Fractal 1/f Temporal Trends in Minesite Drainage from Waste-Rock Dumps

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Minesites are industrial facilities for resource recovery, entailing intensive disturbance of the local subsurface and environment. Consequently, most minesites are “open systems” to the physical, chemical, and biological processes taking place on and around them. One result can be contamination of drainage waters. Acid mine drainage (AMD) is the most famous variety, but near-neutral and alkaline drainages can also be toxic and more expensive to mitigate.

At large open-pit mines (>10^8-10^9 metric tonnes of rock), large volumes are blasted, excavated, and removed on a near-daily basis. Most mined rock is usually of sub-economic value at the time, and this “waste rock” is disposed of in “dumps” often in a pseudo-random manner. Thus, the physical and geochemical properties of many dumps appear random in three-dimensional space and time. Furthermore, the blasting, excavation, hauling, dumping, and dozer-grading enhance the percentages of finer particles and the reaction rates of many minerals.

Precipitation falling on waste-rock dumps infiltrates and typically flows through complex sequences of coarse channels (turbulent flow) and fine-grained layers (laminar Darcian flow). This drainage then exits waste-rock dumps at one or more locations around the base (the “toe”).

Based on geochemical observations, aqueous concentrations (e.g., mg/L) will increase in each liter of water flowing through waste rock as scale increases (e.g., increasing weight, volume, time, solid:liquid ratio, reaction rate, residence time, or distance along flowpath in reactive materials). However, a liter will not accumulate an infinite number of mg/L. Thus, the accumulation stops at some concentration, despite scale continuing to increase, leading to the emergence of some type of loosely-termed “equilibrium” of contaminant concentrations. This equilibrium has been described previously through logarithmic-transformed Gaussian statistics.

At the now-closed Island Copper Minesite, at the northern end of Vancouver Island, British Columbia, intensive monitoring of minesite drainage took place primarily in the later years of operation. Flows and chemistry were measured as often as every 15 minutes and every four hours, respectively. Analyses included pH, electrical conductivity, alkalinity, acidity, sulfate, copper, zinc, cadmium, calcium, magnesium, and aluminum. This resulted in a geochemical database containing approximately 60,000 individual chemical analyses for nearly 6000 samples. Several monitoring locations were close to the toes of waste-rock dumps, and others were near the open pit and “downstream” where several individual flows converged before discharge to the environment. This minesite had both acidic and near-neutral drainages.

Because the data are discontinuous and not equally spaced, the Lomb-Scargle algorithm was used for least-squares spectral analysis.
Daily measurements of rain+snow (8077 values) primarily produced a white-noise spectrum, except a prominent peak at a wavelength of one year. However, the spectra of drainage flows from dumps receiving this precipitation (up to 78,685 measurements each) generally showed 1/f slopes at wavelengths greater than about 0.01 years ($f < 100 \text{ yr}^{-1}$). Steeper slopes to about $1/f^{2.2}$ were detected at shorter wavelengths (Fig. 1). Similar studies in non-mining watersheds indicated the steeper slope below wavelengths of 0.01 years represents a rapid response to storm events. The mining 1/f slope at longer wavelengths contrasts with some reported flow spectra from non-mining watersheds, perhaps reflecting the relative lack of water retention (“memory” or storage) in coarse-rock dumps.

For aqueous chemical concentrations in non-mining-watershed drainages, past studies found universality of 1/f spectra across orders of magnitudes, for elements spanning the Periodic Table. However, such universality was not seen in this mining study, although approximate 1/f slopes were common based on up to nearly 1500 analyses for each element at each monitoring station (e.g., Fig. 2). This discrepancy may be due to the more pronounced geochemical reactivity of mining waste rock and the contrasting geochemical behaviours of elements at elevated concentrations.

Based on literature searches, this is apparently the first report of 1/f$^\alpha$ trends in minesite drainage. These trends, obtained pseudo-experimentally, are notable because they originate in a large, relatively young, highly disturbed, human-constructed system composed of blasted rock.

**Keywords:** Mining, Waste Rock, Scale, Acid Mine Drainage, AMD, Near-Neutral Drainage, Solid-Liquid Interaction, High-Frequency Water Analyses, Lomb-Scargle, Fractal, 1/f Slope

**FIG. 1.** Power spectrum of flow based on 78,685 measurements nominally every 15 minutes.  
**FIG. 2.** Power spectrum of aqueous zinc based on 1440 analyses nominally every four hours.
Fractal 1/f Temporal Trends in Minesite Drainage from Waste-Rock Dumps

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Most mined rock is usually of sub-economic value at the time, and this “waste rock” is disposed of in “dumps” often in a pseudo-random manner.
Thus, the physical and geochemical properties of many dumps appear random in three-dimensional space and time.

