0.016</td>
<td>1.38 ± 0.197</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.945 ± 0.015</td>
<td>0.035 ± 0.007</td>
</tr>
<tr>
<td>Potassium</td>
<td>26.0 ± 0.286</td>
<td>31.1 ± 4.82</td>
</tr>
<tr>
<td>Sodium</td>
<td>94.9 ± 1.63</td>
<td>96.6 ± 4.23</td>
</tr>
<tr>
<td>Sulfate</td>
<td>2,239 ± 26</td>
<td>2,047 ± 72</td>
</tr>
<tr>
<td>Zinc</td>
<td>8.29 ± 0.078</td>
<td>0.096 ± 0.037</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Treatment System</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>48.6</td>
<td>55.8</td>
<td>LD</td>
<td>Influent and effluent data reported in Table 3</td>
</tr>
<tr>
<td>Aluminum</td>
<td>48.6</td>
<td>3.3</td>
<td>ALD</td>
<td>Influent and effluent data reported in Table 2</td>
</tr>
<tr>
<td>Aluminum</td>
<td>48.6</td>
<td>75.8</td>
<td>LF</td>
<td>Influent and effluent data reported in Table 1</td>
</tr>
<tr>
<td>Arsenic</td>
<td>2.7</td>
<td>0.0</td>
<td>LD</td>
<td>Influent and effluent data reported in Table 3</td>
</tr>
<tr>
<td>Arsenic</td>
<td>2.7</td>
<td>0.0</td>
<td>ALD</td>
<td>Influent and effluent data reported in Table 2</td>
</tr>
<tr>
<td>Arsenic</td>
<td>2.7</td>
<td>0.0</td>
<td>LF</td>
<td>Influent and effluent data reported in Table 1</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.1</td>
<td>0.0</td>
<td>LD</td>
<td>Influent and effluent data reported in Table 3</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.1</td>
<td>0.0</td>
<td>ALD</td>
<td>Influent and effluent data reported in Table 2</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.1</td>
<td>0.0</td>
<td>LF</td>
<td>Influent and effluent data reported in Table 1</td>
</tr>
<tr>
<td>Copper</td>
<td>0.4</td>
<td>0.1</td>
<td>LD</td>
<td>Influent and effluent data reported in Table 3</td>
</tr>
</tbody>
</table>
### Table E-13: Average Influent and Effluent Concentrations – Wheal Jane Mine

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

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

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

*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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Removal Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>99.99%</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
<tr>
<td>Copper</td>
<td>99.99%</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
</tbody>
</table>
## Table E-15: Removal Efficiencies – Golden Sunlight Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Removal Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>98.68%</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
<tr>
<td>Manganese</td>
<td>42.05%</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
<tr>
<td>Zinc</td>
<td>99.97%</td>
<td>Data originated from Table 4, collected March 12, 2003</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Removal Efficiency</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>99.6%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Total</td>
<td>98.7%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Dissolved</td>
<td>99.7%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Total</td>
<td>99.7%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>14.3%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Total</td>
<td>47.6%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Dissolved</td>
<td>-600%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Total</td>
<td>-548%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>42.5%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Total</td>
<td>43.9%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Dissolved</td>
<td>83.0%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Total</td>
<td>85.5%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>62.8%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Chromium</td>
<td>Total</td>
<td>51.2%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Chromium</td>
<td>Dissolved</td>
<td>39.9%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Chromium</td>
<td>Total</td>
<td>33.3%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>99.1%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Copper</td>
<td>Total</td>
<td>98.8%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Copper</td>
<td>Dissolved</td>
<td>98.8%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
</tbody>
</table>
Table E-16: Removal Efficiencies – Leviathan Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Water Sample</th>
<th>Removal Efficiencya</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Total</td>
<td>99%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>99.7%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>98.5%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Iron</td>
<td>Dissolved</td>
<td>99.7%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Iron</td>
<td>Total</td>
<td>99.5%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>35.8%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Lead</td>
<td>Total</td>
<td>40.8%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Lead</td>
<td>Dissolved</td>
<td>47.5%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Lead</td>
<td>Total</td>
<td>9.7%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>89%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Nickel</td>
<td>Total</td>
<td>85%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Nickel</td>
<td>Dissolved</td>
<td>96.4%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Nickel</td>
<td>Total</td>
<td>95.8%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Selenium</td>
<td>Dissolved</td>
<td>9.4%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Selenium</td>
<td>Total</td>
<td>57.4%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Selenium</td>
<td>Dissolved</td>
<td>45.8%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Selenium</td>
<td>Total</td>
<td>45.7%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
<tr>
<td>Sulfate</td>
<td>Total</td>
<td>23.18%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-9</td>
</tr>
<tr>
<td>Sulfate</td>
<td>Total</td>
<td>26.38%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-11</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>98.5%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-13</td>
</tr>
<tr>
<td>Zinc</td>
<td>Total</td>
<td>97.9%</td>
<td>Gravity mode</td>
<td>Data extracted from Table 2-17</td>
</tr>
<tr>
<td>Zinc</td>
<td>Dissolved</td>
<td>99.4%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-15</td>
</tr>
<tr>
<td>Zinc</td>
<td>Total</td>
<td>98.6%</td>
<td>Recirculation mode</td>
<td>Data extracted from Table 2-18</td>
</tr>
</tbody>
</table>

