ADTI-MMS Sampling and Monitoring for the Mine-life Cycle[1]

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ABSTRACT

Water quality is an environmental concern at many mines. The Metals Mining Sector of the Acid Drainage Technology Initiative (ADTI-MMS) addresses technical drainage-quality issues related to metal mining and metallurgical operations for future, active, and historical mines, and mining districts. One of the projects of ADTI-MMS is to develop a handbook describing the best scientific and engineering practices for sampling, monitoring, predicting, mitigating, and modeling of mining-influenced waters draining from metal mines, pit lakes and metallurgical facilities. The handbook, titled "*Sampling and monitoring for the mine-life cycle*," emphasizes that one of the important aspects of planning a new mine in today's regulatory environment is the approach in designing sampling and monitoring programs to account for all aspects of the mine-life cycle. This paper summarizes this handbook. Data required for the closure of the operation are obtained throughout the mine-life cycle, from exploration through post-closure. Some of the most commonly used sampling and monitoring techniques are discussed, along with opinions about which techniques provide the best data.

Key Words: acid drainage, mining-influenced waters, MIW, mine-life cycle

INTRODUCTION

Water quality is a major environmental concern at many mines. Depending on the contaminants, their concentration, and their contact with living organisms (receptors), water has the potential to harm plants, aquatic organisms, or other animals, including humans. Deposits that most typically cause drainage-quality problems are base- and precious-metal deposits, uranium deposits, and high-sulfur coal deposits, although certainly not all deposits produce water-quality problems and other types of deposits, even some industrial mineral deposits, can exhibit poor drainage quality.

Whether a mining operation will produce poor-quality water depends on, for example, the mineral composition of the disturbed rock, physical characteristics of the deposit that could promote or inhibit weathering of problematic minerals, mining methods, and remediation. Confirmation of environmental protection relies on numerous forms of sampling of fluids and solids. For this reason, it is important to conduct proper sampling and to monitor appropriately.

Problematic mine drainage is given many names including acid rock drainage (ARD), acid mine drainage (AMD) and mining influenced waters (MIW), among other names. Generally speaking, the distinction between ARD and AMD depends upon whether drainage quality has been degraded by mining or is of poor quality due, in part, to natural causes. These two terms best describe acidic, high Fe, high sulfate waters from mines where Fe sulfides have weathered in the presence of oxygen and water to form acid/metals drainage. MIW (Schmiermund and Drozd, 1997) is the preferred term used to refer to all mining-related waters because acidic, neutral, and alkaline waters can all transport metals and other contaminants.

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This paper describes an approach and guidance on the design of sampling and monitoring programs, which will be presented in more detail in the Acid Drainage Technology Initiative (ADTI) handbook, entitled "*Sampling and monitoring for the mine-life cycle*." This paper, a summary of the ADTI handbook, provides awareness of the critical components and complexities of sampling and monitoring at mining sites; it is not intended to be an in-depth and exhaustive presentation of the subject. ADTI is a coalition of government agencies, industry, academia, and consulting firms whose mission is to identify, evaluate, and develop cost-effective and practical AMD treatment technologies and to address other drainage-quality issues related to mining (Hornberger et al., 2000; Williams, 2003; McLemore, 2008).

SAMPLING AND MONITORING APPROACH

At present, there is no single authoritative guide or manual for evaluating the best sampling and monitoring techniques for situations involving MIW. Over the past 30 years, numerous sampling and monitoring techniques have been developed throughout the world (Popeck, 2003; Schreuder et al., 2004; Downing, 2008). The holistic approach suggested here endorses the belief that sampling and monitoring programs be designed to account for all aspects of the mine-life cycle, from exploration (Hartman, 1992), through feasibility studies, into mine planning, actual mining, reclamation, and closure. For example, it is important to ensure that the samples and data quality collected during the exploration phase also are acceptable for subsequent environmental modeling and prediction studies, and that the data can be used for the program leading towards remediation and mine closure. In brief, before sampling, it is necessary to anticipate and incorporate data needs that will be required during later stages of the mine-life cycle.

