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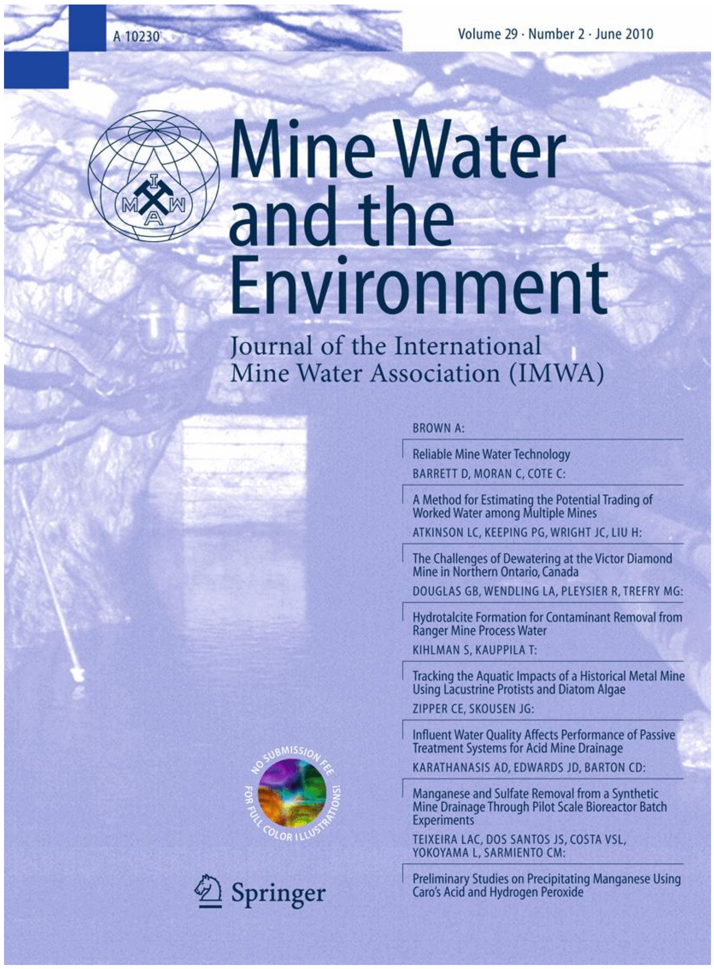

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TECHNICLE ARTICLE

Reliable Mine Water Technology

Adrian Brown

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Abstract Mine planning, permitting and operation require reliable water technology in all its aspects: water inflow, water use, water disposal and discharge, and water impact. Mine water evaluations are relied upon by mining companies, mine regulators and the public to determine whether the mine is technically feasible, optimally designed, financially sound, socially acceptable, and environmentally benign. Review of the water management performance of mines world-wide indicates that the results obtained from mine water evaluations are frequently unreliable. The magnitude of error is often significant, and the direction of the error is usually to underestimate mine inflow, water usage, water contamination, water discharge, and/or environmental impacts. Examples of mine water evaluations where the results have proven to be unreliable were used to formulate and illustrate a set of general principles that should be applied to every mine water evaluation to ensure that the results reflect the full range of possible outcomes, with that range centered on the most likely outcome. Mine water evaluations performed using these principles can be demonstrably reliable, credible to all of the mine stakeholders, and improve the profitability, public acceptance, and environmental protection of mining projects.

Keywords Acid rock drainage · Dewatering · Inflow · Geochemistry · Reliable and relevant science · Reliability · Professionalism

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A. Brown (✉)
Adrian Brown Consultants, Inc, 130 West 4th Ave, Denver, CO, USA
e-mail: abrown@abch2o.com

Introduction

Mine planning, permitting, and operation require reliable water technology in all its aspects: water inflow, water use, water disposal and discharge, and water impact. Mine water evaluations performed to provide water management plans and operations are the domain of mine water technologists, for which the International Mine Water Association is the world-wide representative organization.

Most mines producing more than a few tonnes (t) a day of ore have a water management plan, and operate within mining, water rights, and environmental regulations. As a result, mine water evaluations are relied upon by mining companies, mine regulators, and the public to determine whether the mine is technically feasible, optimally designed, financially sound, socially acceptable, and environmentally benign.