Notes:
Source: U.S. EPA, 2006a
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>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Maximum Removal Efficiency</th>
<th>Average Removal Efficiency</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>99.5%</td>
<td>99.9%</td>
<td>99.7%</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Aluminum</td>
<td>99.7%</td>
<td>99.9%</td>
<td>99.9%</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Arsenic</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Arsenic</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Cadmium</td>
<td>42.5%</td>
<td>79%</td>
<td>65.3%</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Cadmium</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Chromium</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Chromium</td>
<td>21.2%</td>
<td>84.8%</td>
<td>42.5%</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Copper</td>
<td>99.1%</td>
<td>99.7%</td>
<td>99.3%</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Copper</td>
<td>98.8%</td>
<td>99.8%</td>
<td>99.4%</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Iron</td>
<td>65.6%</td>
<td>99.9%</td>
<td>95.8%</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Iron</td>
<td>92.8%</td>
<td>99.7%</td>
<td>97.7%</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Lead</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Lead</td>
<td>22.0%</td>
<td>57.1%</td>
<td>41.3%</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Nickel</td>
<td>72.1%</td>
<td>92.6%</td>
<td>86.6%</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Nickel</td>
<td>71.0%</td>
<td>96.4%</td>
<td>86.8%</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
</tbody>
</table>
Appendix E: Treatment Trains Data Tables

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Minimum Removal Efficiency</th>
<th>Maximum Removal Efficiency</th>
<th>Average Removal Efficiency</th>
<th>Mode</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selenium</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Selenium</td>
<td>NC</td>
<td>NC</td>
<td>NC</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
<tr>
<td>Zinc</td>
<td>95.9%</td>
<td>98.6%</td>
<td>97.8%</td>
<td>Gravity mode</td>
<td>Data from Table 2-2, based on 6 sampling events</td>
</tr>
<tr>
<td>Zinc</td>
<td>97.7%</td>
<td>99.8%</td>
<td>98.9%</td>
<td>Recirculation mode</td>
<td>Data from Table 2-3, based on 7 sampling events</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>99.34%</td>
<td>Removal efficiency calculated from average influent and average APC effluent.</td>
</tr>
<tr>
<td>Copper</td>
<td>97.2%</td>
<td>Removal efficiency calculated from average influent and average APC effluent.</td>
</tr>
<tr>
<td>Iron</td>
<td>95.18%</td>
<td>Removal efficiency calculated from average influent and average APC effluent.</td>
</tr>
<tr>
<td>Lead</td>
<td>97.16%</td>
<td>Removal efficiency calculated from average influent and average APC effluent.</td>
</tr>
<tr>
<td>Manganese</td>
<td>42.2% (2009) 87.7% (2010)</td>
<td>Removal efficiencies provided in text.</td>
</tr>
<tr>
<td>Sulfate</td>
<td>56.58%</td>
<td>Data from Table 4</td>
</tr>
<tr>
<td>Zinc</td>
<td>99.23%</td>
<td>Removal efficiency calculated from average influent and average APC effluent.</td>
</tr>
</tbody>
</table>
Appendix E: Treatment Trains Data Tables

