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Effects of Water-Retention Structures on Temporal Power Spectra for Drainage Waters

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Abstract

This MDAG case study expands on issues raised in the book, *Spectral Analysis of Drainage from Highly Reactive Geologic Materials* (Morin, 2016a). In particular, this case study examines how water-retention structures like ponds, lakes, and aquitards affect power spectra (in the frequency-wavelength domain) of inflowing waters. These structures are collectively called "ponds" here for simplicity.

Alteration of inflowing power spectra by ponds can be important. They can alter the variability and frequency of aqueous concentrations and their associated toxicities. Even changes in spectral slopes can alter the dynamics of exposed biological populations.

The focus of this case study is on relatively well mixed ponds, where one day's inflow mixes rapidly with previous days' inflows. Ponds with geochemical stratification in the water column preclude general conclusions, because the results depend on the nature of the stratification and whether water sampling correctly detects this stratification.

To start, random normal Gaussian, and random lognormal Gaussian, daily time series showed highly variable values through time. The corresponding power spectra confirmed that these time series were generally random, with "white" spectral slopes around $\alpha \sim 0$, with minor periodicity. Next, each day's value was added to previous days' values, simulating ongoing, long-term retention in a pond. In all cases, these summations resulted in "red" power spectra with slopes of $\alpha \sim 2.0$. Furthermore, spectral analysis of summations of these already-summed series still produced only red slopes.

Therefore, retention of drainage can "redden" a spectral slope (increase the slope) from its initial value to $\alpha \sim 2.0$. However, this does not mean the reddening has to result exactly in $\alpha = 2.0$ under real environmental conditions.

Real, more complex, full-scale examples of precipitation, flow, and 1-over-f aqueous concentrations were subjected to simulated long-term retention. When the time series had a power spectrum close to white noise, the retained spectra (based on summation) displayed reddened slopes, but in one case

only to α ~ 1.6. Thus, simulated retention of these real white-noise trends showed the expected reddening, but not necessarily to α = 2.0. Further retention of the retained values did not change the spectral slope.

In contrast to retained white noise, retention of real, full-scale examples of 1-over-f (α ~ 1.0) slopes caused two spectral slopes to appear: white noise (α ~ 0) at shorter wavelengths and reddened slopes up to α ~ 2.0 at longer wavelengths.

A more complex full-scale example with red noise at intermediate wavelengths, and generally white noise at shorter and longer wavelengths, was mathematically retained in a pond. The results were (1) the red slope remained red (the previous paragraphs explained that no further reddening occurs with repeated summation), (2) the longer-wavelength white noise became red (as explained in previous paragraphs), but (3) the short-wavelength white noise remained white.

Notably, summation of daily values to simulate retention in a pond only applies to parameters like flow volumes. In contrast, aqueous geochemical concentrations and loadings are averaged, rather than summed, upon retention. A suite of Scenarios simulated geochemical retention (averaging) of lognormal white-noise inflow values, with each Scenario differing by the length of time that periodic inflows were retained (attenuated) or not retained (no attenuation) in a pond.

Long-term retention and averaging of geochemical white noise, when the retention interval between emptying of the pond was at least one year, produced reddened spectral slopes. The slopes were α ~ 1.4 at shorter wavelengths, and α ~ 0.8 at longer wavelengths. When retention was less than one year, such as for three or seven days in a season, more complex results were obtained.

For one Scenario with a sequence of short-term retentions in spring and 25-day retention intervals during other seasons, the spectral slope was α ~ 1.0. This suggests 1-over-f slopes for water chemistry may not necessarily require self-organization of many factors.

For another Scenario, longer non-spring retention intervals with no changes in high-flow, low-retention spring flows produced two overlapping spectral slopes (α ~ 0 and 0.8) at longer wavelengths. Such overlapping slopes were documented for relatively large water-retaining ponds in Case Study 2 of Morin (2016a), and one sampling location suggested the presence of an "upstream", internal pond hidden within the waste-rock pile.

Comparisons of various Scenarios led to the following additional observations.

- The change from spectral-power step-down to slope break was due to the increased non-spring retention intervals, which also decreased the wavelength at which the break occurred.

- Near-continuous consecutive periods of retention, even when variable in length, were needed throughout each annual period to avoid overall white noise. Furthermore, some retention, however long, was needed at least every season to avoid nearly unattenuated white spectral slopes in ponds. However, a short period of only seven days each year with no retention did not substantially reduce spectral slopes towards white noise, but a non-retention period of 30 days annually caused an intermediate whitening of the slope.

- Short intervals of no retention in spring resulted in the appearance of a third spectral slope, of white noise ($\alpha \sim 0$), at wavelengths shorter than 0.015 yrs (5.5 days). This passing of unfiltered short-wavelength white noise was reported in Case Study 1 of Morin (2016a). In that Case Study, at wavelengths below 9-26 hours, high-frequency monitoring of waste-rock drainage in a ditch detected rapid plug flow through internal coarse-rock channels.

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1. Introduction

Morin (2016a) noted that relatively large water-retention ponds along drainage-ditch systems could significantly alter power spectra (in the wavelength-frequency domain) of inflowing waters. The altered power spectra represented both physical flow and aqueous geochemical concentrations.

This can be important geochemically. Alteration of a spectrum often leads to different temporal patterns and different quantitative values of maximum and minimal aqueous concentrations.