Review of the water management performance of mines world-wide indicates that the results obtained from mine water evaluations are frequently unreliable. The magnitude of error is usually significant, in that if the correct result had been obtained, different mining methods, water management systems, and permitting decisions would have been made. Finally, and importantly, the direction of the error is almost always to underestimate mine inflow, water usage, water contamination, water discharge, and/or environmental impacts.

This paper has two objectives:

- To evaluate why mine hydrology evaluations are frequently unreliable; and
- To recommend methods to facilitate improvement of the reliability and credibility of the determinations in mine water technology.

Reliability of Mine Water Evaluations

The actual reliability of mine water evaluations is difficult to determine. Review of papers in Mine Water and the Environment and its predecessor publication disclose few examples of incorrect mine water evaluation. This is not surprising; there is little incentive to publish unsuccessful project outcomes. However, it is clear from the number of reported mine water failures in the popular and mining press that many mine water evaluations are sufficiently in error that projects were allowed to proceed in ways that resulted in unforeseen and unacceptable economic, safety, and environmental results. This can be seen in evaluations covering the entire spectrum of mine water technology. Examples in four mine water areas are presented to illustrate the cause and results of unreliable mine water determinations.

Mine Inflow

Mine inflow predictions are an important component of mine design, mine permitting, and mine operation. Frequently, mine inflow constitutes the majority of the water handled by a mine, and dewatering, treatment, and disposal are major cost and environmental issues.

As part of the initial design and environmental evaluation of a major diamond development in the Canadian north, a mine inflow evaluation was performed. The mine exploits a number of vertical kimberlite pipes beside a major lake in the region. The evaluation concluded that a relatively modest inflow of less than 5,000 m^3/day could be expected in the fully developed mine (Canada 1999).

The mine design and water management system were based on this low inflow estimate. A surface mine strategy was selected to mine the upper portions of the deposit, changing to underground methods when the stripping ratio became economically unattractive. It was also concluded that the quality of the water that would be discharged to the lake from the project would in general be good, and in particular would meet stringent chemical limitations for discharge of project water into the pristine lake. Accordingly, the developer committed to limiting the concentration of total ammonia in an average discharge of 2 ppm.

Within two years operation, the flow had reached more than three times the predicted rate, and was expected to increase to eight times the predicted rate with further mine development. The reason for the underestimate of inflow was the failure to identify or consider the effect of the permeable, 100 m wide vertical Dewey's Fault zone that connects the principal kimberlite pipe with the nearby lake (Fig. 1).

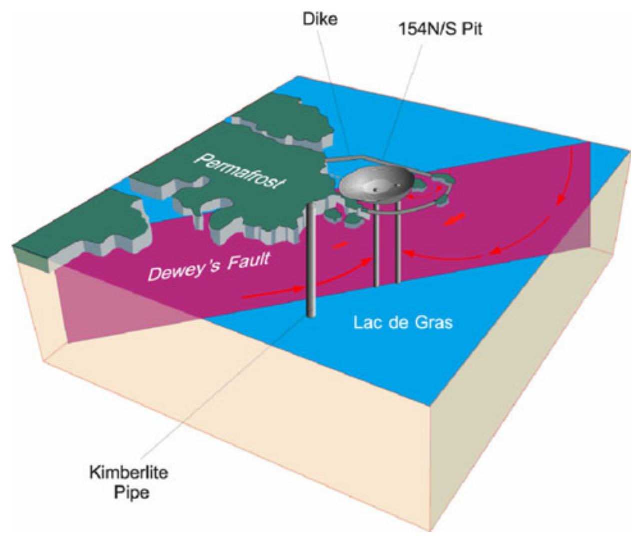

Fig. 1 Diamond mine showing permeable fault (WLWB 2007)

The high inflow posed problems for the mine:

- Higher mine dewatering flows, resulting in excessive pumping costs.
- Higher discharge of waste water to the lake, making environmental protection treatment prohibitively expensive.
- Mining was conducted under wet bench and flooded blast-hole conditions, resulting in partial dissolution of the large quantity of ammonium nitrate/fuel oil emulsion used for blasting.
- Rapid exceedance of ammonia concentration limits in the discharge, requiring petition to the regulatory agency to allow a tenfold increase in the ammonia discharge limit.

