UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
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MEMORANDUM

SUBJECT: Planning for Response Actions at Abandoned Mines with Underground Workings: Best Practices for Preventing Sudden, Uncontrolled Fluid Mining Waste Releases Reference Document

FROM: James E. Woolford, Director
Office of Superfund Remediation and Technology Innovation

Reggie Cheatham, Director
Office of Emergency Management

TO: EPA Superfund National Program Managers, Regions I-X

PURPOSE

This memorandum transmits "Planning for Response Actions at Abandoned Mines with Underground Workings: Best Practices for Preventing Sudden, Uncontrolled Fluid Mining Waste Releases," a technical reference document identifying best practices to minimize the potential for sudden, uncontrolled releases of fluid mine waste as a result of U.S. Environmental Protection Agency (EPA) site investigations and response actions. The Office of Superfund Remediation and Technology Innovation (OSRTI) and the Office of Emergency Management (OEM) recommend applying these best practices, as appropriate, when carrying out EPA-lead activities under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) at hardrock mining and mineral processing sites with underground mine workings posing actual or potential fluid release hazards.

BACKGROUND

The August 2015 Gold King Mine (GKM) release drew widespread attention to the potential for sudden, uncontrolled fluid mine waste releases. Both EPA and the U.S. Department of the

Interior's (DOI) Bureau of Reclamation conducted post-GKM incident reviews recommending the application of best practices to help prevent future releases. To that end, EPA developed the attached reference document to support site-specific decision-making at sites with underground workings where mine influenced water (MIW) may be pooled. EPA intends for the document to inform practitioners and their managers about best practices to help reduce the risk and uncertainty of MIW-related blowouts. It is important to note that site-specific conditions may warrant the application of technologies and approaches *not* described in this report.

The report's best practices emanate from: (1) existing technical resources and publications, (2) lessons learned from relevant incidents, and (3) technical contributions from professionals with mine waste characterization and mitigation expertise. Information from these sources draws upon Federal and state governmental agencies, international organizations and academic experts in pooled MIW blowout assessment and prevention.

The document underwent a number of reviews including those conducted by: DOI's Bureau of Land Management and Office of Surface Mining Reclamation and Enforcement, the U.S. Department of Agriculture's Forest Service, the U.S. Department of Defense's U.S. Army Corps of Engineers, the Association of State and Territorial Solid Waste Management Officials, and EPA mining experts. Additionally, independent peer review was conducted by experts from the Department of Interior's U.S. Geological Survey, the West Virginia Department of Environmental Protection, the Pennsylvania Department of Environmental Protection, the Colorado School of Mines, the University of Nevada Reno (on behalf of an environmental interest group), NOVAGOLD Resources (on behalf of the American Exploration and Mining Association) and a tribal consultant.

IMPLEMENTATION

Regions engaging in site activities related to removal or remedial characterization, investigation, or cleanup with underground mine workings should review and implement the best practices and approaches outlined in the attached document, as applicable. We also want to emphasize the importance of documenting how these best practices were considered in the site consultation packages submitted for headquarters' review as required in the EPA Office of Land and Emergency Management's April 4, 2017, memorandum, "Developing Consultation Packages for CERCLA Activities at Abandoned Hardrock Mining and Mineral Processing Sites in Preparation for the Fiscal Year 2017 Construction Season."

Generally, the critical activities that should be conducted as part of the work planning for a mining site with underground workings with actual or potential fluid hazards include:

- Conducting an initial site screening;
- Developing a conceptual site model of mine workings and pooled MIW risks;
- Collecting data by non-invasive, minimally invasive and invasive (drilling) methods;
- Performing a "failure modes and effects analysis" of proposed work activities;
- Developing or revising plans for contingencies, notifications emergency actions and other activities; and
- Mitigating identified pooled MIW risks.

CONCLUSION

If you have any questions, please contact Shahid Mahmud of my staff at (703) 603-8789 or by email at mahmud.shahid@epa.gov.

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Planning for Response Actions at Abandoned Mines with Underground Workings:

Best Practices for Preventing Sudden, Uncontrolled Fluid Mining Waste Releases

www.epa.gov/aboutepa/about-office-land-and-emergency-management
www.epa.gov/superfund/abandoned-mine-lands

NOTICE AND DISCLAIMER

This report provides topical information rather than guidance and does not impose legally binding requirements, nor does it confer legal rights, impose legal obligations, implement any statutory or regulatory provisions, or change or substitute for any statutory or regulatory provisions. Users are referred to applicable regulations, policies, and guidance documents. Selected references and additional resources are provided herein.

This report compiles and presents best practices and approaches for reducing the risk of sudden, uncontrolled releases of fluid mine waste prior to conducting response actions at abandoned mine sites with underground workings under the jurisdiction of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). The best practices presented in this report were selected based on research conducted by, and the practical experience of, Tetra Tech, Inc. and serves as a technical resource to guide response actions at abandoned mine sites with underground workings. Mention of specific products in this report does not constitute promotion of that product.

This best practices report was prepared by Tetra Tech, Inc. for the U.S. Environmental Protection Agency (EPA) under EPA Superfund Technical Assistance and Response Team (START) contract EP-S5-13-01.

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ACRONYMS AND ABBREVIATIONS

3DVA	3-Dimensional Data Visualization and Analysis
AML	Abandoned Mine Lands
ASTM	American Society for Testing and Materials
BOP	Blowout Preventer
BOPE	Blowout Prevention Equipment
BOR	Bureau of Reclamation
CBI	Confidential business information
CDMRS	Colorado Division of Mining Reclamation and Safety
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSoM	Colorado School of Mines
COC	Contaminants of Concern
CSM	Conceptual Site Model
DHS	Department of Homeland Security
DO	Dissolved Oxygen
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOL	U.S. Department of Labor
DOT	U.S. Department of Transportation
DPT	Direct Push Technologies
EC	Engineering Control
EM	Electromagnetics
EPA	U.S. Environmental Protection Agency
ERI	Electrical Resistivity Imaging
ETA	Event Tree Analysis
FEMA	Federal Emergency Management Agency
FHWA	Federal Highways Administration
FMEA	Failure Modes and Effects Analysis
FSP	Field Sampling Plan
GKM	Gold King Mine
GMS	Groundwater Modeling System
gpd	Gallons Per Day
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HASP	Health and Safety Plan
HDD	Horizontal Directional Drilling
HEM	Helicopter Electromagnetic
HP	Heat Pulse
HSA	Hollow Stem Auger
ICMM	International Council on Mining and Metals
IP	Induced Polarization
LIDAR	Light Imaging, Detection and Radar
LLD	Linear Leak Detection
MALM	Mise-a-la-Masse
MIW	Mining Influenced Water
MSHA	Mine Safety and Health Administration
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NMMR	National Mine Map Repository
ORCR	Office of Resource Conservation and Recovery
ORP	Oxidation/Reduction Potential
OSRTI	Office of Superfund Remediation and Technology Innovation
OSMRE	Office of Surface Mining Reclamation and Enforcement
PE	Professional Engineer
PG	Professional Geologist
QAPP	Quality Assurance Project Plan
RAB	Rotary Air Blast
RC	Reverse Circulation
SAP	Sampling and Analysis Plan
SC	Specific Conductance
SP	Spontaneous Potential
TDS	Total Dissolved Solids
UAV	Unmanned Aerial Vehicle
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environment Program
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VLF	Very Low Frequency

1.0 INTRODUCTION

Under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the U.S. Environmental Protection Agency (EPA) may perform remedial and removal (known together as "response") actions, including removal, pre-remedial and remedial activities at abandoned mine land (AML) sites where the potential exists for sudden, uncontrolled releases (commonly known as "blowouts") of fluid mine wastes, such as impounded or "pooled" mining-influenced water (MIW) in underground mine workings. This report compiles, analyzes, and summarizes common best practices and approaches used or researched nationally and internationally by federal and state agencies, industry, and academic institutions to assess, reduce the risk of, or mitigate blowouts at AML sites as a result of response actions at mining sites with underground mine workings.

The critical activities for assessing, reducing the risk of, and mitigating such releases include:

- Conducting an initial site screening;
- Developing a conceptual site model (CSM) of mine workings and pooled MIW risks;
- Collecting data by non-invasive, minimally invasive, and invasive[1] (drilling) methods;
- Performing a Failure Modes and Effects Analysis (FMEA) of proposed work activities;
- Developing or revising plans for contingency, notifications, and emergency action; and
- Mitigating identified pooled MIW risks.

The best practices laid out in this report do not constitute guidance, rather they are best professional judgment on a range of approaches that can be applied on a site-specific basis to reduce the risks and uncertainty of sudden, uncontrolled releases of MIW. However, risk and uncertainty of MIW releases cannot be completely eliminated from many mine sites, particularly for those sites that have not been maintained or inspected for decades or longer, and given the often complex conditions that exist in underground mine workings with MIW pooling. Furthermore, the report does not provide best practices for conducting MIW remediation activities. Such actions are highly diverse and site-specific, and they are addressed in later project phases through existing EPA, state, and other agency guidance. Remediation activities require detailed planning and execution, the best practices for which are beyond the scope and intent of the report.

The term "fluid mine waste" is used in this report to describe one or a combination of MIW, sludge, and other fluidized or liquefiable mine wastes in mine workings that may be suddenly released during MIW pool blowouts.

The CERCLA response process is an established regulatory structure with major steps, and the best practices described in this document can be integrated into them. The best practices for preventing uncontrolled MIW releases can be applied at any phase of the CERCLA response process when planning is necessary to perform activities that may disturb pooled MIW in underground mine workings. Nothing in this report replaces or circumvents the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) or any CERCLA guidance.

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[1] **Non-invasive** – work that does not disturb the subsurface, such as site reconnaissance, topographic surveys, and sampling, sonar imaging, and tracer dye testing of directly accessible MIW and surface water bodies.
Minimally invasive – work that minimally disturbs the subsurface, such as measurement or sampling using existing wells, boreholes, or other safely accessible surface openings; water elevation measurement and sampling; downhole assessment and monitoring using technologies such as video, downhole 3-dimensional laser mapping, pressure transducers, flow meters and surface geophysical surveys.
Invasive – work that disturbs the subsurface, such as drilling; probing; excavating; blasting; grading; and dewatering that may be conducted to assess or mitigate MIW pooling and discharge.

1.1 Report Purpose

This report provides EPA Regions and others with additional information to support site-specific decisions in addressing underground workings that may have pooled MIW. The goal of this report is to minimize the potential for sudden, uncontrolled releases of fluid mine waste from underground mine workings as a result of an EPA or other state or federal land management agencies' response action. It is intended to inform practitioners and their managers on best practices to reduce the risk and uncertainty of blowouts of MIW from underground mine workings. It is important to note that application of these best practices depends on site-specific conditions that in limited cases may warrant the application of alternative technologies and approaches to those described in this report.

1.2 Background

On August 5, 2015, removal assessment activities being conducted by EPA triggered a sudden, uncontrolled release of approximately 3 million gallons of MIW from the Gold King Mine (GKM) into tributaries of the Animas River, located upstream of Silverton, Colorado. This incident drew widespread attention to the potential for sudden, uncontrolled releases of fluid mine wastes at other mine sites with underground workings.

EPA and the U.S. Department of the Interior (DOI) Bureau of Reclamation (BOR) both conducted reviews after the GKM incident, and produced the following reports:

1. Summary Report: *EPA Internal Review of the August 5, 2015, Gold King Mine Blowout* (EPA 2015a); and
2. *Technical Evaluation of the Gold King Mine Incident* report (BOR 2015).

Both reports recommended applying best practices to help prevent future releases (EPA 2015a and BOR 2015). This best practices report was developed primarily in response to the following recommendations made in the two reports reviewing the GKM release incident:

The EPA report states:

> *"EPA should develop guidance to outline the steps that should be undertaken to minimize the risk of an adit blowout associated with investigation or cleanup activities.*
>
> *"Even though the chance of encountering pressurized mine water was investigated in many ways at the Gold King Mine, the Gold King Mine blowout suggests that EPA should develop a toolbox of additional investigative tools such as remote sensing or drilling into the mine pool from the top or side that should be more seriously considered at similar sites. It's important to recognize that underground mines may be extremely complex, making characterization of the internal hydraulic conditions and flow paths challenging. Adding to this complexity is that older mine workings are often not well mapped and that some underground mines may also be structurally unstable and prone to cave-ins and internal plugging making them very difficult to assess. The toolbox should identify techniques which could be used to minimize uncertainties associated with these types of mines. Site specific conditions may make certain investigative tools prohibitive or extremely challenging and costly. In the end, while additional information gathering may reduce the uncertainty, a complete understanding of the underground conditions may not be attainable."* (EPA 2015a)

The BOR report states:

> *"The standards of practice for reopening and remediating flooded inactive and abandoned mines are inconsistent from one agency to another. Various guidelines exist for this type of work, but there is little in actual written requirements that government agencies are required to follow when reopening an abandoned mine."* (BOR 2015)

This report incorporates many of the standards of practice referenced in the EPA and BOR reports. As noted previously, this report is not intended to be a guidance document but rather a toolbox which lays out techniques and approaches which can minimize MIW-related uncertainties associated with these types of mines. Exhibits 1 and 2 provide the complete recommendations from the EPA and BOR GKM review reports.

1.3 Primary Resources

The best practices and approaches presented in this report were developed from a variety of resources, including (1) review of existing technical resources and publications, (2) compilation of lessons learned from similar incidents, and (3) technical contributions from expert professionals with relevant experience in mine waste characterization and mitigation. In developing this report, EPA's contractor conducted interviews with, or received material contributions from, federal and state government agencies, international organizations, and academic experts in MIW pool blowout assessment and prevention.

The following federal agencies were consulted or contributed materials to the development of this report:

- Department of the Interior:
    - Office of Surface Mining Reclamation and Enforcement (OSMRE);
    - U.S. Geological Survey (USGS); and
    - Bureau of Reclamation.
- U.S. Environmental Protection Agency.
- Department of Labor, Mine Safety and Health Administration (MSHA).
- Federal Highways Administration, Interstate (FHWA) Technical Group on Abandoned Underground Mines.
- U.S. Army Corps of Engineers.
- Department of Homeland Security, Federal Emergency Management Agency (FEMA).
- U.S. Department of Agriculture (USDA), U.S. Forest Service (USFS).

The Agency's contractor also consulted with the International Council on Mining and Metals (ICMM), the National Academy of Sciences Committee on Subsurface Characterization, the University of Nevada Reno, the West Virginia University and Virginia Tech, and the Colorado Division of Mining Reclamation and Safety (CDMRS).

1.4 Report Organization

This report is organized into six sections, a bibliography and four appendices, as follows:

Section 1: introduces this report.
Section 2: provides an overview of the best practices and approaches presented in this report.
Section 3: describes the initial site screening.
Section 4: describes the CSM of mine workings and pooled MIW risks, including planning and execution of data collection to develop a more comprehensive CSM.
Section 5: describes mitigation measures for pooled MIW.
Section 6: describes the qualifications of individuals on the technical team.
Bibliography: provides references for material used in the development of this report as well as additional resources available for referral; where applicable, web site addresses (URLs) are provided for additional resources available on the Internet.
Appendix A: provides a checklist tool for applying the best practices described in this report.
Appendix B: presents general resources and information on groundwater modeling.
Appendix C: presents additional resources for developing an MIW CSM.
Appendix D: is a topical matrix associating bibliographic sources with report topics.

Exhibit 1
Recommendations Summarized from EPA's Internal Review of GKM Incident (EPA 2015a)

1. *EPA should develop guidance to outline the steps that should be undertaken to minimize the risk of an adit blowout associated with investigation or cleanup activities. The guidance, at a minimum, should:*
    - a *Identify a tiered approach that requires increased detail regarding the proposed action based on the complexity of the site conditions or the potential nature of any release.*
    - b *Provide criteria to identify whether a proposed investigation or cleanup action presents a low, moderate, or high risk with respect to the potential for an adit blowout and significant release of acid mine drainage or mine waste.*
    - c *Require that a management review meeting(s), including the key state (and other federal agencies when appropriate) be held to determine whether sufficient information exists to meet the criteria established in the guidance or whether additional information is necessary before undertaking the investigation or cleanup activity.*
    - d *Outline the outreach activities to inform the local community and stakeholders.*
    - e *Identify the contingency planning that may be appropriate based upon the risk of blowout and the nature of the potential release.*
2. *Even though the chance of encountering pressurized mine water was investigated in many ways at the Gold King Mine, the Gold King Mine blowout suggests that EPA should develop a toolbox of additional investigative tools such as remote sensing or drilling into the mine pool from the top or side that should be more seriously considered at similar sites. It's important to recognize that underground mines may be extremely complex, making characterization of the internal hydraulic conditions and flow paths challenging. Adding to this complexity is that older mine workings are often not well mapped and that some underground mines may also be structurally unstable and prone to cave-ins and internal plugging making them very difficult to assess. The toolbox should identify techniques which could be used to minimize uncertainties associated with these types of mines. Site specific conditions may make certain investigative tools prohibitive or extremely challenging and costly. In the end, while additional information gathering may reduce the uncertainty, a complete understanding of the underground conditions may not be attainable.*
3. *Emergency Action Plans should include protocols should a blowout occur at those mine sites where there is a potential for such an event to occur.*
4. *Information and rationale developed by a site team in anticipation of an investigation or cleanup action for sites where an adit blowout could be a concern (e.g., available pressure information, a reasonable estimate of the volume of water within the mine workings, or adit drainage flow rate data) should be critically reviewed by a qualified and experienced Regional Mining engineer and or Mining Hydrologist/Geologist. The Region may want to consider getting assistance from qualified outside parties such as other federal agencies, state agencies, or outside consultants in conducting this critical review.*
5. *The Team also recommends that subsequent reviews of the Gold King Mine Adit Blowout by an Independent External Review Group or the Office of Inspector General consider the possibility of assembling a panel of experts consisting of mining industry experts, other federal and state mining experts, academia, consultants, non-governmental organizations and tribal governments to further analyze the situation encountered at this site and come up with recommendations on additional safeguard measures to reduce the risk and minimize the consequences of such incidents in the future.*

Exhibit 2
Recommendations from the BOR Technical Evaluation of the GKM Incident (BOR 2015)

1. *"Because of the complexity of reopening a flooded abandoned mine, a potential failure modes analysis should be incorporated into project planning.*
2. *Before opening an abandoned mine adit, review mine maps, production records, dump size, and local history about the mine to evaluate the potential volume of mine workings. If the volume is large, consider what would happen if there were an accidental release and what could be done to protect against it. A downstream-consequences analysis should be a part of every complex mine remediation.*
3. *Water conditions within the mine should be directly measured prior to opening a blocked mine. Indirect evidence is insufficient if the potential for a blowout exists.*
4. *Where significant consequences of failure are possible, independent expertise should be obtained to review project plans and designs prior to implementation."*

2.0 BEST PRACTICES AND APPROACHES OVERVIEW

Underground workings of abandoned mines experience infilling by groundwater, surface water, and by communication with interconnected underground mine workings, including continuous "mine pools." MIW can subsequently discharge from the mine workings via openings to the ground surface, including but not limited to, adit and tunnel portals, open shafts, air vents, bedrock fractures, bore holes, and springs or seeps. When mine workings are blocked or drainage is impeded, mine pools can form and undergo increasing pressurization as water levels increase. MIW pooling can form as a result of natural and anthropogenic conditions. Example causes of mine pooling include:

- Structural geologic conditions dictating mine void shape (for example, doubly plunging synclinal basins);
- Natural blockages or man-made seals (for example, seismic events, collapses, subsidence events, clogged pipes, bulkheads, and coffer dams);
- Down dip direction horizontal openings;
- Opening locations below the water table or surface drainage; and
- Changes in subsurface hydraulic conductivity.

