

Case Studies of Thousands of Water Analyses through Decades of Monitoring: Selected Observations from Three Minesites in British Columbia, Canada

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Abstract

Large and long-term monitoring databases are needed to refine or refute models and theories for minesite-drainage chemistry. However, databases containing thousands of drainage analyses spanning 20-30 years seem relatively rare. This paper presents selected observations from three such databases for minesites in British Columbia, Canada, namely Equity Silver, Bell and Granisle Minesites. Web links are provided for downloading, free of charge, the documents containing detailed interpretations and additional insights.

For Equity Silver Minesite, ARD trends from waste rock were evaluated from 1986 through the end of December 2009, and included more than 5300 datapoints of pH vs. acidity. In the Main ARD collection pond, seasonal and annual variabilities of acidity concentrations and loadings have remained consistently within a factor-of-six range, despite substantially decreasing maximum temperatures and highly variable levels of pore-gas oxygen. Mass-balance calculations suggested non-regularly-flushed flowpaths contributed more than 20,000 tonnes of acidity, mostly during soil-cover construction around 1991-1994.

For Bell Minesite, drainage-chemistry analyses during operation and closure included nearly 5400 datapoints for pH vs. dissolved copper, from 1978 through 2009. For Granisle Minesite, drainage-chemistry monitoring from 1980 through 2009 included 1371 datapoints for pH vs. dissolved copper. Empirical Drainage-Chemistry Models (EDCMs) for both sites were updated.

Key Words: Mining, Drainage Chemistry, Monitoring, Equity Silver, Bell, Granisle

Introduction

Minesite components can affect the chemistries of waters draining over and through them, during operation and through closure, for decades to millennia (e.g., Morin and Hutt, 1997 and 2001). Despite these long-term effects, studies of minesite-drainage chemistry tend to be short term. For example, synoptic sampling at a site and its surrounding environment may occur only a few times. Regulatory reporting may require only annual information with no compilation of past information. Based on this short-term information, major conclusions have been made on environmental effects, mitigation, and remediation.

Optimum decisions on mitigation and remediation require long-term understanding and prediction of drainage chemistry. Also, models and theories for minesite-drainage chemistry should be refined or refuted with large and long-term monitoring databases. However, databases containing thousands of drainage analyses spanning decades seem relatively rare.

The objective of this paper is to present selected observations from three large, long-term databases for minesites in British Columbia, Canada. These minesites are Equity Silver, Bell, and Granisle. The case-study documents, containing detailed interpretations and additional insights for these sites, can be downloaded without charge.

Equity Silver Minesite

The Equity Silver Minesite is located near Houston, British Columbia, and is known for its management and treatment of ARD (e.g., Aziz and Ferguson, 1997). Mining of net-acid-generating waste rock started in 1980. To minimize ARD, a compacted till/soil cover was placed over the waste rock in the final years of operation before the site closed in 1994. Infiltration through this cover, combined with basal groundwater flow from upland areas, moves through the mined rock and becomes ARD.

Chemical analyses of the ARD at Equity Silver extend over 23 years, from 1986 to 2009. This includes more than 5300 pairs of measurements for pH and acidity (Figure 1). In the following paragraphs, some observations and conclusions are summarized on ARD flows and loadings, precipitation, internal waste-rock temperatures, and pore gases. More details can be found at: http://mdag.com/case_studies/cs35.html (Morin, Hutt, and Aziz, 2010).

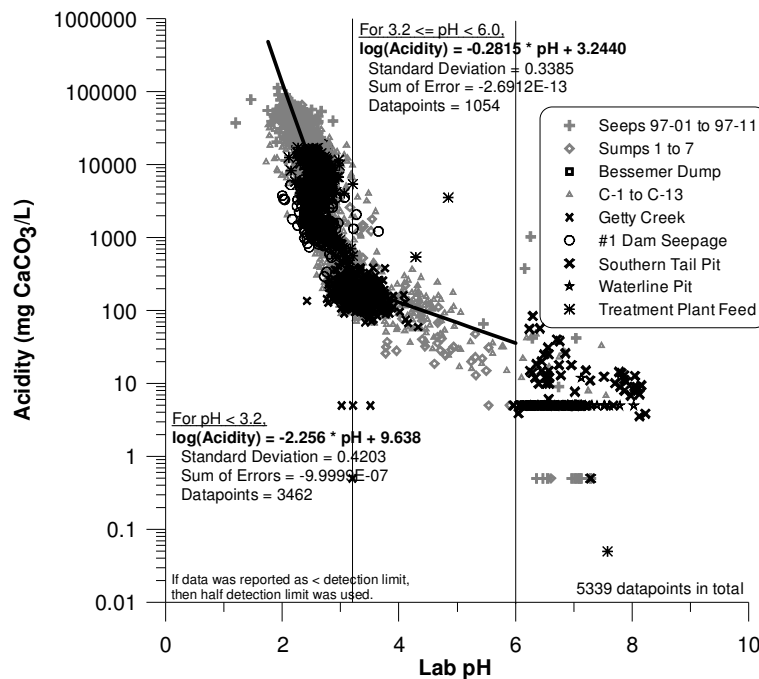


Figure 1. Equity Silver Minesite – pH vs. acidity for 5339 datapoints, showing correlation equations below pH 6.