Review of the mine operation, water management system, and ammonia management plan (WLWB 2007) indicates that if the mine inflow had not been misjudged, it should have been determined at mine design and regulatory review time that an underground mining strategy would be more economical and environmentally attractive for this deposit. This would have:

- Eliminated the mining of overburden.
- Minimized ANFO use and discharge of ammonia to the lake.
- Largely eliminated surface disposal of potentially acid-generating waste rock.
- Offered the developer the option to control mine inflow by grouting or freezing the small volume of fault rock around the kimberlite pipes.

Mine Dewatering

Large surface mines frequently require significant dewatering to allow access to the ore body for excavation. For projects set in permeable rocks, and/or near large bodies of water (surface or ground water), there is a potential for large dewatering flows to occur. The removal and disposal of this water can have significant impacts on the feasibility of the mining project, and on the environmental and water resource impact of the project. Accordingly, it is important that a reliable dewatering study be performed prior to implementation, so that full economic, environmental, and resource evaluation can be made of the dewatering required for development.

A large gold ore body was proposed for development in the eastern Nevada desert in the early 1990s. The new discovery extended to a depth of over 500 m below ground surface in a highly permeable, saturated limestone/dolomite rock mass. Early dewatering of a shallow surface mine in the area required a flow on the order of 70 L/s to reduce the water level in the aquifer 2 m. Extensive studies of the groundwater system were performed, and groundwater flow models were prepared to determine the dewatering requirements for mining. It was concluded that dewatering would require extraction of 850 L/s. This value was used for mine planning, mine economics, and mine permitting (BLM 1992).

The mine permitting process involved the preparation of an Environmental Impact Statement under the US National Environmental Policy Act (NEPA) by the Bureau of Land Management (BLM 1992). This process included an evaluation by the BLM of the mine dewatering flow estimated provided by the mine proponent, and a review of the acceptability of the water resource, environmental, and economic impacts of dewatering and disposal. The mine was permitted based on the original dewatering flow estimate.

Early in the development of the mine, it became apparent that the dewatering estimate was incorrect. By 1994, the flow from the mine was approximately 4,400 L/s, more than 5 times the original estimate, and increasing (White and Kral 1994). Application was required to the regulatory agencies to allow production and disposal of the greatly increased flow. The dewatering underestimate had substantial implications for mining costs, water treatment, water discharge, environmental impact, mitigation, and water resource utilization.

Slope Stabilization

Mine slopes are frequently stabilized by reducing water pressure in the materials forming the slopes. Mine water evaluations are required to determine the stability of the slopes and to establish safe water pressure requirements for given slope geometries.

In November 2007, a slope of a major Australian coal mine failed (Sullivan 2008). The failure involved movement of 6×10^6 t of coal and overburden up to 250 m into the mine. A copy of a photograph of the failure is available as an electronic image at the Springer site (accessible for free for all IMWA members); the resolution is not sufficient to reproduce it here in this journal. The failure diverted the local river into the mine, destroyed mine equipment, interrupted coal supply to local power stations, impacted regional electrical power supply, and placed personnel at risk. Fortunately, the failure occurred at 2 a.m. when the mine, while operating, was lightly staffed, and no injuries or fatalities resulted.

Prior to the failure, studies had been conducted that supported the cessation of long-established water pressure control techniques in the mine slope. Depressurization of the slope using horizontal drains, and dewatering of underlying aquifers using vertical wells was therefore terminated (Sullivan 2008; The Age 2009). When signs normally associated with incipient failure were observed in the mine wall (including large scale earth movement and inflows through fissures of up to 500 L/s of water), these evaluations were revisited by additional investigators, who also concluded that the slope was safe and would not fail.

Acid Rock Drainage

Development of mine deposits that contain sulfide minerals presents the possibility that exposure of the sulfides to air by mining processes will result in oxidation, acid production, and metal mobilization to surface and groundwater. This process is frequently described as acid rock drainage (ARD).