The presence and extent of mine pools can be difficult to identify and evaluate because of limited physical and visual access. Seasonal variations in precipitation, runoff, and snow melt, as well as remote locations, limit worker and equipment access for field investigations. Sudden, uncontrolled releases of MIW pools can occur as a result of changing conditions in the mine caused by natural or anthropogenic mechanisms.

A range of investigation and remediation activities undertaken during CERCLA response actions at mine sites could impair the stability of MIW pooling. Example activities include, but are not limited to, drilling, earth work, mine workings stabilization, debris removal, backfilling, flow-through bulkhead installation, plugging, and road construction/maintenance. An overarching best practice is not to initiate such "invasive" activities at underground mine sites unless sufficient information is available or collected to determine whether MIW pooling exists, is likely to exist, or may be caused by activities. If MIW pooling is confirmed or suspected, a better understanding of the cause and extent of MIW pooling should be developed before undertaking such site activities. See Exhibit 3 for a site-specific best practice example.

Exhibit 3
Best Practice Example:
Leadville Mine Drainage Tunnel Risk Assessment

The DOI BOR performed a risk assessment for the Leadville Mine Drainage Tunnel in Colorado at EPA's request. The Leadville risk assessment evaluated the likelihood of mine tunnel failures and potential water buildup. A key feature at the Leadville site is that the workings had a higher degree of physical access than typically exists at many abandoned mine sites. For less accessible workings, risk assessment must rely more on data derived from invasive investigations and best professional judgement. While the Leadville risk assessment provides a number of best practices that apply to AML sites, this best practices report also includes considerations to address MIW pooling in sites with limited physical access.

Source: BOR 2008. The full Leadville Mine Drainage Tunnel Risk Assessment can be found at: *https://www.usbr.gov/gp/ecao/leadville/combined_risk_assessment.pdf*

This report presents best practices and approaches compiled from, (1) lessons learned from past MIW pool releases, and (2) best practices used in similar industries (for example, coal mining), where MIW in underground workings is present under atmospheric or confined pressure (and may discharge as a result of sudden, uncontrolled releases). While this report uses the terms "MIW pool" and "MIW pooling" generally to describe water or fluids accumulating within mine workings, conditions in underground workings can result in multiple MIW pools within the same workings. Separate pools are commonly hydraulically connected and thus behave as a unified pool similar to groundwater aquifers; however, hydraulically separate MIW pool conditions can also occur. The overall objective of this document is to provide site teams with a broad range of information and techniques to support site specific planning to prevent the sudden, uncontrolled releases of fluids from MIW pools as a result of site activities.

3.0 CONDUCT INITIAL SCREENING

Before any invasive activities associated with the underground workings of an AML site are undertaken, an initial screening should generally be performed to document whether potential exists for MIW pooling and how the MIW pooling relates to planned activities. The initial screening typically involves collection and review of existing site information, a site visit or visits, interviewing individuals familiar with the site, and an initial determination of the potential for MIW pooling.

The initial screening includes a review of available site information and a site visit by a qualified technical team to assess whether or not MIW pooling exists. If pooling is known or suspected to be present, the initial screening also considers the possibility of conditions that pose risk of a blowout. If MIW pooling is confirmed not to be present within the hydraulically connected area of proposed response activities, there likely will be no potential to cause a blowout. Similarly, if MIW pooling is present but stable, and diligent assessment indicates no activities threaten this stability, then proposed response activities will likely have little potential to cause a blowout.

When the results of an initial screening indicate that there is limited potential for a blowout, an informed decision to proceed with the CERCLA response action can be made. Further evaluations are warranted if any uncertainty regarding the existence of MIW pooling or the potential for a sudden, uncontrolled release is identified. Table 1 shows the focus area and potential outcomes associated with an initial screening.

Table 1: Initial Screening Focus Areas and Potential Outcomes

Focus Areas	Potential Outcomes
1. **Understanding underground and above ground mine workings** (including interconnection with other mine workings and hydrogeologic conditions connected with, but potentially distant from the mine) 2. **Gathering information on hydrology and hydrogeology** (including a geologic and surface hydrology assessments to determine inter-connections between the mine workings, surface water, surface openings and groundwater) 3. **Understanding proposed response actions** and their potential to impact the subsurface 4. **Evaluating downstream surface water bodies and their uses** (for example, public water supply), considering loss of human life, infrastructure disruption, environmental and ecological damage, and economic loss	• **Finding of Limited Potential for Release** (analysis and documentation of the absence of pooled MIW or that MIW pooling is present but stable and that any proposed actions will not adversely affect the mine pooling) OR • **Finding of Uncertainty or Potential for Release** (data indicate a potential exists for a mine pool blowout or data gaps that leave uncertainty about the MIW pool and the risk for a blowout). Best practices for further study are warranted.

3.1 Review Available Documents and Data

The technical team should review pertinent site documentation including, but not limited to, reports on operational history; past investigation and remediation efforts; mine working maps and drawings; and historical MIW discharge information and lists of local mine experts. It is recommended that former site workers and nearby land owners be interviewed during a site visit. The technical team should also consider consulting with applicable state and federal agencies to determine if any studies were conducted at the site or for other sites in the area that can provide insight into site conditions related to MIW pooling and discharge.

After reviewing available site-specific information, the technical team should identify data gaps and collect additional information, as needed. Gathering information that is as location-specific as possible will improve the understanding of site MIW pooling. However, regional information can provide important supporting perspectives. For example, it may be useful to review USGS maps of the site with overlays generated using satellite imagery, such as Google Maps. OSMRE also operates the National Mine Map Repository (NMMR), which collects and maintains mine map information and images for the entire country (including data and maps of hardrock mines in the west). Searching the NMMR's Mine Map Index could identify workings maps for sites. NMMR has more than 180,000 maps of closed or abandoned mines (http://mmr.osmre.gov/MultiPub.aspx). Caution should be used when reviewing historical mine maps, as they may not be accurate, current, or complete; thus, information on mine conditions key to formation of MIW pooling may be absent in site documents or missing from site files.

Historical aerial photography and overlays from on-line databases at the USGS and USDA can provide useful information on mine workings and conditions. Stereo-paired aerial photography dating back to the late 1930s is typically available at 10-year intervals. Often, surface features (such as shafts, drifts, slope entries, waste piles, seeps, and discharges) are visible on these photos that may no longer be recognizable or present at the site.

After collecting and reviewing desktop information, it is recommended that the technical team consult with site experts and others with general site knowledge, including:

- Nearby land owners, local miners, mine operators, experts, and historians;
- Local government personnel;
- Local document repositories (libraries, municipal records departments, non-profit organizations);
- State experts, including geologists, state engineers, mining offices, geological surveys, and AML programs;
- DOI's BOR, USGS, and BLM State Office experts; and
- Regional USFS experts.

This initial screening step ensures that the available information about an AML site is identified for the assessment of geotechnical, hydrogeologic, hydrologic, hydraulic, and geochemical attributes as early in the review process as possible. This information can be used to focus the site visit on areas of interest such as potential MIW pools or to resolve related data gaps. See Appendix D for examples of additional sources of information.

3.2 Conduct a Site Visit

The purpose of the site visit is to further familiarize the technical team with the mine workings and other important features of the site, to evaluate current conditions, and to resolve data gaps identified during document and data review. The site visit should generally include, but not be limited to:

- Identifying relevant features in the area of interest;
- Documenting all impounded water, both natural and man-made;
- Noting differing conditions from reviewed information, such as collapsed workings, recent vegetation die-off/stress, or changed MIW discharge conditions;
- Measuring MIW discharge rates;
- Collecting non-invasive field measurements (for example, pH, conductivity, dissolved oxygen);
- Photo-documenting key features and conditions;
- Taking global positioning system (GPS) coordinates for all salient features;
- Inspecting easily and safely accessible open portions of mine workings;

- Identifying any time-sensitive conditions posing potential risk; and
- Identifying conditions that might impede access or future work.

The site visit is conducted to assess site conditions for the locations of the proposed activities relative to mine features, with a focus on identifying and locating features that are commonly associated with blockages and MIW pooling. Observe site conditions, such as seeps or springs with cloudy or low pH water, or discharges from mine openings that may indicate the presence of internal blockages that are not visible during surface inspection. The site visit should include viewing maps of adjacent mine site workings with known or potential interconnections. Consider participation of key federal, local, and state experts and reviews of local file repositories as part of the site visit.

3.3 Potential Outcomes

The technical team evaluates the available documents and data to determine if the proposed activity poses no blowout risk (for example, no MIW pooling, or stable MIW pooling that the response action will not impact). The team also evaluates whether further study is needed to make this determination (for example, unknown potential for MIW pooling; or potential that MIW is not stable; or that response actions can make the MIW pool unstable). The quality of the data is evaluated to assess its usability for making these determinations. If further study is needed, the technical team develops a CSM of the pooled MIW risks (see Section 4.0) and identifies additional data needs.

The certainty of any decision to proceed with a proposed response action must be based on sound scientific data and analysis informed by current conditions, and made by qualified personnel. Therefore, initial screenings are advised to be performed by qualified mining engineers, civil/environmental engineers, geologists, hydrogeologists, and geochemists with experience in assessing and addressing MIW pooling (see Section 6.0).

4.0 DEVELOP MIW CONCEPTUAL SITE MODEL

Updating the existing CSM with data and information specific to the MIW pool, or creating an MIW CSM if a CSM has not been developed, is a best practice for integrating site information and identifying key data gaps. This section presents the common best practices for developing an MIW CSM to identify and assess risks and uncertainty regarding the potential for MIW blowout. It is critical that this CSM focus on the physical structure of mine workings, regional and local structural geology, regional and local meteorology and hydrology, and defining the nature and the extent of MIW pooling, including known and suspected blockages and conditions for future potential workings collapse and blockage. It is recommended that the technical team develop graphical depictions of the CSM (for example, maps of workings, cross-sections and 3-dimensional visualizations) that show the physical structure, areal extent, cross-sectional area, and condition of mine workings and related features. The MIW CSM supplements the environmentally focused site CSM prepared for the site cleanup.

The MIW CSM integrates geotechnical data about the mine workings with hydrogeologic, hydrologic, hydraulic, and geochemical data to assess the risk of a sudden, uncontrolled release in relation to planned response actions. Given the specialized focus of these assessments on MIW pooling, the use of "geotechnical, hydrogeologic, hydrologic, hydraulic and geochemical assessment" in this report is not intended to equate with any traditional site assessment, remedial investigation, or other characterization stage in the CERCLA pipeline.

The stated "problem" for which the MIW CSM is developed is:

What is the nature and extent of MIW pooling and what are the potential failure modes for an MIW blowout?

A variety of references support the best practices for performing an FMEA are described in this report. The BOR's *Risk Assessment of the Leadville Mine Drainage Tunnel* (BOR 2008) contains many best practices for conducting geotechnical assessments and FMEA. Appendix A of the *EPA and Hardrock Mining: A Source Book for Industry in the Northwest and Alaska* (EPA 2003) addresses geologic, hydrogeologic, hydrologic, and geochemical assessment practices, which are necessary to quantify the nature and extent of mine pooling and develop a water balance. The USDA, USFS *Investigative Methods for Controlling Groundwater Flow to Underground Mine Workings* provides another resource for developing the hydrogeologic elements of the MIW pool CSM (USFS 2006). These and other important references are provided in the bibliography at the end of this report. Appendix D comprises a Reference Materials Matrix that maps specific best practice topics to references listed in the bibliography.

MIW CSM development begins by defining the area of interest and the watershed/aquifer boundary of that area. Boundary conditions may include definitions of flow or hydraulic conditions across the boundary. The subsequent steps are described in the following subsections. The MIW CSM should generally be updated or developed, as applicable, in conjunction with the performance of a FMEA on proposed or potential actions, to identify potential failure modes that could affect MIW pooling (BOR 2008). The discussion below includes common components of a CSM for MIW pooling.

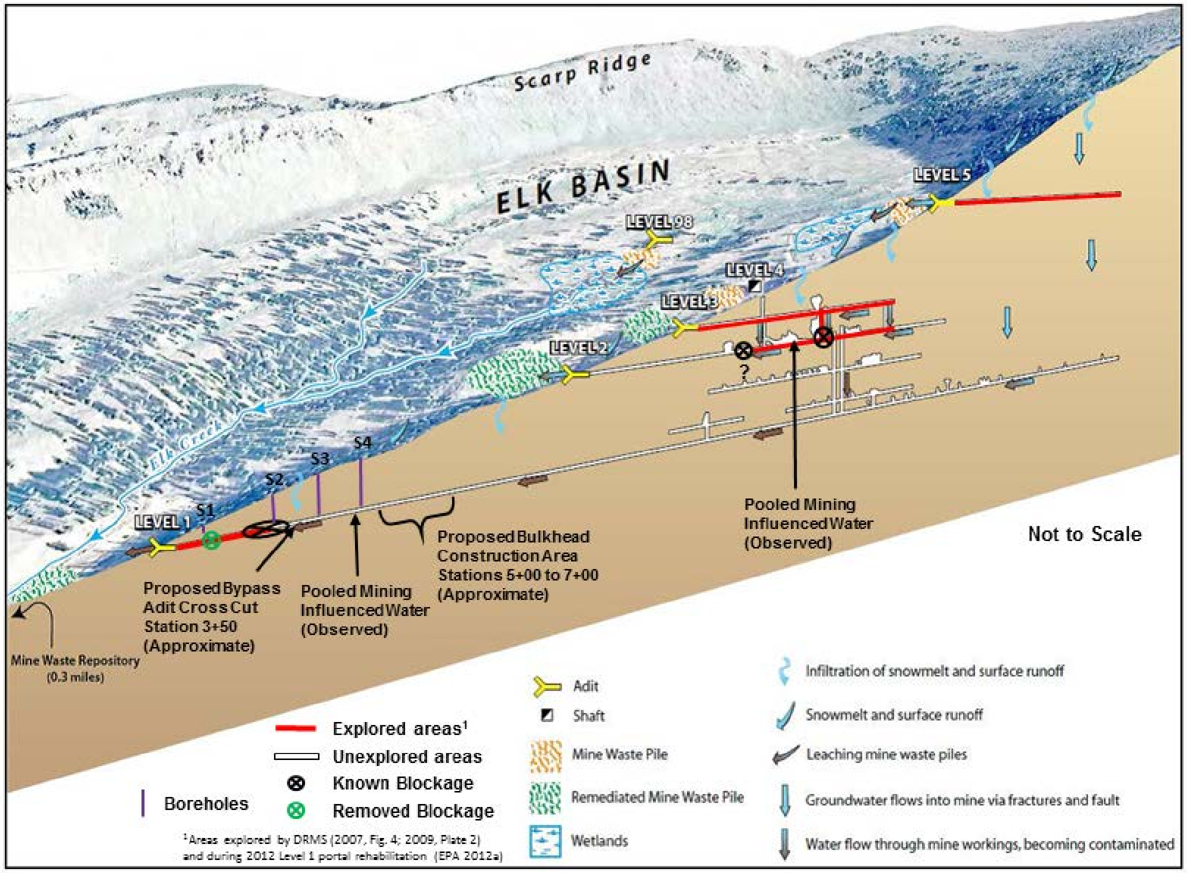
4.1 Visualize and Assess Mine Workings

A critical element of visualizing and assessing the CSM for MIW pooling is understanding the extent, features, and geospatial orientations of the mine workings. This element should include any mine openings or surface expressions and any known or suspected blockages or collapses. This step is best performed through a comprehensive assessment of available mineral exploration planning and final development maps, geologic maps, cross-sections, reports, models, and other information that illustrate the historical evolution and operation of the mine workings. Similar information should be collected for other mines near the mine site of concern, particularly where there are known or suspected interconnections between mines. Any information or reports on known or suspected locations of blockages, zones of known collapse, or zones of potential instability are also important. The MIW CSM should clearly indicate where information is generated from direct observations, the level of uncertainty, and where assumptions have been made, to clarify for other users the level the information being relied on in assessing the potential for fluid hazards. Attributes of mine workings to consider as a part of developing the CSM of MIW are discussed in Section 4.2. Figure 1 provides an example CSM visualization of mine workings and adit flows, with notes on MIW flow direction and uncertainties.