WHY SAMPLE?

A sampling and monitoring program can be the driving force for practical decision making at a mine site, especially with respect to environmental and financial risks. Sampling and monitoring plans are written documents that outline procedures to ensure that samples, analytical data, and scientific interpretations are sufficient to meet the goals and objectives of the program. Sampling provides values for parameters and attributes that are representative of larger entities (including spatial and/or temporal) that are required to make decisions. Sampling strategies should be site specific and consider site characteristics such as geology, uniformity of the sample media, size of sample media, access, etc. Numerous sampling and monitoring plans are utilized during the life of a mine to address different issues, and it is important to keep records of each plan in such a way that data can be evaluated and used for purposes other than what was initially intended. For example, modeling of ground-water flow could require water chemistry data that were obtained during the exploration stage. Similarly, chemical analyses of bench samples of blast holes during open-pit production could be utilized in characterizing the mine-waste piles for reclamation.

Monitoring and assessment of data are usually conducted to answer specific questions about potential environmental problems (Harrison, 1998). Data quality objectives (DQOs) for monitoring must be tailored to each specific site in order to answer these questions. Data-quality objective process to develop a sampling and monitoring program is summarized in Figure 1.

SAMPLING AND MONITORING PROGRAM

There are different objectives in a program for an undeveloped, new site as compared to an abandoned site. For a new property, an objective is certainly to determine whether reclamation and closure are possible, or whether the deposit should not be developed because of environmental risks. Many sampling and monitoring programs are frequently imposed and technically constrained by regulation, whereas other programs are necessary as part of the mine operations. For an abandoned site, closure has already occurred and the objectives include whether this site can be reclaimed in a reasonable and economic manner. Also it is important to understand and define the differences between university research studies and regulatory programs. Some programs are suitable for academic research conducted by a university, whereas other studies are for achieving regulatory requirements.

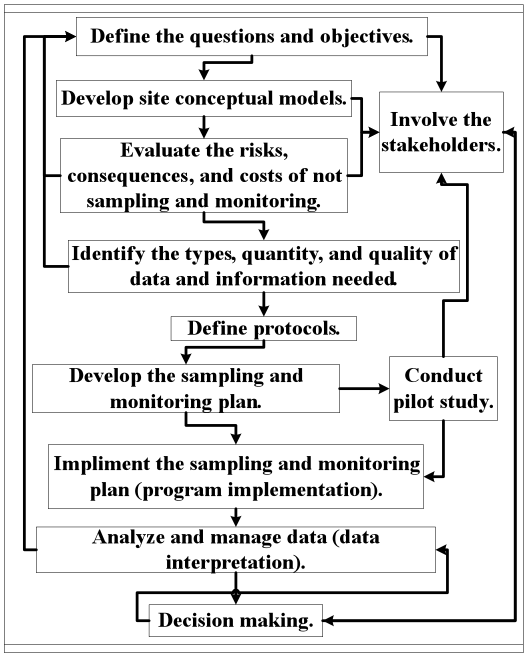

Figure 1. Data-quality-objective steps for implementing a sampling and monitoring program (modified from McLemore et al., 2004, 2007).

Define the questions and objectives

The first stage before undertaking a sampling and monitoring program is to determine why this sampling effort is needed. Collecting samples and conducting a monitoring program takes significant time, manpower, and money. Typically, samples are collected to assess the risks from MIW to aquatic life, wildlife, or humans or to meet some regulatory requirements. Some environmental problems are complex combinations of technical, economic, social, and political issues, and it is critical to separate each issue, define it completely, and express it in an uncomplicated format. A well-structured planning team needs to be identified, and should be comprised of the technical experts and stakeholders participating in the program.