Table E-18: Average Removal Efficiencies – Standard Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Source: Gallagher et al., 2012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>APC = Aerobic Polishing Cell</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All constituent concentrations reported as dissolved except for iron, which was reported as total</td>
</tr>
</tbody>
</table>

Table E-19: Removal Efficiencies - Surething Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Removal Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>&gt;99.86%</td>
<td>Source: Nordwick and Bless, 2008</td>
</tr>
<tr>
<td>Arsenic</td>
<td>&gt;92.13%</td>
<td>EPA calculated removal efficiencies based on data presented in Table 4-2 in Nordwick and Bless, 2008 and reported in Table E-20.</td>
</tr>
<tr>
<td>Cadmium</td>
<td>&gt;99.96%</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>&gt;99.87%</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>&gt;99.91%</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>97.35%</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>99.86%</td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>&gt;99.97%</td>
<td></td>
</tr>
</tbody>
</table>

Table E-20: Average Removal Efficiencies – Tar Creek

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>99.7%</td>
</tr>
<tr>
<td>Nickel</td>
<td>98.8%</td>
</tr>
<tr>
<td>Zinc</td>
<td>96.3%</td>
</tr>
</tbody>
</table>

Notes:
### Table E-20: Average Removal Efficiencies – Tar Creek

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>98%</td>
</tr>
<tr>
<td>Iron</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>Iron</td>
<td>&gt;98%</td>
</tr>
<tr>
<td>Zinc</td>
<td>65%</td>
</tr>
<tr>
<td>Zinc</td>
<td>58%</td>
</tr>
<tr>
<td>Zinc</td>
<td>98%</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-40%</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-66%</td>
</tr>
<tr>
<td>Sulfate</td>
<td>23%</td>
</tr>
</tbody>
</table>