Active interest in re-starting operations for some mines for additional mineral extraction may have resulted in consolidation of information on past mine workings and collection of additional data. These efforts may provide the best and most current information on mine workings and should generally be identified and reviewed. However, because these data are frequently considered confidential business information (CBI), they may not be readily available. It is recommended that technical teams specifically inquire about such information and recognize that gaining access to this information may require confidentiality or may not be possible.

Mine workings information is best synthesized using current off-the-shelf 3-dimensional data visualization and analysis (3DVA) software, which include those designed for use as active mine planning tools and those adapted to support environmental evaluations. The resulting visualizations can serve as the basis for a project life cycle CSM (EPA 2011), wherein the CSM is updated as new data are generated from overall site assessment, investigation, and response actions.

Figure 1. Example CSM visualization: Standard Mine adit levels and underground workings. Note: The angle of view exaggerates the apparent dip of the adits beyond their actual 1 percent grade. (EPA 2015f)



To the maximum extent practicable, representations of the mine workings should be as geospatially accurate in three dimensions as possible. Geo-referencing the underground mine workings to the surface (vertically and horizontally) is essential, as well as ensuring that the volumetric measurements of the workings dimensions are reasonable, given the general uncertainty commonly associated with mine development maps and measurements. Estimates of MIW volume within workings are dependent on the accuracy of these maps and measurements. The vertical dimension is also particularly important because elevation differences are critical to determining hydrostatic connectivity and MIW conditions. Achieving this accuracy may require focused topographic surveys to locate reference points during additional site visits.

4.2 Evaluate Geotechnical, Hydrogeologic, Hydrologic and Hydraulic, and Geochemical Attributes of the MIW Pooling

Understanding MIW pooling requires evaluating the geotechnical, hydrogeologic, hydrologic, hydraulic, and geochemical attributes of the mine, evidence of MIW pooling, and underground workings and adjacent surroundings. Specifically, the team should generally evaluate:

1. The geotechnical conditions of the mine workings, including attributes that influence collapses, blockages, releases, or potential slope instability;
2. The hydrogeologic conditions that create inflow into, and outflow (discharge) from the workings;
3. Hydrologic and hydraulic conditions of the MIW pooling and the surface water features (including water management infrastructures) that receive or influence MIW; and

4. The geochemical characteristics of the MIW quality and acid generating/neutralizing characteristics of the ore zones and adjacent rock.

These attributes inform the risk assessment and contingency planning. The information available for each site will vary and the data collection should be related to the proposed specific site activity. Below are some of the mine workings and MIW pooling attributes to consider in assessing MIW pool blowout risks.

Geotechnical Attributes

Geotechnical attributes evaluated as a common best practice in assessing MIW pooling risks include, but are not limited to (BOR 2008, EPA 2000, EPA 2003, EPA 2015f, USFS 2006):

- Dimensions and extent of mine workings, including adits, drifts, cross-cuts, haulage routes, shafts, raises, winzes, manways, air vents;
- Types and conditions of support/rehabilitation structures such as timbering, beams, cribbing, square sets, ribs, pillars, crossbars, steel beams, pinning, bolts, concrete;
- Workings storage – volume of mine workings above and below mine potential blockage locations to estimate MIW pooling volume;
- Mine working openings at the surface that serve or could potentially serve as MIW inflow or outflow locations, as well as air inflow locations, key contributors to MIW acidification;
- Portal or other mine opening stability assessment;
- Known or suspected mine workings interconnections between mines;
- Presence of faults, joints, folding or other geologic features that could affect mine stability;
- Thickness and integrity of overburden cover above the mine workings (for example, fracturing is typically more prevalent and fractures have wider aperture at shallower depths);
- Types, strengths, and competency of bedrock and other strata;
- Location, composition, and dimensions of known or suspected flow blockages, and the forces acting on the blockages;
- Surface expressions of underground workings such as structure failure subsidence and slope collapses;
- Potential for liquefaction of soils near mine openings or comprising blockages; and
- Slope stability: physical, mechanical, and seismic properties (for possible naturally occurring slope failure or failure as a result of drilling and/or construction equipment).

Hydrogeologic Attributes

Hydrogeologic attributes evaluated as a common best practice in assessing MIW pooling risks include, but are not limited to (BOR 2008, EPA 2000, EPA 2003, EPA 2015f, USFS 2006):

- Types and nature of hydrogeologic units (unconsolidated deposits, bedrock);
- Hydraulic properties of hydrogeologic units (hydraulic conductivity, transmissivity, storability, porosity, dispersity);
- Thickness and areal extent of hydrogeologic units;
- Type of porosity (primary, such as intergranular pore space in unconsolidated deposits or porous bedrock matrices; or secondary, such as bedrock discontinuities, fractures, or solution cavities);
- Groundwater flow through faults, joint fractures, mineral veins;
- Presence or absence of confining or semi-confining lithologic units;
- Depth to water table and seasonal variation, thickness of vadose zone, potentiometric surface, and confined, unconfined, or leaky confined conditions;
- Groundwater flow directions (hydraulic gradients, both horizontal and vertical), volumes (specific discharge), rate (average linear velocity);
- Catchment area and groundwater recharge zones;

- Groundwater/surface water interactions, areas of groundwater discharge to surface water (gaining), and surface water recharge of groundwater (losing); and
- Seasonal variations in groundwater conditions.

Hydrologic and Hydraulic Attributes

Hydrologic and hydraulic attributes evaluated as a common best practice in assessing MIW pooling risks include, but are not limited to (BOR 2008, EPA 2000, EPA 2003, EPA 2015f, Triad Engineering, Inc. 2013, USFS 2006):

- Site topography, watersheds, drainage basins, and associated natural surface water bodies; including lakes, ponds, rivers, active and temporal streams, and constructed drainage systems.
- Surface and subsurface man-made impounded water bodies;
- Workings inflow – groundwater/surface water inflow rate, including precipitation and infiltration;
- Workings outflow – MIW outflow, discharge rates, seasonal variations (maximum and minimum);
- Location, nature, and condition of MIW management systems in workings such as bulkheads (including type, material and thickness), pressure grouting, coffer dams, discharge piping, floor channels, and sumps;
- Confirmation that no MIW pooling is present, where initial evidence indicates no pooling;
- Direction and rate of MIW flow through workings;
- MIW discharge locations, flow and receiving surface water bodies or infrastructure, including potential downstream receptors that may be impacted by a release (for emergency planning);
- Pressure conditions of MIW within mine workings (confined, unconfined, or leaky confined) such as pool elevation, hydraulic head, and hydrostatic pressure;
- Presence of springs or seeps (aerial photography of vegetative growth can be an indicator);
- Climatic conditions as related to precipitation, snow melt, evaporation, infiltration and runoff;
- Vegetative cover and seasonal transpiration rates; and
- Hydraulic interconnections with other mines.

Geochemical Attributes

Geochemical attributes evaluated as a common best practice when completing assessments of MIW pooling risks include, but are not limited to (BOR 2008, EPA 2000, EPA 2003, EPA 2015f, USFS 2006):

- MIW geochemistry data such as physical and chemical water quality data in oxygenated and reduced conditions, anion/cation chemistry, bioassay;
- Background water quality data from other mine seeps and springs for comparison with MIW, and to conduct anion/cation chemistry, if necessary for geochemical modeling/charge balance;
- Geochemical material characteristics that contribute to MIW water quality;
- Baseline characterization of water quality, sediment quality, and macroinvertebrates population metrics of downstream water bodies for comparison if a release occurs;
- Location of MIW acidification/neutralization sources within the mine such as high sulfide areas, ore piles, chemically oxidized zones, or exposed mineralized material;
- Location and types of potential MIW monitoring points such as monitoring wells, weirs, boreholes, and ventilation raises;
- Location and type of existing MIW monitoring devices such as pressure gauges, transducers, and sondes;
- Isotopic MIW analysis may provide information on MIW residence time to indicate groundwater recharge (longer) or precipitation infiltration (shorter);
- Anticipated effects of MIW chemistry on downstream receptors for consequence analysis;
- Existence of MIW containment and treatment systems such as run-on/runoff control, ponds, biotreatment, and water treatment plants;

- Chemical and physical characteristics of natural water bodies upgradient of MIW discharge points;
- Presence, nature, and extent of sedimentation within workings; and
- Presence and type of biological activity within workings such as algae, bacteria, molds, or mosses.

Many AML sites lack adequate monitoring data to characterize these attributes; therefore, a best practice for mining sites with discharging MIW is to institute a regular monitoring program and review the resulting data for a year or more to understand seasonal fluctuations. MIW pool monitoring may require conducting invasive activities (for example, drilling wells into the mine workings) that could trigger a blowout. Conducting invasive activities is described in Section 4.2.3.

4.2.1 Develop an Initial Water Balance

Developing a water balance (sometimes referred to as a water budget) supports the determination of whether MIW pooling is occurring and helps define mine pooling characteristics that aid in assessing the potential and likelihood of MIW release. The primary purpose of an initial water balance is to estimate whether there is a net gain or loss of water entering into and discharging from mine workings, and not to determine the specific, steady state quantity of water. Therefore, its use is limited, but helpful, in determining whether MIW pooling is occurring and whether it is more likely to occur during certain times of the year.

The following equation summarizes the basic elements of an initial water balance:

$$S = I - O$$

Where: S = Storage Rate (Volume/Time); I = Inflow Rate (Volume/Time); and O = Outflow Rate (Volume/Time)

To initiate the evaluation, determine the potential pooled MIW volume of the mine based on current knowledge of the mine workings. Next, calculate the percentage of that pooled MIW volume that would be filled at the estimated daily storage rate since the MIW started to accumulate, assuming a constant storage rate. Finally, determine whether the calculated stored water volume is reasonable given the available pooled MIW volume of workings and losses, such as potential seep areas.

When “S” is a positive number, a mine receives more inflow than it discharges as outflow, and MIW is likely accumulating in the mine workings. If “S” is a negative number, then the outflows exceed the inflows and the works are likely draining faster than MIW is accumulating. If the “time” measure is constant (such as days or years), then the storage, inflow, and outflow are simply the total volume for the time period.

Table 2 presents a simplified example of an initial water balance showing an increase in pooled MIW volume per day (indicating potential MIW pooling exists).

Table 2: Example Initial Water Balance

Origin	Description	Inflow (GPD)	Outflow (GPD)
Groundwater	Infiltration into workings	150,000	20,000
	Drainage from connected workings	80,000	
Surface Water	Precipitation infiltration	90,000	
	Intermittent stream entering Portal B	50,000	
Discharge	Collapsed Adit A		120,000
	Seep B		25,000
Air	Evaporation/Transpiration		50,000
Subtotal		**+370,000**	**-215,000**
Estimated Water Balance		**+155,000 GPD**	

GPD = Gallons Per Day

In developing a water balance, consider water level and discharge rate response to precipitation events or snow melt. Recharge rates and lag times factor strongly into the hydrology of the mine workings. Substantial mine water elevation increases in response to recharge events need to be accounted for in terms of commensurate increases in discharge and hydrostatic pressures on blockages or bulkheads.

The USGS has prepared many water balances for estimating water budgets in coal mine regions. An example of a regional water budget is *Water Budgets and Groundwater Volumes for Abandoned Underground Mines in the Western Middle Anthracite Coalfield, Schuylkill, Columbia and Northumberland Counties, Pennsylvania – Estimates with Identification of Data Needs. USGS Report 2010-5261* (USGS 2011c). An example water balance for a specific mine tunnel is the *Water Balance for the Jeddo Tunnel Basin, Luzerne County, Pennsylvania* (Ballaron 1999).

4.2.2 Conduct Additional Site Visits

After reviewing available site information, the technical team may benefit from one or more additional site visits to address any remaining data gaps, or to support planning of additional field data collection efforts to support the CSM and MIW pooling risk assessment. Examples of activities that might be conducted during follow-up site visits are listed below.

1. Determining how adit flow monitoring should be conducted through modifications to a current monitoring program (considering how measurements were taken previously) or through new program development.
2. Collecting samples and measurements from boreholes, shafts, vents, or other surface openings to assess potential for surface water inflows.
3. Monitoring springs and seeps around the site to provide supplemental data on the physical and chemical parameters of outflows.
4. Verifying specific information on site conditions noted in prior site studies, and identifying any changes to those conditions.
5. Identifying changes in potential downstream receptors and impacts for use in contingency, notifications and emergency action planning, as well as any environmental or safety issues not previously identified.
6. Conducting geophysical studies to evaluate stability of materials for conducting invasive activities.
7. Assessing locations and conditions for conducting invasive measurement activities.
8. Identifying areas that can be used for mine dewatering or for emergency storage/solids settling for contingent storage capacity planning.
9. Employing unmanned aerial vehicles (UAV) equipped with light imaging, detection and radar (LIDAR) or other imaging tools to improve terrain modeling by identifying or clarifying the extent of past surface disturbance and mine opening locations.

4.2.3 Conduct Minimally Invasive Measurements

Based on the state of site knowledge, it may be beneficial or necessary to collect minimally invasive measurements to better characterize site conditions related to MIW pooling and discharge. The purpose of minimally invasive measurements is to collect data from existing, accessible locations using field methods which pose no risk of causing an MIW blowout. Findings of minimally invasive measurements that show no or minimal MIW risks, may reduce the need to perform (or the scope of) an FMEA. Minimally invasive measurements may include activities such as surface water sampling, use of existing access points for groundwater or mine pool sample collection, and remote technological measurement such as electromagnetics and radar.

Any monitoring or water quality sampling activities need to follow EPA or appropriate guidance to ensure proper sample collection, handling, and analysis, including: development of a sampling and analysis plan (SAP); a quality assurance project plan (QAPP); a health and safety plan (HASP); and a field sampling plan (FSP), if necessary (EPA 2006). Contingency, notifications, and emergency action planning is discussed in more detail in Section 4.2.6.

Provided workings can be accessed safely, samples and data should generally be collected from open shafts, boreholes, and other openings identified to the mine workings, using downhole measurement technologies and sampling techniques that produce useful and valid results. Consistent methods and techniques should be used so that each new set of results can be compared with prior results to support trend and pattern analysis of MIW characteristics. Both proven and emerging technologies for open subsurface and downhole sampling through existing boreholes and monitoring wells should be considered. Exhibit 4 provides examples of parameters that should generally be considered when conducting minimally invasive measurement and sampling of an MIW pool.

The depth of a mine pool and the elevation of the groundwater potentiometric surface are significant data points to determine the hydrostatic state and quantity of pooled MIW. Physical and chemical parameters (such as turbidity, pH, specific conductance, total dissolved solids, dissolved oxygen, and oxidation/reduction potential) can also be important to compare to measurements from other locations where MIW is discharged, to help determine whether mine pools are connected (SME 2014). However, caution should be exercised when comparing physical and chemical water parameters since these parameters may vary significantly, even within connected mine pools. In some cases, water quality can vary spatially, both horizontally and vertically, over short distances within a single mine pool.

Measurements of MIW discharge flow from mine openings, seeps, springs and other discharge points are important for determining current MIW pooling conditions. When compared with past measurements, these data may indicate and help confirm changes in MIW pooling over time. MIW discharges are often found on hillsides, in gullies, existing streams or discharging through unstable substrates; which in certain circumstances can make installation of calibrated gages with permanent weirs or flumes impracticable. Where weirs and flumes (or other more accurate means of flow measurement) are installed, past measurement techniques should be compared with the current approaches so that new data can be compared and calibrated with past flow measurements.

Best practices for conducting flow measurement of discharge from mine openings, seeps or other locations are provided in EPA's *Quality Flow Measurements at Mine Sites* guidebook (EPA 2001). While the technologies for conducting these measurements have evolved since 2001, the general principles for using such technologies remain a best practice. USGS has also developed best practices in measuring stream flow, which while primarily for measuring flow in streams and other natural water bodies, can be applied in measuring MIW discharge in ditches and culverts (Buchanan and Somers 1969, USGS 1982a, USGS 1982b).

Exhibit 4
Examples of Minimally Invasive Measurements through Open Bore Holes or Existing Mine Openings

- Mine pool depth
  - Useful for determining pool volume and seasonal variability
- Mine pool hydraulic head
  - Useful for determining hydrostatic pressure of the mine pool
- Measures of MIW discharge flow rates
  - Useful for determining the rate of outflow of MIW
- MIW discharge chemical/physical parameters
  - Useful in determining permanence of pool seasonally and indicators of ore zones and blockage material characteristics

Source: EPA 2003, EPA 2013

Geophysical Studies

Geophysical surveys can be performed on land, on water, from the air, and within boreholes. The use of geophysics to survey underground MIW pooling can be limited by highly mineralized soils, extensive tree cover, and accessibility, but certain techniques may be important to identify buried mine openings, near-surface mine workings, and optimal drilling locations. Geophysical tools may be of limited utility in highly metals-mineralized areas and where access is limited or steeply sloped, or by the inherent capabilities and limitations of the geophysical method.

Underground mine workings have been mapped from the surface using multi-phase surface and cross-borehole geophysical techniques. For example, time-domain dipole-dipole resistivity and frequency domain Mise-a-la-Masse (MALM) surveys were conducted at the Captain Jack Mill mine site located near Ward, Colorado. Using a flooded mine adit as a transmitting electrode, the MALM survey technique was able to image the mine workings' approximate position up to 2,000 feet into the mountainside, at depths of up to 500 feet (Pendrigh 2012). The effectiveness of using mine workings as electrical transmitters may depend on the presence and seasonal variations in MIW levels. Given optimal seasonal conditions and continuity of infrastructure features (for example, rails) and water, the MALM in-tunnel electrode techniques can be used to estimate the extent of MIW pooling (Pendrigh 2012).