Equity Silver has constructed a series of ditches and ponds to collect ARD seepage, for neutralization by lime at the water-treatment plant. ARD from the Main Dump is directed into the Main ARD Pond (Station C8), where it is joined by ARD drainage from the Bessemer Dump. The focus in this paper is on the Main ARD Pond, because it best represents the composite ARD sent to the treatment plant. Other locations with acidity concentrations up to 100,000 mg/L are discussed in Morin *et al.* (2010).

Although precipitation is one source of water that becomes ARD at Equity Silver, precipitation was found not to be a good predictor of ARD flows. This was due to the lack of correlation, reflecting the importance of other factors like snowmelt and groundwater inflows.

Acidity loadings from the Main ARD Pond were calculated by multiplying monthly flows by average monthly aqueous concentrations (in mg/L). The relative variation in ARD flow was much larger than that of acidity concentration (Figure 2). Thus, flow was the primary determinant of loading at the Main ARD Pond.

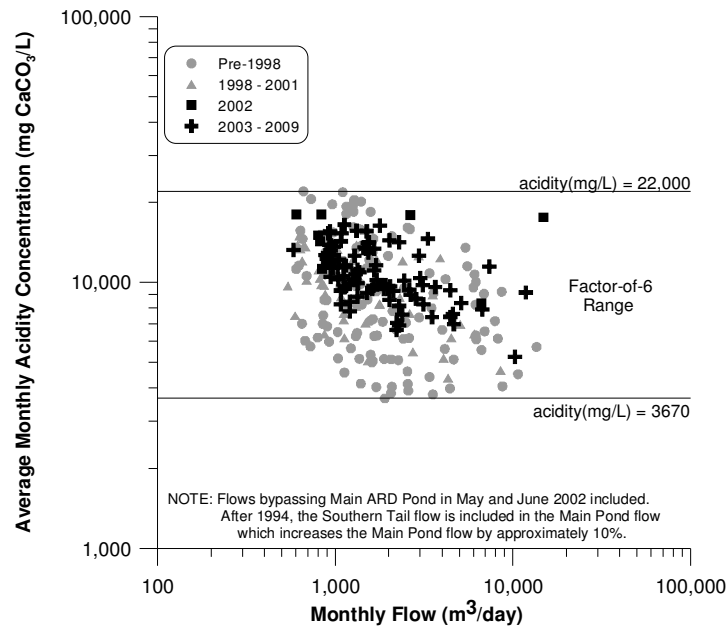


Figure 2. Equity Silver Minesite – Average monthly acidity concentrations vs. monthly flows, showing flow is relatively more variable (more than an order of magnitude) than concentration (factor of six).

Over the decades of monitoring (e.g., Figure 3), (a) 255 values for monthly acidity loading displayed a general lognormal distribution (Figure 4), (b) acidity concentrations consistently remained within a factor-of-six range (Figure 2), and (c) acidity loadings consistently remained within a factor-of-six range at a particular flow (Figure 5). This factor-of-six constraint even applied to more extreme hydrological events (>1:100 year flow).

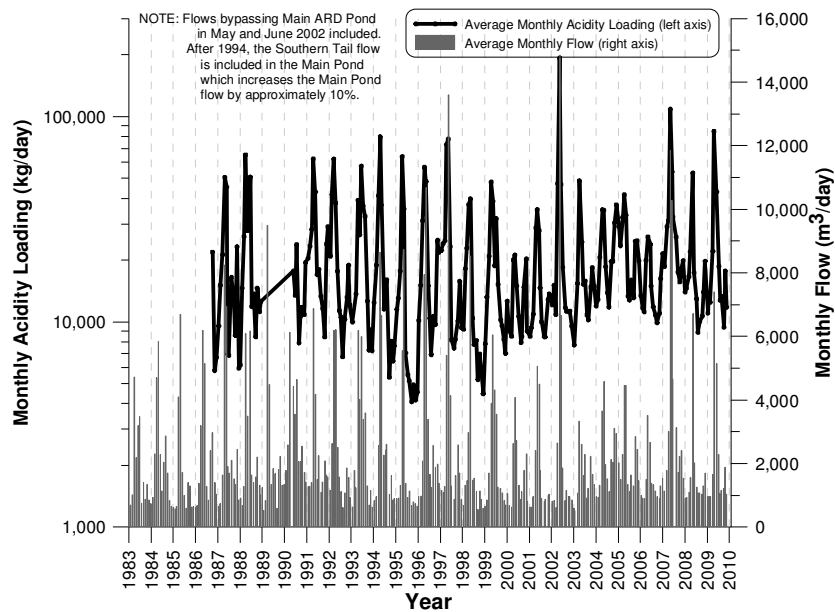


Figure 3. Equity Silver Minesite – Temporal trends in monthly acidity loadings and monthly flows at the Main ARD Pond over more than twenty years.

