

Prediction of Drainage Chemistry in Post-Mining Landscapes Using Operational Monitoring Data

by

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Abstract

Studies at numerous minesites around the world have shown that post-mining drainage chemistry depends strongly on geochemical and hydrogeologic processes that occur during the operational years. Many of these processes can be identified using standard operational monitoring data, with no special studies required. As a result, post-mining drainage chemistry can be predicted with confidence.

This paper presents monitoring databases from several minesites, each containing thousands of analyses spanning up to 30 years of operation and closure. Simple statistical interpretations of these databases reveal the annual cycles and trends that drainage chemistry displays during operation and through closure.

Introduction

Concentrations in minesite-drainage waters are primarily created by the dissolution of minerals into those waters. According to basic principles of geochemistry, there are two basic, endpoint controls on aqueous concentrations: kinetic and equilibrium processes (Table 1). Kinetic-controlled concentrations fluctuate significantly with time and are dependent on physical factors like flow rates. On the other hand, equilibrium-controlled concentrations are more stable and persistent through time.

The implication for post-mining water chemistry is that, if equilibrium is the major control on aqueous concentrations during operation, then post-mining concentrations can be predicted more reliably. These predictions remain applicable, for example, even if flow rates change due to covers over waste rock and tailings or if pH changes due to oxygen depletion. In contrast to equilibrium, such changes under kinetic controls would lessen the reliability of post-mining predictions.

While equilibrium controls are relatively simple in concept, they are difficult to delineate at a minesite. There are computer programs, like MINTEQA2 (Allison et al., 1990), that calculate equilibrium conditions based on solubility products from published literature. However, the solubility of many minerals vary from literature values due to natural complications like solid solutions (e.g., Morin and Cherry, 1986) and crystallinity. For example, calcite (CaCO_3) with a small amount of substituted iron, which would be typical at metal minesites, could be in equilibrium at one order of magnitude below the literature value in a computer program like MINTEQA2. This “apparent equilibrium” for calcite varies from minesite to minesite depending on the amount of substituted iron.

To overcome site-specific mineral solubilities, a simple empirical technique has been developed, named the “empirical drainage-chemistry model” or EDCM, to identify site-specific equilibrium controls based on existing monitoring data (Morin and Hutt, 1997 and 1993; Morin et al., 1993; Morin et al., 1994a and b; Morin et al., 1995a and b). As a result, no additional studies or special monitoring is required, thereby lessening the cost of predictions. When equilibrium controls are identified by an EDCM during mining, then predictions for post-mining drainage chemistry become more reliable.

The EDCM approach has been in use for relatively large databases since 1991, and was later tested for strengths and weaknesses on small databases by the former Canadian MEND (Mine Environment Neutral Drainage) Program (Norecol, Dames and Moore, 1996; Morin and Hutt, 1997). For reasonably valid information to be obtained, at least 1000 datapoints spanning several years at a particular site are needed. While such databases are apparently uncommon, several do exist, extending up to nearly 30,000 analyses over 40 years.

It is important to understand that the EDCM approach does not adhere to standard statistical procedures (Norecol, Dames and Moore, 1996), because it is intended to delineate site-specific conditions (Morin and Hutt, 1997). For example, it uses least-linear, rather than least-squares, fitting because one datapoint should not automatically be given more weighting than any other. Otherwise one season’s data might be given more weighting and thus distort annual averages. Also, the approach uses standard deviations rather than standard errors, because an independent variable, like pH, does not often fluctuate significantly through a year at a particular location.

The EDCM Approach

If the aqueous concentration of a metal is controlled primarily by equilibrium, then its concentration will remain relatively constant year after year, as long as the “independent” variables like pH remain relatively constant. This does not mean the concentration remains exactly the same and, in fact, seasonal variations around an annual mean should be expected due to changing seasonal conditions like temperature. The EDCM approach delineates the annual mean and the short-term variations using simple scatterplots and simple statistical procedures available in any spreadsheet software.