ARD evaluations for 71 large mines on public lands in the United States have been presented as part of environmental impact statements under the US National Environmental Policy Act (NEPA). The mines include all important metal mining sectors (gold, silver, copper, platinum group metals, molybdenum, lead, and zinc) and ten mining states (Alaska, Arizona, California, Idaho, Montana, New Mexico, Nevada, South Dakota, Utah, and Wisconsin). An evaluation has been performed to determine the accuracy of the water quality predictions in these environmental impact statements (Kuipers et al. 2006). The study selected 25 of the mines, and compared mine water quality predictions for surface water, groundwater, and mine drainage with actual water quality conditions during and after mining. The selection of these sites was based on proving a range of mineral types and locations, and upon availability of data during mining. The study does not evaluate whether the 25 selected sites are representative of the total sample.

All the environmental impact statements predicted that water quality during and after mining would be acceptable within the then-current regulatory requirements at the mine's location. The reported results of impacts experienced during and after mining were:

- 76% of all mines exceeded surface and/or groundwater quality standards;
- 93% of those mines with elevated potential for acid drainage exceeded water quality standards, and;
- 89% of the sites that did develop ARD had predicted that they would not.

The authors of the study conclude that the reasons for this high rate of predictive failure include:

- Inadequate hydrologic and/or geochemical characterization;
- Inadequate or incorrect application of models to predict future chemistry;
- Failure to compare predictions to actual outcomes, and correct predictive methods, and;
- Bias in mine water quality predictions made by organizations paid for by the mine operator.

Sources of Uncertainty in Mine Water Evaluations

Mine water evaluations are uncertain for what generally fall into five categories:

Highly Variable and Poorly Defined Parameters

High variability and poor definition of parameters is a source of uncertainty for evaluations in each of the technical areas of mine water evaluations:

- Surface water. Precipitation, runoff, infiltration, evaporation, pumping rates, and flow measurements are often critical to mine water evaluations. All have high uncertainty, particularly because the data are often collected in remote mining project locations, and because it is very difficult to measure long enough and frequently enough to capture or allow estimation of the extreme precipitation and flow conditions that drive mine water evaluations, and subsequently cause failures.
- Groundwater. Ore bodies are usually geologically and hydrologically anomalous, so groundwater evaluations for mines are correspondingly complex. Hydrogeologic systems are difficult to define, expensive to investigate, and tests frequently produce highly variable and sometimes conflicting results. The parameters of those systems, including hydraulic conductivity, storage, dispersion, head, piezometric pressure, gradient, infiltration, and aquifer geometry, are difficult and expensive to define, and the results are highly variable.
- Geochemistry. Most ore bodies are also geochemically anomalous. Accordingly, in mine water hydrogeochemistry, reactions, thermodynamics, and kinetics are often complex and poorly defined; parameter testing is expensive, highly variable, often inconclusive, and contentious; application of test results to mine water evaluation is difficult, and analysis often requires evolving and unproven technology.

Analytical Complexity

Mine water evaluations almost always require computation of outcomes using analytical methods that are complex. Tools are used from many technical areas, including hydrodynamics, fluid mechanics, geology, chemistry, rock mechanics, soil mechanics, thermodynamics, and statistics. Analysis methods are frequently complex, often relying on computers to perform numerical analysis of the complicated processes and interactions that determine behavior.

These powerful analysis methods are in general difficult to set up, use, and verify, and it is difficult to check the results. In general, the person performing an analysis did not develop the analytical tool, and does not have a detailed understanding of its technical basis, its solution algorithm, or its limitations. As a result, misuse, misinterpretation of inputs, misinterpretation of outputs, and erroneous results from the use of these complex analytical tools is common. And for the same reasons, such errors are difficult to identify during review.