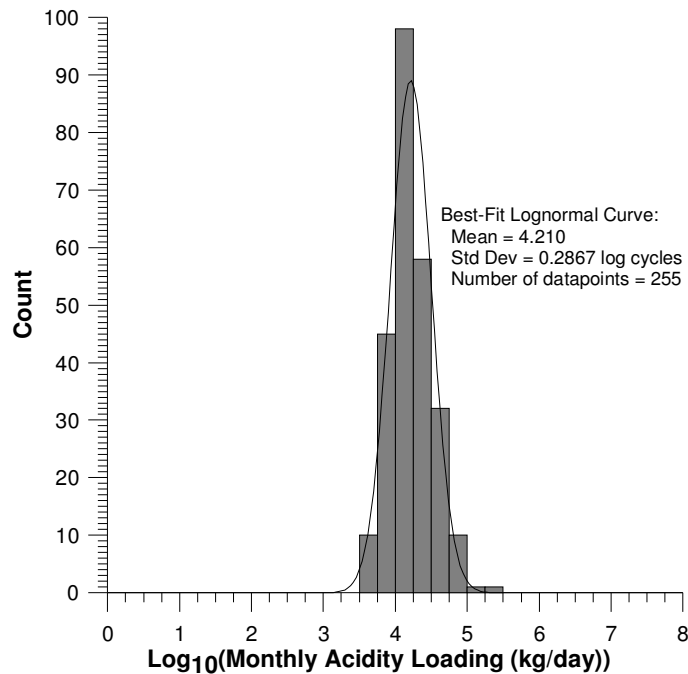


Figure 4. Equity Silver Minesite - Histogram of logarithmic values of monthly loading (kg/day) spanning more than 20 years, showing a general logarithmic distribution.

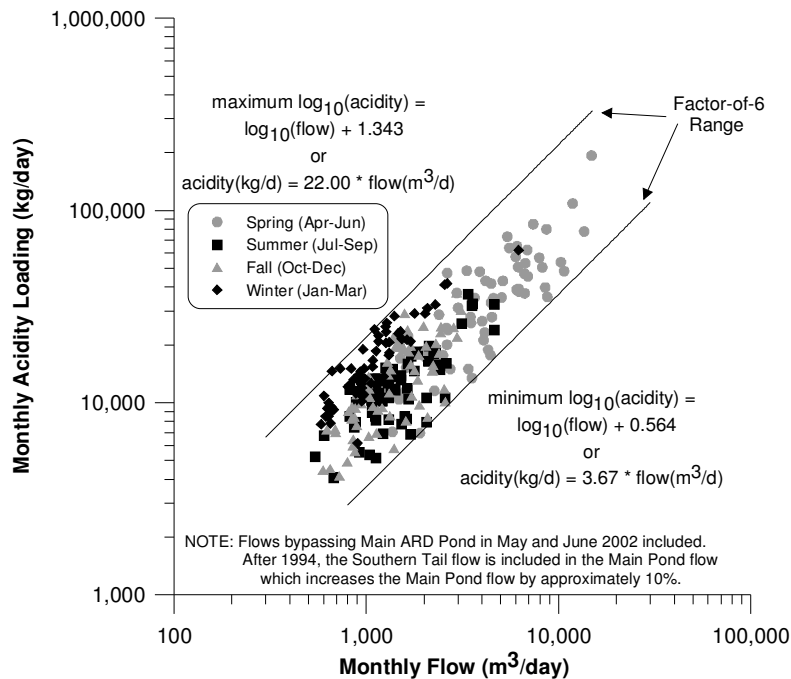


Figure 5. Equity Silver Minesite - Monthly acidity loadings vs. monthly flows, showing all datapoints have remained within a factor-of-six range even during extreme hydrologic events.

Also, few elements were clearly decreasing or increasing in aqueous concentrations over the years of monitoring, but the annual variabilities in concentrations did typically decrease (e.g., Figures 6 and 7). These seasonally variable, but relatively steady, concentrations in the long term were not affected by substantially decreasing maximum internal temperatures or by complex variations of pore-gas oxygen in four dimensions, as discussed below.

