ABSTRACT
Aqueous concentrations in drainages from minesites, and from other areas of highly reactive geologic materials, reflect the composite effects of many physical, geochemical, and biological processes. Spectral analysis in the frequency-wavelength domain assists in discerning the contribution of each process to the observed aqueous concentrations. Spectral analysis produces peaks at wavelengths where significant periodic processes are affecting the concentrations. In addition to the importance of individual spectral peaks, the slopes connecting these peaks can reveal interactions and feedback loops among the contributing processes. They show, for example:
- the self-organization of many processes into critically balanced trends;
- short time periods over which unattenuated rapid water flow moves through minesite components; and
- how different sources of inflowing waters can be differentiated in the outflow.

1 INTRODUCTION
The primary method of checking for environmentally unacceptable drainages from minesite components is through “water-quality monitoring”. This involves periodic collection of water samples for chemical analysis and periodic measurements of flow. However, such monitoring can fail to identify releases of contaminants, with a major reason for this failure centered in the word, “periodic”. As a simple example, if toxic, contaminated drainage water flows into the environment one week each year, then monthly monitoring could fail to explain the resulting damage in the downstream ecosystem.

Water-quality monitoring can be informative and reliable only if its frequency exceeds the time duration of contaminant pulses leaving a minesite component. These pulses reflect the combined result of the physical, geochemical, and biological processes operating in a minesite component. All these processes are often not considered in regulatory permits that require less frequent monitoring such as quarterly, monthly, or weekly. This is one reason why environmental-effects monitoring is important.

What would we find if we monitored for aqueous pulses at high frequency (e.g., hourly) and over long periods of time (e.g., decades)? What could this tell us about the physical, geochemical, and biological processes creating these pulses? This paper gives examples of what we find, and more are provided in Morin (2016a). They show that the standard regulatory approach of assigning a typical monitoring frequency, like monthly, is not sufficiently informative and protective of the environment.

An illustration of this issue can be found in Kirchner et al. (2004) for a non-mining catchment (Figure 1). Weekly monitoring of conductivity showed no value over 80 (top of Figure 1). If we assume the water-quality limit were 80, then there was no evidence of the release of contaminated water. However, hourly values lead to the opposite conclusion (bottom of Figure 1) – there were releases. It should be alarming that the answer is dependent on sampling frequency, which is rarely addressed or considered for minesite drainage.

If predictive models are developed from, or calibrated to, weekly monitoring (top of Figure 1), are they reliably simulating reality (bottom of Figure 1)? If active or passive water treatment is designed and costed based on weekly monitoring, will it successfully and economically handle hourly pulses? These are important questions often ignored in ML-ARD (Metal Leaching and Acid Rock Drainage) studies.

There is no doubt that minesite drainage is highly variable in time and includes pulses and peaks (e.g., Figures 2 and 3), like drainage from non-mining catchments. However, this is proven only in rare cases when high-frequency and long-term sampling took place.
High-frequency pulses have rarely been documented at minesites, because they have rarely been searched for. Technically speaking, minesite drainage is both dynamic and non-linear (Morin, 2015a). An intriguing question is whether minesite drainage from full-scale minesite components, like rock piles, tailings impoundments, and open pits, is also chaotic. As shown in this paper and in Morin (2016a), the answer so far is that minesite drainage is rarely chaotic.

At most temporal wavelengths, full-scale components act as signal filters and signal generators that smooth and attenuate input randomness and chaos. Even 1-kg humidity cells provide some filtering (Morin 2016b). Nevertheless, this paper also discusses the very short wavelengths at which signal filtering does not occur, representing rapid “plug flow” through full-scale rock piles within hours.

2 TEMPORAL FRACTALS IN MINESITE DRAINAGE

A fractal is (1) a mathematical set, or (2) a natural feature, that repeats a pattern or trend on various scales. Put
simply, the pattern looks the same as one “zooms in” to smaller and smaller scales, such as seen with a snowflake or a coastline.

Past studies of fractal patterns in mining geochemistry focused on spatial dimensions of ore zones and mineral intergrowths. In contrast, studies of fractal patterns in time series of minesite drainages are lacking. The reason for this, as with short-term pulses of contamination, is the general lack of high-frequency monitoring needed to confirm fractal patterns. Nevertheless, some time series of minesite drainages have been confirmed as fractal, through comparison with the Weierstrass Function (Morin, 2015b and 2016a; see also Figure 4) and with spectral analysis (Morin, 2016c and 2016a).

Figure 4. Example of a fractal time series using the first five terms of the Weierstrass Function applied to a specific yearly cycle; compare with real full-scale minesite-drainage time series in Figures 2 and 3.

