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MDAG-com Case Study 59 - Wavelet Transforms of Flow in Full-Scale Minesite Drainage: Effect of Installing a Fine-Grained Cover over Waste Rock

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Abstract

In this full-scale case study, a fine-grained till-soil cover was placed over 132 hectares of waste rock releasing acid rock drainage (ARD). This included an early mined-out pit that was backfilled with waste rock. The cover was installed late in the final years of mine operation.

Several decades of monitoring data were used to identify the full-scale effects of cover installation on flow rates at various monitoring locations downgradient of the waste rock. These effects were sought in (1) the time series of flow rates and (2) the periodicities of the flow rates.

Time series of flow rates revealed no major effects from cover installation, even two decades after installation. This was supported by monthly and yearly statistics.

Additionally, the time series of flow rates displayed strong oscillations each year. Least-squares spectral analysis showed that these oscillations in flow were occurring not just yearly, but at many shorter wavelengths. The corresponding log-log straight slopes in spectral periodograms indicated fractal distributions, ranging from random to random-walk, including 1-over-f slopes.

Wavelet transforms showed that flow from the full-scale waste rock was relatively aperiodic before and just after cover installation, except for persistent ongoing annual periodicity (log10 0.0) and for weak weekly periodicity (log10 -1.7) that ceased shortly after cover completion. However, four years after installation, periodicities in flow at all examined monitoring locations showed major increases in strength across a large range of wavelengths.

In other words, flow rates became much more cyclical each day, week, month, and year (and between these wavelengths), four years after the cover was completed. This suggests about four years were needed for the cover to stabilize and significantly influence infiltration patterns throughout the waste rock. The strongest periodicity across the wavelengths occurred sharply in spring months, when flows were highest.

About nine years after the cover was completed, the high strength of springtime periodicity in flow began to weaken and become more diffuse, approaching pre-cover periodicity. This is consistent with reports of till-soil covers significantly degrading in 10 to 20 years.

Therefore, the wavelet transforms of flow were able to provide important information on full-scale effects of a fine-grained cover over waste rock, not available from time series and spectral analysis. The corresponding aqueous chemistry showed markedly different trends than flow, but this is discussed elsewhere.

1. Introduction

The Equity Silver Minesite is located near Houston, British Columbia, Canada, and is known for its management and treatment of acid rock drainage (ARD; e.g., Aziz and Ferguson, 1997; Morin and Hutt, 1997 and 2001; Morin et al., 2003, 2010, and 2012). Most of this ARD originates from net-acid-generating waste rock, which was mined starting in 1980 (Mine Year 0). This includes the relatively small Southern Tail Pit, backfilled with waste rock early in mine operation. Work continues on modelling and understanding the movement of water, and the ongoing causes of strong ARD, in this waste rock (Liu et al., 2017, 2018a, and 2018b).

Water primarily enters the Equity Silver site from two sources. First, precipitation falls directly onto the minesite components. This includes an accumulating snowpack during winter months. Spring freshet produces relatively high flows at the site. Second, groundwater originating from uphill precipitation flows onto the site, including the base of the waste rock, from higher elevations. Many studies have failed to conclusively prove the percentages of ARD attributable to these two sources.

To minimize ARD and divert uncontaminated water, a fine-grained till-soil cover was placed over the waste rock in the final years of operation, from around 1991 (Mine Year 11) to site closure in 1994 (Mine Year 14). The cover consists of 0.5 m of compacted till overlain by 0.3 m of uncompacted till. Despite the original design objectives, some water and oxygen pass through the cover into the underlying waste rock. Thus, infiltration through the cover, combined with basal groundwater flow, moves through the waste rock and becomes ARD.

Decades of monitoring data are available at Equity Silver. These data include precipitation, infiltration rates, groundwater levels, flow rates, 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 (Morin et al., 2003, 2010, and 2012).

Based on spectral peaks in periodograms, Morin (2016) identified groundwater flow into the base of the waste rock as the main source of water in most seepage/outflow locations. This was consistent with a long-term mass balance in acidity, indicating a certain amount of acidity was generated each year but not always removed as ARD each year (Morin et al., 2003, 2010, and 2012).