This can also be important environmentally. Altered power spectra can signal a change in the variability and frequency of toxicity. More generally, simply a change in spectral slopes can lead to short-term and long-term changes in the dynamics of exposed biological populations (e.g., Cyr et al., 2003; Pantel et al., 2014; Ranta et al., 2000; Reuman et al., 2008; Ripa and Lundberg, 1996; Ripa et al., 1998; Rouyer et al., 2010; Vasseur, 2007; Vasseur and Yodzis, 2004).

This MDAG case study examines in detail the spectral alterations caused by constructed ponds. However, similar observations can be made for natural ponds, lakes, subsurface aquitards, and other water-retention structures. For brevity, “pond” will often be used here to represent all such structures.

For simplicity, time in this case study is discretized into days. Any other time unit would lead to similar conclusions.

2. Trivial Examples

If the storage volume and average residence time of a water-retention structure are small compared with the smallest inflow, then there is little retention. As a result, the power spectrum of inflowing and outflowing water will be virtually unaltered. This is an example of "piston" or "plug" flow, and is not examined here in detail.

For large water-retention structures compared with the smallest daily inflow, water will be retained at least occasionally for a few days. However, during high inflows, there may be virtually no retention at all, and at these times plug flow will occur.

Effects of water retention on temporal power spectra can be, in some cases, pond-specific and difficult to identify. This is due to two primary, linked issues: (1) geochemical stratification of the water column and (2) water-sampling location. These are not significant concerns for rapidly well-mixed (non-stratified) ponds, which are discussed in later sections.

In a simple example, a pond is stratified and each day's inflow enters the pond as the uppermost layer. If the pond is drained from the top, then each day's inflow becomes the next day's outflow, which is basically short-circuited plug flow. This would have little effect on inflow/pond/outflow power spectra if each day's water sample were collected at the top of the pond. However, there would be a major effect on the (incorrectly delineated) spectra if the water were sampled from the bottom layer or as a mixture of the entire water column (all layers mixed together in the sample bottle).

On the other hand, if this stratified pond is drained from the bottom and this bottom drainage is sampled each day, then there would only be a temporal delay between inflow and outflow timing. The delay would reflect the residence time of each layer in the pond. However, there would be a major effect on the (incorrectly delineated) outflow spectra if the water were sampled from the top layer or as a mixture of the entire water column.

More complex scenarios can be envisioned. Examples would be:

- ponds drained from intermediate depths, but with water sampling from the top or bottom;
- mixing of some adjacent geochemical strata and not others, and
- each day's inflow forming a layer at differing depths.

In effect, geochemical stratification and sampling location of a stratified pond can complicate interpretations. The differences between inflow and outflow spectra can be unique to such ponds, and can be erroneously defined by sampling as illustrated above. Therefore, no general conclusions can be drawn here about such ponds.

In contrast, rapidly well-mixed ponds offer more opportunities for general conclusions, as the remainder of this case study shows.

3. Basic Effects of Water Retention on Power Spectra

As explained in Section 2, effects on power spectra can be site-specific and difficult to define accurately for geochemically stratified ponds. This section and the following sections look only at relatively well-mixed ponds in which inflows mix rapidly with water already in the pond. This allows a pond to be validly sampled at any location.

To create daily values of inflow, a random, predominantly white-noise spectrum ($\alpha \sim 0$) was created in Excel using the formula: NORM.INV(RAND(),MEAN,STANDARD DEVIATION). This yielded random values from the Gaussian distribution represented by the specified mean and standard deviation. Different values for the mean and standard deviation were used, but spectral results remained similar.

Morin (2016a) noted that drainage concentrations in case studies were often generally lognormally distributed, and this is also the case in general for much geochemical data. To include this here in the spectral analysis of retention effects, the normally distributed values in the previous paragraph were transformed to lognormal using antilog10. This yielded similar spectral results as the normal data, as explained below.

For spectral analysis, this MDAG case study used the Lomb-Scargle algorithm implemented on the NASA Exoplanet Archive website (Akeson et al., 2013). This algorithm is explained in more detail in Chapter 4 of Morin (2016a).

Because different values of means and standard deviations in the NORM.INV equation yielded similar spectral results[1], only one set of results will be discussed here. With a mean of 3.0 and a standard deviation of 0.25, the resulting random time series of inflow is shown in Figure 3-1 and its corresponding white-noise ($\alpha \sim 0$) spectrum shown in Figure 3-2. Based on antilog10 values, the parallel random lognormal time series of inflow is shown in Figure 3-3 and its white-noise spectrum in Figure 3-4. If the y-axis of Figure 3-3 were shown as logarithmic, the time series would appear identical in shape to Figure 3-1.

The relationship between white and red noise is critically important in this section, and some elaboration is warranted. A white-noise spectral slope of zero ($\alpha = 0$) for a time series represents a random trend or chaos (discussed in more detail in Section 5.3 of Morin, 2016a). White noise is statistically stationary with no persistence or "memory". In contrast, a spectral slope of $\alpha = 2$ is called "red noise" and represents random walk that implies statistical non-stationarity and strong persistence and memory. Brownian motion is a type of red noise. Random and random walk are related mathematically by integration, which accounts for their difference in spectral slope of two.

An important observation is that mathematical integration can be approximated by summation, such as "summing the area under a curve". In turn, summation is similar to real-world retention in a pond, where one day's inflow to a pond is added to the next day's, and added to the next day's, etc. Therefore, when the daily values in Figures 3-1 are summed (retained in a pond) and spectrally analyzed, the resulting spectrum is indeed red (Figure 3-5). Figure 3-6 shows the similar result for the lognormal time series of Figure 3-3.

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[1] Although similar spectral results were obtained, the random time series generated by Excel contained various degrees of periodicity which affected power spectra. Random time series with less periodicity were used here.