Investigation Pressures and Limitations

Mine water evaluations are often performed during the exploration or developmental phase of the mine, frequently in support of mine feasibility, mine engineering, and/or mine permitting. Access to the site is often limited, and information-gathering on the site is frequently in its infancy. This investigation setting leads to many issues:

- Lack of resources. Early in projects, resources are limited, and are generally directed mainly towards ore body definition and valuation. At this phase of mine investigation, mine water issues are seen as secondary, and investigations are frequently underfunded and limited for this reason.
- Lack of focus. Mine water issues are frequently dominated by site conditions outside the ore body. Investigations in locations where there is not expected to be any economic ore are difficult to fund and justify early in mine development, and are often under-performed as a result.
- Lack of time. Much of the information required for mine water evaluation requires significant lead time. At least one annual cycle is needed for collection of much surface water, groundwater, and water quality data. Collection of sufficient information to allow evaluation of extreme events, such as peak precipitation and flooding, takes years. Some geochemical and groundwater tests require long periods (up to years) for their completion. The tight

schedules of feasibility studies can lead to the omission or compression of needed evaluations.
- Lack of integration. In any mine development, a large amount of information is collected. A significant amount of it is relevant to mine water evaluations, even if it is not collected for that reason, e.g. water production during drilling, sulfur and carbon assays from exploration, and geologic structural information from core. However, there is little time or opportunity to include this information in a mine water evaluation.

Stakeholder Pressure

A mine water evaluation is usually associated with the development of major mineral resources. These developments have the capability to create significant economic wealth, and also have the capability to create significant social and environmental impacts. Mine water issues are central to the evaluation of the magnitude of these potential impacts and the evaluation of the relative merits of the mining project.

The stakeholders in the mine development process have different interests in the outcome of the mine water evaluations, and have a fiduciary or social responsibility to exert pressure to ensure that their interests are represented. As a result, mine water professionals perform their evaluations under pressure from the organization for which the work is being done. Given that there is significant uncertainty in any mine water evaluation, this provides the opportunity for stakeholders to influence the results to favor the end of the uncertainty spectrum that is most beneficial to their interest.

Diversity of Technical Disciplines

There are many disciplines under which mine water evaluations are performed (e.g. Nordstrom and Alpers 1999). A full mine water evaluation requires expertise in at least the following disciplines: surface water hydrology; groundwater hydrology; geology/hydrogeology; geochemistry/hydrogeochemistry; geotechnical engineering; chemical engineering; mining engineering; and environmental science. Each of these disciplines has its own method of approach to mine water evaluation, and while there is significant cross-discipline overlap, the differences between each discipline can make integration of the mine water evaluations difficult, and error-prone.

Importantly, each of these disciplines has different methods of training, and different (or no) methods of qualification and certification. There is no over-arching method of determining whether mine water evaluations have been performed by an appropriately qualified person or organization, and few generally accepted standards for the performance of such work. This is a further source of potential error.

Principles for Reliable Mine Water Evaluations

Reliable mine water evaluations can be verifiably achieved if a number of steps are taken and certified. Some of these are available and in place, some are partially implemented, while others are proposed for implementation herein. The steps are as follows:

Certification of Reliable and Relevant Science

Mine water evaluations must use reliable and relevant science. A workable definition of reliable and relevant science can be found in US law as encompassing those methods and approaches that meet the following standards (Daubert 1993):

- They must be testable, falsifiable,[1] and refutable.
- They must have been subjected to peer review and publication.
- They must have a known and knowable error rate.
- They must be subject to standards and controls.
- They must be generally accepted by a relevant scientific community.

Quantification of Reliability

The reliability of the results of mine water evaluations must be established and stated. The purpose of requiring a reliability determination as a part of all mine water evaluations is to require the analyst to certify the extent to which the evaluation can be relied upon, and to quantify the uncertainty of the results of the analysis.

This can be achieved by a number of methods, including the following:

- Calibration of evaluation results against the observed behavior of the evaluated system. Reliability can be optimized and quantified by calibration of the results of the evaluation against the actual behavior of the system being analyzed (or a demonstrably similar system) under similar conditions that will be applied to the evaluated mining system. Calibration involves adjusting parameters used in the evaluation within their observed ranges to produce the best fit between observed and computed results. The reliability of the best fit solution predicts the reliability of the actual analysis. The use of this approach requires the

[1] The term “falsifiable” in this context means capable of being demonstrated to be false (if that is the case).

availability of the measured response of the system or a demonstrably similar system to the stresses that will be applied to the evaluated system. An example of calibration is to use the flow and drawdown resulting from a large scale pumping test of an aquifer to calibrate the behavior of that aquifer in a hydrology model for a proposed mine. A further example is to use the results of long-term monitoring of a groundwater transport system to verify the results of modeled computation of that system; however, calibration using such data may only be possible after irreversible impacts have occurred, and in such cases, are not useful for preventing such impacts.