All waste rock at Equity Silver, including the backfill in the Southern Tail Pit, was combined into one management unit, approximately 132 hectares in size and containing approximately 80×10^6 tonnes of rock. This unit includes a series of ditches and ponds to collect ARD (shown conceptually in Figure 1), so that ARD can be pumped to, and neutralized by lime at, the water-treatment plant. The monitoring stations of interest in this paper are (1) overflow from the backfilled Southern Tail Pit (STailP), located at the head of the main ARD-collection ditch, (2) C-7 at the end of the main ditch before the Main ARD pond, and (3) C-11 at the outflow from another portion of the waste rock.

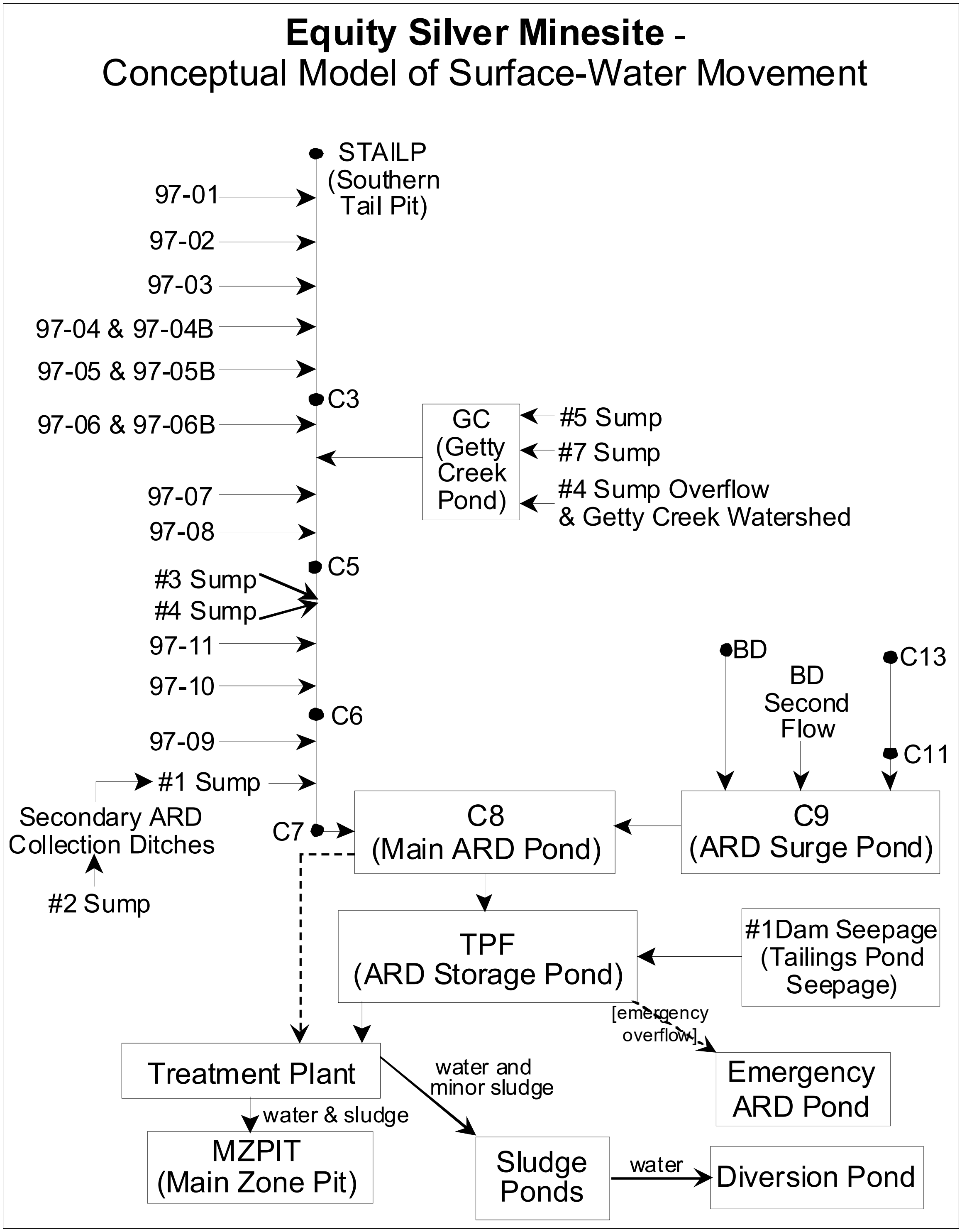


Figure 1. Schematic diagram of the ARD collection system at the Equity Silver Minesite (from Morin et al., 2010 and 2012).