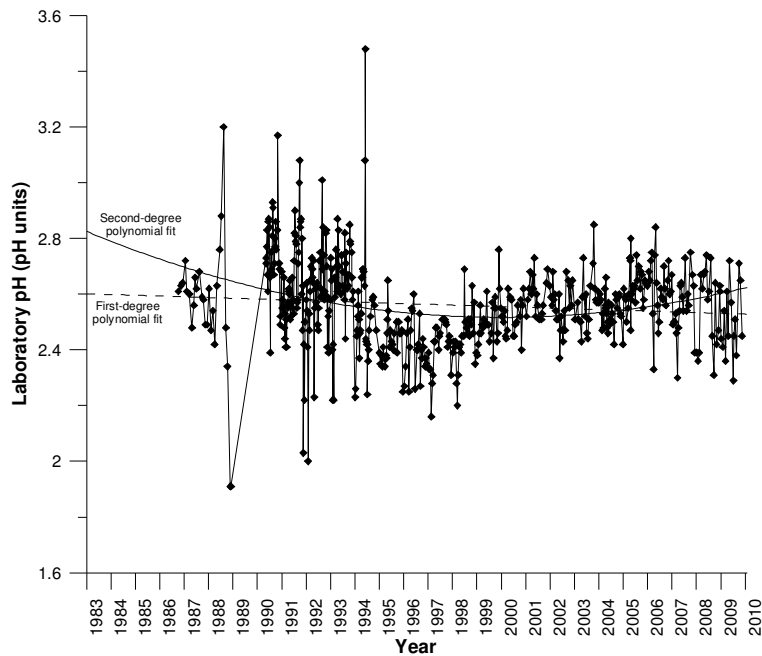


Figure 6. Equity Silver Minesite – Temporal trend in pH in the Main ARD Pond, showing that the long-term trend is not clear but seasonal variability has decreased.

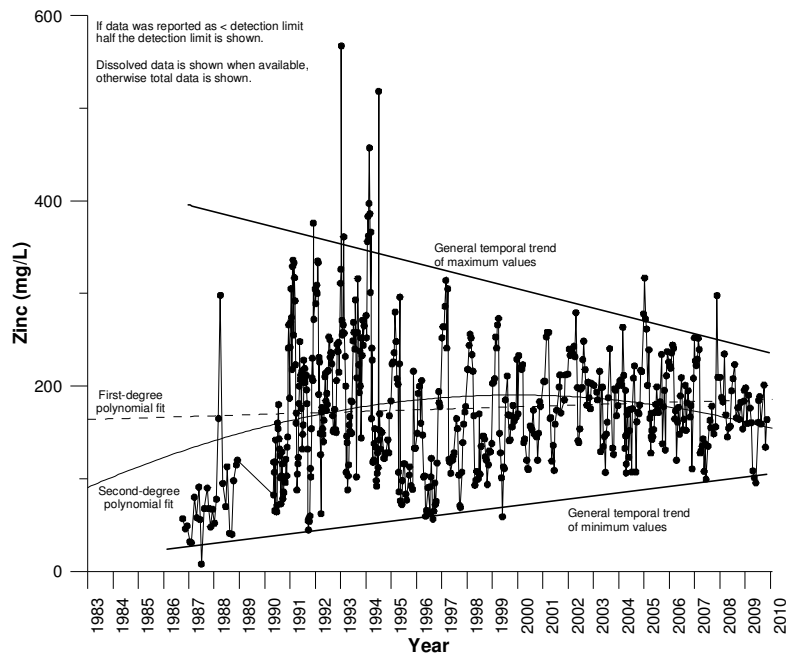


Figure 7. Equity Silver Minesite – Temporal trend in zinc in the Main ARD Pond, showing that the long-term trend is not clear but seasonal variability has decreased.

Mass-balance calculations for regularly flushed waste-rock flowpaths showed that the peak acidity flushing in May 2002 was primarily due to four previous years of low flows (Figure 3), allowing

substantial acidity accumulation within the waste rock. The May 2002 flushing removed much of the accumulated acidity, with the remainder flushed by the later May-June 2007 event. As a result, the regularly flushed pathway accumulation has been recently “reset” roughly to zero. More elaborate mass-balance calculations suggested other, non-regularly-flushed flowpaths have contributed more than 20,000 tonnes of acidity over the decades. Most of this additional acidity was released to the Main ARD Pond during cover construction around 1991-1994, with little contribution in recent years.

For internal temperatures, up to sixteen years of data were available for nine monitoring locations and depths. Maximum internal temperatures have fallen from highs of 54°C in the early 1990’s when monitoring began, towards 30°C in later 2009 (Figure 8). At other locations and depths, temperatures mimicked the seasonally varying ambient surface-air temperatures, but without the short-term peak highs in summer and without the sub-zero temperatures in winter. Other locations and depths were between ambient and maximum levels. Thus, thermal gradients exist within the waste rock, and vary with time and location. These, in combination with barometric gradients, can cause seasonally variable, convective air movement in, through, and from the waste rock. This can be seen in the complex trends of pore gases, as discussed below. Such convection can also lead to internal condensation within the waste rock, flushing ARD downward from higher levels.

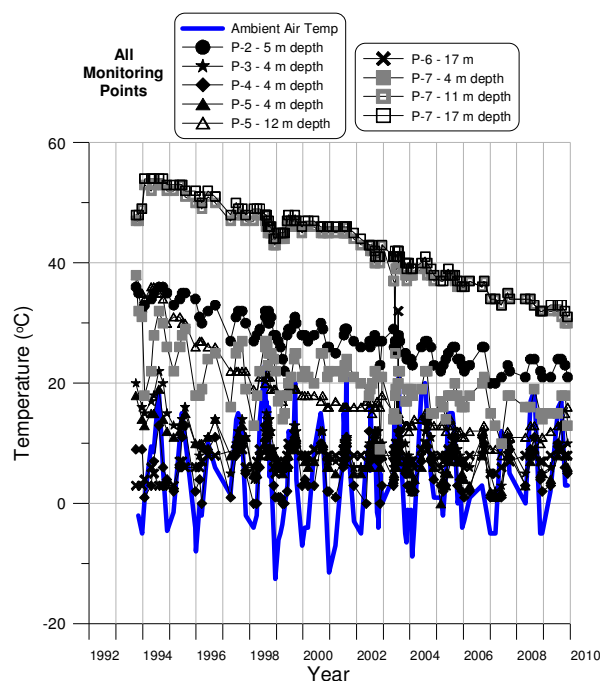


Figure 8. Equity Silver Minesite – Temporal trends in internal waste-rock temperatures at various depths and lateral locations, showing maximum temperatures have been decreasing.