As the questions to be answered are defined, the quality of the data collected needs to be determined. The more specific the question and the better the data quality objectives (DQOs) are, the more useful the information is in making decisions. All available data from the site should be examined, including published literature and data, which are not always in electronic form. For example, if the project goal is to establish a trout fishery by remediating abandoned mines, the objectives could be to 1) collect baseline water-quality data in a stream, 2) determine and assess contamination loads from mining sites, 3) evaluate the effectiveness of the remediation activities, and finally, 4) resample the in-stream water quality to see if the water quality is improving.

Involve the stakeholders

The stakeholders (i.e., all interested parties) should be involved throughout the project to maintain transparency. Stakeholders can help identify the purpose of the program, identify specific sites that should be sampled or monitored, and assist in obtaining access to private land. Adverse public perceptions can be avoided if the stakeholders are informed throughout program. It also is important to involve other scientists to ensure their data requirements are met. For example, if modeling is to be conducted, the modelers need to be involved at the beginning of the project to define their data requirements. Modelers should spend some time in the field to ensure they understand the site-specific issues and data-acquisition procedures.

Develop site conceptual models

The next component of a sampling and monitoring program is to develop conceptual models for the site. Generally more than one conceptual model is beneficial in describing the site conditions and identifying possible sources of pollutants, release mechanisms, exposure pathways, and environmental receptors (McLemore and the Questa Rock Pile Weathering and Stability Team, 2008). Also, conceptual models can identify data-information gaps and the need for additional types of analyses. The steps for developing a conceptual model are described below.

Site conditions and source characterization

It is important to initially define the site conditions, including climatic conditions, physical characteristics (topography), geology and hydrology, water balance, type of ore deposit and associated alteration, potential receptors, and mining and processing methods. Sampling and monitoring plans are generally dependent upon understanding site conditions, which vary from site to site. Detailed written field and mapping notes during field activities are critical. Source characterization includes an inventory and review of existing source data and, if necessary, collection of additional data. This information can help to identify likely contaminants, and the location and approximate size of sources known to have released contaminants. Mining history and photographs can be useful in establishing premining conditions. Outcomes of this step include determining possible contaminants and pinpointing their likely sources. It is good practice to determine the quality, reliability, and limitations of the available data.

An example of a useful approach for predicting site conditions at mining sites is the use of geoenvironmental models (GEMs), which are descriptive models of the environmental behavior of different mineral-deposit types (Plumlee et al., 1999). GEMs can be effectively used to guide the acquisition of data, highlight potential environmental challenges associated with particular types of mineral deposits (which impacts permitting, developing, and closing mines), and serve as a reality check for modeling efforts.

Pathway delineation

Pathway delineation involves the quantitative assessment of release mechanisms, and transport and migration from contaminant sources to potential biological receptors. One could begin by compiling a list of possible contaminants and sources derived from site characterization, and then assembling existing information on contaminated media, contaminant migration, and the geographical extent of current and potential contamination. Physical characteristics of transport are important to consider when determining the extent of contamination. An understanding of the controlling geochemical reactions also is important. It is useful to identify any habitats that are known to be contaminated or located within, between, or down gradient of areas of known contamination. Additional details one could consider at this step are information about sensitive species or critical habitats, location of potential deposition areas for contaminated soils and sediments (e.g., bends in rivers), and identity of other types of hot spots. Metals fate and transport modeling in streams and watersheds is frequently a tool needed for assessment and restoration of surface waters (Caruso et al., 2008).

Once the contaminants of concern for ecological or human health are identified, it is important to determine the extent of contamination in onsite and offsite media. It is helpful to put this information into the context of potential exposure pathways, bioavailability, and background levels of the contaminants. Knowledge of the attributes of a contaminant is very helpful in understanding its behavior in the environment (Smith, 2007). Examples of such attributes include 1) physicochemical properties (e.g., volatility, solubility, persistence), 2) bioavailability (i.e., presence in a form that can adversely affect organisms; Smith et al., 2006), 3) potential for bioaccumulation or bioconcentration, 4) toxicity (i.e., the amount of toxicant capable of producing adverse effects in organisms; Wildeman et al., 2007), 5) time necessary to produce adverse effects, and 6) types of effects (e.g., synergistic effects).