- System confidence determination. Reliability can be quantified by determining the statistical distribution of results based on the variability of all the inputs, and computing the probability of the result falling within a given range (or confidence limits). When using this technique, possible unobserved features or conditions should be included. This method is available when there is no measured information on actual responses to the stresses that will be applied to the evaluated system. The approach establishes the reliability of the analysis, assuming that the analytical method is correct. A simple example of system confidence determination is in the use of Darcy's Law to compute flow to a mine using hydraulic conductivity, head gradient, and flow geometry; the mean flow and standard deviation of the flow can under appropriate conditions be approximated from the statistical distributions of the input parameters using the following fundamental equations (after NIST/SEMATECH 2010):

$$\bar{Q} = \bar{K}\bar{I}\bar{A}$$

$$\left(\frac{\sigma_Q}{\bar{Q}}\right)^2 = \left\{\left(\frac{\sigma_K}{\bar{K}}\right)^2 + \left(\frac{\sigma_I}{\bar{I}}\right)^2 + \left(\frac{\sigma_A}{\bar{A}}\right)^2\right\}$$

where: Q = volumetric flow rate; K = hydraulic conductivity; I = hydraulic gradient; and A = area normal to flow direction. These statistical parameters allow quantification of the reliability of the determination (in this case of flow).

- Vastly more complex methods of system confidence determination have been developed and used, for example in evaluations with high potential societal impact such as geological disposal of high level nuclear waste (e.g. IAEA 2004; NEA/OECD 2003). For geoscience and mine water reliability evaluation, see the pioneering work of Harr (1987) and the more recent work of Baecher and Christian (2003).
- Analysis method reliability determination. The reliability of the method of analysis of a mine water evaluation can be determined by application of a number of different analytical approaches to the same evaluation, and comparing the results. An example of determination of the reliability of analysis methodology is benchmarking of computer codes, where the same analysis is performed using a number of different codes, and the results compared (ASTM 2008). This method is particularly powerful if the result is known, e.g. as a result of a proven analytical computation or an actual measurement in the field.

Reliability determination methods are more powerful to the extent that they are empirical. Those methods that are based on actual observations of the behavior of interest in the system of interest are themselves more reliable than those that are based on computations alone. There are many opportunities for reliability to be quantified in this fashion in mine water evaluations, for example:

- Modeling of inflow into exploratory underground mine workings to calibrate a model of underground flow to entire mine.
- Extrapolation of the modeling of humidity cell tests or larger scale ARD testing to represent the ARD behavior of overburden storage facilities.
- Modeling of precipitation and flow in similar catchments where data is available to calibrate a surface water model of the project.
- Modeling of the fate and transport of a natural or artificial constituent or tracer (e.g. arsenic, tritium, fluorocarbons, nitrates) to calibrate a model of fate and transport of project-related constituents.

Certification of Professionalism

Mine water evaluations must be performed by persons who are professionally qualified in the discipline relevant to the work being performed. Such qualification requires appropriate and current education and training; experience; and adherence to codes of practice and ethical standards. Professionals whose work has the ability to impact the public, such as engineers, medical practitioners, and surveyors are subject to professional certification and registration. However, there is currently no specific certification of mine water professionals. To provide that opportunity, the International Mine Water Association (IMWA) is creating a committee to explore certification of mine water professionals. This certification will provide internationally accepted professional credentials for individuals performing mine water evaluations. This program will provide members with certification for the performance of evaluations in mine water technology world-wide, and will provide mining organizations, regulatory bodies, and the public with assurance that evaluations are being performed by qualified professionals to appropriate technical, professional, and ethical standards.

Conclusion

Mine planning, permitting and operation require reliable water management in all its aspects. The reliability of mine water evaluations can be ensured by the application of three principles:

- Certification of the use of reliable and relevant science
- Quantification of reliability
- Certification of professionalism

The establishment of a process to certify mine water professionals by IMWA is proposed. This will create an umbrella certification for the varied technical specialties that are used in mine water evaluations, and will provide confidence that these evaluations are being conducted competently, fairly, and reliably.

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