2. Objectives

The primary objective of this paper is to examine how flows from the full-scale waste rock were affected by installation of the fine-grained cover. To be clear, aqueous chemistry does not correlate well with flow, and displays different trends and behaviour, which is typical of many minesites. This paper is specifically about physical flow rates, with chemistry discussed in Morin et al. (2003, 2010, and 2012) and Morin (2016 and 2018).

Furthermore, this paper discusses the effect of the cover on flows in two ways. First, time series of flow rates at the overflow from the Southern Tail Pit, C-7, and C-11 are examined for significant changes before and after cover installation. Second, the periodicities of flows at these three stations are examined for significant changes. As this paper shows, these two different examinations lead to different observations.

3. Effects on Flow Rates after Cover Installation

The time series for flow rates are on the left sides of Figures 2, 3, and 4. Initial predictions and modelling for this cover indicated infiltration, would be reduced by more than one order of magnitude, from the estimated 40% of precipitation (e.g., O'Kane, 1995; Swanson, 1995). In contrast, the time series show no significant effects of cover installation, even after almost two decades after installation in Mine Year 14. In fact, the time series for C-7 (left side of Figure 3) shows that flow rates generally increased after cover installation.

Therefore, the effect of cover installation on flow rates was not major. It did not substantially reduce the flow rates (or aqueous chemistry) of the ARD in the system. This was supported by monthly and yearly statistics (Morin et al., 2010 and 2012).

4. Effect on Periodicities of Flow after Cover Installation

The time series of flow rates (left sides of Figures 2, 3, and 4), and of aqueous concentrations (not shown, see Morin, 2016 and 2018), show strong oscillations and periodicities during one-year periods. Put simply, there are large increases and decreases in flow rates through each year. However, this is only the visibly obvious part, with more complexity present than first apparent.

As a general tool, least-squares spectral analysis (a generalization of Fourier analysis) is needed to see the true complexity (Morin, 2016; VanderPlas, 2018). The resulting periodograms (right sides of Figures 2, 3, and 4) show that periodicity in those time series is occurring at many more wavelengths than just one year.

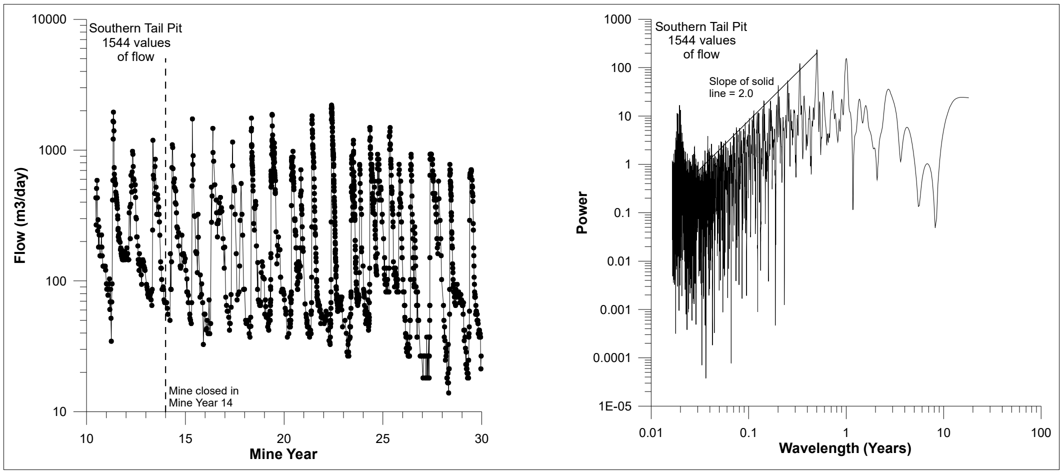


Figure 2. Flow rates of the overflow from the backfilled Southern Tail Pit at the head of the main ARD ditch: (left side) time series and (right side) spectral periodogram.