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

### Table E-21: Removal Efficiencies – Wheal Jane Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Removal Efficiency</th>
<th>Treatment System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>98%</td>
<td>LD</td>
</tr>
<tr>
<td>Iron</td>
<td>&gt;99%</td>
<td>ALD</td>
</tr>
<tr>
<td>Iron</td>
<td>&gt;98%</td>
<td>LF</td>
</tr>
<tr>
<td>Zinc</td>
<td>65%</td>
<td>LD</td>
</tr>
<tr>
<td>Zinc</td>
<td>58%</td>
<td>ALD</td>
</tr>
<tr>
<td>Zinc</td>
<td>98%</td>
<td>LF</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-40%</td>
<td>LD</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-66%</td>
<td>ALD</td>
</tr>
<tr>
<td>Sulfate</td>
<td>23%</td>
<td>LF</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Median Removal Efficiency</th>
<th>Treatment System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>65%</td>
<td>LD</td>
</tr>
<tr>
<td>Aluminum</td>
<td>90%</td>
<td>ALD</td>
</tr>
<tr>
<td>Aluminum</td>
<td>35%</td>
<td>LF</td>
</tr>
<tr>
<td>Cadmium</td>
<td>78%</td>
<td>LD</td>
</tr>
<tr>
<td>Cadmium</td>
<td>98%</td>
<td>ALD</td>
</tr>
<tr>
<td>Cadmium</td>
<td>53%</td>
<td>LF</td>
</tr>
<tr>
<td>Copper</td>
<td>73%</td>
<td>LD</td>
</tr>
<tr>
<td>Copper</td>
<td>95%</td>
<td>ALD</td>
</tr>
<tr>
<td>Copper</td>
<td>42%</td>
<td>LF</td>
</tr>
<tr>
<td>Manganese</td>
<td>54%</td>
<td>LD</td>
</tr>
<tr>
<td>Manganese</td>
<td>60%</td>
<td>ALD</td>
</tr>
<tr>
<td>Manganese</td>
<td>45%</td>
<td>LF</td>
</tr>
<tr>
<td>Zinc</td>
<td>66%</td>
<td>LD</td>
</tr>
<tr>
<td>Zinc</td>
<td>73%</td>
<td>ALD</td>
</tr>
<tr>
<td>Zinc</td>
<td>47%</td>
<td>LF</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Pre-Reclamation Concentration</th>
<th>Post-Reclamation Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>Mean</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.6 – 19.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0032 – 0.088</td>
<td>0.0152</td>
</tr>
<tr>
<td>Copper</td>
<td>0.049 – 2.2</td>
<td>0.3116</td>
</tr>
<tr>
<td>Iron</td>
<td>5.0 – 69.7</td>
<td>17.7</td>
</tr>
<tr>
<td>Lead</td>
<td>0.170 – 1.3</td>
<td>0.349</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.410 – 2.1</td>
<td>0.779</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.002 – 0.037</td>
<td>0.0085</td>
</tr>
<tr>
<td>Sulfate</td>
<td>27.0 – 1,400</td>
<td>204</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.9 – 27.0</td>
<td>5.75</td>
</tr>
<tr>
<td>Hardness</td>
<td>10.0 – 62.0</td>
<td>21.2</td>
</tr>
<tr>
<td>pH</td>
<td>2.6 – 4.0</td>
<td>3.4</td>
</tr>
</tbody>
</table>

*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 CaCO₃
- 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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Influent</th>
<th>Maximum Effluent</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1.423</td>
<td>0.055</td>
<td>Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006</td>
</tr>
<tr>
<td>Copper</td>
<td>0.197</td>
<td>0.017</td>
<td>Data from Table 1 in source, represent the maximum influent and the maximum effluent observed between 2004 and 2006</td>
</tr>
</tbody>
</table>
### Table E-24: Influent and Effluent Concentrations – Copper Basin Mining District

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

**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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>0.015</td>
<td>0.006</td>
<td>Jan. to Sept. 1998</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>0.026</td>
<td>0.009</td>
<td>1999 to 2004</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005</td>
</tr>
</tbody>
</table>
Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>0.029</td>
<td>0.011</td>
<td>Jan. to Sept. 1998</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>Nickel</td>
<td>2.08</td>
<td>1.4</td>
<td>1999 to 2004</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.600</td>
<td>0.902</td>
<td>Jan. to Sept. 1998</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.052</td>
<td>0.032</td>
<td>1999 to 2004</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.059</td>
<td>0.033</td>
<td>Jan. to Sept. 1998</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>pH</td>
<td>7.41</td>
<td>7.3</td>
<td>1999 to 2004</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH</td>
<td>7.20</td>
<td>7.01</td>
<td>Jan. to Sept. 1998</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.13</td>
<td>0.04</td>
<td>1995 to 1997</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.15</td>
<td>0.05</td>
<td>1995 to 1997</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.325</td>
<td>0.043</td>
<td>1999 to 2004</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>5.39</td>
<td>1.85</td>
<td>1995 to 1997</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>6.64</td>
<td>3.27</td>
<td>1999 to 2004</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.65</td>
<td>0.29</td>
<td>1995 to 1997</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.928</td>
<td>0.385</td>
<td>1999 to 2004</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH</td>
<td>6.94</td>
<td>7.23</td>
<td>1995 to 1997</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
</tbody>
</table>
### Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.28</td>
<td>7.34</td>
<td>1999 to 2004</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.08</td>
<td>0.02</td>
<td>1995 to 1997</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.33</td>
<td>0.08</td>
<td>1995 to 1997</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.37</td>
<td>0.11</td>
<td>1999 to 2004</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.5</td>
<td>0.61</td>
<td>1995 to 1997</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.82</td>
<td>1.09</td>
<td>1999 to 2004</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.48</td>
<td>0.21</td>
<td>1995 to 1997</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.58</td>
<td>0.37</td>
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<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH</td>
<td>7.03</td>
<td>7.13</td>
<td>1995 to 1997</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH</td>
<td>7.38</td>
<td>7.35</td>
<td>1999 to 2004</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.02</td>
<td>0.002</td>
<td>1992 to 1994</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.02</td>
<td>0.002</td>
<td>1992 to 1997</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010</td>
</tr>
<tr>
<td>Cobalt</td>
<td>0.02</td>
<td>NR</td>
<td>1996 to 1998</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Cobaltb</td>
<td>0.02</td>
<td>NR</td>
<td>1999 to 2004</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>0.05</td>
<td>0.004</td>
<td>1992 to 1994</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
</tbody>
</table>
### Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