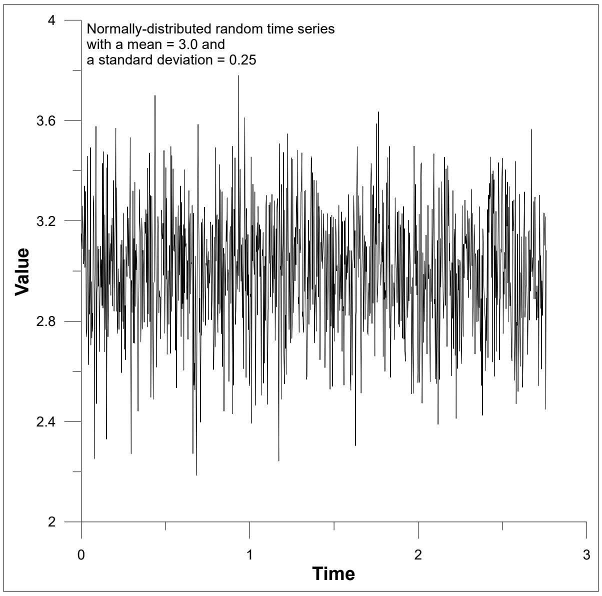

Figure 3-1. A normally distributed random time series.

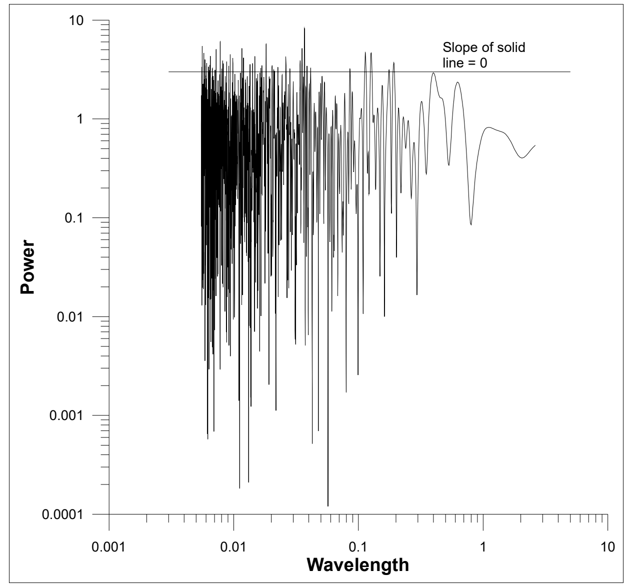

Figure 3-2. The predominantly white-noise power spectrum of Figure 3-1.

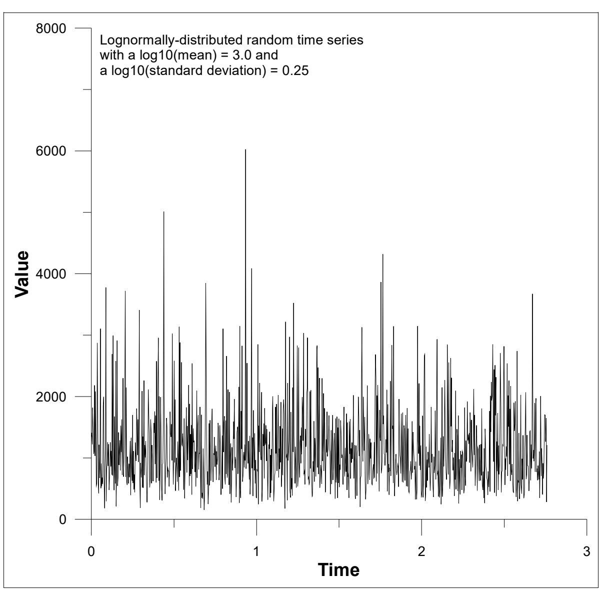

Figure 3-3. A lognormally distributed random time series.

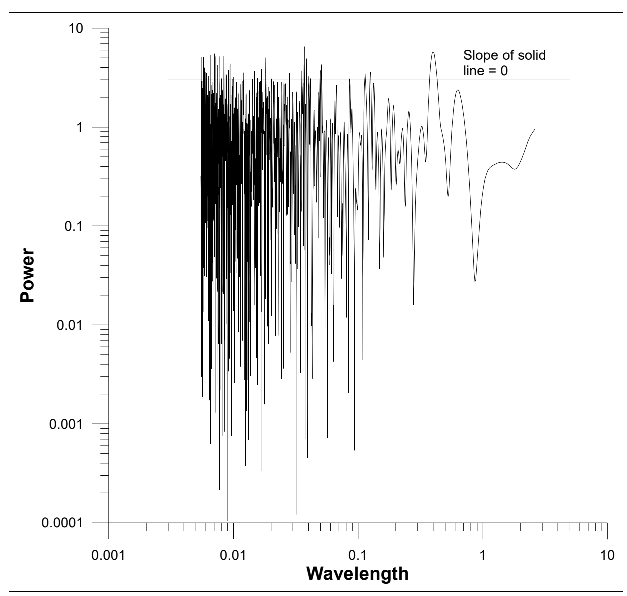

Figure 3-4. The predominantly white-noise power spectrum of Figure 3-3.