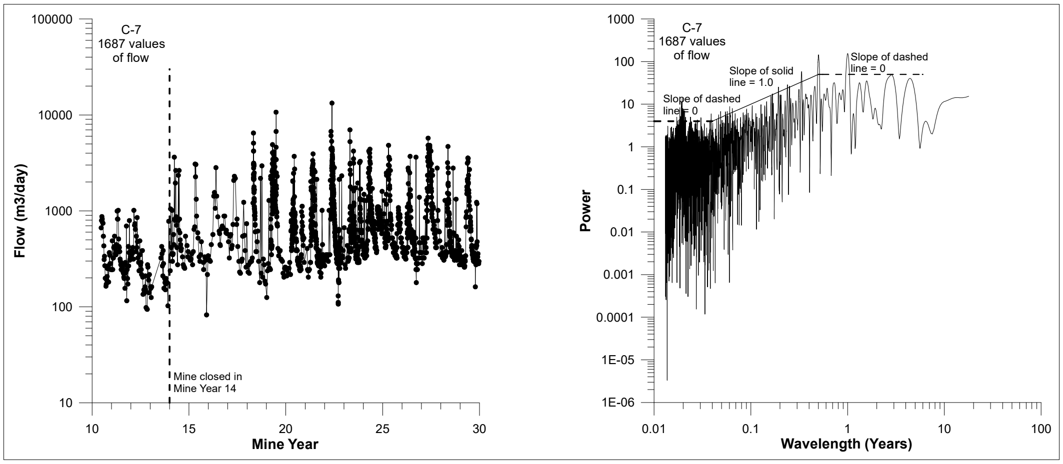


Figure 3. Flow rates at Station C-7 at the end of the main ARD ditch: (left side) time series and (right side) spectral periodogram.

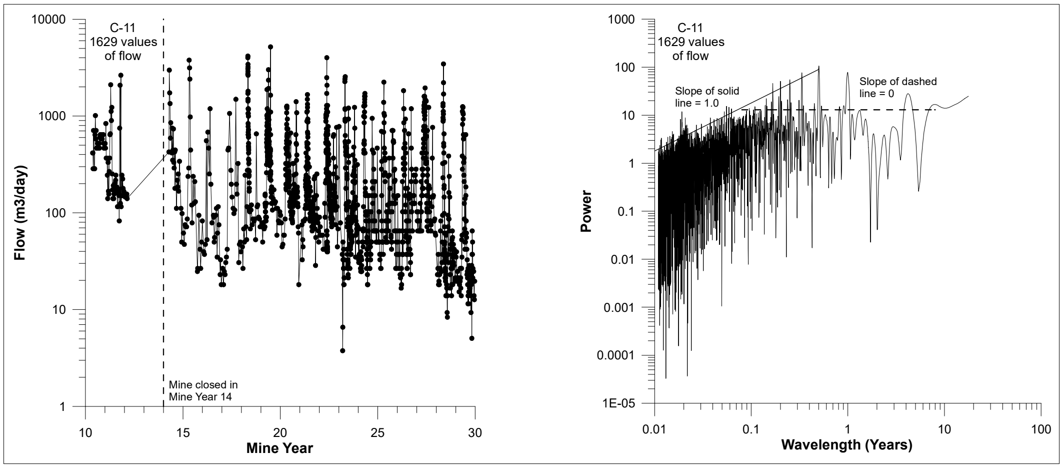


Figure 4. Flow rates at Station C-11 monitoring another portion of the waste rock: (left side) time series and (right side) spectral periodogram.

Moreover, the spectral power decreases as wavelength decreases, forming straight-line power-law slopes on the log-log plots. These slopes range from zero (random, or "white noise") to two (random walk, or "red noise"). They include slopes of one (1-over-f, or "pink noise"), which are topics of intensive current research and modelling in many fields of science and art. These slopes represent fractal distributions, so large ranges of spectral power are needed for valid interpretations.