Some downhole geophysical survey techniques such as borehole radar surveys or cross-hole seismic tomography require the existence, or drilling, of one or more boreholes to install the subsurface transmitters and receivers necessary to map the location of subsurface voids, such as mine workings. Such techniques may be of limited value in locating underground workings because of the cost of drilling through rock and other limitations, but may have some use in finding underground workings when boreholes miss their targeted mine tunnel (CSoM 2007).

The U.S. Department of Transportation (DOT) FHWA has implemented more recent research and identified best practices for assessing underground abandoned mine tunnels, voids, and sinkholes. FHWA maintains an Interstate Technical Group on Abandoned Underground Mines, which is responsible for developing methods to identify and prevent collapses of underground mines beneath transportation facilities (FHWA 2016). FHWA actively researches emerging geophysical methods to detect abandoned mines and other subsurface voids in karst bedrock (which may be at risk of collapsing and forming sinkholes). Exhibit 5 identifies common geophysical methods that FHWA uses to identify abandoned mines and underground voids as part of transportation planning.

Exhibit 5
Common Geophysical Methods

- Gravity/Microgravity*
- Electromagnetics (EM)
- Radio Detection
- Magnetics
- Very Low Frequency EM (VLF)
- Ground Penetrating Radar (GPR)
- Electrical Resistivity Imaging (ERI)
- ER Hydraulic Tomography
- Induced Polarization (IP)
- Spontaneous Potential (SP)
- Liner Leak Detection (LLD)
- Seismic Refraction/Reflection/Cross-Hole Tomography
- Surface Wave Methods
- Side-Scan Sonar

*Underlined methods represent commonly used methods for underground mine detection.

Source: Davis 2015

The U.S. Department of Energy (DOE) has evaluated the use of helicopter electromagnetic (HEM) surveys to detect and map pools of acidic water impounded in underground mines. HEM can locate pools of water in underground mines if: (1) the water is conductive (acid mine drainage is conductive); (2) the overburden is electrically resistive; and (3) the depth to the workings is not more than 150 feet (Hammack et al. 2007, Hammack 2016, Love et al. 2005).

The USGS has conducted a wide range of studies assessing the viability of various geophysical tools to evaluate MIW pooling. USGS maintains a Geophysical Technology Transfer clearinghouse with information on traditional and emerging geophysical technologies and their applications (see http://water.usgs.gov/ogw/bgas/g2t.html). EPA conducted some of the early work on using geophysics to detect abandoned mines [see *Detection of Abandoned Underground Coal Mines by Geophysical Methods* (EPA 1971)].

Other Minimally Invasive Measurement Methods

Various tools and technologies used for mine exploration and management can be adapted to make measurements and gather data to assess MIW pooling. Some of the measuring and monitoring devices described in this section require an existing borehole, monitoring well, or other direct, unobstructed access to the mine workings. Long-term use of downhole monitoring tools is possible in acidic conditions when tool materials are compatible with corrosive water, and regular cleaning, calibration, and data download schedule are maintained. Drilling and coring, which are considered invasive activities that could cause a sudden, uncontrolled MIW release, are discussed in Section 4.2.4.

A summary of other minimally invasive measurement techniques and technologies, with descriptions of possible uses is provided below:

- **Tracer Techniques:** Tracer testing of MIW in mine workings can help assess MIW pooling. Several types of materials can be used as tracers, but the most common are optical (fluorescent) dyes and chemical (ionic) tracers. Tracer studies may be used to further characterize known or suspected mine pools, or to characterize hydraulic connections between adits and mine pools (for example, flow rates and flow paths through workings, discharge points, connections between mine pools, inflow points and interconnections between different mine workings). Tracer studies have been performed with various degrees of success in flooded mine workings. For example, a dye-tracer study was performed at the Leadville, Colorado site with only limited success. Therefore, it is important to adequately plan the tracer studies. Consideration should be given to anticipating possible or unlikely flow paths; time ranges for travel; the ability to detect the tracer in target water; researching possible tracer interferences; and the need for quantitative tracer detection or simply a positive/negative response. Potential problems with tracer tests include degradation of dye in mining water conditions, false negative results, and misinterpretation of positive results (OSMRE 2013a). Adsorption of the tracer by clays, iron hydroxide, and organic materials; pH interferences; and matrix interference can prevent detection of optical tracers, which can produce false negative results. For this reason, chemical or ionic tracers are recommended for degraded water. Existing background concentration of the tracer (ionic) can produce false positive results. Any tracer has to be introduced at a concentration that will be clearly detectable at the anticipated outfall. Therefore, some level of mine pool volume calculation (for example, dilution ratio) needs to be performed before a tracer can be introduced. Additionally, baseline samples need to be analyzed for the tracer at the target location prior to the running the test.

- **3-Dimensional Mapping:** A number of firms offer technologies that use laser scanning technologies to generate detailed 3-dimensional underground mine workings maps. Some of these technologies are deployable down boreholes, while others require deployment within workings. Each use laser scanning to safely and quickly scan inaccessible underground workings. Associated software typically provides modeling, manipulation, and export capabilities, including data on the size of workings, collapse locations, water levels, and accurate volume and distance measurements. Because laser measurements can be made only within the line-of-sight, mine workings with numerous directional shifts or blockages might be difficult to survey fully or effectively using this approach. Another potential limitation is that the majority of the 3-D mapping equipment is intended for unflooded mine workings. A flooded mine may reduce the effectiveness of this type of data collection. While subaqueous 3-D equipment is available, the quality of the data can be degraded by the lack water clarity.

- **Downhole Video:** Small gauge video cameras lowered down boreholes to provide visual information about the mine workings and mine pooling can be an effective way to confirm MIW pooling presence and depth. Visual evidence of precipitate water marks on the walls and roofs of mine workings can also provide evidence of seasonal or known historical events-based variation in mine pool water levels. Limited light can reduce downhole video effectiveness since camera lighting reduces with distance, particularly under water.

- **Physical or Visual Measurement:** If the blockage that creates mine pooling is accessible or visible from within the mine workings, direct measurements of the open portion of the mine tunnel and of the blockage can provide confirmation of the blockage location and useful data on its dimensions and the material properties of the exposed rock debris.

- **Downhole Pressure Transducers:** Submersible pressure transducers have been used in groundwater investigations for more than 4 decades. These pressure-sensing devices, typically installed at a fixed depth in a well, sense the change in pressure against a membrane. Pressure changes occur in response to changes in the height, and thus in the weight of the water column in the well above the transducer. Substantial improvements in design, operation, and accuracy of pressure transducers and data recording systems have led to a significant increase in their use in recent years. Many are equipped with temperature sensors, which can provide valuable data about surface infiltration (such as snow melt). Small-scale, battery-powered transducer technologies can be deployed to capture data for months and require only a USB data storage key to download data.

- **Downhole Flow Meters:** There are three main types of borehole flowmeters: impeller (also known as a spinner flow meter); heat pulse (HP) and electromagnetic (EM). Impeller and electromagnetic types of flow meters can be used in either trolling (moving vertically up or down the well bore) or in stationary mode. The heat pulse flow meter can only be used in stationary mode. In trolling, the flow meter is advanced up or down the borehole at a constant speed while measurements are made. In stationary mode, the flow meter is stopped at a series of depths within the borehole and measurements are made while the device is stationary. The impeller flow meters cannot resolve flow rates as low as the EM and HP types. All flow meters require boreholes or cased wells that fully penetrate the target horizon of the flow system of interest. Doppler flow meters can also be used, but require particulates or bubbles in the water to be effective. More information is available at http://water.usgs.gov/ogw/bgas/flowmeter/.

Note: Before any electrical equipment is deployed into mine workings, determine whether the equipment complies with intrinsic safety requirements and whether the mine workings atmosphere contains any combustible or explosive levels of gases or materials.

4.2.4 Conduct Invasive Measurement Activities: Drilling

Before remedial response actions can be undertaken at mine sites, it is a best practice to confirm the hydrostatic conditions of known or suspected MIW pooling in the underground workings. In the absence of other confirming data, the inaccessibility of pooled MIW in underground workings typically requires collection of hydrostatic conditions data using invasive measurements technologies. The primary approach to conducting invasive measurement is by drilling from the ground surface either above, horizontally, or from an intermediate lateral location into targeted sections of mine workings, followed by deploying downhole measurement technologies through the drilled boreholes. This section provides information on commonly used drilling methods to consider.

Drilling is conducted to: (1) confirm the presence, depth, and hydraulic head of MIW pooling; (2) determine water quality and flow characteristics; and (3) confirm the location of blockages and extent of pooling. These data can be used to determine the water levels; the hydraulic head pressure; whether MIW pooling is under atmospheric or confining conditions; and if confined, to what degree. As applicable, boreholes may also be used as access points to pump MIW out of the mine under subsequent mitigation measures.

When planning a drilling program for MIW assessment, it is critical to carefully plan drilling locations and directions because underground mine workings generally are limited in width. Careful surveying and an understanding of the local structural geology and lithology enhance the likelihood that drilling will intersect the target workings. Driller experience and knowledge of local geology and drilling conditions also increase the likelihood of intersecting the target workings. Notwithstanding recommendations for release prevention, the borehole should generally be sized for planned and possible future uses such as insertion of exploratory tooling, water sampling, or installing a pump for dewatering.

As drilling is an invasive activity, it is critical that an FMEA be performed before drilling plans are completed and field mobilization. The FMEA should generally evaluate the drilling plan for each borehole location for the potential to result in a sudden, uncontrolled release of MIW. FMEA results should be provided to responsible personnel in each organization that will be involved in drilling activities to ensure each of the organizations is fully aware of risks and consequences identified, and work collaboratively to develop and implement plans to mitigate and manage those risks. Exhibit 6 provides examples of failure modes from drilling that may cause blowouts of MIW pooling.

Exhibit 6

Examples of Drilling-Related Failure Modes for Possible Blowouts of MIW Pooling

- Drilling vibration liquefying soil or other material workings blockages
- Collapses or cave-ins within workings
- Artesian releases through drilled boreholes
- Failure of soil or rock material under drilling equipment
- Piping of pressurized water around drill steel/augers in unconsolidated material
- Rapid hydraulic head pressure changes

The drilling approach will vary by site and a combination of drilling techniques may be required to characterize the mine workings. Many small drill rigs can now be deployed on tracks and adjustable platforms to work on the side of steep slopes. Drilling is most commonly performed via traditional auger drilling, sonic (vibratory), percussive action, or air and hydraulic rotary methods. Common drilling methods for hardrock mineral exploration, AML investigations, or mine workings studies include:

- **Hollow Stem Auger (HSA) Drilling:** HSA drilling is fast, especially in shallow applications, in soft unconsolidated material, or in weak weathered bedrock. HSA is effective for collecting samples to characterizing overburden, waste rock, and tailings at mine sites. A conventional and cost-effective drilling method, HSA uses a hollow stem auger to penetrate the subsurface. As the auger rotates, cuttings are conveyed to the surface via auger flights. Grab samples can be obtained from cuttings or sampling tools deployed inside the hollow augers. The large openings allow access to the bottom of the borehole after the pilot bit is removed without withdrawing the auger drill string. The auger acts as a temporary casing during drilling to facilitate sampling soils and unconsolidated material and installing monitoring wells.

- **Sonic (Vibration) Drilling:** This method uses varying high frequency vibrations through the drill string to the bit or core barrel to match site geology or harmonic frequency of the drill string. Sonic provides relatively easy and fast drilling through most formations. Sonic drilling is more cost effective for rock drilling. It can produce high quality rock cores and provides very straight borings. Sonic drill rigs are available in small, track-mounted designs that can be used to drill on slopes and in difficult access areas where conventional drill rig size and weight might preclude their use.

- **Percussion Rotary Air Blast (RAB) Drilling:** RAB is commonly used for mineral exploration, water bore drilling, and blast-hole drilling in mines. RAB provides fairly rapid advancement, but produces poor bedrock sample material and can be limiting if groundwater is encountered because cuttings will clog the outside of the hole with debris. RAB employs downhole technology, which is basically a mini-hammer that screws on the bottom of a drill string and crushes hard rock into small flakes, with the resulting dust drawn by the air exhaust to the surface.

- **Reverse Circulation (RC) Drilling:** RC drilling uses a pneumatic reciprocating piston called the "hammer" which drives a tungsten-steel drill bit. RC drilling typically requires larger rigs and, therefore, may be less versatile in remote or steep areas. RC drilling can achieve depths of more than 1,500 feet. RC drilling produces dry rock pieces and dust, as large air compressors dry the rock out ahead of the advancing drill bit. RC drilling is slower and costlier than RAB. However, it is less expensive than diamond coring and is thus preferred for most mineral exploration work.

- **Diamond Core Drilling:** This technology uses a circular, diamond-fitted drill bit attached to a hollow core cylinder to produce solid rock cores. Water is used for cooling and removing cuttings instead of air. It is slower and more expensive than RAB or RC drilling, but can be advanced to greater depths and provide additional information about the subsurface rock formations (for example, dip/strike, porosity, and degree and orientation of fracturing), which are useful data for characterizing the sources of MIW pooling. Rock strength testing on the recovered core provides data on the geotechnical characteristics of mine roof when the mine workings are intersected.

- **Hydraulic Rotary Drilling:** This method is commonly used in the mining industry to drill blast holes in open pit mine and surface mines. It is used in the oil and gas industry because no continuous sample is returned or needed. The technology can use a variety of drill bit types (for example, diamond-impregnated, carbide, or tri-cone roller) and uses mud/bentonite to cool and clean the bit and capture cuttings. The technology can be advanced to depths exceeding 1 mile.

- **Air Rotary Drilling:** This method is used to drill deep boreholes in rock formations. It is used for drilling in igneous, metamorphic, and sedimentary rock. The mining industry uses rotary drilling to drill ore body test boreholes and pilot boreholes for guiding larger shaft borings. The rotary drilling method requires the use of a rock cutting or crushing drill bit, typically a mill tooth tri-cone roller cone bit. This type of drill bit uses more of a crushing action to advance the bit in the rock. Impact energy is supplied to the drill bit from either an aboveground impact or a downhole impact hammer.

Decisions about drilling technologies should consider drilling program goals, access, rock type, joints and faults, dip of strata, surface slope stability, and factors such as drill rig capability, cost per foot, and availability and experience of driller. Slope, ground stability, and physical accessibility commonly limit the size and type of the drill rig that can be deployed. These issues may also prevent vertical drilling from directly over the mine workings. Under these circumstances, other drilling methods such as horizontal or directional drilling can be considered.

Directional drilling controls the direction and deviation of a wellbore from the point of surface entry to a predetermined underground target or location. This technology may be used when a suitable drilling location is not accessible directly above the desired mine workings. Directional drilling is commonly used in the oil and gas industry and involves gradual redirection of the borehole, frequently requiring hundreds of feet to perform a turn. Its use in drilling to access mine workings, however, is not common and may be limited when workings are within approximately 100 feet of the surface. Directional drilling should not be confused with Horizontal Directional Drilling (HDD), or angular drilling, which is a steerable, trenchless method of installing underground pipe, conduit, or cable in a shallow arc along a prescribed bore path through soils (not rock).

Similarly, HDD should not be confused with simple horizontal drilling, the method of drilling horizontally from one within one mine working to another or drilling horizontally from the surface into mine workings. Horizontal drilling can be an effective method of drilling from one working to another when there is adequate space within a nearby working to deploy a drill rig or rock drill. Directional drilling is completed from the surface at a direction other than vertical. Early applications of horizontal drilling included exploration and workings ventilation.

Directional control of some drilling technologies can be less accurate in complex geological settings. A drill bit can be deflected in unpredictable directions by changes in geologic properties, potentially causing the drill string to miss the target mine workings. (EPA 2003, ASTM 2014).

Originally developed to support environmental investigation drilling and sampling, direct push technology (DPT) is a drilling method that can be used to conduct a wide variety of invasive measurements activities, including sonic drilling and coring of bedrock.

Prevention of MIW Releases when Drilling into Mine Pools

Mine pools in mine workings may have a hydraulic head pressure that is capable of producing a direct pressurized release within a horizontal boring into flooded workings; or an artesian rise within the drill tooling when workings that are under confined conditions are intercepted. In these cases, significant groundwater may not be detected until the mine workings void is encountered, at which point the water will either directly release from a horizontal boring or rise up into a vertical boring to the potentiometric water level of the mine pool. To prevent MIW releases during drilling, the following precautions should generally be undertaken: (1) use small-diameter borehole bits and drill rods; (2) drill into workings through competent rock; and (3) use blowout preventer technologies.

A variety of equipment is used during drilling to control pressure from fluids encountered during drilling. Most of the equipment is routinely used in the oil/gas and geothermal industries to prevent "blow outs" from gases, oil, or pressurized water while drilling. These types of equipment can be used during mine sites drilling to reduce the possibility of encountering a pressurized mine pool; their use has been demonstrated to reduce the threat of a sudden release up the well bore. The apparatus that controls outflow at the wellhead is called the blowout preventer (BOP) or blowout prevention equipment (BOPE). The BOP stack comprises five types of devices to shut off the wellbore and prevent fluid flow out of it: rotating heads, annular preventers, pipe rams, blind rams, and shear rams. The basic function of each is to prevent artesian pressurized water from escaping a newly drilled borehole (DOE 2010).

States establish blowout prevention guidance for oil/gas and geothermal wells. A best practices is to consult with the state office regulating oil/gas or geothermal drilling, as well as drilling services companies, to discuss the specific blowout equipment that can be used during drilling into potentially pressurized mine pools.