The first step is to compile all available monitoring data for a minesite or a minesite component, spanning at least several years. More than 100, and preferably more than 1000, analyses are needed. Concentrations are then plotted against independent, or “master”, geochemical parameters which are typically pH and sulphate at sulphide-bearing minesites. If there are equilibrium controls, then there will be a noticeable correlation (e.g., Figures 1 to 4). A “best-fit” line can then be drawn through the correlation using least-linear fitting (left sides of Figures 1 to 4), and this line often reflects the annual mean concentration at a particular value of the master parameter.

A graphical distribution of the difference between measured data and the best-fit line often shows lognormally distributed differences (right sides of Figures 1 to 4). The logarithmic standard deviation, in logarithmic cycles, often represents seasonal variations in concentrations. Such standard deviations can be calculated for specific ranges of a master parameter, but one value for the entire measured range is often acceptable and representative.

The standard deviation can be used to estimate short-term extreme (high-low) concentrations, even for time intervals shorter than the monitoring program, like one-day high-lows. This is based on probability tables (Table 2), which indicate, for example, that the one-day high will be 3.00 log standard deviations above the annual mean concentration. This approach has been confirmed on monitoring data with a frequency of 4 hours over several months (Morin and Hutt, 1997; Morin et al., 1994a). However, extrapolations beyond the measured frequency may not detect physical and non-equilibrium chemical limits to maximum and minimum concentrations.

The compilation of all best-fit equations and standard deviations for a minesite or a component provides the EDCM (e.g., Table 3). This table serves several functions, such as concisely summarizing past drainage chemistry, providing annual mean concentrations at a particular value of the master variable, and predicting post-mining chemistry even if a master variable like pH changes after closure. The table can also contribute to other tasks, like (1) estimating acceptable failure rates of control technologies like clay covers so that a specified downstream concentration is not exceeded, and (2) determining the optimum retention time and size for a holding pond to a water-treatment plant so that a very short-term concentration will be diluted in the pond and not exceeded in the plant feed.

The EDCM approach has been applied to more than a dozen databases with over 1000 analyses. Approximately 80-90% have been successful, with notably strong trends and correlations. A compilation of 12 best-fit equations for copper shows that all minesites display similar, but not exactly the same, trend (Figure 5), with differences in concentrations at a particular pH reaching up to three orders of magnitude. This is consistent with the observation that equilibrium controls and solubilities are site specific and thus require site-by-site evaluation.

Approximately 10-20% of the EDCMs have not been useful, displaying erratic trends or poor correlations with master parameters. These sites are subject to kinetic controls (Table 1) and thus their drainage chemistries are significantly affected by many factors like flow rates. As a result,

predictions of post-mining water chemistry for these kinetic sites have a higher degree of uncertainty unless all the significant physical and chemical factors are characterized.

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TABLE 1 Idealized Kinetic vs. Equilibrium Mineral Reactions	
<u>Kinetic</u>	<u>Equilibrium</u>
aqueous concentrations (as mg/L) change with time	aqueous concentrations (as mg/L) do not change with time
aqueous concentrations (as mg/L) can depend on the ratio of water to mineral	aqueous concentrations (as mg/L) are independent of the amount of water and mineral
if water remains in contact with minerals long enough (stagnant drainage), equilibrium will eventually be reached	if drainage moves into contact with other minerals, equilibrium will change, resulting in either new equilibrium or kinetic conditions

TABLE 2 Probability Levels and Corresponding Time Intervals within a Year					
<u>Time interval</u>	<u>1 Year</u>	<u>1 Month</u>	<u>1 Week</u>	<u>1 Day</u>	<u>1 Hour</u>
Probability	100%	8.3%	1.9%	0.27%	0.011%
No. of standard deviations above/below mean ¹	0	1.73	2.34	3	3.85

¹ From normal-distribution tables (e.g., Pollard, 1977) after dividing probability by 2

TABLE 3
Example of an Empirical Drainage-Chemistry Model (EDCM)
Including an Open Pit, Several Waste-Rock Dumps, and a Tailings Impoundment
(adapted from Morin et al., 1995b)