Field validation

Field validation is an important step to evaluate reliability of a conceptual model. This step also assists in setting the boundaries of what can be monitored and what assumptions need to be documented. Field validation involves field reconnaissance and observations to determine any incompatibilities with the conceptual model.

Evaluate the risks, consequences, and costs of not sampling and monitoring

The objective of sampling and monitoring is to address potential environmental risks in a cost-effective manner and to minimize potential liabilities. Evaluation of the costs and potential consequences of not sampling and monitoring can be considered a type of cost/benefit evaluation or mining operation risk analysis (such as from a banking or insurance company perspective). Throughout the mine-life cycle, balancing the costs and benefits of monitoring are advised. For example, monitoring of background and baseline conditions during the exploration phase can provide the first important assessment of whether the mine site can be reclaimed and closed if it is developed. Monitoring during design can provide better operating procedures, which can minimize environmental and bonding costs. Monitoring during mining can identify problems before they become major issues and while there is a cash-flow to mitigate such issues. Finally, post-mining monitoring can minimize long-term costs and expedite bond release.

The planning and operational risk to a mining company is based upon the reliability of the data compared to the importance or value of the ecological, regulatory, or economic component being studied. The mining profession estimates mineral resources as Measured or Proven, Indicated or Probable, and ore reserves as Inferred or Possible after technical and economic feasibility has been established, and is based not just on the volumes and grades of the ore, but also on the amount and reliability of the data. In a similar manner, planning and operational risks can be placed in perspective based on the value placed on the potentially impacted part of the environment and the reliability of the data. Figure 2 presents a reliability matrix that can be used to assess the degree of knowledge and variability of data to determine risks for a mining site.

Environmental risk analyses for closure based on unreliable data can be under-protective or overprotective of ecosystems, with the result that there are added cost penalties on society or on industry to achieve these levels of protection. Some risks are potentially so serious, and the time for recovery so long, that risk reduction actions should be viewed as a kind of insurance premium and initiated in the face of incomplete and uncertain data. The risks entailed in postponing action can be greater than the risks entailed in taking inefficient or unnecessary action. In short, the only way to decrease one's exposure to risk is to increase the reliability of the data or to decrease the risk using risk-management practices.

VARIABILITY	**High**	Low	Low	Medium
	Medium	Low	Medium	High
	Low	Medium	High	High
		Low	**Medium**	**High**
		KNOWLEDGE		

Figure 2. Reliability matrix (developed by V.T. McLemore, M. Logsdon, and D. van Zyl for the Questa project, November 2008).

Identify the types, quantity, and quality of data and information needed

Prior to beginning a sampling and monitoring program, it is necessary to define the reasons for sampling, the questions to be answered, and the desired degree of confidence in the answer(s). Inherent in this process is defining the types of data to be collected, the methods of collection, and how the data will be analyzed and interpreted. There are four main groups of sampling media (liquid, solid, biological, and air) that can be considered by a sampling and monitoring program. The types of media sampled will be determined by the anticipated sources, transport mechanisms, and receptors impacted by mining, as well as other parameters, such as climate and regulatory requirements. It could be helpful to consider use of indicator species, either aqueous or biological, to provide an early-warning system for potential contamination problems. The types of variation in sample, i.e. spatial and temporal, must be addressed.

Since new data collection can be expensive and time consuming, it is important to conduct a literature review of all existing data and information concerning the site. This is a step that is often overlooked or cut short. These data are not limited to just the mining company and their consultants, but can include data from state and federal government agencies, environmental groups, universities, and other groups.