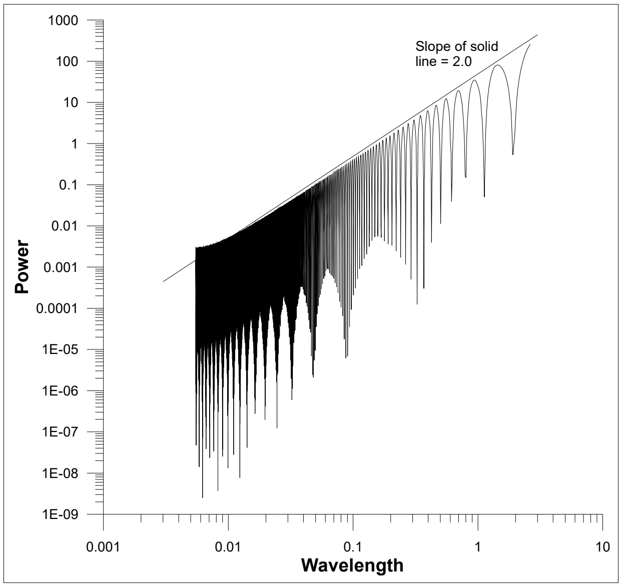

Figure 3-5. The red-noise power spectrum resulting from the summation of the time series in Figure 3-1.

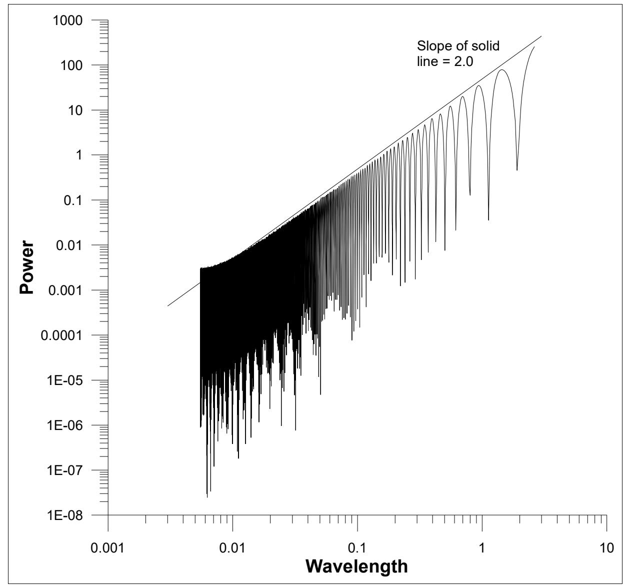

Figure 3-6. The red-noise power spectrum resulting from the summation of the time series in Figure 3-3.

The differences in spectra between the summed normal-distributed time series (Figure 3-5) and the summed lognormal series (Figure 3-6) are minor and primarily involve small differences in spectral power values. Thus, the logarithmic function causes little difference in the spectra.

In comparison with long-term retention, red noise is still obtained when each year's data is summed (annual retention) and the sum is reset to zero (instantaneous release of annual accumulation) at the beginning of the next year. The resulting power spectrum is similar in appearance to Figure 3-5, with the only notable difference being a change in spectral power. Also, summation of an already-summed time series produces red noise (similar to Figure 3-5). In other words, periodic resets in the summation to zero, and summation of a summed time series, still produce red noise ($\alpha = 2.0$).

Therefore, retention of drainage can "redden" a spectral slope (increase the slope) from its initial value to $\alpha \sim 2.0$. However, this does not mean the reddening has to result exactly in $\alpha = 2.0$ under real environmental conditions, which is shown below. Also, retention of red (already-summed) data does not change the spectral slope.

4. Effects of Water Retention on Power Spectra for Time Series Subject to Accumulation, like Drainage Flows

As real, full-scale examples of retention effects on power spectra, daily precipitation data for two minesite case studies (Chapters 6 and 8 of Morin, 2016a), spanning 20 to 40 years, generally produced white noise (Figures 4-1 and 4-2). However, these spectra also showed prominent peaks around a wavelength of one year, highlighting the strong periodicity at one year, and around wavelengths of a few months. Upon summing the precipitation time series, a red-noise trend of $\alpha \sim 2.0$ was seen for the first site (Figure 4-3), but the overall slope was around $\alpha \sim 1.6$ for the second site (Figure 4-4). The summation of the already-summed time series represented by Figure 4-4 increased spectral power but did not change the slope.

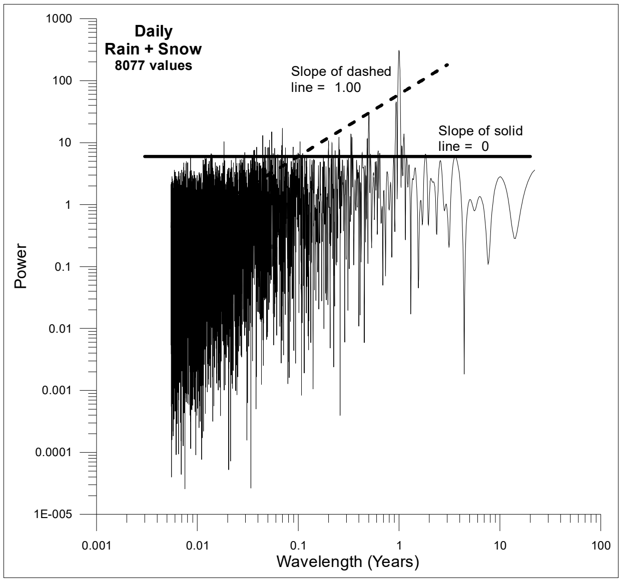

Figure 4-1. The predominantly white-noise power spectrum, plus some significant peaks, for 20 years of precipitation at Case Study 1 in Morin (2016a).