4.2.5 Conduct Failure Modes and Effects Analysis

An FMEA identifies potential failure modes, triggering events, likelihood of occurrence, severity of consequences, and receptors associated with an MIW blowout. Mitigation measures are identified to manage risk of failure and impacts by reducing the likelihood of occurrence or the severity of the consequence or both. The scope of the FMEA is defined by an FMEA team and includes delineating the primary purposes, establishing the scope of the evaluation, and establishing the level of detail for review — for example, a site-wide, a specific plan, or a specific plan component or task to be performed. Examples of FMEA scope include review of contingency, notifications and emergency action plans, and planned activities for constructing a flow-through bulkhead; in situ MIW treatment; and advancing or rehabilitating underground entries.

An FMEA is typically conducted to identify where and how a planned action might fail and to assess the relative impact of different failures, such as drilling into mine workings or opening a blocked adit portal. An FMEA may also be conducted to evaluate the failure mode and effects of natural events or conditions that may lead to a failure event, such as flooding or seismic activity. Unexpected failure modes may also include anthropogenic activities such as road construction, well drilling, or human error.

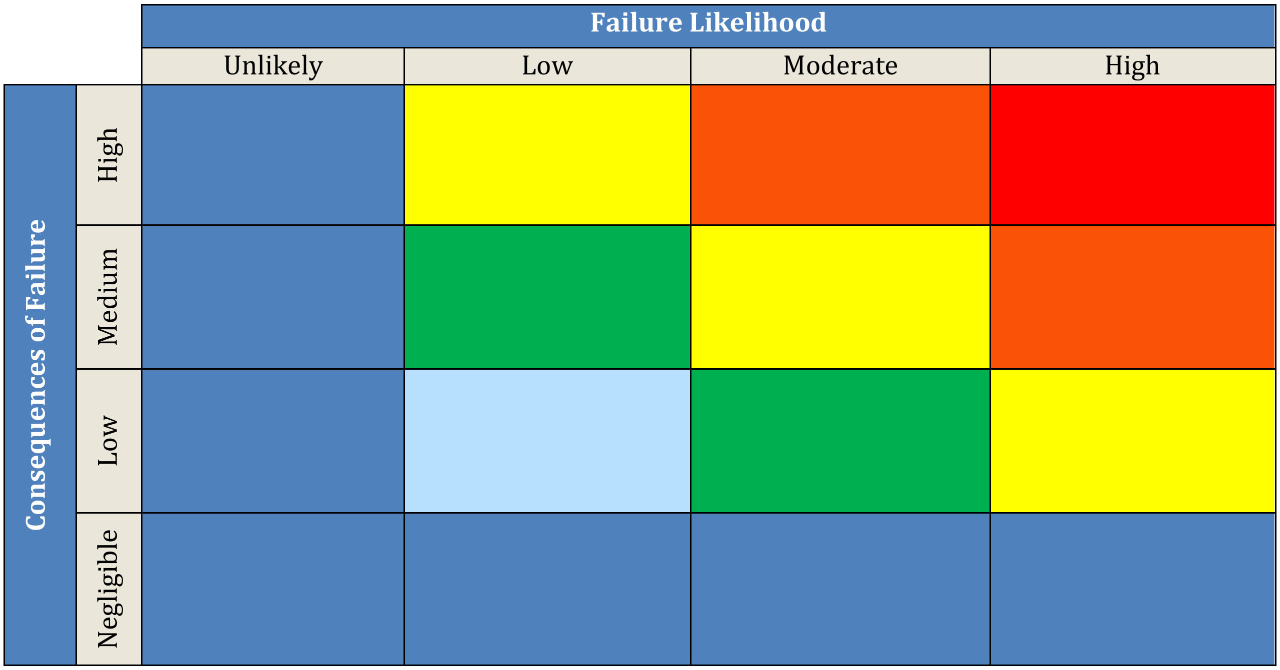
To conduct an FMEA, a multi-discipline team is assembled with diverse knowledge of mining and civil engineering; mine geochemistry; environmental site investigation and remediation; geology, hydrogeology, and mine site construction and remediation; MIW control, capture, and treatment; emergency action planning and response; general mine site safety; and other expertise as relevant to the site activity to be evaluated. For complex site conditions or planned activities, it is a best practice to have the FMEA developed using a facilitator who leads the multi-disciplined team in evaluating the mine structures, hydrogeology, and MIW pooling conditions (BOR 2008).

A worksheet is used to guide and document the FMEA and typically contains:

- Identifying and numbering of task and components;
- Identifying potential modes of failure;
- Identifying triggering events;
- Identifying potential failure consequences and assigning a severity rating from negligible to high. The consequences of failure can be economic (such as property damage), environmental (such as erosion and entrainment of waste rock or tailings; impacts to aquatic life), or health-related (such as drinking water impacts or even loss of life). They range from no significant economic impact at the low end of the spectrum to loss of life at the high end of the spectrum (BOR 2008);
- Identifying the likelihood of failure and assigning a rating from unlikely to high;
- Assessing the confidence in the risk analysis as low, medium, or high. The confidence level of the failure risk analysis can indicate whether additional evaluation is needed to predict both the risk and mitigation measures to reduce risk. For instance, a low confidence level for a high-risk site indicates that additional evaluation is needed; and
- Identifying mitigation measures, including additional site investigation, water quality testing, plan revisions, or remedy design changes. The effectiveness of the mitigations can be assessed by performing another FMEA (or updating the FMEA) using new data derived from these activities to see if the severity of consequence has been reduced, the likelihood of occurrence has lessened, and the confidence level in the risk analysis has increased.

FMEA provides a hierarchy of risks posed by each potential failure mode. A risk matrix is typically used to present the likelihood of failure occurring with the consequences of the failure to identify the highest-priority tasks or components requiring mitigations. Figure 2 provides an example of an FMEA risk categorization matrix, which can be modified for project and stakeholder needs, as warranted.

Figure 2. Example FMEA Risk Categorization Matrix
Source: BOR 2008



		Failure Likelihood			
		Unlikely	Low	Moderate	High
Consequences of Failure	High	🟦	🟨	🟧	🟥
	Medium	🟦	🟩	🟨	🟧
	Low	🟦	◻	🟩	🟨
	Negligible	🟦	🟦	🟦	🟦

The colors indicate the hierarchy of risk as follows:

- Red – Extreme risk
- Orange – High risk
- Yellow – Moderate risk
- Green – Tolerable risk
- Blue – Well within tolerable limits. Risk reduction continues as good operating practice.

Activities that present a high or moderate failure likelihood of an uncontrolled release of MIW should not be undertaken, unless there is certainty that the consequences are negligible or can be controlled through effective contingency measures. Mitigation actions are developed based on level of risk starting with high (red) and working down to unlikely (green or blue). Site-specific conditions should be used to adjust the ranking of risk determinations, because in some cases the severity of consequences may make even a negligible likelihood of consequences unacceptable. Uncertainty will be associated with missing information, measurement inaccuracy, and human error used to assess failure mode risks. An appropriate level of conservatism should generally be applied based on the level of uncertainty for each failure mode analysis.

The FMEA can either be qualitative or quantitative, depending on the FMEA team preference or potential consequences. The methodology described in this report is a qualitative measure of risk to inform the contingency, notification, and emergency action planning. FMEAs that produce a quantitative risk measure are more applicable to infrastructure construction or other construction where activities are more uniform and procedures are able to provide quantifiable outputs. However, quantitative likelihood probabilities and consequence costs may warrant such a quantitative FMEA for potentially high consequence scenarios.

While it is a best practice, FMEA is not the only method of failure, reliability, or dependability risk analysis. Other risk analysis methods include, but are not limited to (1) preliminary hazard analysis and functional failure analysis, which may be effective for identifying possible failure modes; (2) common cause analysis, which allows evaluation of risks posed by multiple, concurrent failure modes; and (3) event tree analysis (ETA), which can be used to identify all sequences including assessing probabilities and consequences of outcomes that follow an initiating event. ETA can also be used to test the failure modes for specific actions or events potentially affecting an MIW pool system (Kaplan, et al. 2005).

4.2.6 Plan for Invasive Measurement Activities: Contingency, Notification, and Emergency Action Planning

Any invasive activity conducted in support of investigation or remediation at a mine site should generally be conducted in accordance with careful contingency, notifications, and emergency action planning. A plan (or plans) is recommended be developed to serve a critical function as the central document for comprehensive contingency, notifications, and emergency action planning for potential major site emergencies. A best practice is to have all other site documents that address related topics defer to and reference the plan (for example, site work plans such as the FSP and the QAPP, remedial designs; technical specifications for construction; monitoring plans, project management plans, and HASPs). Development or modifications to the plan should be directly supported by the results of the FMEA performed to identify and manage risks associated with planned activities. Conditions at the time of the FMEA should be confirmed when conducting contingency and emergency action planning and again when response actions are being initiated. The FMEA process is discussed in Section 4.2.5.

Adaptive management planning principles are a best practice to apply when developing contingency, notification, and emergency action plans. Comprehensive monitoring and data collection help field managers adapt their knowledge of site conditions in an iterative learning process, while enhancing their understanding of the risks. To ensure that adaptive management principles are applied across the project, all site personnel should be familiar with contingency, notification, and emergency action planning materials prior to initiating work.

Contingency Planning

Contingency plans typically focus on the types of emergencies that could occur, potential impacts, and the engineering controls (EC) in place and other actions that should generally be implemented in case of such an emergency. ECs typically address the mitigation of MIW release, abatement of water pollution, erosion protection, and sedimentation control.

While this report identifies some best practices for containing releases, it does not provide an exhaustive treatment of this topic. Contingency planning for invasive activities to be conducted at mine sites are presented below.

- Planning and documenting approaches to mitigate an uncontrolled release of MIW pooling, if present, including:
    - Calculating the maximum potential MIW blowout volume (with a 10 percent margin of safety, or more if uncertainty is high);
    - Evaluating the current site infrastructure’s ability to contain and treat the maximum potential MIW blowout volume;
    - Considering safeguards to implement should a blowout occur (for example, geotextiles, channelization, or other stability safeguards);
    - Evaluating the suitability of the site’s footprint and topography for increasing containment capacity; and
    - Recommending solutions for containment capacity increases (for example, expansion of existing containment ponds or augmenting storage through the temporary use of large, portable bladder bags or permanent storage tanks to provide the site with capacity in excess of the maximum potential release volume).
- Planning and documenting contingencies to control and mitigate minor uncontrolled releases of MIW that do not pose significant risk to human health or the environment.

- Monitoring changes in MIW discharge rates and water quality at the site and at receiving water bodies before, during, and after actions.
- Using the FMEA to mitigate risk and as the basis for developing instructions related to contingencies and emergency action requirements and procedures.
- Providing a list of training or qualifications needed or required for personnel responsible for leading and supporting notifications and emergency action efforts.

Notifications

It is a best practice to develop a comprehensive notification plan during activities at a mine site with known or potential MIW blowout risks. Notifications vary depending on the type of emergency at the site. It is critical that notification planning for blowouts include notifications of downstream receptors, including names and contact information. Site personnel should be familiar with the notifications plans and procedures and have reliable telecommunications capabilities to support immediate notifications (for example, satellite phones in remote areas without cell phone coverage).

Emergency Action Planning

Emergency action plans for mine sites may include, but are not limited to the following content.

- Specification of emergency actions to be performed in the event of a blowout, including responsible personnel, resources, and equipment needed to perform the emergency actions.
- Use and regular update of existing maps, or development of new maps, that depict site roads, features, infrastructure, and areas of sensitive and hazardous or dangerous environments; including, but not limited to, protected areas, erosion controls and steep, heavily forested topography.
- Procedures for storing caustic or acidic treatment chemicals, such as those used for making pH adjustments.
- Inspection forms, plan views and associated details, including corrective and maintenance action procedures, for pertinent features such as detention ponds.
- Procedures to (1) ensure that off-site first responders tour a site before high-risk work is started to increase their preparedness to respond in the event of a serious incident; and (2) provide them advance notice of such high-risk work activities.
- A list of internal experts or services vendors for specialty technologies to be used for high-risk activities, and notification procedures to ensure that such vendors are on call or on site (as applicable) to assist with their technologies during such high-risk activities.

4.2.7 Use Monitoring Well Data to Determine Mine Pool Elevation

When direct measurement of mine pooling is necessary, borings, monitoring wells, or other surface openings to mine workings can be used to measure water levels. EPA’s Superfund program has conducted many groundwater studies and developed procedures to measure water levels within boreholes and wells. Such procedures are closely related to establishing mine pool water levels under atmospheric pressure conditions. When a bedrock aquifer is hydraulically interconnected with the mine workings, the water level in a static (little to no flow) mine pool under atmospheric pressure conditions will equilibrate with the surrounding groundwater level under unconfined conditions. Collecting water level measurements from nearby wells or boreholes can help to define mine pool water levels for workings known to be in equilibrium with groundwater. However, the mine tunnel system may not be in equilibrium with water encountered in a fracture zone with fracture flow conditions that are typical at hardrock mine sites. Water in the mine pool or in the fractures may be confined and under pressure. These situations require additional caution, and direct measurements of the potentiometric surface (or hydraulic pressure or head) will add to an understanding of the degree of MIW pooling present.

Water levels can be directly measured by drilling into the mine workings and collecting data on the MIW pool conditions. An FMEA provides input for the contingency, notification, and emergency action plans, including contingency measures for invasive activities such as drilling into mine workings. An FMEA process will reduce the chances of a sudden, uncontrolled release during drilling with careful planning. An example best practice for measuring groundwater levels in existing wells or boreholes at mine sites can be found in the *Monitoring Well Water Measurement Standard Operating Procedure* that EPA prepared for the Yerrington Mine in Nevada (EPA 2007).

Water level measurement is intended to answer important questions about the MIW pooling, such as:

- What is the volume of MIW in the workings?
- What are MIW pool elevation fluctuations after a recharge event?
- Is the recharge response fast indicating a direct recharge path or slow, indicating a longer flow path?
- How does the pool level relate to the surrounding water table outside of the mine?
- Is the MIW pooling level higher than the surrounding water table, indicating the potential for blockage and pressurized conditions with an upgradient recharge?

4.2.8 Hydraulic Head Prediction Modeling

Understanding the inflows and outflows of an MIW pool can be improved by analyzing hydrogeologic, mining, climatic, and geologic data. Modeling groundwater flow and storage in MIW pools can initially be approached with basic data and analytical solutions. In many instances, the first level approach is sufficient to characterize the mine pool system and assess the risk of uncontrolled outflow. Key data needs for basic analysis include:

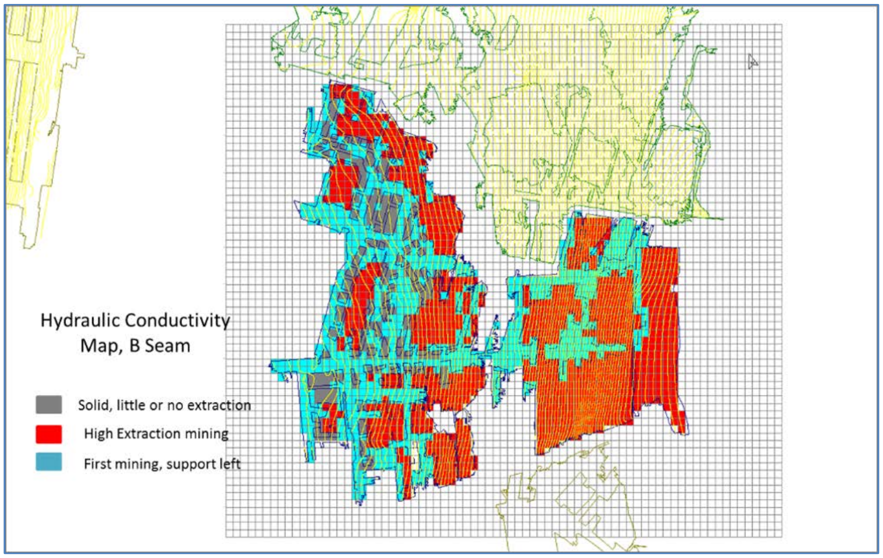
- Mine maps showing the extent, elevation, and orientation of mine workings, location of mine seals and blockages, entries, shafts and other openings;
- Hydraulic head and MIW pool elevation measurements for at least a year;
- Climatic data, in particular, precipitation and snow pack;
- Geologic mapping including fractures and faults;
- MIW pool discharge data; and
- CSM visualizations.

These data are used to: (1) estimate the extent of MIW pooling; (2) estimate storage volume and storage changes; (3) identify potential outflows; (4) estimate hydrostatic head; (5) estimate flow between sections of MIW pool complexes; and (6) estimate outflow to surrounding rock. Flooding extent and flow within the MIW pool can also serve as a basis for inferring general geochemical conditions within the pool (for example, oxidizing [aerobic] or reducing [anaerobic] conditions).

Hardrock mines have relatively unique 3-dimensional mine layout and geometry as determined by the ore body and past mining operations. Thus, specifics of outflow/seepage analysis will vary from site to site. The level of data typically present for a MIW pool assessment lends itself to a “spreadsheet” analysis as a first step.

As a second step, numeric groundwater flow modeling using software based on USGS’s MODFLOW model may provide additional value for MIW pool assessments when more data are available. Underground mines contain large voids that create conduit-type flow. These features are poorly simulated in conventional MODFLOW models. Additional packages and modifications are used to simulate the properties of underground mines. These include simulating mine voids as drains or as modified conduits similar to flow in a karst aquifer, or using unstructured grids. Numeric modeling includes construction of a grid, assigning properties and boundary conditions, calibration, and sensitivity analysis. This second level analysis is characteristically more data intensive. Figure 3 illustrates one application of MODFLOW outputs to present a 2-dimensional illustration of underground workings at a coal mine. A limited number of numeric modeling studies of MIW pools are available in the bibliography. MODFLOW provides a software platform that is capable of quantitative water balance modeling to estimate MIW pool volumes. Without an adequate understanding of the mine workings, multiple water level data points, and flow data, modeling hydraulic head of MIW pools using MODFLOW or other quantitative models is likely to be of limited value.