<u>Parameter</u>	<u>pH Range</u>	<u>Best-Fit Equation</u>	<u>Log (Std Deviation)</u>
Acidity	pH < 3.5	log(acid) = -0.932pH+5.864	0.345
	pH > 3.5	log(acid) = -0.360pH+3.862	
Alkalinity		log(alk) = +0.698pH-3.141	0.654
Diss Aluminum	pH < 6.0	log(Al) = -0.925pH+4.851	0.429
	pH > 6.0	Al = 0.2 mg/L	
Total Aluminum		If diss Al>0.3 mg/L, total Al=diss Al	
Diss Arsenic		< 0.2 mg/L	
Diss Cadmium	pH < 3.0	Cd = 0.07 mg/L	
	pH > 3.0	Cd = 0.015 mg/L	
Diss Calcium		log(Ca) = +0.619log(SO4)+0.524	0.375
Diss Chromium	pH < 3.0	Cr = 0.08 mg/L	
	pH > 3.0	Cr = 0.015 mg/L	
Diss Copper	pH < 3.4	log(Cu) = -1.485pH+6.605	0.692
	3.4 <pH< 5.4	log(Cu) = -0.327pH+2.666	
	pH > 5.4	log(Cu) = -1.001pH+6.307	
Total Copper		log(CuT) = +0.962log(CuD)+0.180	0.230
Diss Iron	pH < 4.4	log(Fe) = -1.429pH+6.286	0.807
	pH > 4.4	log(Fe) = -0.455pH+2.000	
Total Iron		If diss Fe>1.0, total Fe = diss Fe	
Diss Lead		Pb = 0.05 mg/L	
Diss Nickel		log(Ni) = -0.317pH+0.853	0.607
Total Nickel		total Ni = dissolved Ni	0.613
Diss Selenium		Se = 0.2 mg/L	
Diss Silver		Ag = 0.015 mg/L	
Diss Zinc		log(Zn) = -0.441pH+1.838	0.667
Total Zinc		total Zn = dissolved Zn	0.144

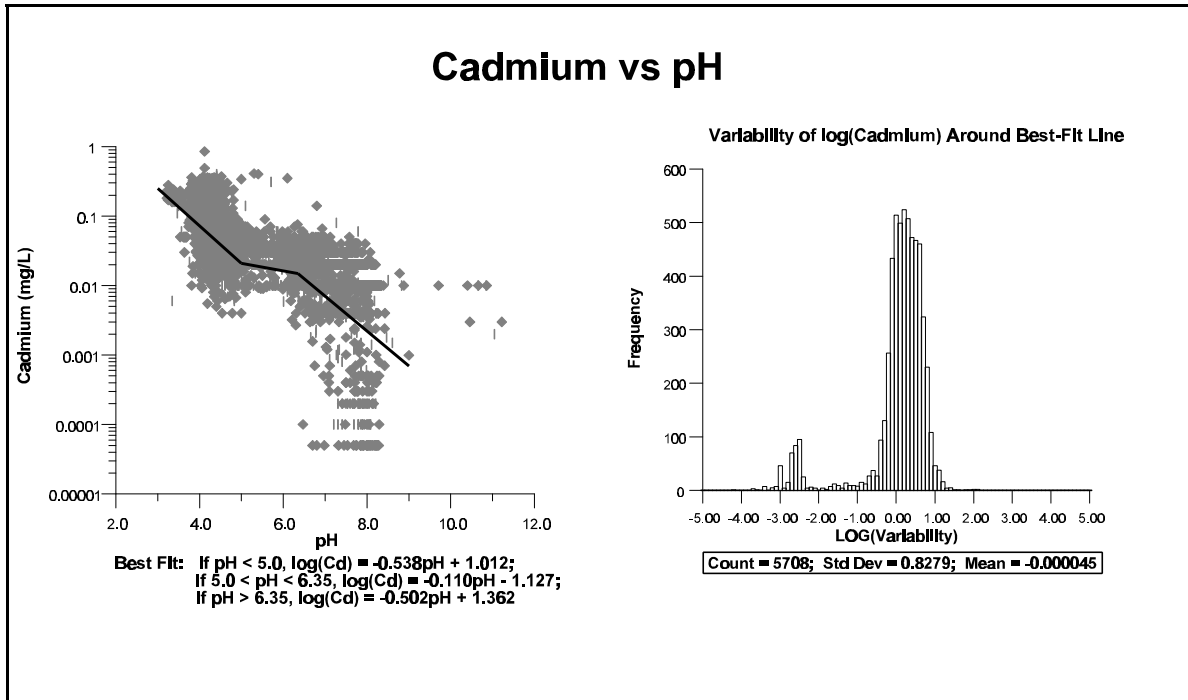


FIGURE 1. Example of a Best-Fit Line for Cadmium and pH (left side) and Variability Around the Best-Fit Line (right side) for 5708 Analyses from an Entire Minesite Spanning 25 Years.