3 SPECTRAL ANALYSIS

Least-squares spectral analysis (LSSA) is a method for estimating a wavelength-frequency spectrum. The analysis is based on statistical least-squares fitting of multiple sine-wave curves, with differing wavelengths (frequencies) of periodicity and with differing amplitudes, to data samples. This analysis can be applied to any periodic process, including step functions and sawtooth time series. LSSA is similar to Fourier analysis, the most common spectral method. However, Fourier analyses generally boost long-periodic noise in long gapped records, whereas least-squares spectral analysis mitigates such problems.

The Lomb-Scargle method is commonly used for least-squares spectral analysis. It is particularly suited for incomplete datasets with unequal spacing (data gaps), which is common in environmental monitoring due to problems like equipment failure. Lomb-Scargle results (periodograms) are directly comparable to those from Fourier analyses. This paper used the Lomb-Scargle algorithm implemented on the NASA Exoplanet Archive website. This website is operated by the California Institute of Technology.

As a simple example, a time series like Figure 5 represents the sum of three sine curves with wavelengths of one year, one month, and one day. The amplitude of each of the three curves decreases with wavelength.

![Figure 4. Example of a fractal time series using the first five terms of the Weierstrass Function applied to a specific yearly cycle; compare with real full-scale minesite-drainage time series in Figures 2 and 3.](image)

Figure 5. A time series representing the sum of three sine curves with wavelengths of one year, one month, and one day; see also Figure 6.

![Figure 6. The result for spectral analysis of Figure 5, correctly identifying the wavelengths of the three sine curves combined into one, and showing in this case the spectral peaks are connected by a log-log slope of 1.0](image)
Spectral analysis correctly identified those three wavelengths as peaks in spectral power (Figure 6). The log-log slope connecting these peaks is 1.0 in this case, which is known as a “1-over-f slope” or $\alpha = 1.0$. Fractals can create linear log-log spectral slopes of many values. Although Figure 6 is hypothetical and created as an illustration, it shows how information can be obtained about cyclical processes with periodicities creating the values seen in Figure 5. In other words, the time series in Figure 5 is created by overlapping effects of three processes that operate daily, monthly, and yearly. Returning to Figures 2 and 3, the identification of the periodic processes of various wavelengths creating those real concentrations at minesites can help to decode:

- the operative physical, geochemical, and biological processes in a minesite component,
- their interactions with each other, and
- the durations of pulses and peak concentrations.

4 ONE-OVER-F SPECTRAL SLOPES IN MINESITE-DRAINAGE TIME SERIES

The slope ($\alpha$) on a log-log plot of spectral power and wavelength (e.g., Figure 6) typically varies between zero and two for minesite drainage (Morin, 2016a). An $\alpha$ slope of zero is a random trend or chaos, often called “white noise”, which is statistically stationary with no persistence or “memory”. An $\alpha$ slope of two signifies “red noise” or “brown noise” such as Brownian motion, and represents random walk that implies statistical non-stationarity and strong persistence.

Between the spectral slopes of zero and two lies a major, complex field of science being intensively studied and debated, the “1-over-f” slopes. Such slopes can reflect complexity and the cumulative interactive effect of many processes and mechanisms. One-over-f slopes can have an exact or approximate definition. The exact definition is $\alpha = 1.0$, also called “pink noise”; the approximate definition is $0 < \alpha < 2$ (Bak, 1996).

One-over-f slopes are common, sometimes “ubiquitous”, across the fields of science and art. Some examples include earthquakes and their aftershocks, landslides, light from quasars, DNA sequences, weather data such as temperature and precipitation, highway traffic flow, river flow, tides, heart beats, neural activity, biologic evolution, solar flares, psychological models of mental states, electrical current in solid-state devices, epidemics, variations in musical styles, insulin uptake by diabetics, economic trends, forest fires, application of automotive paint, and cavitation in pumps.

In non-mining catchments, fractals and 1-over-f slopes are nearly “universal” in the power spectra of aqueous concentrations in drainages, for elements spanning the Periodic Table (e.g., Aubert et al. 2013; Kirchner and Neal, 2013). Similar 1-over-f slopes have only recently been confirmed in minesite drainage (Morin 2016c and 2016a). However, they are not universal, apparently due to the higher aqueous concentrations and associated dynamic geochemical tension in minesite drainage (Morin, 2016d). Some examples for full-scale minesite drainage are shown in Figures 7 and 8.