Based on long-term temperature trends, the Equity Silver waste-rock dump is generally cooling, and thus the rates of pyrite oxidation and acid generation are probably slowing. However, this has not substantially affected drainage chemistry to date (Figures 2, 6, and 7), and does not mean that the strength of the ARD draining from the rock will substantially decrease within a few years.

For pore-gas oxygen and carbon dioxide, up to seventeen years of monitoring data were available from 55 monitoring locations and depths. All monitoring points showed seasonal variability within an annual period, that is, none showed flat-line trends in pore gas through the years. Some points produced more variability, such as near-zero oxygen to near-atmospheric 21%, than others with just a few percent variability in oxygen. Also, peak annual values of carbon dioxide often occurred in summer-fall months

while peak oxygen occurred in winter months, but there were exceptions. These and other observations highlight the notable spatial and temporal complexities of the mobile pore gases within the Equity Silver waste rock. These complexities are not consistent with typical modelling of pore gases within waste rock, such as one- and two-dimensional models. In any case, pore-gas variability does not result in abnormal variations in ARD chemistry (Figures 2, 6, and 7).

The relationships among internal temperatures, oxygen, and carbon dioxide showed that areas of the waste-rock dump considered relatively non-reactive, based on their low, near-ambient temperatures, still experienced notable seasonal fluctuations in oxygen and carbon dioxide. Thus, the local pore-gas levels do not necessarily reflect the reactivity of the local waste rock. Instead, local pore gases reflect larger-scale movements within the dump, like the intake of oxygen-rich air at certain times and the exhaust of oxygen-poor gas at other times.

In summary, decades of monitoring data are available at Equity Silver for precipitation, infiltration rates, groundwater levels, internal temperatures, pore-gas concentrations of oxygen and carbon dioxide, and aqueous concentrations and loadings for several elements at many locations in the ARD collection system. Based on monitoring data to the end of December 2009, many parameters display seasonal and/or annual variabilities, usually within definable and repeating ranges, with the exception of a few, smoother long-term trends. Acidity concentrations and loadings at the Main ARD Pond, on which treatment and lime consumption are based, have remained consistently within the factor-of-six range observed for decades. No deviation from this has yet been observed.

Bell Minesite

The Bell Minesite is located on the Newman Peninsula of Babine Lake, approximately 15 km north of the Village of Granisle, British Columbia, Canada. This site formally opened in 1972 and closed in 1992, with two extended periods of inactivity. Approximately 150×10^6 metric tonnes of waste and ore rock was mined from a single pit, and delivered to various dumps, tailings-impoundment dams, and mine roads. Most ore rock was delivered to the mill for processing, and the resulting discharge was slurried to the tailings impoundment. However, some ore rock was reportedly used in tailings-dam construction in early years of mining, and minor quantities of low-grade ore rock were occasionally delivered to dumps and the low-grade stockpile through the years.

Drainage-chemistry analyses for the Bell Minesite span more than thirty years, from mid operation in 1978 to seventeen years after closure (2009). This included nearly 5400 pairs of measurements for pH and dissolved copper (Figure 9), with best-fit equations showing lognormal seasonal variations above and below the average-annual values (e.g., Figure 10). Overall, pH displayed a bimodal distribution with preferred values for acidic and near-neutral drainages.

Long-term trends in frequently analyzed parameters showed that drainage chemistry was generally steady, and thus in local equilibrium, at some monitoring stations. However, pH and other parameters were changing at other stations due to remedial activities and natural geochemical evolution (e.g., Figure 11). This was expected, based on predictions made at the time of closure in 1992.

This information led to an Empirical Drainage-Chemistry Model (EDCM, Table 1) statistically linking drainage-chemistry parameters (Morin and Hutt, 1993, 1997, 2000, and 2001; Morin, 1994; Morin et al., 1993, 1995a, 1995b, and 2001; Day et al., 1996). This includes the importance of vertical (y-axis) distributions seen in Figure 9, displayed in Figure 10, and characterized by logarithmic standard deviations in Table 1. This is not a weakness for prediction, but important in predicting short-term peak concentrations and “geochemical storms”. More details can be found at: http://mdag.com/case_studies/cs33.html (Morin and Hutt, 2010a).