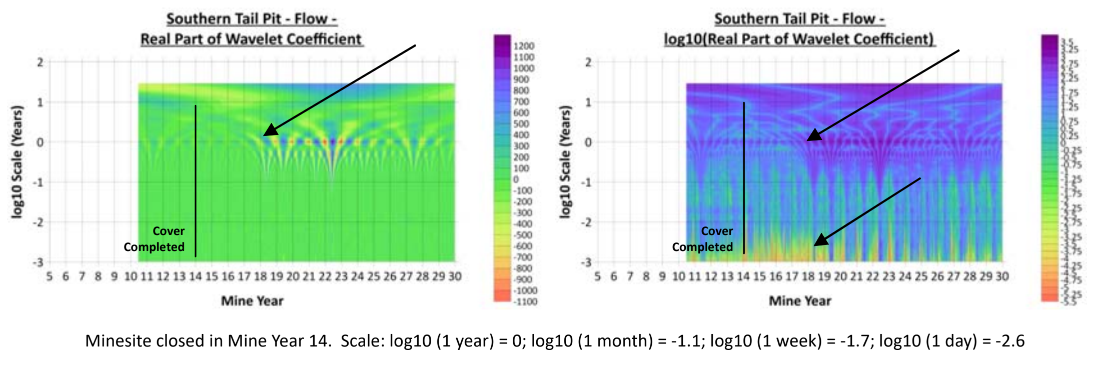
These periodograms in Figures 2 to 4 show there is fractal self-organization of processes and fluxes that govern outflows from the waste rock. Additionally, there are clear wavelengths of periodicity, but they do not reveal whether there were any effects of cover installation. This is partly due to the mathematics of spectral analysis, which examines the entire monitoring period as a whole, rather than year-by-year intervals. To reveal the yearly details in periodicity and power, windowed spectral analyses can be conducted, but this has some major drawbacks (Morin, 2018).

Instead, wavelet transforms provide the details needed here. The mathematics behind wavelet transforms can be daunting, and it is not the objective of this paper to delve into those equations. Instead, Morin (2018) provides a relatively simple introduction to wavelets for full-scale drainages, and lists many references for more detailed and intensive information.

As a basic summary of what was done here, this paper used a continuous complex-valued Morlet wavelet, with a method (Keitt, 2008) for handling the unevenly spaced and irregular minesite-monitoring data that invalidates most wavelet software. For each wavelet diagram, many tens of thousands of wavelet coefficients were obtained using Package "mvcwt" in the R Language Version 3.4.4 (R Core Team, 2016), with the Rstudio 1.1.447 user interface (Rstudio Team, 2015). Package "mvcwt" provided phase information (positive and negative) through the real parts of these coefficients to reveal periodicity. Results were imported into Surfer 15 (Golden Software, 2018) for plotting as a 5000-by-5000 grid, using a base-10 logarithm for Scale (equivalent to wavelength in this case). Edge effects, scale leakage, and "detection limits" were included in the interpretations. However, statistical significance was dismissed so that log-log slopes, like 1-over-f slopes, were still evaluated. All these points are discussed in detail in Morin (2018).

In this paper, the real parts of the complex-valued wavelet coefficients are shown in two ways: arithmetic and logarithmic. Arithmetic values show periodicity as positive (increasing) and negative (decreasing) values using dark and bright colours, respectively. However, this first approach cannot show important lower-power trends, so logarithmic values of the real parts are used as the second approach. Logarithms for negative values are undefined, so the absolute value of the real part is used. The downside of this logarithmic approach is that positive and negative aspects of periodicity are lost in exchange for finer details. For the three monitoring stations examined in this paper, the arithmetic and logarithmic plots of periodicity in flow are shown in Figures 5, 6, and 7.

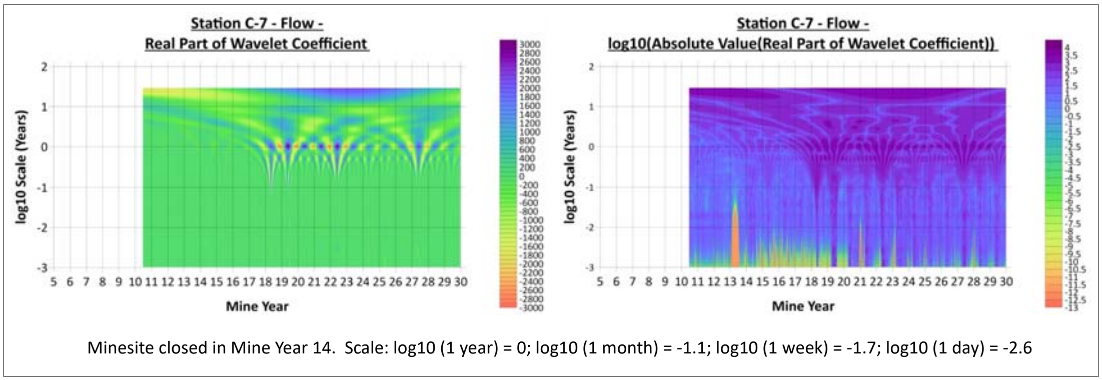
For outflow from the Southern Tail Pit (Figure 5), the completion of the cover in Mine Year 14 had no significant effect on periodicity, with annual cycles continuing as the climate changed annually. This can be seen on the right side of Figure 5, with darker colours at log10 Scale of 0.0 (yearly) forming a horizontal band. Overall, periodicity was relatively weak before the cover, except for persistent ongoing annual periodicity (log10 0.0) and for weak weekly periodicity (the horizontal band of darker colour at log10 -1.7) that disappeared within a year after cover completion.