Figure 3. Example of MODFLOW grid overlaid on mine outlines with various properties assigned.



Source: Unpublished Tetra Tech project for a coal mine in Pennsylvania.

4.2.9 Detailed Water Balance

Should the initial water balance be inadequate for assessing the MIW release risk, it is recommended that a detailed water balance be performed to determine or verify estimated MIW pool volumes. A detailed water balance may be necessary for complex hydrogeology with varied conductivities and fracture-controlled flow; extensive workings with multiple pools and blockages; or potentially high consequence scenarios.

The detailed water balance should update the initial water balance (see Section 4.2.1) to account for additional data collected as part of the MIW CSM development. The groundwater system is conceptualized as a 3-dimensional aquifer recharged by uniform infiltration of precipitation and approximated loss from seepage of streamflow in losing stream reaches. Initially, steady-state recharge, movement, and discharge of groundwater should guide development of the corresponding numerical groundwater-flow model of the study area. Transient changes caused by seasonal variations in recharge or changes in discharge can be simulated separately. Automatic parameter estimation and 3-dimensional simulations of the MIW pool can be developed using MODFLOW with manual adjustments to constrain parameter values to realistic ranges. USGS (2011c) provides a best practice example for performing quantitative water balance modeling of abandoned underground MIW pools. Information about other groundwater modeling approaches can be found in Appendix B. Assumptions used in many groundwater model calculations, such as uniform infiltration or Darcian flow, can lead to inaccurate results for fractured rock and MIW pools, particularly when the site scale is relatively small.

4.3 Evaluate Data, Report Findings, and Determine Next Steps

It is recommended that a report or other comprehensive documentation be produced to present the results of the geotechnical, hydrogeologic, hydrologic and hydraulic (including water balance), and geochemical assessments and the FMEA to support the assessment of MIW pooling. Findings and conclusions drawn from the results should clearly articulate the need for action to reduce MIW pooling and the proposed mitigation measures. Independent review of the report is a best practice to ensure that findings are reproducible and recommendations are objective and reasonable. If the MIW CSM assessment identifies a potential risk for a sudden, uncontrolled release of the mine pool, then appropriate mitigation measures should be taken before any further site investigation or remediation work continues. A separate report may not be necessary when the results of the assessments and FMEA are incorporated into a report prepared under CERCLA, such as a Remedial Investigation or an Engineering Evaluation/Cost Analysis.

Data from non-invasive and invasive methods, as well as other information gathered throughout the previous data collection steps, should be reviewed and analyzed to understand relative elevations of MIW encountered in boreholes and to determine the presence and nature of MIW pooling within mine workings. This information is used to update the MIW CSM and supporting visualizations, which become a part of the information used to make mitigation decisions. Data from drilling to investigate MIW pooling will typically result in one of the following scenarios:

- **Scenario 1 - MIW pooling present in one location under atmospheric pressure -** A boring intercepts mine workings with MIW, and the water level is below the elevation of the roof of the workings. The greater the depth of the water, the greater the hydrostatic head pressure on the blockage. If the boring is one of a number of borings known to be intercepting connected workings but the others reveal no MIW, then the extent of MIW pooling may be limited.

- **Scenario 2 - MIW pooling present in one location under pressure -** A boring intercepts mine workings with MIW, and the water level inside the boring rises up to an elevation higher than the elevation of the roof of the workings. The greater the elevation differential, the greater the degree of hydraulic confinement and pressurization. It is possible for MIW to discharge from the top of the boring as artesian flow if the MIW head elevation rises above the boring opening elevation. Under extreme pressure conditions, abatement of artesian flow during and after drilling is addressed through the use of release prevention and capping technologies. If the boring is one of a number of borings known to be intercepting connected workings but the others reveal no MIW or lower pressure MIW, then the extent of MIW pooling may be limited or the extent of confined conditions might be limited, indicating potentially unique conditions within the workings, such as multiple blockages or high rates of MIW inflow from the surface.

- **Scenario 3 - MIW pooling present under atmospheric pressure in multiple locations –** A distributed set of borings intercepts mine workings at various depths and orientations and the water levels are below the elevations of the roofs of the workings at each location. If the water level elevations in all boreholes are at equal elevations, MIW may be present in a single pool whose inflow/outflow rate is relatively stable or low. If the water level elevations are different but trend linearly in a given direction, then MIW may be present in a single pool with a relatively high inflow/outflow rate. If the water level elevations are significantly different and seemingly randomly distributed, then separate MIW pooling is likely present in multiple locations and the degree of hydraulic interconnectivity requires additional corroborating data to confirm. Depending on the information value of other collaborative data, determining the extent of pooling may require the advancement of additional boreholes.

- **Scenario 4 - MIW pooling present in multiple locations with equivalent water level elevations –** A distributed set of borings intercepts mine workings at various depths and orientations and the water levels are above the elevations of the roofs of the workings at each location. If the water level elevations in all boreholes are at or near equivalent elevations, then the MIW may be present in a single pool caused by a significant blockage with constant inflow. The higher the water level elevations, the higher the rate and volume of inflow or the larger the differential in hydraulic head between the MIW sourcing area and the blockage. If the water level elevations are different but linearly trend in a given direction, then the MIW may be present in a singular pool that may or may not be interconnected with other workings. The higher the water level elevations within the workings, the more extensive the pooling is also likely to be. Depending on the information value of other collaborative data, delineating the extent of pooling may require the advancement of additional boreholes.

- **Scenario 5 - MIW pooling present in multiple locations with variable water level elevations -** A distributed set of borings intercepts mine workings at various depths and orientations and the water levels are at various elevations within the workings at each location. If the water level elevations are significantly different and seemingly randomly distributed, then separate MIW pooling is likely present in multiple locations resulting from multiple blockages, and the nature and degree of hydraulic interconnectivity require additional data to confirm. Depending on the information value of other collaborative data, determining the extent of pooling may require advancement of additional boreholes.

5.0 MITIGATE POOLED MIW UNDER PRESSURE

This section addresses mitigation measures that can be applied as best practices when MIW pooling has been characterized and response actions may pose the potential for a sudden, uncontrolled release of MIW. As indicated previously, this report does not provide best practices for conducting removal or remediation activities, as might be undertaken after dewatering or stabilization of MIW pooling. Such actions are highly diverse and site-specific and require detailed planning and execution, and the related best practices are beyond the scope and intent of the report. Stabilization of a mine pool may be necessary if site management issues necessitate leaving the conditions for pooled MIW in place.

5.1 Evaluate, Select, and Implement Mitigation Options for Pressurized MIW Pools

In most cases, mitigation of pressurized MIW pools will require dewatering the mine pool before conducting response activities. Depending on the condition of the mine workings and their accessibility, various best practices exist for dewatering MIW pools. A dewatering plan may require modifying or supplementing site plans, including updating contingency, notifications and emergency action plans to address dewatering failure risks and effects. Once a proposed mitigation plan is developed, it is recommended that the selected dewatering option undergo an FMEA (see Section 4.2.5) to characterize risk associated with potential failure modes. Physical site conditions will dictate many aspects of mitigation plans.

The risk of a blowout in pressurized MIW pools can be reduced by controlled dewatering to lower the hydrostatic pressure and reduce the MIW pool volume. Dewatering (partial to complete) may be accomplished through existing adits, boreholes, and shafts, or through new boreholes located and installed for the express purpose of mitigating and managing the MIW pool. Dewatering of MIW pool to lower hydrostatic pressure and volume includes the steps below.

1. Identifying a target range and maximum not-to-exceed potentiometric water level is the foundation of the mitigation plan.

2. Determining the volume of MIW to be removed based on mine geometry, adit elevation, water balance, and water level information. Dewatering volume may be seasonally adjusted based on seasonal inflow and outflow variability and site access considerations. For example, spring snow melt typically provides inflows into the mine, and snow pack may limit or preclude site access for portions of the year.

3. Developing a dewatering plan and schedule that is based on the maximum capacity of the site facilities to capture, treat, store, or convey mine water. For sites with adequate area and amenable topography,

contingent capacity can potentially be augmented through the use of temporary or permanent storage systems. Dewatering may be planned as a one-time activity or as part of an ongoing mine-pool management program, as determined by project objectives. If the objective is to open a blocked adit or tunnel, the mitigation plan should consider long-term management of the MIW discharge from the adit. The dewatering plan should also take into consideration destabilizing effects of dewatering (for example, rapid drawdown) on the structural and geotechnical stability of the mine workings caused by the alteration of the long-term, steady state, saturated condition of the pool. Consideration should also be given to changes in MIW geochemistry created by dewatering (see Exhibit 7).

4. Implementing a dewatering system to achieve and maintain the target mine-pool elevation. Dewatering systems may include: (1) dewatering pumps; (2) flow-through bulkhead; (3) boreholes that decant or discharge at a specified pool elevation; and (4) discharge through a pipe and valve system installed through competent bedrock into workings behind blockages. Vertical lift or pumped discharges require an available power source, but are a best practice when pressurized conditions complicate gravity discharges.

Exhibit 7
Geochemical Changes in MIW Caused by Draining an MIW Pool

In saturated mine workings, acid generation is limited by low oxygen in the water, while drained mine workings expose reactive sulfide minerals to atmospheric oxygen. As with any remedial or removal action, careful consideration should be given to the impacts of draining mine workings of MIW before draining the MIW.

Sites in remote locations may lack access to adequate and consistent, year-round electric power. Remote sites generally require on-site power generation if pumping is part of the mitigation plan. Pump capacity will be dictated by the discharge rate limitations and vertical lift. Mine waters are commonly acidic or otherwise corrosive, and use of pump hardware suited to the expected operating conditions is advised. Three general options are commonly used in the hardrock and coal mining industries to manage water removed from a pressurized MIW pool:

- Collecting and treating mine water at, or in proximity to, the dewatering location;
- Collecting and conveying mine pool water to a centralized facility, where it may be treated and managed with other mine waters; and
- Temporary storage in another MIW pool or nearby facilities.

The first of these options is the most likely for most abandoned hardrock mines. Temporary storage (for example, ponds or storage tanks/bladders) at or near the dewatering location can be utilized on immediate or urgent dewatering actions, when time or on-site capacity does not permit long-term MIW management prior to the need to take action. Collection, storage, and treatment of mine water at, or in proximity to, the mine requires sufficient space, conveyance infrastructure, and suitable topography. Severe weather can adversely affect the performance of collection, storage, and treatment systems. Collecting and conveying multiple mine water sources to a central water treatment facility may be an option for managing discharges within a mining district watershed. While the capacity of existing storage and treatment facilities can be a limiting factor, one-time dewatering of a mine pool should be evaluated for applicability. Feasibility should consider site conditions, project objectives, and pumping operations around water treatment plant capacity and project needs. While treatment of contaminated MIW is a critical aspect of any response action, and should be incorporated into the mitigation plan, this best practices report does not directly address contamination remediation best practices.

MIW pool stabilization may be an alternative to dewatering. Mine pool stabilization may include such actions as:

- Installing flow-through bulkheads downgradient of mine pool blockages to control MIW discharge and hydrostatic pressure. This action may be feasible only when the blockage is farther back in the workings from a mine opening so that the bulkhead can be installed in competent bedrock; and
- Controlling mine pool pressure via changes in drainage rates through existing MIW management systems, such as a flow-through bulkhead located in hydraulically connected mine workings.

An MIW pool or MIW flow control structures should generally be monitored through wells or mine openings to check MIW pool elevation and identify excessive pressure on the blockage. If wells or mine openings do not exist, the site team should consider installing monitoring wells before stabilization actions are implemented. Mine pool stabilization efforts requiring such invasive activities should generally be evaluated using FMEA or similar risk analysis.

6.0 QUALIFICATIONS OF THE TECHNICAL TEAM

Abandoned mines are very different from other sites. Conditions associated with underground workings require specialized knowledge, training, and experience. To conduct the investigations and reviews of MIW pooling conditions described in this best practices report, specific qualifications of the technical team should be considered. State-specific qualifications for conducting hydrogeological investigations or geotechnical evaluations may be required by law for permitting or other certification purposes. The following are common expertise requirements for the technical team.

- Mining Geologist, with more than 10 years of specific experience in mining district studies, mine workings, and bedrock geology. Professional Geologist license in the state of study is typically required.
- Hydrogeologist, with more than 10 years of specific experience with bedrock hydrogeology and water balance. Professional Geologist (PG) license in the state of study is typically required.
- Mining/Civil Engineer, with more than 10 years of field experience in underground mines design, operation and reclamation/closure. Professional Engineer (PE) license in the state of study is typically required.
- Geotechnical Engineer, with a PE license in the state of study and more than 10 years of experience in underground mine hydraulic structures, stability design, reclamation, and closure.
- Geochemist, with more than 10 years of mine water geochemistry and treatment experience. Experience in conducting tracer studies is preferred.

When an FMEA is necessary, it is recommended that at least one member of the technical team have experience in performing FMEAs related to MIW pools and blowouts.

Conducting studies of mine pools at abandoned mines will likely require the use of contractors for a wide range of activities, including drilling and heavy equipment operation. These contractors should meet appropriate federal, state, or local training and licensing requirements, have specific and relevant experience operating at abandoned mines, and operate in compliance with the site contingency, notification, and emergency action plans. Experience with on-site contractor oversight during site work is also preferred.

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APPENDIX A. BEST PRACTICES CHECKLIST TOOL

Checklist Tool for Developing a Conceptual Site Model for Assessing Risks Associated with Pooling of Mining-Influenced Water

Item #	Activity Description	Completed?* (Yes / No / NA)
1. CONDUCT INITIAL SITE SCREENING		
1a	Identify, obtain and review site documents and data	
1b	Assess structure of mine workings using available information	
1c	Identify data gaps	
1d	Conduct site visit	
1e	Make initial screening determination ☐No MIW pool ☐Stable MIW pool ☐Unknown ☐Unstable MIW pool	
2. DEVELOP MIW CONCEPTUAL SITE MODEL		
2a	Develop MIW CSM visualization(s) of mine workings and MIW conditions	
3. EVALUATE HYDROGEOLOGIC, HYDROLOGIC, GEOCHEMICAL AND GEOTECHNICAL ATTRIBUTES OF MIW POOLING		
3a	Evaluate geotechnical attributes	
3b	Evaluate hydrogeologic attributes	
3c	Evaluate hydrologic attributes	
3d	Evaluate geochemical attributes	
3e	Develop initial water balance	
4. PLAN AND CONDUCT MINIMALLY INVASIVE MEASUREMENTS		
4a	Conduct geophysical surveys	
4b	Measure groundwater/MIW pooling water levels	
4c	Measure surface water flows	
4d	Measure surface water quality	
4e	Identify possible drilling locations	
4f	Develop detailed water balance, calculate or estimate hydrostatic conditions	
5. PLAN AND CONDUCT INVASIVE MEASUREMENTS VIA DRILLING OR OTHER METHODS		
5a	Develop investigation work plans	
5b	Perform failure mode and effects analysis (FMEA)	
5c	Develop or refine contingency, notification and emergency action plans	
5d	Mobilize and execute invasive measurements work plan	
5e	Review and analyze invasive measurements data	
6. COLLECT AND EVALUATE DATA, REPORT FINDINGS, AND DETERMINE NEXT STEPS		
6a	Install and monitor pressure transducers	
6b	Install and monitor MIW discharge flow measuring devices	
6c	Install and monitor MIW pool and discharge water quality measuring devices	
6d	Collect mine pooling monitoring data for approximately one calendar year	
6e	Correlate MIW pool water levels with the elevation of MIW discharge location	
6f	Update detailed water balance; calculate hydrostatic conditions	
6g	Update MIW CSM and visualization(s)	
7. MITIGATE POOLED MIW		
7a	Select mitigation approach and develop mitigation work plan	
7b	Perform FMEA	
7c	Update contingency, notification and emergency action planning	
7d	Mobilize and implement mitigation work plan	

*No and NA answers should be explained; Yes answers should be accompanied by documentation and references.

Instructions

The following instructions provide information and considerations for each row in the checklist.

1. CONDUCT INITIAL SITE SCREENING

1a. Identify, obtain, and review site documents and data to develop overall understanding of site history; site topography and features; site mineralogy and geology; mine workings; MIW discharges; known or potential MIW pooling; and environmental condition from prior site investigation and remediation efforts. Interview nearby landowners, local mining experts and government agencies, and representatives of responsible state and federal agencies.

1b. Assess structure of mine workings to understand the extent, features and geospatial orientations of the mine workings and any known or suspected blockages. Review available mineral exploitation planning and development maps; historical and recent maps, cross-sections and 3-dimensional representations from site investigation and remediation; and other information that illustrate the historical evolution and operation of the mine workings. Additional data may include mine maps from EPA, Office of Surface Mining, Reclamation and Enforcement (OSMRE) National Mine Repository, USGS National Geochemical Survey Database for geochemistry of stream sediments and soils, aerial photogrammetry; and fracture trace analysis (fracture zones and other linear geologic and geomorphologic features).

1c. Identify data gaps as the basis for design of the initial site visit, data gaps in desktop information should be identified and data quality and reliability should be evaluated.

1d. Conduct site visit to evaluate or confirm whether proposed response actions could potentially result in a sudden, uncontrolled release of MIW. Perform site walk-through and photo-documentation of mine and locations of proposed response actions to identify the presence and location of features commonly associated with MIW pooling. Note features not previously known to exist or not shown in the correct locations on site maps; and document location coordinates using global positioning system (GPS). Assess site for areas to contain, treat, or store MIW as release contingency and for dewatering efforts. Confirm downstream surface water bodies, uses and potential receptors. View adjacent mine sites with known or potential interconnections. Meet with former site workers, local mining experts, and nearby land owners to increase understanding of site history. Review of local file repositories to increase overall site knowledge.