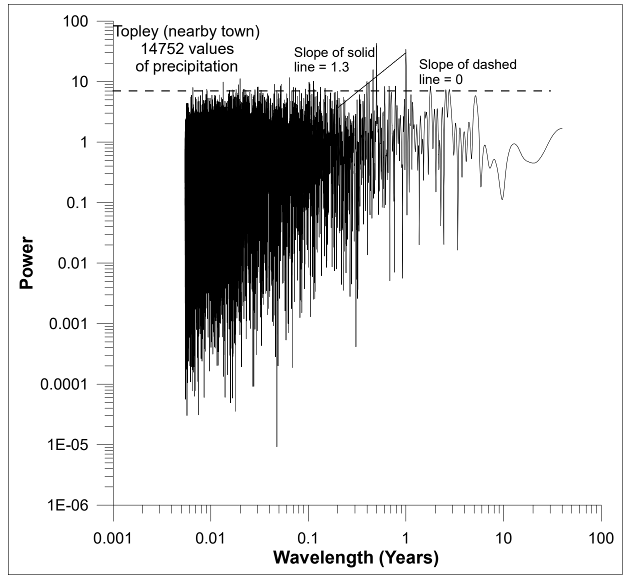

Figure 4-2. The predominantly white-noise power spectrum, plus some significant peaks, for 40 years of precipitation at Case Study 3 in Morin (2016a).

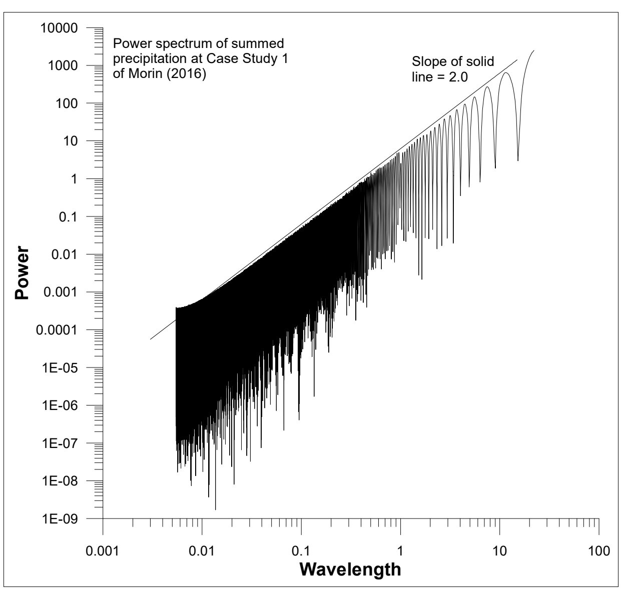

Figure 4-3. The reddened power spectrum resulting from the summation of the long-term precipitation time series corresponding to Figure 4-1.

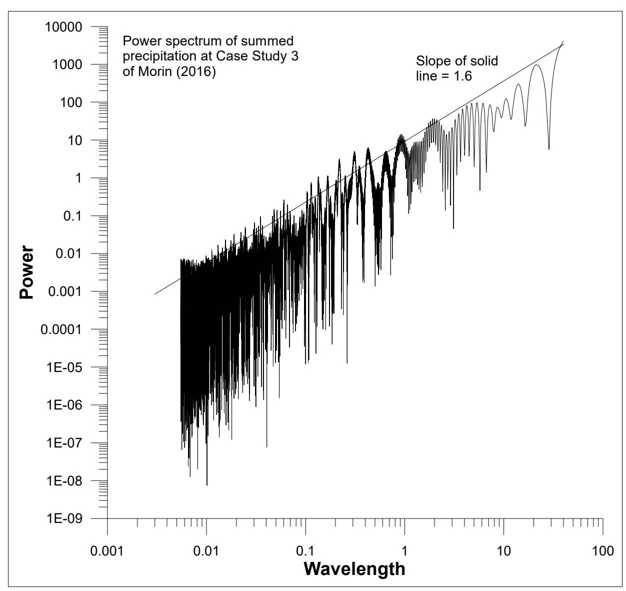

Figure 4-4. The reddened power spectrum resulting from the summation of the long-term precipitation time series corresponding to Figure 4-2.

Thus, "retention" of these real trends in precipitation showed the expected reddening, but not necessarily to $\alpha = 2.0$. Further retention of the retained values did not change the spectral slope.

As other real, full-scale examples, data for drainage flow, copper concentrations, and zinc concentrations were compiled from the backfilled Southern Tail Pit (see Case Study 2 of Morin, 2016a). These parameters were recorded for more than 20 years.

Based on data starting in Mine Year 7.5, the power spectrum for flow showed a spectral slope of $\alpha \sim 2.0$ at wavelengths from about 0.03 to 0.5 years and with poorly defined, but generally white, slopes at shorter and longer wavelengths (Figure 4-5). The power spectrum for the summation of these flows, reflecting retention, was also complex (Figure 4-6). Two adjacent wavelength intervals showed red noise, at 0.1-1.0 years and 1.3-20 years, but were separated by a step-down offset in power. At lower wavelengths, a white-noise interval arose. In this case, retention caused:

- the slope of the $\alpha \sim 2.0$ interval in Figure 4-5 to stay around 2.0 in Figure 4-6, in agreement with the observations in Section 3,
- the generally white slope at the longest wavelengths to become red, in agreement with the observations in Section 3, and
- for the generally white slope at shortest wavelengths to remain white, which was not expected based on Section 3.

Thus, the summation of a flow time series with a complex spectrum led to another complex spectrum, and did not consistently redden the spectral slopes.