Furthermore, the blasting, excavation, hauling, dumping, and dozer-grading enhance the percentages of finer particles, the cumulative surface area of minerals, and the reaction rates of many minerals. Through time, coarser particles continue to break apart, exposing new mineral surfaces for long periods of time.
This activity results in a very large range of particles sizes, often from boulders down to silt.

In places, horizontal or sloping layers of a particular particle size form.
Precipitation falling on waste-rock dumps infiltrates and typically flows through complex sequences of coarse channels (turbulent flow) and fine-grained layers (laminar Darcian flow).

This drainage then exits waste-rock dumps at one or more locations around the base (the “toe”).
Island Copper Minesite, British Columbia, Canada


Station EMO at the North Dump

Flow often ~0.1 – 50 L/s
Island Copper Minesite, British Columbia, Canada

Station NDD at the North Dump

Hard hat for scale

Waste rock

Original land surface and former creek channel

Flow often
~10 – 100 L/s
High-Frequency Sampling at This Minesite

- This high-frequency monitoring database is rare for minesites. It includes:
  - Eight stations around the minesite, monitored at high frequency for up to three years and less intensively at other times.
  - Flow measured as frequently as every 15 minutes, providing nearly 90,000 measurements.
  - Water samples collected for analysis as frequently as every four hours, providing nearly 6000 samples.
  - Water analyzed for: pH, conductivity, alkalinity, acidity, sulphate, copper, zinc, cadmium, calcium, magnesium, and aluminum. This yielded approximately 60,000 individual chemical analyses.
Approximate Statistical Stationarity of Annual Logarithmic Geochemical Means and Standard Deviations

<table>
<thead>
<tr>
<th>Hydrologic Year of Operation</th>
<th>log10 Mean</th>
<th>log10 Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH (arithmetic)</td>
<td>6.27</td>
<td>6.93</td>
</tr>
<tr>
<td>Conductivity (uS/cm)</td>
<td>3.06</td>
<td>3.09</td>
</tr>
<tr>
<td>Alkalinity (mg/L)</td>
<td>1.74</td>
<td>1.71</td>
</tr>
<tr>
<td>Acidity (mg/L)</td>
<td>1.32</td>
<td>1.33</td>
</tr>
<tr>
<td>Copper (mg/L)</td>
<td>-0.94</td>
<td>-1.23</td>
</tr>
<tr>
<td>Zinc (mg/L)</td>
<td>0.41</td>
<td>0.22</td>
</tr>
<tr>
<td>Cadmium (mg/L)</td>
<td>-1.74</td>
<td>-1.82</td>
</tr>
<tr>
<td>Sulphate (mg/L)</td>
<td>2.89</td>
<td>2.90</td>
</tr>
<tr>
<td>Calcium (mg/L)</td>
<td>2.37</td>
<td>2.39</td>
</tr>
<tr>
<td>Magnesium (mg/L)</td>
<td>1.46</td>
<td>1.51</td>
</tr>
<tr>
<td>Aluminum (mg/L)</td>
<td>-0.78</td>
<td>-0.71</td>
</tr>
</tbody>
</table>
Acidity (pH 8.3) vs pH

Best Fit: \[ \log(\text{Acidity}) = -0.932 \times \text{pH} + 6.381 \]

**NOTE:** pH is a logarithmic scale; pH = -\log_{10}[H^+]
Variability of log(Acidity) Around Best-Fit Line

Count = 2032; Std Dev = 0.3373; Mean = -0.00053
NOTE: pH is a logarithmic scale; $\text{pH} = -\log_{10}[H^+]$

Best Fit: If pH < 6.5, $\log(\text{Cu}) = -0.406\text{pH} + 1.486$; If pH > 6.5, $\log(\text{Cu}) = -0.640\text{pH} + 3.006$
Statistical Distribution around the Average-Annual “Best-Fit” Correlations - Copper

Variability of log(Copper) Around Best-Fit Line

Count = 5720; Std Dev = 0.7088; Mean = +0.000351
The Empirical Drainage-Chemistry Model (EDCM) for This Minesite
(Compilation of pH-Dependent Correlation Equations)

<table>
<thead>
<tr>
<th>Parameter (mg/L)</th>
<th>Valid pH Range</th>
<th>Predictive Equation for Mean</th>
<th>Standard Deviation from Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acidity (to pH 8.3, N=2032)</td>
<td>pH &lt; 8.0</td>
<td>= -0.932 pH + 6.381</td>
<td>0.3373</td>
</tr>
<tr>
<td>Copper (N=5720)</td>
<td>pH ≤ 6.5</td>
<td>= -0.406 pH + 1.486</td>
<td>0.7088</td>
</tr>
<tr>
<td></td>
<td>pH &gt; 6.5</td>
<td>= -0.640 pH + 3.006</td>
<td></td>
</tr>
<tr>
<td>Zinc (N=5775)</td>
<td>pH ≤ 5.0</td>
<td>= -0.559 pH + 3.482</td>
<td>0.9851</td>
</tr>
<tr>
<td></td>
<td>5.0 &lt; pH &lt; 6.5</td>
<td>= -0.245 pH + 1.912</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pH &gt; 6.5</td>
<td>= -0.974 pH + 6.650</td>
<td></td>
</tr>
<tr>
<td>Aluminum (N=4186)</td>
<td>pH ≤ 5.65</td>
<td>= -1.341 pH + 6.908</td>
<td>1.3156</td>
</tr>
<tr>
<td></td>
<td>pH &gt; 5.65</td>
<td>= -0.068 pH - 0.285</td>
<td></td>
</tr>
</tbody>
</table>