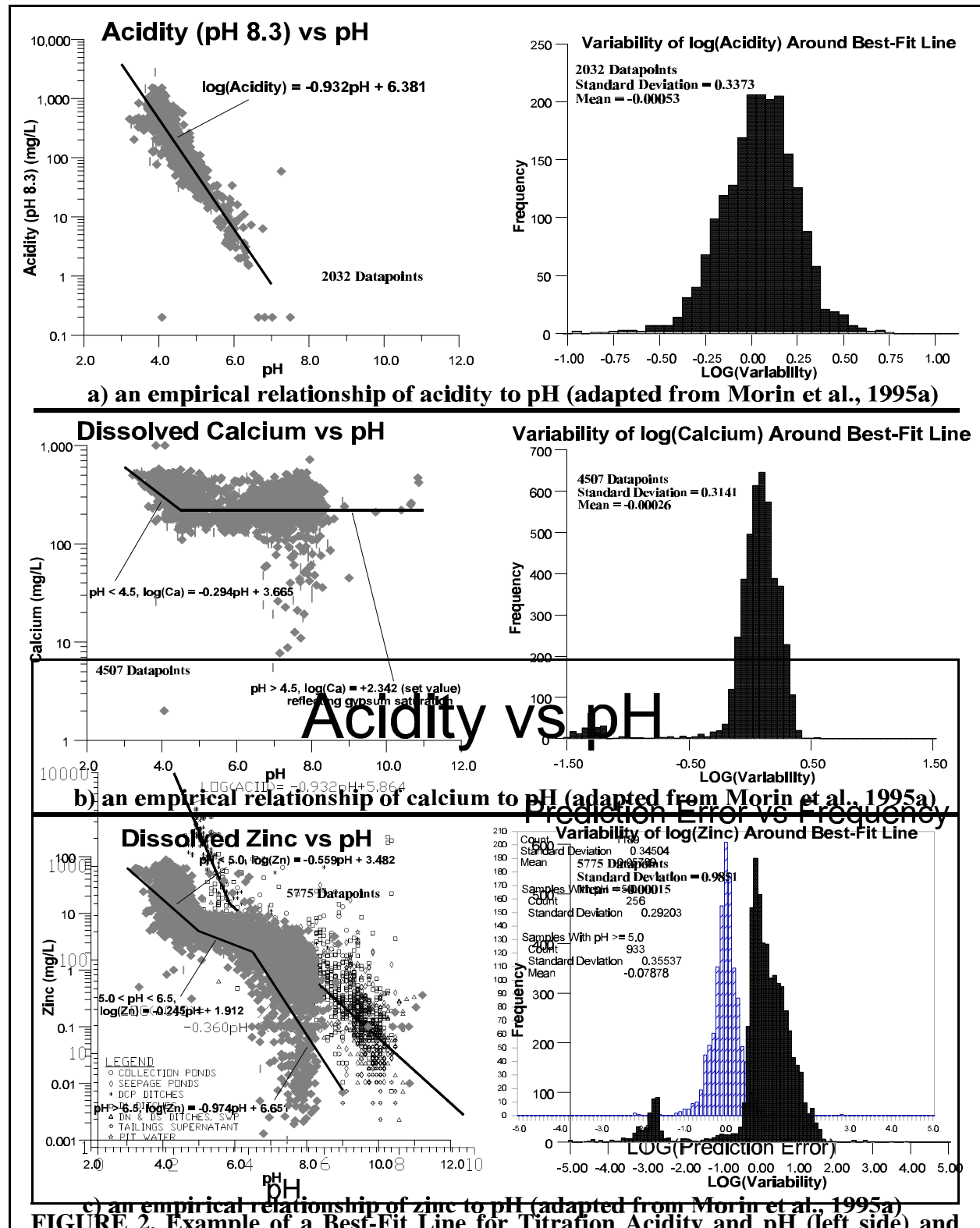


FIGURE 2. Example of a Best-Fit Line for Titration Acidity and pH (left side) and FIGURE 3. Empirical Drainage Best-Fit Line (right side) of SEMRA Analyses from Mining Operations (Morin and Hutt, 1997).