Based on data starting in Mine Year 11 (incorrectly stated as starting in Mine Year 10 in the original reference), geochemical spectra for copper and zinc concentrations in drainage from the Southern Tail Pit displayed 1-over-f "pink" slopes (Figures 4-7 and 4-8). They represented the second documented case of 1-over-f in minesite drainage (Morin, 2016a and 2016b).

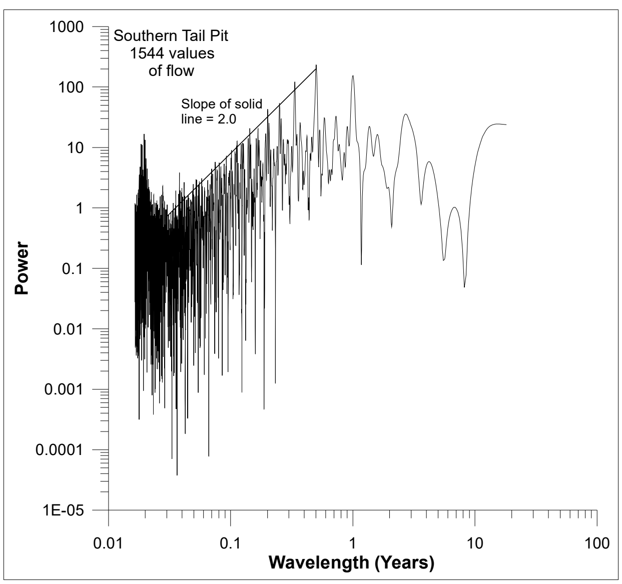

Figure 4-5. The complex power spectrum for flow from the backfilled Southern Tail Pit at Case Study 2 in Morin (2016).

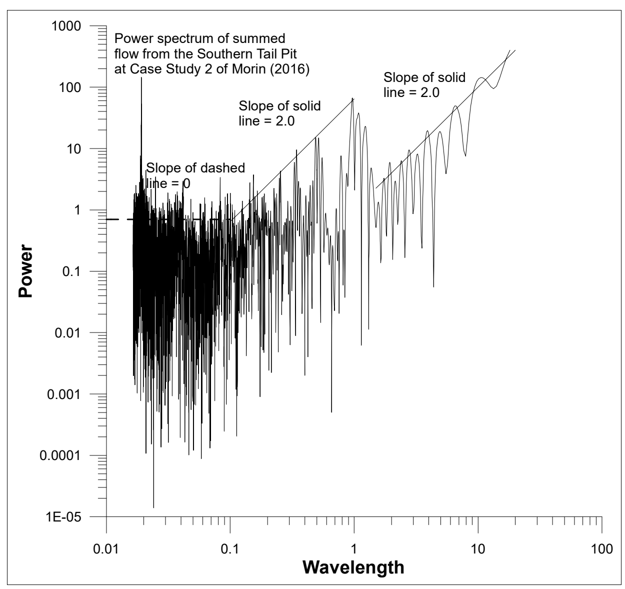

Figure 4-6. The complex power spectrum resulting from the summation of the long-term flow times series corresponding to Figure 4-5.

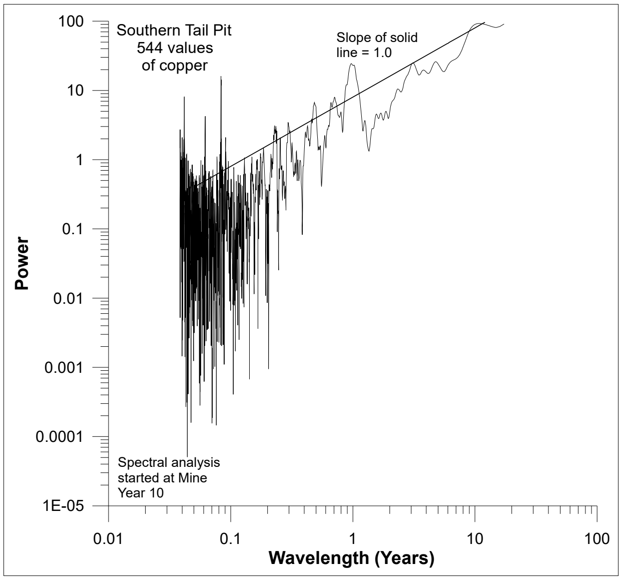

Figure 4-7. The 1-over-f power spectrum for copper from the backfilled Southern Tail Pit at Case Study 2 in Morin (2016).

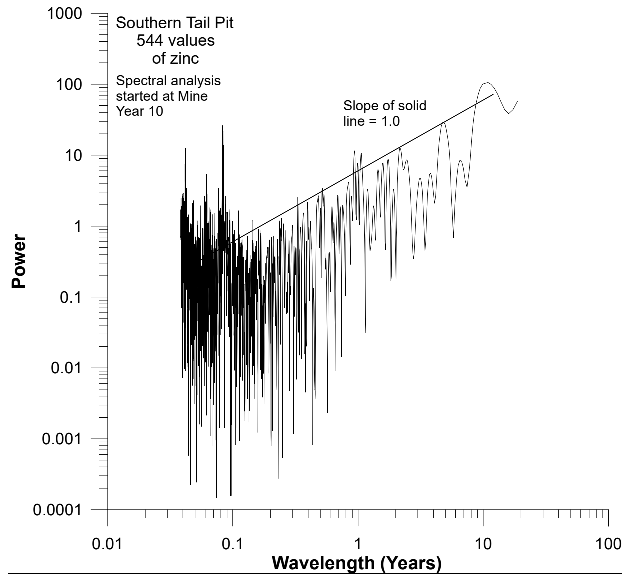

Figure 4-8. The 1-over-f power spectrum for zinc from the backfilled Southern Tail Pit at Case Study 2 in Morin (2016).