For pH, the complete EDCM for this minesite shows correlations and power slopes for most parameters, except near-neutral ranges of acidity and calcium. Several elements display a break in the power slope at certain pH values.
Dynamic Geochemical Tension, and the Onset of Acidic Conditions

The pH Pendulum
Faster-reacting, recently disturbed minerals lead to more tension on the springs, and more buffering of pH.

For most natural waters, near-neutral pH is typical.

Minesites and other disturbances of earthen materials can create and expose faster-reacting minerals. Faster-reacting minerals lead to more tension on the geochemical springs, and more buffering of pH.

Changes in minesite-drainage pH do not occur smoothly, but in discrete steps. This is often caused by the depletion (dissolution) of a primary mineral, which in turn causes a secondary mineral to begin dissolving.

This is a geochemical version of a “phase transition”.

Dynamic Geochemical Tension, and the Onset of Acidic Conditions

The pH Pendulum

The reaction rates of some acidity-generating minerals can accelerate as aqueous pH becomes acidic, causing more tension (to the right) and pulling the pH farther into acidic values.

Shifts in pH can cause reaction rates of certain minerals to accelerate.

In this case, acidic pH accelerates the rate of acid generation. As a result, this leads to more geochemical tension to the right and more acidic pH.

The onset of acidic conditions under full-scale conditions was preceded by an increasing temporal trend in aqueous sulphate that represents the rate of acidity generation. This has also been observed in small-scale laboratory-based tests containing ~1 kg. In effect, the increasing sulphate represents increasing geochemical tension by the acidity-generating minerals, eventually leading to a periodic and then complete shift to acidic pH.

At locations where the dynamic geochemical tension is high (all “springs are pulled tight”), there may be little variation in pH as flow varies. In these cases, flow within a single dataset can show:

- little correlation with pH (left) and some aqueous elements (below left);
- a dilution-like effect (below centre); and
- an enriching-flushing effect (below right).

In all these cases, there is no 1:1 correlation with flow.
Some objectives and questions:

- Can the timing of the fast-response turbulent flow be distinguished from the slower-response laminar flow based on changes in slope (α) in the spectral analysis?

- If the turbulent flow can be distinguished, does the spectral slopes of the aqueous chemical elements also show matching slope changes and thus indicate chemical trends vary with flow regime?

- Do spectral slopes of various elements show similar trends, noted as "universal" in non-mining-related watersheds with lower aqueous concentrations?

- Because pH is an indicator of minesite-drainage chemistry and the dynamic geochemical tension controlling it, which elements show spectral slopes similar to pH?

- Can electrical conductivity, which can be recorded and logged in-field at high frequencies, act as a surrogate for spectra of individual elements?

- What do the spectral slopes tell us about the myriad physical, chemical, and biological processes operative in "open systems" at minesites?
Due to occasional issues such as equipment failure and laboratory problems, the data in this study are discontinuous and not equally spaced. Therefore, the Lomb-Scargle algorithm was used for least-squares spectral analysis, as provided on line by NASA.

“This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.”

This minesite is located on the coast of Vancouver Island, which has a wet climate (average of ~1.8 m rain+snow / yr) and cool temperatures. Any snow that falls often melts within a few days. The power spectra of rain+snow (right diagram) generally shows white noise ($\alpha \sim 0$) except a prominent peak at one year representing the obvious annual cycles of precipitation (left diagram).
After the white-noise precipitation passed through a waste-rock dump at this minesite:

- The annual peak was attenuated, and no prominent peaks were seen above wavelengths of ~ 0.08 yr (~1 month). Thus, 1/f trends were not seen at longer wavelengths, but this might be due to less than 1 year of monitoring at this location.

- A slope of $\alpha \sim 1.3$ occurs between wavelengths of ~0.001-0.003 yr (~9-26 hours) and 0.07 yr (~1 month). This may represent fractal filtering, but the limitation to about 1.5 orders of magnitude of wavelength is not strong evidence.
Spectral Analysis –
Shorter-Duration Monitoring (< 1 Yr) of Hourly Flows
at the Toe of a Waste-Rock Dump (Slide 2)

• At wavelengths shorter than ~9-26 hours, white noise dominates, which is well above the Nyquist frequency of 2 hours in this case. This is considered “undampened” or “unfiltered” precipitation passing quickly through coarse channels as turbulent flow.