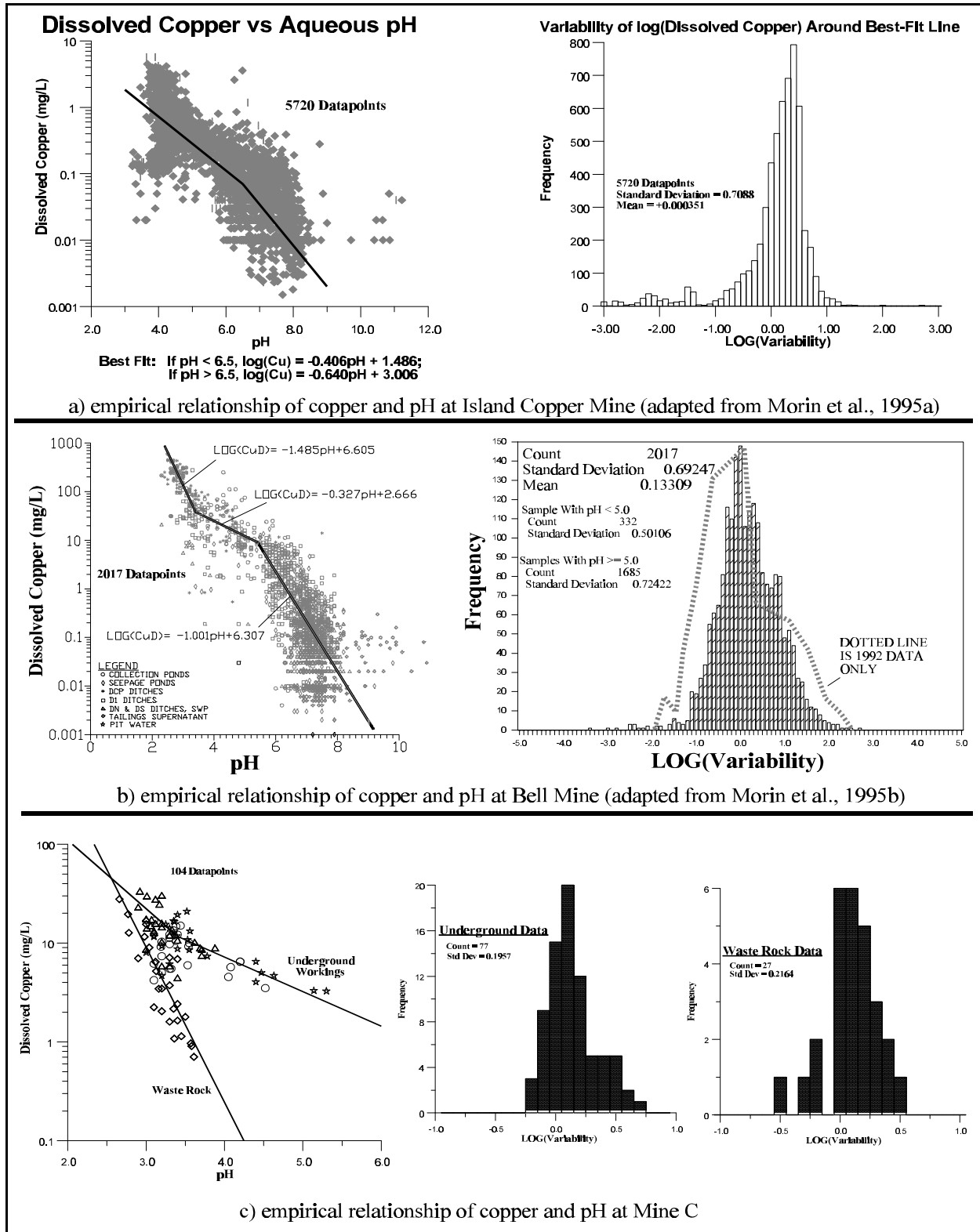


FIGURE 4. EDCM Copper Correlations with pH at Three Minesites (from Morin and Hutt, 1997).