Southern Tail Pit - Flow - Real Part of Wavelet Coefficient

Southern Tail Pit - Flow - log10(Real Part of Wavelet Coefficient)

Minesite closed in Mine Year 14. Scale: log10 (1 year) = 0; log10 (1 month) = -1.1; log10 (1 week) = -1.7; log10 (1 day) = -2.6

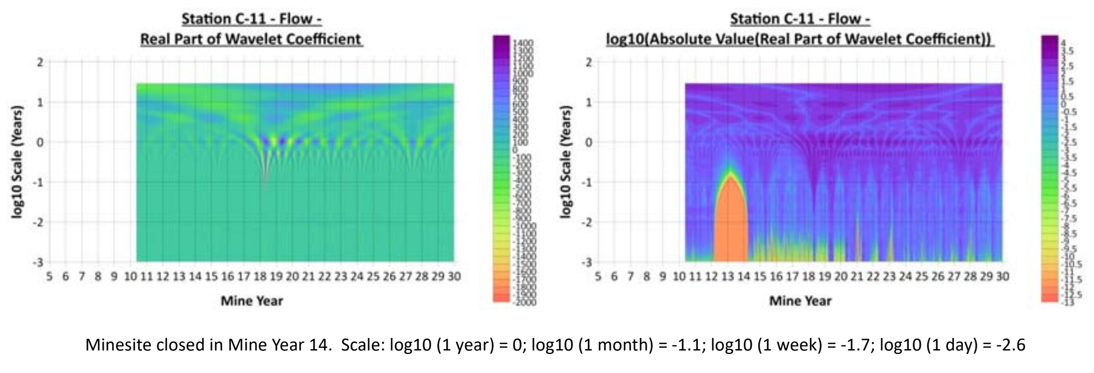
Figure 5. Flow rates of the overflow from the backfilled Southern Tail Pit at the head of the main ARD ditch: (left side) arithmetic wavelet coefficients and (right side) logarithmic wavelet coefficients. Arrows show significant annual periodicity (log10 0) starting at Mine Year 18, fours years after the cover was completed; the logarithmic diagram also shows the strong periodicity extending down to sub-daily oscillations.


Station C-7 - Flow - Real Part of Wavelet Coefficient

Station C-7 - Flow - log10(Absolute Value(Real Part of Wavelet Coefficient))

Minesite closed in Mine Year 14. Scale: log10 (1 year) = 0; log10 (1 month) = -1.1; log10 (1 week) = -1.7; log10 (1 day) = -2.6

Figure 6. Flow rates at Station C-7 at the end of the main ARD ditch: (left side) arithmetic wavelet coefficients and (right side) logarithmic wavelet coefficients.


Station C-11 - Flow - Real Part of Wavelet Coefficient

Station C-11 - Flow - log10(Absolute Value(Real Part of Wavelet Coefficient))

Minesite closed in Mine Year 14. Scale: log10 (1 year) = 0; log10 (1 month) = -1.1; log10 (1 week) = -1.7; log10 (1 day) = -2.6

Figure 7. Flow rates at Station C-11 monitoring another portion of the waste rock: (left side) arithmetic wavelet coefficients and (right side) logarithmic wavelet coefficients.

However, four years after cover completion, in Mine Year 18, annual periodicity suddenly strengthened (see the top arrows in Figure 5 pointing to increasingly stronger colours). Moreover, the logarithmic diagram shows that this major increase in periodicity extended down to short wavelengths less than one day (see the lower arrow in Figure 5 on the logarithmic diagram).