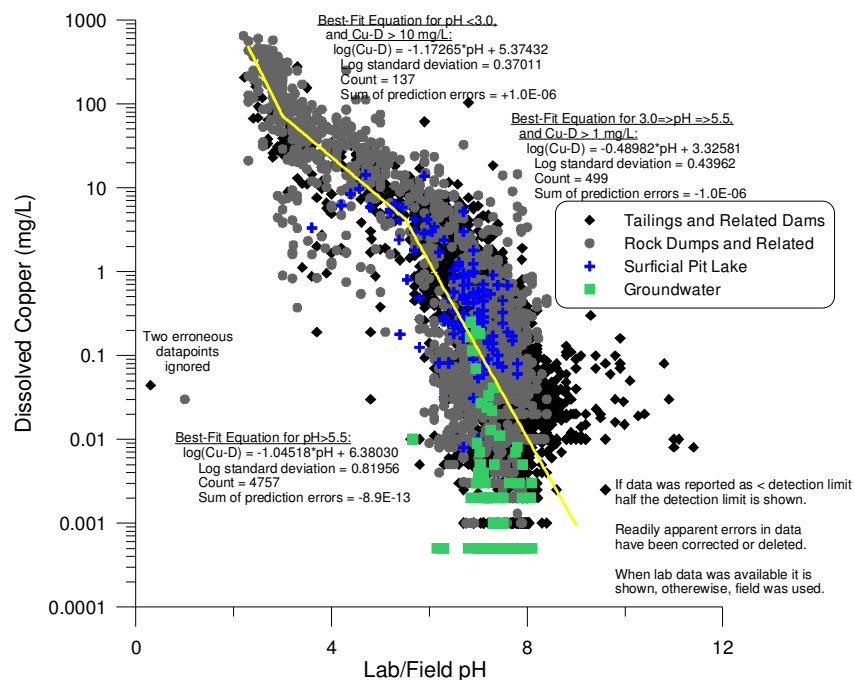


Figure 9. Bell Minesite - pH vs. dissolved copper for 5393 datapoints, showing correlation equations across three pH ranges.

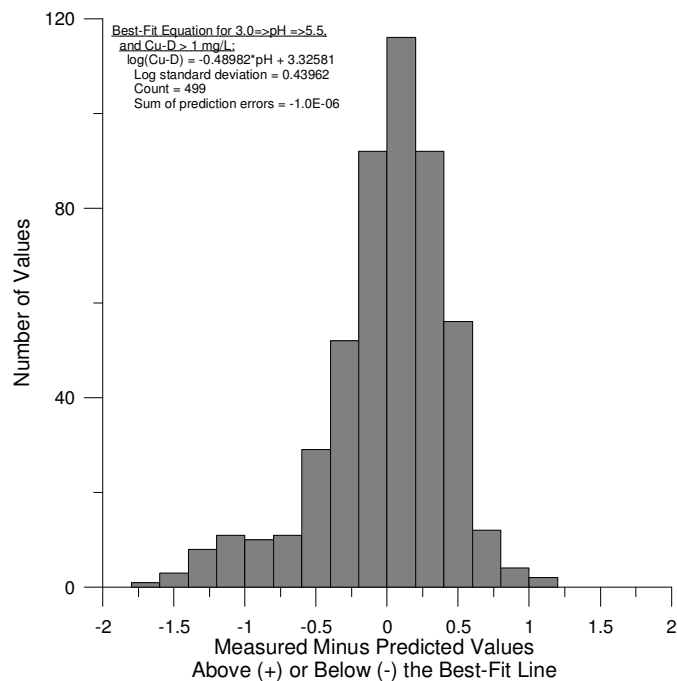


Figure 10. Bell Minesite – Histogram of logarithmic differences between measured and equation-calculated values from Figure 9, between pH 3.0 and 5.5.

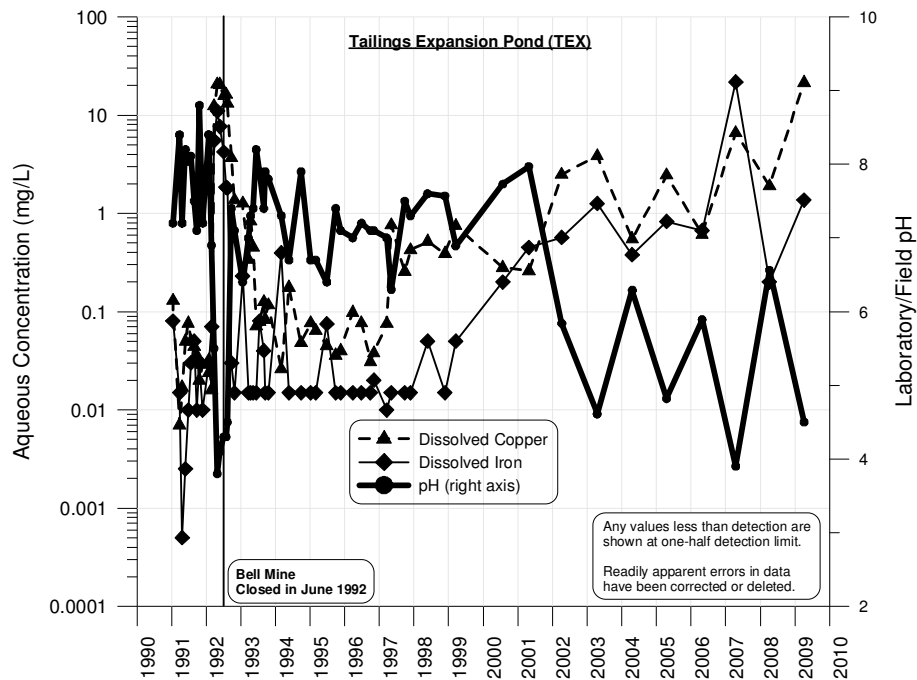


Figure 11. Bell Minesite – Temporal trend of pH (right axis) and of dissolved copper and iron (left axis) at one monitoring station, showing onset of acidic conditions about ten years after closure.