<table>
<thead>
<tr>
<th>Constituent&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>0.05</td>
<td>0.004</td>
<td>1992 to 1997</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>0.05</td>
<td>&lt;0.001</td>
<td>1996 to 1998</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.05</td>
<td>0.002</td>
<td>1999 to 2004</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.90</td>
<td>0.08</td>
<td>1992 to 1994</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1.90</td>
<td>0.06</td>
<td>1996 to 1998</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.90</td>
<td>0.036</td>
<td>1999 to 2004</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.05</td>
<td>0.008</td>
<td>1992 to 1994</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.05</td>
<td>&lt;0.001</td>
<td>1996 to 1998</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.05</td>
<td>0.006</td>
<td>1999 to 2004</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH</td>
<td>7.0</td>
<td>7.0</td>
<td>1992 to 1994</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH</td>
<td>7.0</td>
<td>7.0</td>
<td>1992 to 1997</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010</td>
</tr>
<tr>
<td>pH</td>
<td>7.0</td>
<td>7.0</td>
<td>1996 to 1998</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>pH&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.0</td>
<td>7.4</td>
<td>1999 to 2004</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
</tbody>
</table>
### Table E-25 Average Influent and Effluent Concentrations – Dunka Mine

<table>
<thead>
<tr>
<th>Constituent&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average Influent</th>
<th>Average Effluent</th>
<th>Timeframe</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td></td>
<td>Notes</td>
</tr>
<tr>
<td></td>
<td>Influent</td>
<td>Effluent</td>
<td></td>
<td>Notes</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>Notes:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sources: Eger and Eger, 2005 and ITRC, 2010</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>All analytical results reported in mg/L</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH reported in standard units</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a = total or dissolved not specified</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b = reported values noted as being estimates</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NR = not reported</td>
<td></td>
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<td></td>
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### Table E-26: Average Removal Efficiencies – Dunka Mine

<table>
<thead>
<tr>
<th>Constituent&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Timeframe</th>
<th>Average Removal Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>Jan. to Sept. 1998</td>
<td>60%</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>1999 to 2004</td>
<td>65%</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>Jan. to Sept. 1998</td>
<td>62%</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>Nickel</td>
<td>1999 to 2004</td>
<td>33%</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Jan. to Sept. 1998</td>
<td>44%</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>Zinc</td>
<td>1999 to 2004</td>
<td>38%</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>Jan. to Sept. 1998</td>
<td>44%</td>
<td>EM8 aerobic wetland with limestone beds incorporated into the wetland – ITRC, 2010</td>
</tr>
<tr>
<td>Cobalt</td>
<td>1995 to 1997</td>
<td>69%</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
</tbody>
</table>
### Table E-26: Average Removal Efficiencies – Dunka Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Timeframe</th>
<th>Average Removal Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1995 to 1997</td>
<td>67%</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>1999 to 2004</td>
<td>87%</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1995 to 1997</td>
<td>66%</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1999 to 2004</td>
<td>51%</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1995 to 1997</td>
<td>55%</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1999 to 2004</td>
<td>59%</td>
<td>Seep 1 aerobic wetland with post-treatment limestone bed – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Cobalt</td>
<td>1995 to 1997</td>
<td>75%</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>1995 to 1997</td>
<td>76%</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>1999 to 2004</td>
<td>70%</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1995 to 1997</td>
<td>59%</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1999 to 2004</td>
<td>40%</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1995 to 1997</td>
<td>56%</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1999 to 2004</td>
<td>36%</td>
<td>Seep X aerobic wetland with pre- and post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Cobalt</td>
<td>1992 to 1994</td>
<td>90%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Cobalt</td>
<td>1992 to 1997</td>
<td>90%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010</td>
</tr>
</tbody>
</table>
### Table E-26: Average Removal Efficiencies – Dunka Mine