In other words, flow from the Southern Tail Pit became highly cyclical each day, week, month, and year (and between these wavelengths), four years after the cover was completed.

This increased periodicity across these wavelengths is also observed for C-7 and C-11 (Figures 6 and 7). As a result, the entire waste-rock management system experienced the same effect, except in major holding ponds which smoothed out the oscillations. This suggests about four years were needed for the cover to stabilize and significantly influence infiltration patterns throughout the waste rock.

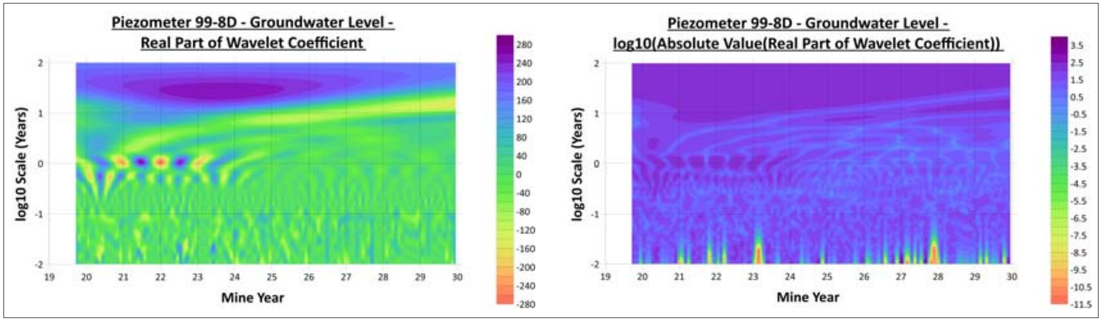
At wavelengths much less than one year (scales less than log10 -1.1, or submonthly), the primary strength of the periodicity lies in the spring months, when precipitation and snowmelt were high and thus infiltration through the cover was high. Such high seasonal variability in periodicities of flow draining from waste rock is consistent with documented significant rapid flow through full-scale waste rock. This can obviously occur even after a fine-grained surficial cover was installed, and even be caused by cover installation. However, it is contrary to most waste-rock models that estimate months to years for significant amounts of infiltration to pass through (Morin, 2017).

About nine years after the cover was completed (Mine Year 23), the high strength of springtime periodicity in flow across the wavelengths began to weaken and become more diffuse, returning towards pre-cover periodicity (Figures 5 to 7). This is consistent with reports of till-soil covers significantly degrading in 10 to 20 years (Taylor et al., 2003; Morin et al., 2003 and 2010; Wilson et al., 2003).

Weakening annual periodicities in groundwater levels within upgradient piezometers coincide with weakening annual periodicity in effluent flows starting in Mine Year 23 (e.g., Figures 8 and 9). This suggests the inflowing groundwater, rather than the infiltration through the cover, can account for the springtime periodicities in the outflows.

However, upgradient groundwater levels do not show the periodicities across the relatively large (vertical) range of wavelengths shorter than 1 yr (Figures 8 and 9), even down to monthly (log -1.1). This is typical of dampening of short-wavelength temporal oscillations in groundwater systems. However, this cannot be confirmed here, because of the relatively less-frequent measurements of the piezometer levels.

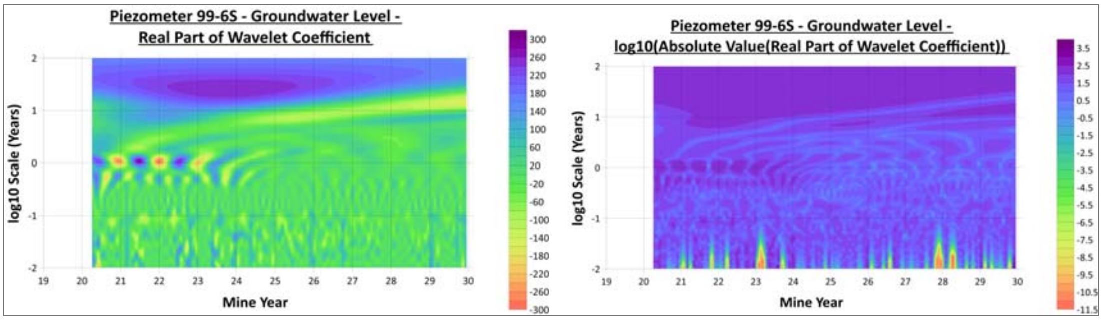
Thus, upgradient groundwater cannot explain the patterns in Figures 5 through 7 attributed to cover degradation. Also, the periodicities at 1 yr wavelengths for infiltration, groundwater levels, and outflows are similar, so this wavelength cannot be used to distinguish water sources.