Table 1. Excerpt of the 2010 Empirical Drainage-Chemistry Model (EDCM) for the Bell Minesite

Parameter	Conditions	Equation	Log (Std Deviation)
Acidity	pH < 3.3	$\log(\text{Acidity}) = -1.05232 \cdot \text{pH} + 6.08223$	0.39142
	$3.3 \leq \text{pH} \leq 6.0$	$\log(\text{Acidity}) = -0.27496 \cdot \text{pH} + 3.51704$	0.32292
	pH > 6.0	$\log(\text{Acidity}) = -0.49283 \cdot \text{pH} + 4.82426$	0.31224
Alkalinity	pH ≥ 4.0	$\log(\text{Alkalinity}) = +0.69570 \cdot \text{pH} - 2.80060$	0.35848
Dissolved As	pH < 4.0	$\log(\text{As-D}) = -1.94657 \cdot \text{pH} + 4.69773$	0.96847
	pH ≥ 4.0	$\log(\text{As-D}) = -3.08856$ (0.0008155 mg/L)	0.50975
Dissolved Cu	pH < 3.0	$\log(\text{Cu-D}) = -1.17265 \cdot \text{pH} + 5.37432$	0.37011
	$3.0 \leq \text{pH} \leq 5.5$	$\log(\text{Cu-D}) = -0.48982 \cdot \text{pH} + 3.32581$	0.43962
	pH > 5.5	$\log(\text{Cu-D}) = -1.04518 \cdot \text{pH} + 6.38030$	0.81956
Dissolved Zn	pH < 3.0	$\log(\text{Zn-D}) = -1.08849 \cdot \text{pH} + 3.56852$	0.34748
	$3.0 \leq \text{pH} \leq 6.0$	$\log(\text{Zn-D}) = -0.15634 \cdot \text{pH} + 0.77207$	0.40923
	pH > 6.0	$\log(\text{Zn-D}) = -0.98600 \cdot \text{pH} + 5.75002$	0.77426

Granisle Minesite

As with the Bell Minesite, the Granisle Minesite is located near the Village of Granisle, British Columbia, Canada. However, rather than on a peninsula, the main part of this minesite consists of two islands in Babine Lake, joined together by the No. 2 tailings impoundment and its waste-rock dams. In total, 132×10^6 metric tonnes were mined from the Granisle Pit, including roughly 61×10^6 t of waste rock and 71×10^6 t of ore and low-grade ore. The Granisle Minesite formally opened in 1967 and closed in 1982. Remedial activities and formal closure planning were conducted in the early 1990's.

For this study, drainage-chemistry analyses for the Granisle Minesite spanned nearly three decades, from 1980 during late operation, to seventeen years after closure in 2009. This included 1371 pairs of measurements for pH and dissolved copper (Figure 12).

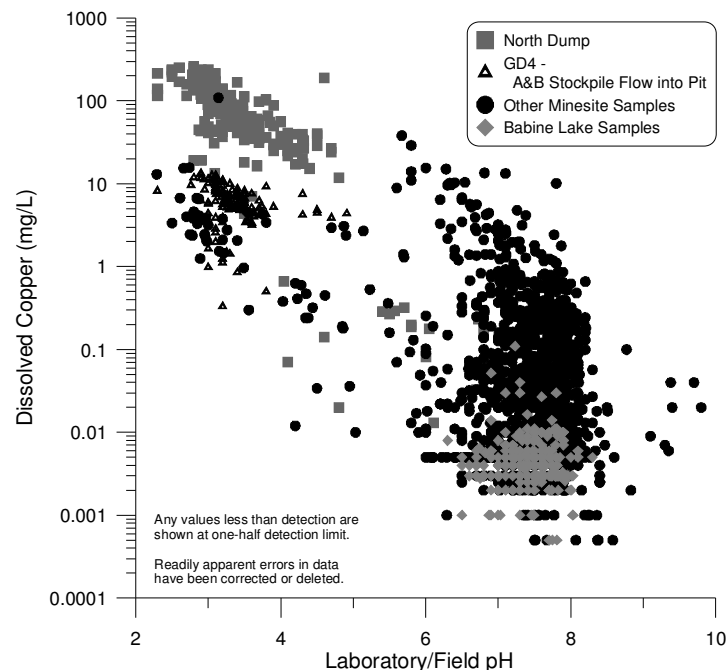


Figure 12. Granisle Minesite - pH vs. dissolved copper for 1371 datapoints.