Sampling methods are the procedures of selecting those sampling units that provide estimates of the whole with associated margins of uncertainty. Poor sampling can introduce sample bias as well as lack of precision. Uncertainty arises because you are examining only a part and not the whole. For example, selecting a specific sample size fraction in characterizing waste rock piles becomes important and a bias can be introduced because the acid-generating and acid-neutralizing minerals are not evenly distributed in the various size fractions. Similarly, surface sampling of pit lakes can underestimate the contaminant loads if the pit lake is stratified with respect to dissolved constituents. In such cases, replicate sampling or increasing sample size will not correct the bias.

Figure 3 presents several sources of uncertainty. The target population is that which is being sampled, and is defined based on the objectives of the study. It is important that the target population be clearly identified in detail at the beginning of the study. A sample is a *representative* subset of the target population that is actually collected during a study. For example, concentrations of stream-water constituents often fluctuate seasonally; therefore, water samples should be collected seasonally to be representative of year-round stream conditions.

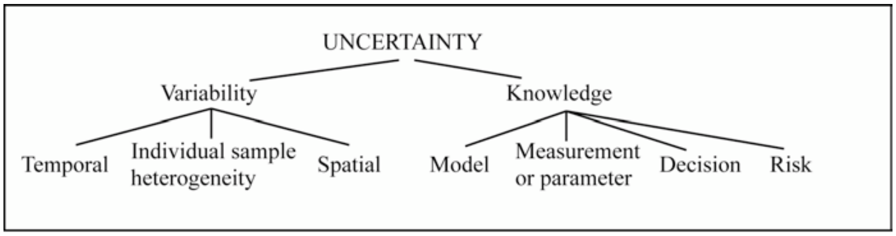

Figure 3. Component sources of knowledge uncertainty (modified from Haimes, 2004).

The desired degree of certainty for the study results also must be decided at the inception of the study. A low degree of certainty in the data can lead to erroneous interpretations and flawed decisions, but a higher degree of certainty generally requires more sampling and higher costs. Among other things, heterogeneity in sampling media introduces sampling error, which is the lack of precision of sample estimates of the target population. Pitard (1993) and Popek (2003) provide a detailed discussion of the estimation of sampling errors, which locally can be minimized by collecting multiple samples or larger samples. Hence, heterogeneity of the sample medium will impact the sampling design, and likely the sampling costs.

Documentation of measurements of precision and accuracy need to be incorporated into every sampling and monitoring program. Precision describes the reproducibility among repeated measurements of the same variable or parameter. Generally, replicate samples or measurements are collected to determine precision in a sampling and monitoring program. Standards also can be determined repeatedly to obtain a measure of precision. Accuracy is independent of precision and is a measure of how close the results are to a true or accepted value. Accuracy can be determined by comparative sampling and/or analyses, or by measuring certified standard materials using the same methods as used in the study. Comparability is the extent to which data can be compared directly between sample locations or periods of time within a project or between projects. Using standardized sampling and analytical methods, and standardized units of reporting with comparable sensitivity helps ensure comparability. For example, if one study collects a particular size fraction of waste material, the same fraction should be collected in a subsequent study to ensure the data are comparable.

Define protocols and standard operating procedures

Protocols are written procedures of practices and methods used in sampling, monitoring, analytical techniques, and data management. Protocols include methods of sampling, sample collection, sample preservation, sample preparation, sample decomposition, sample analysis, sample storage/archival/disposal, data analysis and interpretation, and data management/ archival. Protocols are typically media specific and often are formalized as standard operating procedures (SOPs). It is always important to document any deviations from standard methods.