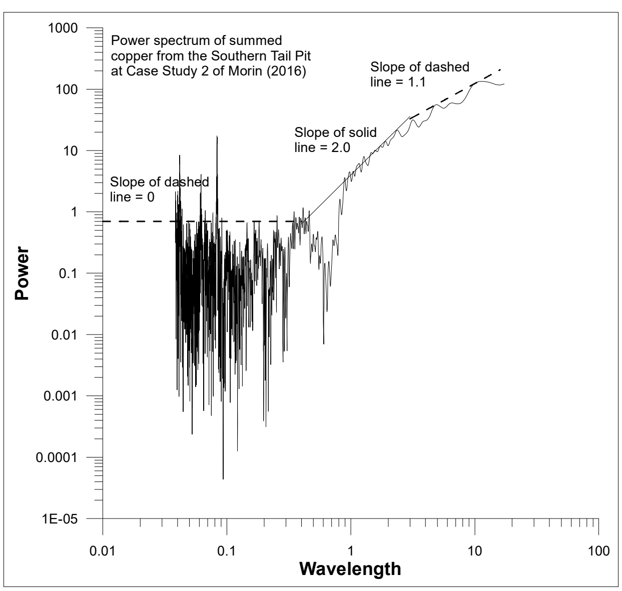

Figure 4-9. The power spectrum resulting from the summation of the long-term copper times series corresponding to Figure 4-7.

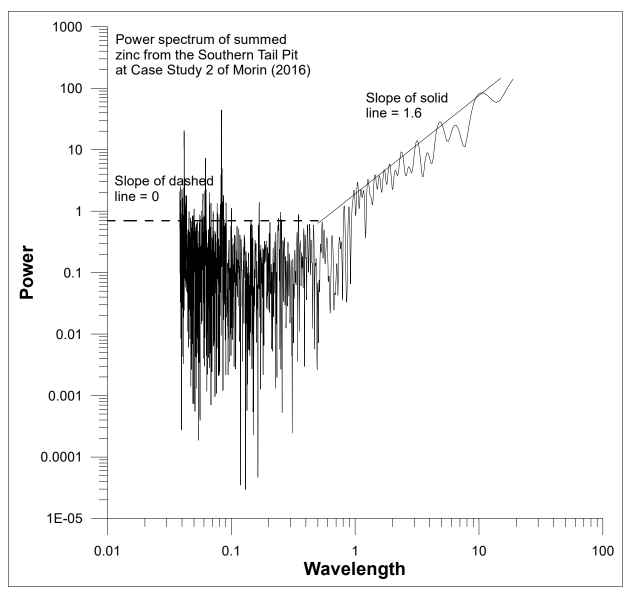

Figure 4-10. The power spectrum resulting from the summation of the long-term zinc times series corresponding to Figure 4-8.

Upon summation of their time series, the resulting “retention” spectra showed a slope reduction (whitening) to $\alpha \sim 0$ up to a wavelength of about 0.5 years, and a slope increase (reddening) above 0.5 years to at least $\alpha \sim 1.6$ (Figures 4-9 and 4-10; see also Figure 4-4 for a reddened slope of $\alpha \sim 1.6$). At wavelengths longer than about three years, copper also showed a slope reduction to $\alpha \sim 1.1$ (Figure 3-15). Summation of the already-summed values for Figure 4-10 changed the spectral power, but not the slopes. As a result, retention of these 1-over-f pink slopes produced adjacent intervals of whiter and redder noise.

In this case of copper and zinc, it is important to note these are aqueous concentrations (mg/L), and thus do not sum upon retention. Instead, they are subject to an accumulating average for the length of retention, which is discussed next. They were used above only to illustrate the effect of retention on a 1-over-f slope where summation is applicable.

5. Effects of Water Retention on Power Spectra for Time Series Subject to Averaging, like Aqueous Concentrations

As explained in Section 2, effects on power spectra can be site-specific and difficult to define accurately for geochemically stratified ponds. This section looks only at relatively well-mixed ponds in which inflows mix rapidly with water already in the pond.

Sections 3 and 4 looked at retention where some parameter such as water volume (inflow) was accumulating in a pond for each day of retention. This section looks at retention from a geochemical perspective, where aqueous concentrations (mg/L) from each day’s inflow are cumulatively averaged with those of the retained previous days’ concentrations.

Mathematically, retained loadings (the sum of each day’s concentration multiplied by its flow, such as mg/day) divided by the sum of each day’s inflow (e.g., L/day) is the proper way of obtaining averaged (well-mixed) concentrations in a pond retaining water. In this section, the effect of flow is simplified by setting the flow as constant for each period of retention, allowing each daily concentration to be cumulatively averaged.

For example, during low inflow, a pond may retain 100 days of flow. Halfway though this period, the aqueous concentration in the pond would be the cumulative average of the first 50 days. After 100 days, the pond is instantaneously emptied, carrying the 100-day cumulative-average concentration.

During high inflow, there may be only enough storage volume in a pond to retain three days’ worth of water. The cumulative average concentrations can then be calculated over each of those three days. During the very high inflows, there may be virtually no retention, and a pond is emptied each day. In this case, there is no averaging of the daily inflow’s concentration, and unattenuated plug flow occurs.

To examine the spectral effects of this water retention with averaging, a Gaussian lognormal random three-year time series was used (Figure 5-1) with a white-noise spectrum (Figure 5-2). The spectrum is similar to Figure 3-4.