By far, the most popular explanation for 1-over-f slopes is self-organized criticality, or SOC (Bak et al., 1987; Bak, 1996). The classic application of SOC is to sand piles on which new sand grains are sequentially placed until the angle of repose is reached and an additional grain could cause “avalanches” of various sizes. The distribution of avalanche size is 1-over-$f$, although $\alpha$ was not necessarily exactly 1.0. Bak (1996) observed, “In the critical state, the sandpile is the functional unit, not the single grains of sand. . . . Studying the individual grains under the microscope doesn’t give a clue as to what is going on in the whole sandpile. Nothing
in the individual grain of sand suggests the emergent properties of the pile.” This can also apply to minesite components with 1-over-f slopes that contain “grains” of minerals, rock, or tailings.

Under the SOC models, Figures 7 and 8 indicate the physical, geochemical, and biological processes are interacting closely to create barely-stable, dynamic aqueous concentrations. Thus, for example, studying or modelling monthly concentrations cannot reliably explain or predict the real, highly variable temporal trend of concentrations. Also, occasional SOC “avalanches” in one or more processes could cause major changes in aqueous concentrations, such as the onset of acidic conditions (ARD).

5 THE MAJOR IMPORTANCE OF MINOR PROCESSES AFFECTING MINESITE DRAINAGE

When considering all the physical, geochemical, and biological processes that can affect minesite drainage and determine aqueous concentrations, it is tempting to think that relatively minor processes have relatively little effect. That would be a mistake. Fractal patterns, straight spectral log-log slopes, power laws, and lognormal distributions (like the minesite EDCMs compiled in Morin and Hutt, 1997, 2001, and 2007; Morin 2015b and 2016a) show the contribution of each process is multiplicative for minesite drainage, not additive. Thus, minor processes have a similar effect on aqueous concentrations as major processes.

As a simple numerical example, we can assume the variability of Process A is 10, and the variability of B is 0.1. The additive variability is 10.1 with a minor contribution from B. In contrast, the multiplicative variability is 1.0, with an important contribution from B.

In light of the minesite EDCMs, all contributing processes and mechanisms are important and relevant for understanding, predicting, and controlling minesite drainage. Spectral slopes help in identifying them across orders of magnitude of wavelength (e.g., Figure 9).

This recognition of multiplication of all contributing processes highlights one of several errors in a common predictive technique for minesite-drainage chemistry. Commonly, empirical single-value reaction rates are taken from small-scale humidity cells, despite cells displaying complex behavior at their own scale (Morin, 2016b). These rates are then multiplied by a selected subset of single-value “scaling factors”, all less than 1.0, to predict full-scale dynamic aqueous concentrations as a single value. This approach of a simplistic subset of small scaling factors for all contributing processes cannot lead to, and has not led to, much predictive success for proposed minesites (Morin, 2010, 2011, 2013, and 2014).

6 SPECTRAL SLOPES HIGHLIGHTING RAPID PLUG FLOW THROUGH WASTE-ROCK PILES

For decades, full-scale waste-rock piles have been recognized as complex minesite components in all three spatial dimensions and through time (Morin et al., 1991). Many waste-rock investigators recognize this complexity of coarser and finer material, but many ignore its reality and oversimplify water movement in full-scale coarser material. It appears the primary reasons for this are (Morin, 2017a and 2017b):

- the lack of high-frequency monitoring data (hourly and more frequently) to characterize the rapid flow of water through full-scale waste rock,
- detailed studies of smaller “test piles” and laboratory columns that are unavoidably unrepresentative of full-scale waste rock, and
- the desire to model water flow through waste rock despite a lack of realistic equations to simulate turbulent, non-Darcian, non-capillary flow in coarse rock.

Figure 9. The composite spectral slope for multiple independent processes, each producing white noise (random values) at longer wavelengths and red noise (random walk) at shorter wavelengths.

Many waste-rock papers have concluded that rapid flow through full-scale waste rock is minor, without hourly measurements to confirm that. High-frequency monitoring with spectral analysis can show this is not the case.

For example, Morin (2016a) examined high-frequency monitoring of effluent flow rates from full-scale, uncovered waste rock. Frequency was hourly at many stations and every 15 minutes at another. The “input signal” of daily precipitation onto the waste rock was random (α = 0) with a significant yearly peak of spectral power (Figure 10). Due to the cool, wet, local climate, precipitation was typically rain with little retained winter snowpack. Thus, precipitation could be used directly as the input signal.

At the toe of the full-scale waste rock, the effluent produced the power spectrum in Figure 11. Across most wavelengths, the filtered and attenuated “output signal” had a spectral slope of about α = 1.3, showing the waste rock smoothed and retained some flow at most wavelengths.
Figure 10. The predominantly random "input signal" of precipitation onto uncovered waste rock at a minesite, based on more than 20 years of daily values.