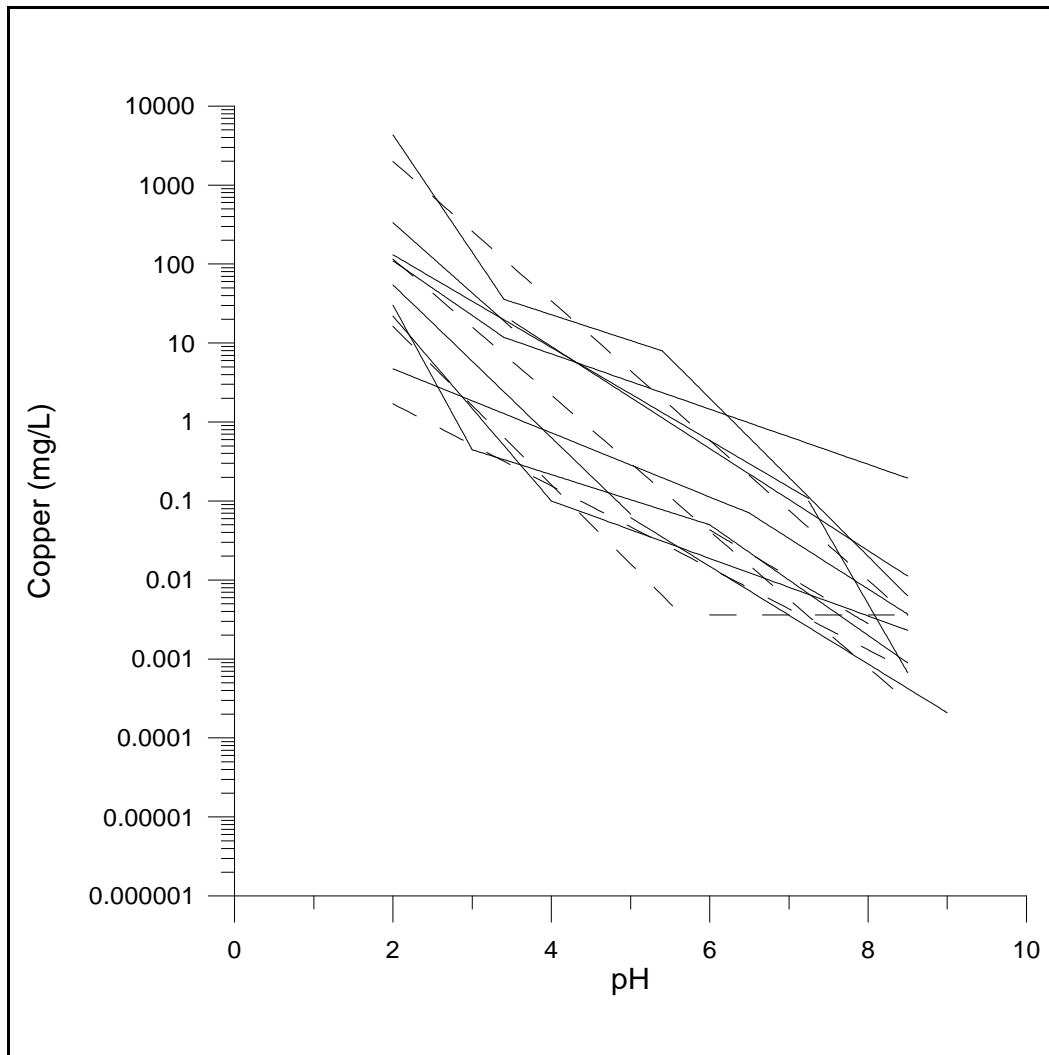


FIGURE 5. Compiled EDCM Copper Correlations for 12 Minesites.