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Timeframe</th>
<th>Average Removal Efficiency</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1992 to 1994</td>
<td>92%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>1992 to 1997</td>
<td>92%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010</td>
</tr>
<tr>
<td>Copper</td>
<td>1996 to 1998</td>
<td>99%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Copper</td>
<td>1999 to 2004</td>
<td>96%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1992 to 1994</td>
<td>96%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1992 to 1997</td>
<td>96%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010</td>
</tr>
<tr>
<td>Nickel</td>
<td>1996 to 1998</td>
<td>97%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Nickel</td>
<td>1999 to 2004</td>
<td>98%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1992 to 1994</td>
<td>84%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1992 to 1997</td>
<td>84%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – ITRC, 2010</td>
</tr>
<tr>
<td>Zinc</td>
<td>1996 to 1998</td>
<td>99%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1999 to 2004</td>
<td>88%</td>
<td>W2D/3D aerobic wetland with post-treatment limestone beds – Eger and Eger, 2005</td>
</tr>
</tbody>
</table>

**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 = $\frac{1}{2}$ the average detection limit used to calculate average removal efficiency
## Table E-27: Flow Rates – All Treatment Train Mine Sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Flow Rate (L/min)</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calliope</td>
<td>3.8 with four months at 7.6</td>
<td>Wilmoth, 2002</td>
<td>Operational flow rate</td>
</tr>
<tr>
<td>Copper Basin</td>
<td>1,102</td>
<td>U.S. EPA, 2006b</td>
<td>Average flow rate</td>
</tr>
<tr>
<td></td>
<td>310</td>
<td>ITRC, 2010</td>
<td>Average flow rate; Jan. to Sept. 1998; EM8 aerobic wetland with limestone beds incorporated into the wetland</td>
</tr>
<tr>
<td>Dunka</td>
<td>400</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1995 to 1997; EM8 aerobic wetland with limestone beds incorporated into the wetland</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1995 to 1997; Seep 1 aerobic wetland with post-treatment limestone bed</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1999 to 2004; Seep 1 aerobic wetland with post-treatment limestone bed</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1995 to 1997; Seep X aerobic wetland with pre- and post-treatment limestone beds</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1999 to 2004; Seep X aerobic wetland with pre- and post-treatment limestone beds</td>
</tr>
</tbody>
</table>
## Table E-27: Flow Rates – All Treatment Train Mine Sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Flow Rate (L/min)</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>75</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1992 to 1994; W2D/3D aerobic wetland with post-treatment limestone beds</td>
</tr>
<tr>
<td>75</td>
<td>75</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1992 to 1997; W2D/3D aerobic wetland with post-treatment limestone beds</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1996 to 1998; W2D/3D aerobic wetland with post-treatment limestone beds</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
<td>Eger and Eger, 2005</td>
<td>Average flow rate; 1999 to 2004; W2D/3D aerobic wetland with post-treatment limestone beds</td>
</tr>
<tr>
<td>Force Crag</td>
<td>510 – 1,464</td>
<td>Jarvis et al., 2015</td>
<td>Influent flow rate range; 2011-2014</td>
</tr>
<tr>
<td></td>
<td>888</td>
<td>Jarvis et al., 2015</td>
<td>Average flow rate; 2011-2014</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>Jarvis et al., 2015</td>
<td>Design flow rate</td>
</tr>
<tr>
<td>Golden Sunlight</td>
<td>11.4</td>
<td>Bless et al., 2008</td>
<td>Design flow rate; BCR operated at 7.6 L/min</td>
</tr>
<tr>
<td>Leviathan</td>
<td>31.8 (gravity-flow mode)</td>
<td>Doshi, 2006</td>
<td>Reported for 2003-2005</td>
</tr>
<tr>
<td></td>
<td>34.2 (recirculation mode)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monte Romero</td>
<td>1</td>
<td>Macias et al., 2012a</td>
<td>Operational flow rate in NFOL</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>Macias et al., 2012a</td>
<td>Influent flow rate</td>
</tr>
<tr>
<td>Standard</td>
<td>3.8</td>
<td>Gallagher et al., 2012</td>
<td>Design flow rate</td>
</tr>
</tbody>
</table>
### Table E-27: Flow Rates – All Treatment Train Mine Sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Flow Rate (L/min)</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surething</td>
<td>7.6</td>
<td>Doshi, 2006</td>
<td>Design flow rate; actual discharge reached peaks of 38 L/min</td>
</tr>
<tr>
<td>Tar Creek</td>
<td>1,000</td>
<td>Nairn et al., 2010a</td>
<td>Design flow rate</td>
</tr>
<tr>
<td>Valzinco</td>
<td>342 – 4,200</td>
<td>Seal et al., 2008</td>
<td>Flow rate range at sample location VLZN-3</td>
</tr>
<tr>
<td>Wheal Jane</td>
<td>12-24</td>
<td>Whitehead et al., 2005</td>
<td>Operational flow rate range</td>
</tr>
</tbody>
</table>