Figure 11. The filtered and attenuated "output signal" from the input of Figure 10 through full-scale waste rock, except below wavelength of about 0.001 years where unattenuated rapid "plug flow" occurred.

However, below a wavelength of about 0.001 years (9 hours), the spectral slope flattened to match the random input. This represented unattenuated rapid "plug flow" through coarse waste rock (Figure 11).

Later detailed examinations of the time series (Morin, 2017a and 2017b) confirmed this rapid flow (e.g., Figure 12). Mass-balance calculations showed 75% or less of the volume of a daily peak of precipitation passed through the local waste rock in less than a day or two, confirming rapid flow was important and could be major.

In Figure 12, the daily values of flow were not sufficient to characterize the real dynamic rapid flow through waste rock, and it is possible the hourly measurements also underestimated the real variability. Again, only high-frequency monitoring can show and confirm the importance of rapid flow, but is commonly missing from many waste-rock studies that unreliably conclude rapid flow is minor.

7 SPECTRAL PEAKS FOR TRACING THE PATHWAYS OF MINESITE DRAINAGES

In Case Study 2 of Morin (2016a), over 100 ha of covered waste rock generated strong ARD up to 100,000 mg/L. The acidic effluent was collected and treated on a periodic basis, mostly during high flows from spring snowmelt and precipitation.

One issue at this minesite was the recognition that part of the effluent ARD originated with infiltration through the till-soil cover, and the remainder originated from upgradient groundwater flowing into the base of the waste rock. Studies had been done over the years, but the primary source of effluent remained unconfirmed. Spectral analysis provides some information on this issue.

Infiltration through the till-soil cover at the minesite could not be reliably monitored. Nevertheless, assumed conditions for both a highly effective cover and a poorly effective cover indicated the power spectrum of infiltration would likely contain a single prominent peak at a wavelength of 1.0 years (e.g., Figure 13). In contrast, spectral analysis of water levels in upgradient piezometers, representing the rate of groundwater flow into basal waste rock, showed two prominent peaks, at 0.5 and 1.0 years (Figure 14).
Figure 13. An example of the power spectrum for a highly effective and a poorly effective till-soil cover at this site, producing one prominent spectral peak at 1.0 years.

Effluent flow at various locations around the toe of the waste rock displayed either one or two prominent peaks (e.g., Figure 15). This provided additional evidence for the primary source of the drainage water at that location.

Moreover, power spectra for some aqueous elements showed one peak at 1.0 years or both peaks at 0.5 and 1.0 wavelengths (e.g., Figure 16). As with flow, this suggested that the primary transport pathway for each aqueous concentration was either upgradient groundwater or infiltration through the cover.

Figure 14. An example of the power spectrum for groundwater levels in an upgradient piezometer, producing prominent spectral peaks at 0.5 and 1.0 years.

Figure 15. The power spectrum for flow at Station C-8, showing two prominent spectral peaks at 0.5 and 1.0 years, similar to Figure 14 but different from Figure 13, suggesting most flow at this location originated as upgradient groundwater.

Figure 16. The power spectrum for aqueous arsenic at Station C-8 showing a prominent peak at only 1.0 years, which suggests most leached arsenic was flushed by infiltration (Figure 13), in contrast to most flow at this station apparently originating as upgradient groundwater (Figure 15).

However, this could be even more complex. For example, the spectral signature in Figure 15 suggests most of the water at that monitoring station originated as upgradient groundwater. However, the spectral signature in Figure 16 suggests aqueous arsenic at that station was flushed mostly by cover infiltration.
In summary, spectral analysis in the frequency-wavelength domain assists in discerning the contributions of operative physical, geochemical, and biological processes to the observed aqueous concentrations in minesite drainage. Each process, whether major or minor, makes a significant contribution. Thus, each is important for proper understanding, prediction, and control of minesite drainage.

Individual spectral peaks can provide useful information. For example, peaks may be used as a tracer, can characterize repeating short-term peaks and pulses of aqueous contamination, and may indicate temporally variable water ponding and water retention upstream of a monitoring station.

In addition to the importance of individual spectral peaks, the slopes connecting these spectral peaks can reveal interactions and feedback loops among the contributing processes. One-over-f slopes are one example. The identification of unattenuated, rapid plug flow through minesite components is another example.

9 REFERENCES


Morin, K.A. 2016c. Fractal 1/f temporal trends in minesite drainage from waste-rock dumps, 14th Experimental Chaos and Complexity Conference, May 16-19, Banff Center, Banff, Canada


