RELIABLE MINE WATER TECHNOLOGY

ADRIAN BROWN

Adrian Brown Consultants, Inc.
Denver, Colorado USA; E-mail: abrown@abch2o.com

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 are 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 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 stakeholders in the mine, and improve the profitability, public acceptance, and environmental protection of mining projects.

1. 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 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.

2. 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 three 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 cubic meters per day could be expected to 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 the discharge to 2 ppm average.

Within two years operation the flow had reached more than 3 times the predicted rate, and was expected to increase to 8 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-meter wide vertical Dewey's Fault zone that connected the principal kimberlite pipe with the nearby lake (Figure 1).

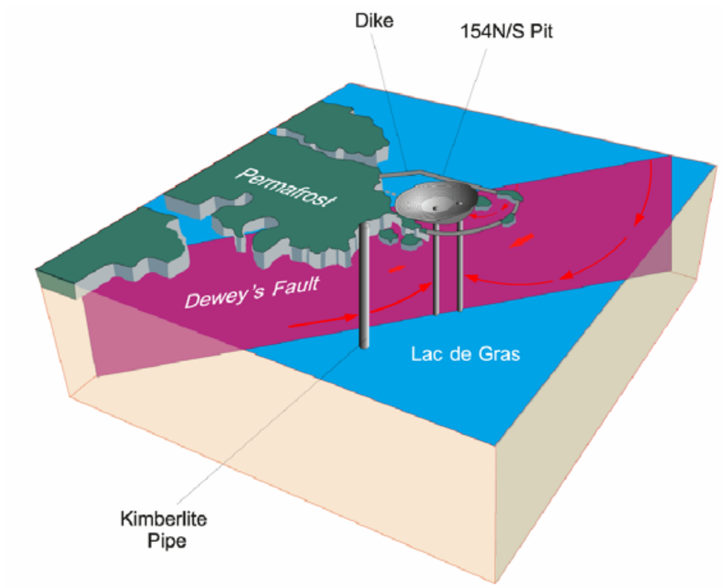

Figure 1. Diamond mine showing permeable fault (WLWB, 2007)

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 conducted under wet bench and flooded blasthole conditions, resulting in excess 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 economically 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.

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 million tonnes of coal and overburden up to 250 meters into the mine, as shown on Figure 2.

The failure diverted the local river into the mine, destroyed mine equipment, interrupted the coal supply system to local power stations, impacted regional electrical power supply, and placed personnel at risk. Fortunately the failure occurred at 2 a.m., 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 (The Age, 2009). When signs of incipient failure were observed in the mine wall, these evaluations were revisited by additional investigators, who also concluded that the slope would not fail and that stabilization measures were not required.

Figure 2. Failure of a Major Coal Mine (Herald-Sun, 2007)

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 Untied States are presented as part of environmental impact statements under the US National Environmental Policy Act (NEPA). The mines include all important mineral 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 evaluate the accuracy of the water quality predictions in these environmental impact statements (Kuiper 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[1].

[1] 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. The reported results of impacts experienced during mining were:

- 76% of all mines exceed surface and groundwater quality standards.
- 93% of those mines with elevated potential for acid drainage exceeded water quality standards
- 89% of the sites that did develop ARD 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.
- Bias in mine water quality predictions made by organizations paid for by the mine operator.

3. SOURCES OF UNCERTAINTY IN MINE WATER EVALUATIONS

Mine water evaluations are uncertain for many reasons:

Highly Variable and Poorly Defined Parameters

The 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 in the often remote mining project locations for which they are performed, and for the peak precipitation and flow conditions that frequently drive mine water evaluation.

- Groundwater. Orebodies are usually geologically and hydrologically anomalous, so groundwater evaluations for mines are 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, such as 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 orebodies 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 developing 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 physical 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.

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 orebody definition and valuation. Mine water issues are at best seen as secondary, and are frequently underfunded and limited for this reason.

- Lack of focus. Mine water issues are frequently dominated by site conditions outside the orebody. 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 many surface water, groundwater, and water quality data. Some geochemical and groundwater tests require long periods 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, for example 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 into 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. 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
- 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 to this discussion, each of these disciplines has different methods of training, and different (or no) methods of qualification/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.

4. 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 Good Science

Mine water evaluations must use good science. Good science has been defined in US law as those methods and approaches that meet the following standards (Daubert, 1995):

- They must be testable, falsifiable[2], 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.

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

Certification 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 prove that the evaluation is reliable, 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 availability of measured response of the system or a demonstrably similar system to the stresses that will be applied to the evaluated system.

- 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.

- Analysis Method Confidence Determination. Application of a number of analytical approaches to the same evaluation, with comparison of the results. This approach establishes reliability of the analytical method.

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 (for example arsenic, tritium, fluorocarbons, nitrates) to calibrate a model of project fate and transport.

Certification f 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.

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 acceptable professional credentials for individuals performing mine water evaluations. Certification under 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.

5. 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 good science
- Certification 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 utilized in mine water evaluations, and will provide confidence that these evaluations are being conducted competently, fairly, and reliably.

6. REFERENCES

The Age, 2009. Experts missed obvious signs before mine collapse. *The Age*, Melbourne, Australia, dated January 4, 2009. Available at: http://www.theage.com.au/national/experts-missed-obvious-signs-before-mine-collapse-20090103-79he.html?page=1

Canada, 1999. *Comprehensive Study Report, Diavik Diamonds Project*. Report prepared under the Canadian Environmental Assessment Act. Dated June 1999.

Daubert, 1993. Daubert v. Merrell Dow Pharmaceuticals, Inc., *509 U.S. 579* (1993). See also Judge Kozinski's opinion in Daubert on remand: Daubert v. Merrell Dow Pharmaceuticals, Inc., *43 F.3d 1311* (U.S. 9th Circuit Court, 1995).

Herald-Sun, 2007. Mine Operator Aware of Leak. *The Herald-Sun*, Melbourne, Australia, dated November 16, 2007. Available at: http://www.news.com.au/heraldsun/story/0,21985,22766158-661,00.html

Kuipers, J.R., Maest, A.S., MacHardy, K.A., and Lawson, G. 2006. Comparison of Predicted and Actual Water Quality at Hardrock Mines: The reliability of predictions in Environmental Impact Statements. Available at: http://www.earthworksaction.org/publications.cfm?pubID=211

Sullivan, T., 2008. Yallourn Mine Batter Failure Inquiry. Report of the Mining Warden to the State of Victoria. Dated June 30, 2008. Available at: http://www.dpi.vic.gov.au/DPI/nrenmp.nsf/LinkView/AB42F446D51294F8CA257515000B2DA88B3DA072DA032386CA2573DF001C56C6/$file/Mining%20Warden%20Report.pdf

WLWB, 2007. Diavik Diamond Mine Ammonia Management Plan - Review Panel Report. Report prepared by Wek’èezhìi Land and Water Board Ammonia Management Plan Expert Panel for the Wek’èezhìi Land and Water Board, Yellowknife, North West Territories, Canada. Dated: February 9, 2007. Available at: http://www.mvlwb.ca/WLWB/registry.aspx