**Notes:**
Wilmuth, 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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Influent</th>
<th>Average Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>100</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.507</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>Calcium</td>
<td>250</td>
<td>850</td>
</tr>
<tr>
<td>Copper</td>
<td>5</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Iron</td>
<td>275</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Lead</td>
<td>0.174</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Magnesium</td>
<td>255</td>
<td>386</td>
</tr>
<tr>
<td>Manganese</td>
<td>18</td>
<td>19</td>
</tr>
<tr>
<td>Potassium</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Silicon</td>
<td>37</td>
<td>11</td>
</tr>
<tr>
<td>Sulfate</td>
<td>3,430</td>
<td>3,770</td>
</tr>
<tr>
<td>Zinc</td>
<td>440</td>
<td>414</td>
</tr>
<tr>
<td>Eh</td>
<td>508</td>
<td>341</td>
</tr>
<tr>
<td>pH</td>
<td>3</td>
<td>6.6</td>
</tr>
</tbody>
</table>
### Table E-28: Average Influent and Effluent Concentrations – Monte Romero Mine

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

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

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Average Removal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>99.90%</td>
</tr>
<tr>
<td>Arsenic</td>
<td>100.00%</td>
</tr>
<tr>
<td>Calcium</td>
<td>-240.00%</td>
</tr>
<tr>
<td>Copper</td>
<td>99.95%</td>
</tr>
<tr>
<td>Iron</td>
<td>99.96%</td>
</tr>
<tr>
<td>Lead</td>
<td>100.00%</td>
</tr>
<tr>
<td>Magnesium</td>
<td>-51.37%</td>
</tr>
<tr>
<td>Manganese</td>
<td>-5.56%</td>
</tr>
<tr>
<td>Potassium</td>
<td>-40.00%</td>
</tr>
<tr>
<td>Silicon</td>
<td>70.27%</td>
</tr>
<tr>
<td>Sulfate</td>
<td>-9.91%</td>
</tr>
<tr>
<td>Zinc</td>
<td>5.91%</td>
</tr>
</tbody>
</table>

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