1e. Make initial screening determination: check box that is appropriate. Determine if the response action does not pose a risk (no MIW pool or stable MIW pool that the response action will not affect) or if further study is needed to make this determination (unknown potential for MIW pool, or potential that MIW is not stable, or that response action can make the MIW pool unstable). If further study is needed, the technical team will develop a conceptual site model (CSM) to assess pooled MIW risks.

2. DEVELOP MIW CONCEPTUAL SITE MODEL

2a. Develop CSM visualizations based on available data, including, but not limited to surface topography; important surface features (boreholes, adit portals, shafts, vents, subsidence features); mine workings configuration; geologic structures, including contacts, strike, and dip; key subsurface features (sump areas, interconnections to adjacent mines, collapse areas, surface water / snow melt inflow areas); and any other salient features needed to characterize MIW pooling. The most effective initial MIW CSM format may be figures, maps, tables, and text. If appropriate and adequate data are available, consider developing spatially accurate visualizations using geographic information system (GIS) or 3-dimensional data visualization and analysis (3DVA) software.

3. EVALUATE GEOTECHNICAL, HYDROGEOLOGIC, HYDROLOGIC, AND GEOCHEMICAL ATTRIBUTES OF MIW POOLING

3a. Evaluate geotechnical attributes as indicated to understand the geotechnical conditions of the mine workings that create blockages. Consider evaluating the following:

- Dimensions and extent of mine workings, including adits, drifts, cross-cuts, haulage routes, shafts, raises, winzes, manways, air vents;

- Types and conditions of support/rehabilitation structures such as timbering, beams, cribbing, square sets, ribs, pillars, crossbars, steel beams, pinning, bolts, concrete;
- Workings storage – volume of mine workings above and below mine potential blockage locations to estimate MIW pooling volume;
- Mine working openings at the surface that serve or could potentially serve as MIW inflow or outflow locations, as well as air inflow locations, key contributors to MIW acidification;
- Portal or other mine opening stability assessment;
- Known or suspected mine workings interconnections between mines;
- Presence of faults, joints, folding or other geologic features that could affect mine stability;
- Thickness and integrity of overburden cover above the mine workings (for example, fracturing is typically more prevalent and fractures have wider aperture at shallower depths);
- Types, strengths, and competency of bedrock and other strata;
- Location, composition, and dimensions of known or suspected flow blockages, and the forces acting on the blockages;
- Surface expressions of underground workings such as structure failure subsidence and slope collapses;
- Potential for liquefaction of soils near mine openings or comprising blockages; and
- Slope stability: physical, mechanical, and seismic properties (for possible naturally occurring slope failure or failure as a result of drilling and/or construction equipment).

3b. Evaluate hydrogeologic attributes as indicated to understand the hydrogeologic conditions that provide inflow to, and outflow from, the mine workings. Consider evaluating the following:

- Types and nature of hydrogeologic units (unconsolidated deposits, bedrock);
- Hydraulic properties of hydrogeologic units (hydraulic conductivity, transmissivity, storability, porosity, dispersity);
- Thickness and areal extent of hydrogeologic units;
- Type of porosity (primary, such as intergranular pore space in unconsolidated deposits or porous bedrock matrices; or secondary, such as bedrock discontinuities, fractures, or solution cavities);
- Groundwater flow through faults, joint fractures, mineral veins;
- Presence or absence of confining or semi-confining lithologic units;
- Depth to water table and seasonal variation, thickness of vadose zone, potentiometric surface, and confined, unconfined, or leaky confined conditions;
- Groundwater flow directions (hydraulic gradients, both horizontal and vertical), volumes (specific discharge), rate (average linear velocity);
- Catchment area and groundwater recharge zones;
- Groundwater/surface water interactions, areas of groundwater discharge to surface water (gaining), and surface water recharge of groundwater (losing); and
- Seasonal variations in groundwater conditions.

3c. Evaluate hydrologic and hydraulic attributes as indicated to understand the hydrologic and hydraulic conditions at the surface that provide inflow to the workings. Consider evaluating the following:

- Site topography, watersheds, drainage basins, and associated natural surface water bodies; including lakes, ponds, rivers, active and temporal streams, and constructed drainage systems.
- Surface and subsurface man-made impounded water bodies;
- Workings inflow – groundwater/surface water inflow rate, including precipitation and infiltration;
- Workings outflow – MIW outflow, discharge rates, seasonal variations (maximum and minimum);
- Location, nature, and condition of MIW management systems in workings such as bulkheads (including type, material and thickness), pressure grouting, coffer dams, discharge piping, floor channels, and sumps;
- Confirmation that no MIW pooling is present, where initial evidence indicates no pooling;
- Direction and rate of MIW flow through workings;
- MIW discharge locations, flow and receiving surface water bodies or infrastructure, including potential downstream receptors that may be impacted by a release (for emergency planning);

- Pressure conditions of MIW within mine workings (confined, unconfined, or leaky confined) such as pool elevation, hydraulic head, and hydrostatic pressure;
- Presence of springs or seeps (aerial photography of vegetative growth can be an indicator);
- Climatic conditions as related to precipitation, snow melt, evaporation, infiltration and runoff;
- Vegetative cover and seasonal transpiration rates; and
- Hydraulic interconnections with other mines.

3d. Evaluate geochemical attributes as indicated to understand the geochemical characteristics that add to the complexity of the mine blockages. Consider evaluating the following:

- MIW geochemistry data such as physical and chemical water quality data in oxygenated and reduced conditions, anion/cation chemistry, bioassay;
- Background water quality data from other mine seeps and springs for comparison with MIW, and to conduct anion/cation chemistry, if necessary for geochemical modeling/charge balance;
- Geochemical material characteristics that contribute to MIW water quality;
- Baseline characterization of water quality, sediment quality, and macroinvertebrates population metrics of downstream water bodies for comparison if a release occurs;
- Location of MIW acidification/neutralization sources within the mine such as high sulfide areas, ore piles, chemically oxidized zones, or exposed mineralized material;
- Location and types of potential MIW monitoring points such as monitoring wells, weirs, boreholes, and ventilation raises;
- Location and type of existing MIW monitoring devices such as pressure gauges, transducers, and sondes;
- Isotopic MIW analysis may provide information on MIW residence time to indicate groundwater recharge (longer) or precipitation infiltration (shorter);
- Anticipated effects of MIW chemistry on downstream receptors for consequence analysis;
- Existence of MIW containment and treatment systems such as run-on/runoff control, ponds, biotreatment, and water treatment plants;
- Chemical and physical characteristics of natural water bodies upgradient of MIW discharge points;
- Presence, nature, and extent of sedimentation within workings; and
- Presence and type of biological activity within workings such as algae, bacteria, molds, or mosses.

3e. Develop initial water balance. The following equation summarizes the basic elements of a water balance:

$$S = I - O$$

Where: S = Storage; I = Inflows; and O = Outflows

When “S” is a positive number, a mine receives more inflow than it discharges as outflow and MIW is likely accumulating in the mine workings. If “S” is a negative number, then the outflows exceed the inflows and the works are likely draining faster than MIW is accumulating.

4. PLAN AND CONDUCT MINIMALLY INVASIVE MEASUREMENTS

4a. Geophysical surveys to identify mine workings and features.

4b. Measure groundwater/MIW pooling water levels in existing monitoring wells, boreholes, and via safely accessible shafts, vents and other surface openings. Is the MIW pool fluctuating or is it stable, and does the fluctuation provide data on the size of the MIW pool? Is there an eventual drop in pool level after the recharge event indicating a drain from the mine or does the pool level increase? How does the pool level relate to the surrounding water table outside of the mine? If the water level in the mine is higher, it would indicate the potential for blockage and pressurized conditions with upgradient recharge or connection with an upgradient mine.

4c. Measure surface water flows (flume, weir) and dimensions of channel (depth, cross sectional area).

4d. Measure surface water quality such as contaminants of concern (COCs), plus complete water chemistry, including pH, specific conductance (SC), cations and anions (including alkalinity), dissolved and total metals, other metals related to the study (for example, iron, manganese, aluminum), total dissolved solids (TDS) dissolved oxygen (DO), oxidation/reduction potential (ORP), turbidity and temperature.

4e. Identify possible drilling locations to confirm rig accessibility, ground stability, and no risk of the collapse of underground mine workings.

4f. Develop detailed water balance to determine whether inflows, outflows and estimated storage in the mine workings indicate the existence of MIW pooling. To the extent possible, calculate or estimate hydrostatic conditions. If pooling is indicated or remains uncertain, drilling may be required to confirm.

5. PLAN AND CONDUCT INVASIVE MEASUREMENTS VIA DRILLING

5a. Develop investigation work plans for field drilling program to advance boreholes into the mine workings for direct assessment of MIW pooling, groundwater flow and inspection of mine workings using visual technologies.

5b. Performance of failure mode and effects analysis (FMEA) on proposed drilling activities and modification of work plan and conduct contingency, notification and emergency action planning.

5c. Conduct or refine contingency, notification and emergency action planning including comprehensive contingency planning to address potential MIW releases during drilling program. Contingency, notifications and emergency action plans should also be developed or modified.

5d. Mobilization and execution of invasive measurements work plan to assess groundwater and MIW pooling.

5e. Review and analyze invasive measurements data to understand relative elevations of MIW encountered in boreholes (for drilling) and determine the presence and nature of MIW pooling within mine workings, based on one or more of the following scenarios:

- **Scenario 1 - MIW pooling present in one location under atmospheric pressure -** A boring intercepts mine workings with MIW, and the water level is below the elevation of the roof of the workings. The greater the depth of the water, the greater the hydrostatic head pressure on the blockage. If the boring is one of a number of borings known to be intercepting connected workings but the others reveal no MIW, then the extent of MIW pooling may be limited.
- **Scenario 2 - MIW pooling present in one location under pressure -** A boring intercepts mine workings with MIW and the water level inside the boring rises up to an elevation higher than the elevation of the roof of the workings. The greater the elevation differential, the greater the degree of hydraulic confinement and pressurization. It is possible for MIW to discharge from the top of the boring as artesian flow if the MIW head elevation rises above the boring opening elevation. Under extreme pressure conditions, abatement of artesian flow during and after drilling is addressed through the use of release prevention and capping technologies, respectively. If the boring is one of a number of borings known to be intercepting connected workings but the others reveal no MIW or lower pressure MIW, then the extent of MIW pooling may be limited or the extent of confined conditions might be limited, indicating potentially unique conditions within the workings such as multiple blockages or high rates of MIW inflow from the surface.
- **Scenario 3 - MIW pooling present under atmospheric pressure in multiple locations –** A distributed set of borings intercepts mine workings at various depths and orientations and the water levels are below the elevations of the roofs of the workings at each location. If the water level elevations in all boreholes are at equal elevations, MIW may be present in a single pool whose inflow/outflow rate is relatively stable or low. If the water level elevations are different but trend linearly in a given direction, then MIW may be present in a single pool with a relatively high inflow/outflow rate. If the water level elevations are significantly different and seemingly randomly distributed, then separate MIW pooling is likely present in multiple locations and the degree of hydraulic interconnectivity requires additional corroborating data to confirm. Depending on the information value of other collaborative data, determining the extent of pooling may require the advancement of additional boreholes.
- **Scenario 4 - MIW pooling present in multiple locations with equivalent water level elevations –** A distributed set of borings intercepts mine workings at various depths and orientations and the water levels are above the elevations of the roofs of the workings at each location. If the water level elevations in all boreholes are at or near equivalent elevations, then the MIW may be present in a single pool

caused by a significant blockage with constant inflow. The higher the water level elevations, the higher the rate and volume of inflow and the larger the differential in hydraulic head between the MIW sourcing area and the blockage. If the water level elevations are different but linearly trend in a given direction, then the MIW may be present in a single pool that may or may not be interconnected with other workings. The higher the water level elevations within the workings, the more extensive the pooling is also likely to be. Depending on the information value of other collaborative data, determining the extent of pooling may require advancement of additional boreholes.

- **Scenario 5 - MIW pooling present in multiple locations with variable water level elevations –** A distributed set of borings intercepts mine workings at various depths and orientations and the water levels are at various elevations within the workings at each location. If the water level elevations are significantly different and seemingly randomly distributed, then separate MIW pooling is likely present in multiple locations resulting from multiple blockages and the nature and degree of hydraulic interconnectivity requires additional data to confirm. Depending on the information value of other collaborative data, determining the extent of pooling may require advancement of additional boreholes.

6. COLLECT AND EVALUATE DATA, REPORT FINDINGS, AND DETERMINE NEXT STEPS

6a. Install and monitor pressure transducers with integral data loggers to monitor MIW pools in select monitoring wells or other access points to identify MIW pooling. Correlate monitoring well water levels and mine pool elevations with basin precipitation events to understand MIW pool recharge and discharge. Do fluctuations in the various measurements correlate and are there lag times indicating flow distance between recharge location and monitoring point, or do water level trends indicate faster inflow to the mine relative to outflow?

6b. Install and monitor MIW discharge flow measuring devices (for example, weirs, flumes, calibrated pipes) with level monitoring devices and data loggers to capture flow rates consistently over time. These data loggers are best if synchronized with those of the monitoring well pressure transducers.

6c. Install and monitor MIW pool and discharge water quality measuring devices (sondes, probes) with data loggers may be warranted depending on data gaps in water chemistry.

6d. Collect mine pooling monitoring data for approximately one calendar year to assess influences on MIW pooling via installation of monitoring systems. If the year is deemed to be overly wet or dry, continued monitoring may be warranted until normal high and low flows and water quality of MIW can be determined.

6e. Correlate MIW pooling water levels with the elevation of the MIW discharge location and with basin precipitation events to understand how water enters, migrates through, pools within, and discharges from the mine workings, based on one of the following scenarios:

- **Scenario 1 - Water level elevations in the workings are higher than the MIW discharge location -** the discharge could be coming from any of the described conditions. If the water level elevations in the workings are higher than the elevation of the MIW discharge location, either MIW at depth is under significantly confined conditions and MIW discharge is artesian, or the MIW is coming from another source location.
- **Scenario 2 - Differential in elevation between measured water levels and the MIW discharge location is large -** the MWI discharge flow rate should be relatively high and constant. If the differential in elevation between the measured water levels and the MIW discharge location is large, but the MWI discharge flow rate is low or intermittent, the flow may be impinged at some locations prior to discharge. In this case, MIW pooing could be under significant excess pressure whose cause and location may require additional corroborating data to determine.

6f. Update detailed water balance to refine estimates of inflows, outflows and estimated storage of MIW pooling based on newly collected drilling and monitoring data. Calculate or estimate hydrostatic conditions.

6g. Update MIW CSM and visualizations to refine the MIW CSM parameters on newly collected non-invasive measurements, drilling and monitoring data. Update the MIW CSM visualizations to inform mitigation measures.

7. MITIGATE POOLED MIW UNDER PRESSURE

7a. Develop mitigation work plans. Develop a work plan to ensure appropriate implementation of selected mitigation measures.

7b. Perform FMEA on proposed mitigation activities. Once a proposed mitigation plan is developed, it is recommended that the selected mitigation measures undergo an FMEA to determine potential failure modes and adverse effects that could occur. Local conditions will dictate many aspects of mitigation plans.

7c. Update contingency, notification and emergency action planning including comprehensive emergency action and contingency plans for addressing potential MIW releases during mitigation efforts. FMEA results may require modifying or supplementing the contingency, notifications and emergency plans to address mitigation-related failure risks and effects.

7d. Mobilize and implement mitigation plan to address MIW release potential. Sites in remote locations may lack access to consistent, year-round electric power. Some sites may require on-site power generation if pumping is part of the mitigation plan. Pump capacity will be determined by the discharge rate limitations and vertical lift. Some mine waters are acidic or otherwise corrosive and pump hardware suited to the expected operating conditions is advised. Three general options are commonly used in the hardrock and coal mining industries for management of water removed from a pressurized MIW pool:

- Collecting and treating mine water at, or in proximity to, the dewatering location;
- Collecting and conveying mine pool water to a centralized facility where it may be treated and managed with other mine waters; and
- Temporary storage in another MIW pool or nearby facilities.

APPENDIX B. GENERAL INFORMATION ON GROUNDWATER MODELS

Groundwater models are used to represent groundwater flow in unconsolidated deposit formations and fractured, porous bedrock aquifers. Models can be used to predict the effects of hydrological changes (such as groundwater recharge or discharge into a void) on the behavior of the aquifer. Some models can accommodate manual inputs that allow modeling of karst conditions, which are the closest natural aquifer analog to a mining-influenced water (MIW) pool in underground mine workings. Below are examples of groundwater models that may be useful for MIW pool modeling and water balancing.

Specific Features and Limitations of Groundwater Modeling Applications in Mines

Mathematical modeling of groundwater flow in a rock massif disturbed by deep mining exploitation can be very complicated. The reasons being that, in a massif with large open mine voids, groundwater flow is often turbulent and, in the case of backfilling, mine workings represent preferential flow pathways with variable and difficult-to-estimate hydraulic properties. Moreover, deep mines are typically situated in hard rocks where the existence of fractures with important hydraulic function is common.

The modeling approach depends on the scale of the modeling application. A strategy for modeling groundwater rebound in abandoned mine systems in relation to the scale of observation was described by Adams and Younger (2001). At the very largest scales, water balance calculations are probably as useful as any other technique, for example standard porous media continuum approach models. For local scale systems, a physically-based modeling approach has been developed (Adams and Younger, 2001), in which 3-dimensional (3-D) pipe networks (representing major mine roadways.) are routed through a variably saturated, porous medium. Alternatively, for systems extending from 100 to 3,000 km^2, a semi-distributed model (groundwater rebound in abandoned mine-workings or GRAM) has been developed in the United Kingdom (Adams and Younger, 2001). This model conceptualizes extensively interconnected volumes of workings as ponds, which are connected to other ponds only at discrete overflow points, such as major roadways, through which flow can be efficiently modelled using the Prandtl-Nikuradse pipe-flow formulation.