Develop the sampling and monitoring plan

Once all the preliminary data and information have been collected, it is time to design the sampling and monitoring plan. At this stage the questions and objectives have been defined, the conceptual model has been developed, the types of media and protocols have been chosen, the confidence levels with appropriate quality assurance recognized, and the budget established. An example of an outline of a sampling and monitoring plan is in Table 1. Additional items that could be included in a sampling and monitoring plan are 1) a formal statement of the purpose of the sampling, 2) a formal statement of assumptions, 3) a list of the parties responsible for implementing each step of the plan, 4) a signed confirmation of participants and their responsibilities in the plan, 5) a formal health and safety plan, 6) an annual schedule of activities, 7) description of the QA/QC (Quality Assurance and Quality Control) procedures, and 8) documentation of arrangements made for access to sampling locations. Allow for unexpected delays, such as training of personnel, change in personnel, ordering and shipping of materials, equipment malfunctions, and adverse weather conditions.

Table 1. Sampling and monitoring plan outline.

Project Management	Project Organization/responsibilities
	Problem Identification
	Data Quality Objectives
	Training Requirements
	Documentation
Data Acquisition and Management	Sampling Design and Methods of collection
	Sample Handling and Custody
	Analytical Methods
	Quality Control Requirements
	Instrument/Equipment Testing, Inspection, and Maintenance
	Data Management
Data Validation	Validation and Verification Methods
	Data Review, Validation, and Verification
	Correspondence with Data Quality Objectives

Conduct pilot study

Conducting a pilot study, a screening test, or orientation survey consists of a series of preliminary experiments prior to conducting the final plan to work out any difficulties or problems that could arise. After conducting the pilot study, it is important to consider what worked and modify the plan, including the protocols, if necessary.

Implement the sampling and monitoring plan (program implementation)

There are basically three steps in implementing the sampling and monitoring plan, also known as program implementation: sampling, analysis, and interpretation. These appear to be independent, but in reality they are interdependent functions. If problems are encountered at the sampling step, all efforts in the succeeding steps can fail. The sampling stage is probably the most important and most difficult to correct once the samples are collected. Therefore, it is imperative that the initial stages previously discussed are well thought out and implemented before samples are collected. Field personnel must adhere to all appropriate protocols.

Analyze and manage data (data interpretation)

Data analysis or interpretation is an integration of the purpose for sampling and monitoring, philosophy of approach, and knowledge of the quality and nature of the data to be interpreted. In theory, data should be collected until the cost equals the benefit derived from those data. Everything needs to be documented, from field studies to modeling runs. Computers are ideal to electronically capture, store, distribute, annotate, display, and disseminate the extensive data collected at mine sites. Data can be stored, processed, transferred, and retrieved using four major types (Computer-aided drafting or CAD software, Geographical Information System or GIS software, Database Management Systems or DBMS, Word processing (WP) software). One of the most effective tools to enter, store, report, and utilize these data are by relational databases. The fields used in the database must be fully explained and documented as metadata. Metadata documents contains information on methods used, sources of data, and any pertinent information that would call into question the data collected, including special handling procedures.

Decision making

In general, decision-making follows a six-step format: 1) formulate the problem (question) to be answered, 2) analyze the risks, 3) define the options or alternatives, 4) make sound decisions, 5) take actions to implement the decisions, and 6) perform an evaluation of the effectiveness of the actions taken. Most decisions based upon data from sampling and monitoring programs are made to avoid risks, reduce risks, reduce the consequences of events, or insure against the financial consequences of risks. Risk assessment is a combination of the probability of an event, usually an adverse event, and the nature and severity of the event (Haimes, 2004). Risk management is what is done to minimize the impacts of the existing or potential risks. Making decisions is, therefore, part of the process of risk management. Finally, the data, interpretation, results, and the decisions should be disseminated in reports and presentations.

SUMMARY

The holistic approach summarized here endorses the belief that sampling and monitoring programs be designed to account for all aspects of the mine-life cycle, from exploration, through feasibility studies, into mine planning, actual mining, waste-rock handling, reclamation, and closure. Sampling and monitoring plans are written documents that outline procedures to ensure that samples, analytical data, and scientific interpretations are sufficient to meet the goals and objectives of the program. An eleven-step data-quality objective process to develop a sampling and monitoring program is summarized in Figure 1.

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