Cumulatively over the decades, aqueous pH was bimodally distributed into two narrow ranges (Figure 13). Also, Figure 13 shows the annual variability of pH at individual monitoring stations generally decreased after remedial activities in the early 1990's, particularly at acidic stations. However, no major changes in pH from acidic to near neutral, or vice versa, were observed over the monitoring period, and thus pH is in general equilibrium at the Granisle Minesite. Nevertheless, cessation of remedial activities coincided with (1) the minor increase of near-neutral pH at one station, and (2) the decrease in pH in the surficial pit lake due to gravity diversion of ARD into it, leading to some increasing aqueous concentrations at the surface.

Overall, aqueous parameters showed correlations with acidity, sulphate, and/or pH. This led to an Empirical Drainage-Chemistry Model (EDCM, Table 2) statistically linking drainage-chemistry parameters (Morin and Hutt, 1993, 1997, 2000, and 2001; Morin, 1994; Morin et al., 1993, 1995a, 1995b, and 2001; Day et al., 1996). More details can be found at: http://mdag.com/case_studies/cs34.html (Morin and Hutt, 2010b).

Conclusion

This paper has summarized some findings from three drainage-chemistry databases, at three minesites in British Columbia, Canada. These databases contain thousands of water analyses spanning at least two decades, which appear relatively rare in the literature. They showed that aqueous concentrations were seasonally variable, with the annual ranges generally stable over decades, but with some exceptions. The Equity Silver database showed that drainage chemistry had not been significantly affected by decreasing internal temperatures and complex four-dimensional trends in pore gases.

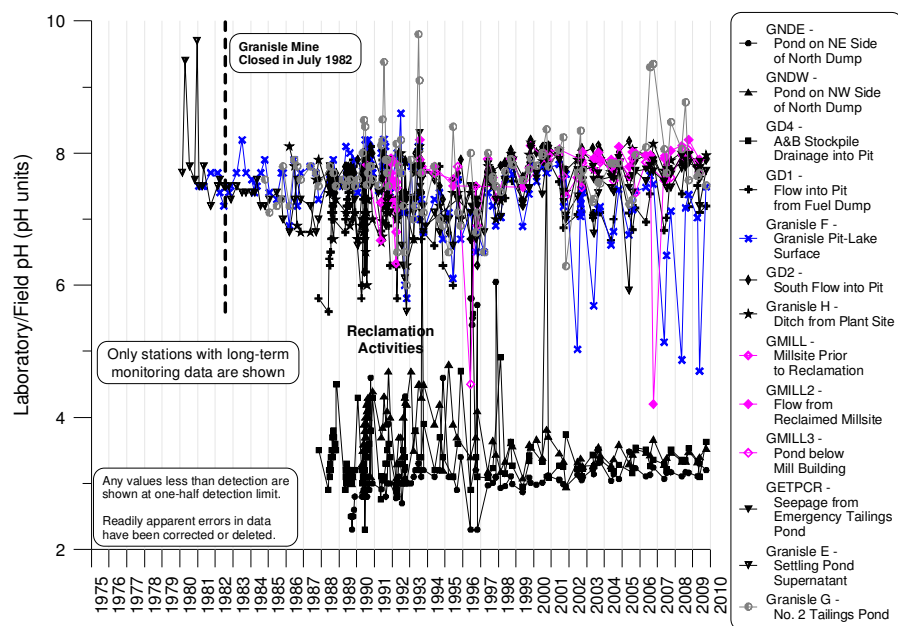


Figure 13. Granisle Minesite – Temporal trends in pH, showing bimodal pH distributions with a preferred near-neutral pH and a preferred acidic pH.

Table 2. Excerpt of the 2010 Empirical Drainage-Chemistry Model (EDCM) for the Granisle Minesite

Parameter	Conditions	Equation	Log (Std Deviation)
Acidity	pH < 5.0 for the North Dump	(Acidity) = -0.80842*pH + 5.99748	0.32638
	pH ≥ 5.0	log(Acidity) = -0.40261*pH + 3.96484	0.45632
Alkalinity	pH ≥ 4.0	log(Alkalinity) = +0.60128*pH - 2.39981	0.37665
	pH < 3.18	log(As-D) = -7.30997*pH + 20.70033	1.2122
Dissolved As	pH ≥ 3.18	log(As-D) = -2.52642 (0.002976 mg/L)	0.65859
Dissolved Cu	pH < 5.0 for the North Dump	log(Cu-D) = -0.66797*pH + 4.04804	0.38670
	pH ≥ 5.0	log(Cu-D) = -0.84950*pH + 4.95551	0.88213
	Acidity ≥ 200 mg/L	log(Cu-D) = +0.94697*log(Acidity) - 1.61716	0.48245
	Acidity < 200 mg/L	log(Cu-D) = +1.33303*log(Acidity) - 2.50550	0.96403
Dissolved Zn	Acidity ≥ 100 mg/L	log(Zn-D) = +0.99866*log(Acidity) - 2.70049	0.45712
	Acidity < 100 mg/L	log(Zn-D) = +0.85191*log(Acidity) - 2.40700	0.83598

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