Routinely applied groundwater flow models (for example MODFLOW) do not enable the correct simulation of dual porosity flow with preferential flow along fractures and leakage through the rock matrix. The application of fracture flow and transport models (for example FEFLOW, FRAC3DVS, FRACTRAN, NETFLO, SWIFT) to mining projects has been very limited, in part due to the complexity of the models and the lack of adequate input.

Modular Finite-Difference Groundwater Flow Model (MODFLOW)

The Modular Finite-Difference Groundwater Flow Model (MODFLOW) developed by McDonald and Harbaugh (1988) for the United States Geological Survey (USGS) can be used to simulate groundwater flow in mines. MODFLOW is a groundwater flow simulator that has been accepted by regulatory agencies and used extensively for a variety of applications. It allows the simulation of steady state and transient flow regimes in both two and three dimensions. A detailed description of MODFLOW is provided in the software package manual (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh et al., 2000. Although MODFLOW was primarily developed to simulate flow in porous media it is often used for groundwater flow modeling in fractured rocks if they behave as equivalent porous media at the scale of study.

An example of mine pool evaluation is described in the USGS report on an abandoned uranium mine in Colorado. This study reflects USGS's approach to evaluating mine pools:

http://pubs.usgs.gov/of/2011/1092/pdf/OF11-1092.pdf

3-D Finite-Element Flow Modeling

A common modeling approach is to develop a 3-D finite-element flow model of the abandoned mine. The first step in developing a 3-D model is analysis of available hydrogeologic data and incorporation of these data into a conceptual hydrogeologic model of the mine area. Based on this conceptual hydrogeologic model, a finite-element groundwater flow model of the mine is constructed. The hydrogeologic units incorporated into the model may include unconsolidated deposits, weathered bedrock, and unweathered bedrock.

Many models rely on pumping test data analysis to better understand the primary (rock matrix) and secondary (fractures) porosities of bedrock. Fault and shear zones can be simulated in a model's sensitivity analysis. A steady-state simulation of the groundwater flow model is then calibrated to the observed water levels in the mine area. Modeling examples are presented below:

Hybrid Finite-Element Mixing Cell (HFEMC) method

The HFEMC method couples groups of mixing cells for the mine workings with finite elements for the unmined zone. The interactions between the mined zones and the unmined zone are considered using internal boundary conditions which are defined at the interfaces between the groups of mixing cells and the finite element mesh. Another feature of this technique lies in its ability to simulate by-pass flows between mine workings using first order transfer equations between the groups of mixing cells. The HFEMC method is particularly useful to simulate mine groundwater problems such as groundwater rebound.

An example of the HFEMC model is available at:

See: http://orbi.ulg.ac.be/bitstream/2268/69485/1/HYDROL9216_Accepted_Manuscript.pdf

Other Modeling Information Sources

Colorado School of Mines

As indicated on their website, "*The Colorado School of Mines operates the Integrated Groundwater Modeling Center (IGWMC) which posts free model software. IGWMC is an internationally oriented information, education and research center for groundwater modeling. IGWMC advises on groundwater modeling problems, distributes groundwater modeling software, organizes short courses, workshops and conferences, conducts research in practical, applied areas of groundwater hydrology and modeling, and provides technical assistance on problems related to groundwater modeling. As a focal point for groundwater professionals, the Center supports and advances the appropriate use of quality-assured models in groundwater resources protection and management.*"

See: http://igwmc.mines.edu/software/freeware_list.html

Office of Surface Mining Reclamation and Enforcement

DOI's OSMRE has developed a groundwater model to simulate flow through underground coal mines. This model may have merit in modeling flows through abandoned hardrock mines,

OSMRE's Groundwater Modeling System (GMS) software is noted at:
www.tips.osmre.gov/Software/Hydro/gms.shtml

As indicated on their website, "*The OSMRE Groundwater model design system converts map data into MODFLOW, MODPATH, and MT3D grid data for running groundwater flow and solute transport simulations. GMS is a comprehensive groundwater modeling package supported by three dimensional visualization tools.*

Users can create a complete groundwater simulation including site characterization, model development, post-processing, calibration, and visualization. Users can construct a conceptual ground water model directly on top of a scanned map of a site using GIS objects. Boundary conditions and parameter values can be assigned directly to the GIS objects. GMS gives the user the option of finite-difference modeling using MODFLOW and related packages, or finite-element modeling techniques."

A list of OSMRE's technical staff dealing with hydrology is:
www.tips.osmre.gov/Software/hydro/Members.shtml

USGS Groundwater Modeling

USGS web site for groundwater modeling:

http://water.usgs.gov/software/lists/groundwater/

APPENDIX C. ADDITIONAL SOURCES OF CONCEPTUAL SITE MODEL INFORMATION

Mine Maps and Mine History

A best practice in identifying the presence of underground workings is to review mine maps, mine histories, and published reports about the mine site.

An important source of abandoned mine maps is the National Mine Map Repository (NMMR) maintained by the DOI's Office of Surface Mining Reclamation and Enforcement (OSMRE) in Pittsburgh, PA. Point of Contact at the time of document publication is Paul Coyle (pcoyle@osmre.gov). This repository holds old mine maps of hardrock and coal mines and has national coverage. Sites can be searched by mine name. Maps are not digital, thus physical copies must be requested. For more information see http://mmr.osmre.gov.

Mine history is important to identify since some records often discuss dewatering the mine or include hydrogeologic information. Some sources of mine history include: historical societies, historical newspaper archives, stock company histories, Masters and Doctoral theses. Resources can also be located via internet search using the mine site or mining district name. State tax archives sometimes can lead to old mining reports as can the State Land Office where mining claims may have been filed.

Another source of historical information including mine maps is the Anaconda Geological Documents Collection in the American Heritage Center at the University of Wyoming. The collection has been indexed and the database is available as a free, searchable online database, although access to the actual documents is not available online, documents can be ordered from the University. The maps and documents in the collection date from the 1890s to 1986. For further information see: http://www.uwyo.edu/ahc/collections/anaconda/

Geologic Information

Another important source of Abandoned Mine Lands (AML) site data is found in each State Geologist Office. A convenient way to access State Geologist files is via the Association of American State Geologists' (http://stategeologists.org), web site, which has links to each State Geologist web site.

For example, the Colorado State Geologists office has a section devoted to AML that includes descriptions of each historical mining district in the state (see http://coloradogeologicalsurvey.org/mineral-resources/abandoned-mine-lands/). The Colorado State Geologist site also includes descriptions and maps of the geology of the state, as well as, geologic maps of the state.

Another example of mine data maintained by states is information available from the California Department of Conservation, Division of Mines and Geology (DMG). The DMG's publications, library, unpublished files, and property reports contain descriptions of specific mining operations, processing techniques, locations and characteristics of ore deposits, mineral resource potential, and mineralogy. Some information dates back to 1880. The DMG has many published and unpublished maps of geology, ore deposits, and individual mines. It also maintains a library of photographs of mining operations, many taken in the late 1800s. Information is maintained in Sacramento.

U.S. Geological Survey National Geologic Map Database

The USGS maintains the National Geologic Map Database. This database contains current digitized geologic maps of most of the U.S. It can be accessed at no cost at http://ngmdb.usgs.gov/maps/MapView.

USGS publications are easily searchable and digitized, and cover virtually all mining districts. It is recommended to first contact the USGS office that covers the site area of concern.

The USGS also provides instruction on how to develop water budgets at abandoned mines, which is focused on coal mines, but relevant to hardrock mines. The information is available in USGS Report 2010-5261 Water Budgets and Groundwater Volumes for Abandoned Underground Mines, available at http://pubs.usgs.gov/sir/2010/5261/ .

U.S. Bureau of Mines Publications

The former U.S. Bureau of Mines (USBM) was the principal federal agency responsible for gathering information on production and consumption of mineral resources from 1910 through 1995. The USBM was abolished in 1996 and certain mineral information functions were transferred to the USGS. In addition to results of analysis and research in the fields of mineral economics, minerals utilization, mining engineering, ore processing, and mine safety, many of the USBM reports contain site-specific mine information that covers all aspects of mining, processing, and recovery. Formal report series include Reports of Investigations (RI series), Information Circulars (IC Series), Bulletins, and Mineral Yearbooks. Informal reports include Open-file Reports, Mineral Commodity Reports, Mineral Land Assessment Reports, and various special publications.

U.S. Defense Minerals Exploration Administration (DMEA) Reports

From 1952 to 1974, the Federal Government funded two minerals exploration units, the Defense Minerals Exploration Administration and the Office of Minerals Exploration (OME), to make loans to individuals and corporations for exploration and development of strategic minerals. All pertinent information, including proposals, exploration agreements, property survey data, geologic data, results of physical exploration, summaries of assay results, owner's progress reports and reports of program officers, including results of field examinations, are included in a docket file for each property. Obtaining information from these files is difficult because much is confidential, and ownership changes subsequent to program involvement are not tracked. Also, some materials in the files are difficult and expensive to reproduce, and program files are no longer maintained regionally, but have been consolidated into archives at only a few locations. The USGS is the custodian of these files, and inquiries should first be made in the same manner as for unpublished USGS material.

Water Management at Abandoned Flooded Underground Mines

A basic primer on understanding the wide range of issues related to characterizing mine pools at abandoned mines is *Water Management at Abandoned Flooded Underground Mines*, C. Wolkerdorfer, 2008. The Wolkerdorker book also includes discussions on how to characterize mine pools and case studies of mine pools. This source can be accessed at:

www.wolkersdorfer.info/publication/pdf/MineAbandonment.pdf

EPA CLU-IN Mine Pool Information

EPA’s Superfund program has been documenting research studies on abandoned mine pools on its CLU-IN website. This resource provides remedial project managers (RPMs) and on-scene coordinators (OSCs) with easy access to four groups of data: a) Characterization and Remediation of Mine Pools, b) Case Studies of Mine Pools, c) Data collected at Mine Pools, and d) References. This information can be accessed at:

https://clu-in.org/issues/default.focus/sec/Characterization,_Cleanup,_and_Revitalization_of_Mining_Sites/cat/Resources/

APPENDIX D. REFERENCE MATERIALS MATRIX

Document Title	Date	CSM	MIW Pooling				Case Studies	Full Reference	Internet URL
		Information Resources	Assessment	Management & Mitigation	Failure Mode and Effects Analysis	Emergency Action Planning	MIW Release		
A Generalized Protocol for Selecting Appropriate Geophysical Techniques.	2016	■	■					Anderson, N., Ismail, A. A Generalized Protocol for Selecting Appropriate Geophysical Techniques. Federal Highways Administration, Interstate Technical Group on Abandoned Underground Mines – An Interactive Forum. University of Missouri-Rolla. Accessed February 2016.	http://www.fhwa.dot.gov/engineering/geotech/hazards/mine/workshops/ktwkshp/ky0307.cfm
Standard Test Method for Particle-Size Analysis of Soils	2007		■					American Society for Testing and Materials (ASTM) International. 2007. Standard Test Method for Particle-Size Analysis of Soils. ASTM D422.	http://www.astm.org/Standards/D422
Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass	2010		■					ASTM. 2010. Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM D2216.	http://www.astm.org/Standards/D2216.htm
Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions	2011		■					ASTM. 2011. Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. ASTM D3080.	http://www.astm.org/Standards/D3080.htm
Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils	2012		■					ASTM. 2012. Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils. ASTM D5778-07. February.	NA
Standard Practice for Rock Core Drilling and Sampling of Rock for Site Exploration	2014		■					ASTM International. 2014. Standard Practice for Rock Core Drilling and Sampling of Rock for Site Exploration. ASTM D2113.	http://www.astm.org/Standards/D2113.htm
Standard Guide for Direct Push Soil Sampling for Environmental Site Characterizations.	2015		■					ASTM. 2015. Standard Guide for Direct Push Soil Sampling for Environmental Site Characterizations. ASTM D6282M.	http://www.astm.org/Standards/D6282.htm
New Test Method for Pocket Penetrometer Test – Under Developmen	2016		■					ASTM. 2016a. New Test Method for Pocket Penetrometer Test – Under Development. ASTM WK27337.	http://www.astm.org/DATABASE.CART/WORKITEMS/WK27337.htm
Standard Test Methods for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil	2016		■					ASTM. 2016b. Standard Test Methods for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil. ASTM D2216.	http://www.astm.org/Standards/D2216.htm
Land Use	2016						■	Auroralights. Land Use. Accessed January 2016.	http://auroralights.org/map_project/theme.php?theme=crm&article=1
Water Balance for the Jeddo Tunnel Basin, Luzerne County, Pennsylvania	1999		■					Ballaron, Paula B. 1999. Water Balance for the Jeddo Tunnel Basin, Luzerne County, Pennsylvania. Susquehanna River Basin Commission. Publication No. 208. August.	http://www.srbc.net/pubinfo/docs/jeddowaterbalance.pdf
Final Hydrogeological Assessment, Cowal Gold Mine, Extension Modification	2013		■					Barrick Australia Limited. 2013. Final Hydrogeological Assessment, Cowal Gold Mine, Extension Modification. September.	www.evolutionmining.com.au/wp-content/uploads/2015/08/Appendix-A-Hydrogeological-Assessment.pdf
Mapping Acid Mine Drainage at an Abandoned Mine Site in Ottawa County, Oklahoma Using 3D Electrical Resistivity Tomography	2015		■					Bridge, Cas F., Bizzell, Karson R., and Ramachandran K., 2015. Mapping Acid Mine Drainage at an Abandoned Mine Site in Ottawa County, Oklahoma Using 3D Electrical Resistivity Tomography. March.	NA
Gold King Mine – A Case of Russian Roulette With an Inevitable Outcome. Arizona Daily Independent	2015						■	Briggs, David F. 2015. Gold King Mine – A Case of Russian Roulette With an Inevitable Outcome. Arizona Daily Independent. September 3.	https://arizonadailyindependent.com/2015/09/03/gold-king-mine-a-case-of-russian-roulette-with-an-inevitable-outcome/
Opekiska Pool Study - Monongahela River	NA		■	■				Bryant, G., Opekiska Pool Study - Monongahela River. USEPA Region III.	http://www.netl.doe.gov/publications/proceedings/99/99apprvr/ar7-4.pdf
Review and interpretation of previous work and new data on the hydrogeology of the Schwartzwalder Uranium Mine and vicinity, Jefferson County	2011	■	■					Caine, J.S. Johnson, R.H., and Wild, E.C., 2011, Review and interpretation of previous work and new data on the hydrogeology of the Schwartzwalder Uranium Mine and vicinity, Jefferson County.	NA
Application of Geophysics to Acid Mine Drainage Investigations	1994	■	■	■				California Department of Conservations, Office of Mine Reclamation. 1994. Application of Geophysics to Acid Mine Drainage Investigations. September.	http://nepis.epa.gov/Exe/ZyNET.exe/2000DHEY.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1995+Thru+1999&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C95thru99%5CTxt%5C00000002%5C2000DHEY.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=p%7Cf&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL
Abandoned Mine Lands Preliminary Assessment Handbook	1998		■					California Environmental Protection Agency, Department of Toxic Substances Control (DTSC). 1998. Abandoned Mine Lands Preliminary Assessment Handbook. January.	https://www.dtsc.ca.gov/SiteCleanup/Brownfields/upload/aml_handbook.pdf
Guidelines for Planning and Implementing Groundwater Characterization of Contaminated Sites	2012		■					CA DTSC. 2012. Guidelines for Planning and Implementing Groundwater Characterization of Contaminated Sites. June.	https://www.dtsc.ca.gov/PublicationsForms/upload/Guidelines_for_Planning_and_Implementing_GW_Characterization_of-Contam_Sites.pdf
Well Design and Construction for Monitoring Groundwater at Contaminated Sites	2014		■					CA DTSC. 2014. Well Design and Construction for Monitoring Groundwater at Contaminated Sites. June.	https://www.dtsc.ca.gov/PublicationsForms/upload/Well_Design_Constr_for_Monitoring_GWContam_Sites1.pdf
Management and Control of Abandoned Mine Pool Discharges-Pennsylvania Case Studies Workshop. 29th Annual NAAMLP Conference	2007			■				Cavazza, E.E., Beam, R.L. 2007. Management and Control of Abandoned Mine Pool Discharges-Pennsylvania Case Studies Workshop. 29th Annual NAAMLP Conference. October.	http://files.dep.state.pa.us/Mining/Abandoned%20Mine%20Reclamation/AbandonedMinePortalFiles/Publications/AMLRelatedTechnicalPapers/Mine_Pool_Workshop-2007.pdf
Coal Extraction—Environmental Prediction. Fact Sheet 073-02	NA				■			Cecil, C.B., Tewalt, S.J. Coal Extraction—Environmental Prediction. Fact Sheet 073-02. U.S. Geological Survey.	http://pubs.usgs.gov/fs/fs073-02/fs073-02.html
Final Hydrogeological Assessment Cowal Gold Mine Extension Modification	2013	■	■					Coffey Geotechnics. 2013. Final Hydrogeological Assessment Cowal Gold Mine Extension Modification. September.	http://www.evolutionmining.com.au/wp-content/uploads/2015/08/Appendix-A-Hydrogeological-Assessment.pdf
Best Practices in Abandoned Mine Land Reclamation	2002		■	■				Colorado Division of Mineral and Geology. 2002. Best Practices in Abandoned Mine Land Reclamation.	http://mining.state.co.us/SiteCollectionDocuments/AMLbmp.pdf
Summary of Minutes, Mined Land Reclamation Board Meeting	2004	■						Colorado Division of Reclamation Mining. 2004. Summary of Minutes, Mined Land Reclamation Board Meeting. November.	http://mining.state.co.us/SiteCollectionDocuments/nov04sum.pdf
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