Piezometer 99-8D - Groundwater Level - Real Part of Wavelet Coefficient

Piezometer 99-8D - Groundwater Level - log10(Absolute Value(Real Part of Wavelet Coefficient))

Figure 8. Groundwater levels in Piezometer 99-8D: (left side) arithmetic wavelet coefficients and (right side) logarithmic wavelet coefficients.



Piezometer 99-6S - Groundwater Level - Real Part of Wavelet Coefficient

Piezometer 99-6S - Groundwater Level - log10(Absolute Value(Real Part of Wavelet Coefficient))

Figure 9. Groundwater levels in Piezometer 99-6S: (left side) arithmetic wavelet coefficients and (right side) logarithmic wavelet coefficients.

It is important to note this delayed effect of the cover, and the later decay of its effectiveness, were not apparent from the time series and spectral periodograms (Figures 2, 3, and 4). Thus, the wavelet transforms of flow were able to provide important information on the effects of a fine-grained cover over waste rock, not available from time series and spectral analysis.

The corresponding aqueous chemistry showed markedly different trends in periodicity than flow. The chemistry is discussed in Morin (2018).

5. Conclusion

In this full-scale case study, a fine-grained till-soil cover was placed over 132 hectares of waste rock releasing acid rock drainage (ARD). This included an early mined-out pit that was backfilled with waste rock. The cover was installed in the final years of mine operation.

The ARD flowing from the waste rock into a series of ditches and ponds originates from some combination of two sources. First, precipitation falls directly onto the cover, and snow packs accumulate on top of the cover in winter. This leads to spring freshet when flows are high, and as much uncontaminated water as possible is diverted off the cover. The remainder infiltrates. Second, subsurface groundwater originating at higher elevations outside the minesite flows into the base of the waste rock.

Several decades of monitoring data, at various monitoring locations downgradient of the waste rock, were used to identify the effects of cover installation on flows. Effects were sought in (1) the time series of flow rates and (2) the periodicities of the flow rates.

Time series of flow revealed no major effects of cover installation even after nearly two decades after installation. This was supported by monthly and yearly statistics.

Time series of flow showed strong oscillations each year. However, there was more complexity hidden in these annual oscillations.

Least-squares spectral analysis (a generalization of Fourier analysis) showed that the oscillations in flow were occurring not just yearly, but at many shorter wavelengths. The log-log straight slopes in spectral periodograms indicated fractal distributions, ranging from random to random-walk, including 1-over-f slopes.

However, spectral analysis examines the entire monitoring interval and was not able to show whether cover installation had any significant short-term effects on periodicities. To avoid problems with windowed spectral analysis, wavelet transforms were used instead to examine periodicity across short portions of the monitoring period.

Wavelet transforms showed that flow from the waste rock was relatively aperiodic before and just after cover installation, except for persistent ongoing annual periodicity (log10 0.0) and weak weekly periodicity (log10 -1.7) that ceased shortly after cover completion. However, four years after installation, periodicities in flow at all examined locations showed major increases in strength across a large range of wavelengths.

In other words, flow rates became much more cyclical each day, week, month, and year (and between these wavelengths), four years after the cover was completed. This suggests about four years were needed for the cover to stabilize and significantly influence infiltration patterns throughout the waste rock. The strongest periodicity across the wavelengths occurred sharply in spring months, when flows were highest.

About nine years after the cover was completed, the high strength of springtime periodicity in flow began to weaken and become more diffuse, approaching pre-cover periodicity. This is consistent with reports of till-soil covers significantly degrading in 10 to 20 years. Changes in upgradient groundwater flow could apparently account for some, but not all, of this weakening in periodicity.

Therefore, the wavelet transforms of flow were able to provide important information on full-scale effects of a fine-grained cover over waste rock, not available from time series and spectral analysis. The corresponding aqueous chemistry showed markedly different trends than flow, but this is discussed elsewhere.

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