• This agrees with studies elsewhere showing infiltration passed through 45 m of waste rock within 12-36 hours based on fluctuations of internal temperature and basal water table (Morin et al., 1994). This was also reported in non-mining-related watersheds.

Spectral Analysis –
Longer-Duration Monitoring (> 1 Yr) of Hourly Flows in Ditches
Downstream of Waste-Rock Dumps

Drainages from the toes of waste-rock dumps flowed downstream through “leaky” ditches. These ditches collected major amounts of additional flows from other portions of waste-rock dumps, cumulating in large spatial distributions of flowpath lengths. In effect, this filtered out the short-wavelength white noise and, with longer monitoring, extended the slope of $\alpha \sim 1.3$ by another log cycle.
After the ditches converged, a different power spectrum was seen. At longer wavelengths (> ~3 days), the spectral slope of $\alpha \sim 1.3$ seen at upstream stations flattened to $\alpha \sim 1.0$. At shorter wavelengths (< ~3 days), the slope steepened to $\alpha \sim 2$, with a break between 2.2 and 1.5 around 12 hours. A slope of $\alpha \sim 2$ can represent random walk, but the concern remains that this may be an “artifact” of converging ditches and flows. The break in slope at ~12 hours coincided with the observation of short-wavelength white noise at the dump toe, which anomalously was not seen at stations between here and the toes.
Spectral Analysis – Longer-Duration Monitoring (> 1 Yr) of Hourly/Every-15-Minute Pumped Flows from the Large Open Pit about 400 m Deep

Water was pumped from basal pit sumps to the surface, up to 400 m vertical lift, when sumps filled. Therefore, water flow at Station PDW reflected:

- low-variability inflow of deep, regional groundwater;
- high-variability rainfall, with some dampening on the pit walls; and
- human-designed decision making for periodic dewatering of pit sumps

This may account for the numerous and inconsistent slopes in this power spectrum. In any case, The white noise at wavelengths shorter than ~0.002 yr matches that seen at the toe of waste rock.
As a general but not 100% consistent statement on geochemical trends to this point, spectral results for stations at dump toes displayed white noise at short wavelengths up to roughly 0.03 to 0.05 years (11 to 18 days). Spectral slopes of $\alpha \sim 1.0$ then extended up to white noise above 1 yr. This included pH.

Farther downstream, spectral trends remained about the same for some parameters, but short-wavelength white noise disappeared for other parameters.

These trends were not a close match to the spectral slopes for flow, and thus flow was not a dominant process in determining aqueous concentrations.
Although spectral slopes of $\alpha \sim 1$ were common, other slopes were detected. The slopes of these other elements were $\alpha \sim 0.5-0.7$ (above), but a few ranged from $\alpha \sim 0$ to $\sim 1.4$ (right).

Most slopes were not a close match to the spectral slopes for flow, and thus flow was not a dominant processes in determining most aqueous concentrations.
Time Series and Spectral Analysis – Observations and Conclusion

• The Empirical Drainage-Chemistry Model (EDCM, showing logarithmic correlations with pH) for this site showed, upon compiling all data for all stations into one dataset, that power-law correlations with pH were seen for all analyzed parameters.

• As a result, the question arose on whether spectral trends of individual elements would match those for pH. The spectra showed that most elements generally reflected the pH spectrum closer to the dump toes. Farther downstream, only the spectra for alkalinity, sulphate, and conductivity generally resembled the pH spectrum.

• Most geochemical spectra did not resemble that of flow, indicting flow was not a major control on aqueous concentrations.

• Electrical conductivity reflects the ionic content of water and is easily measured in-field with a meter and data logger. At some stations, conductivity displayed significant spectral differences from the typical trends, including those of sulphate which dominated conductivity in these minesite drainages. This indicated high-frequency measurement of electrical conductivity was not consistently and reliably a surrogate for laboratory-based chemical analyses, which was also noted in non-mining watersheds.
Time Series and Spectral Analysis – Observations and Conclusion

• The lack of near-100% consistency among spectral slopes for geochemical parameters in this mining-related study is a contrast to “universality of 1/f fractal scaling in water quality time series” reported in the few documented natural, non-mining watersheds with lower concentrations (Aubert et al., 2013).

• In general, the lack of universality for this minesite can be attributed to the large, relatively young, highly disturbed, human-constructed system in this study, composed of blasted rock. This included higher geochemical reaction rates, leaching rates, and dynamic geochemical tension.

• Interpretations are ongoing of this rare high-frequency database for a minesite.

• Based on literature searches, this is apparently the first report of $1/f^\alpha$ trends in minesite drainage.

THE END