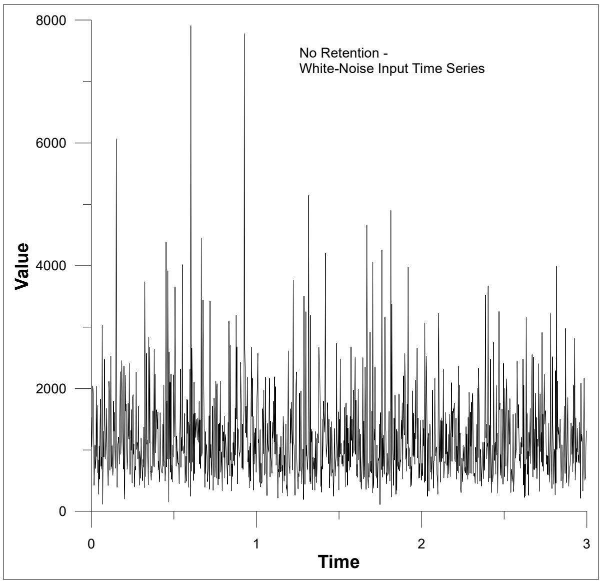

Figure 5-1. The lognormally distributed random time series for averaging of inflow concentrations.

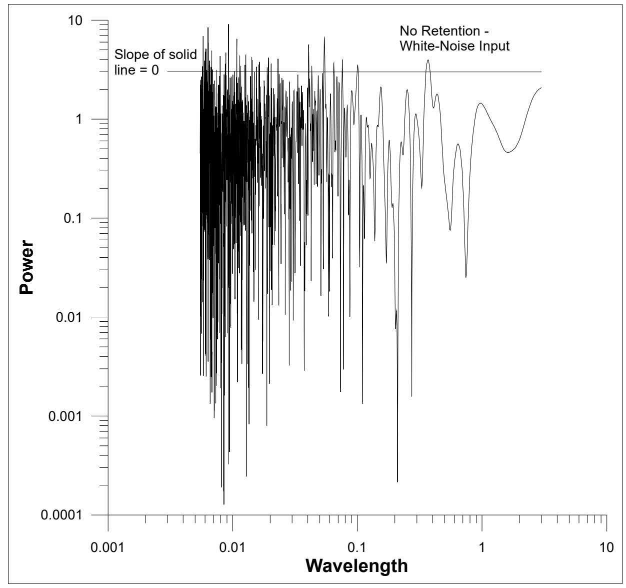

Figure 5-2. The predominantly white-noise power spectrum of Figure 5-1.

In Figure 5-2, there was weakening of spectral power above a wavelength of 0.1 yrs but with a relatively prominent peak at 0.4 yrs, so the input was not completely white noise. This affects some results.

Ten scenarios were considered here (Table 5-1):

- Scenario 10 was complete retention with averaging over the full three years;
- Scenario 9 was retention and averaging over each year with the pond then instantaneously emptied at the end of each year; and
- The remaining Scenarios simulated various seasonal retention patterns, such as high spring precipitation and/or snowmelt with little (few days) or no retention in the pond. Scenario 8 also included a 7-day very high flow (no retention) in the fall.

Scenario 10 simulated complete retention for all years, the opposite of Scenario 0 (Figures 5-1 and 5-2). The time series for Scenario 10 shows the time series becoming less variable as more daily values are included in the accumulating average (Figure 5-3). Spectral analysis of Figure 5-3 showed the power spectrum of Scenario 10 was dominated by a reddened slope of $\alpha \sim 1.4$ (Figure 5-4). However, above a wavelength of 0.3 yrs, the overall slope was $\alpha \sim 0.8$ with significant spectral weakness around 0.7 yrs. This break in slope at 0.3 yrs and the weakness around 0.7 yrs coincide with the spectral weaknesses and the local peak in the random input data (Figure 5-2), and thus they may reflect carry-over effects from the input.

As with all Scenarios, the sequential summation of the daily averaged values for Scenario 10 (Figure 5-3) led to a spectral slope of $\alpha = 2.0$ (not shown, but like Figure 3-5). The square root of this red summation slope for Scenario 10 is 1.4, but it is not clear if the longer slope in Figure 5-4 of $\alpha \sim 1.4$ is a coincidence.

Table 5-1. Retention scenarios for a Gaussian lognormal random three-year time series reflecting seasonal, annual, and longer-term pond retention

Retention Scenario[1]	Retention Intervals			
	Winter (first 100 days)	Spring	Summer	Fall
0	No retention - random time series used as input			
1	25 days each	3-day retention for 4 periods, then 7-day retention for 4 periods	25 days each	25 days each
2	50 days each	30 days of no retention, then 7-day retention for 4 periods	50 days each	50 days each
3	100 days each	60 days of no retention	100 days each	100 days each
4	1st year - no retention (Scenario 0); 2nd year - Scenario 1; 3rd year - Scenario 0			
5	100 days each	3-day retention for 4 periods, then 7-day retention for 4 periods	100 days each	100 days each
6	25 days each	3-day retention for 1 period, then 3 days no retention, then 3-day retention, then no retention, then 7-day retention for 1 period, then no retention, then 7 days retention, then no retention	25 days each	25 days each
7	25 days each	Like Retention 6, but 7 days of no retention before start of first 3-day retention	25 days each	25 days each
8	25 days each	Like Retention 6, but 7 days of no retention before start of first 3-day retention	25 days each	7 days of no retention, starting Day 259
9	Repetitive annual retention			
10	Complete retention for all three years			

[1] The summations of values in all Scenarios consistently produced red noise.

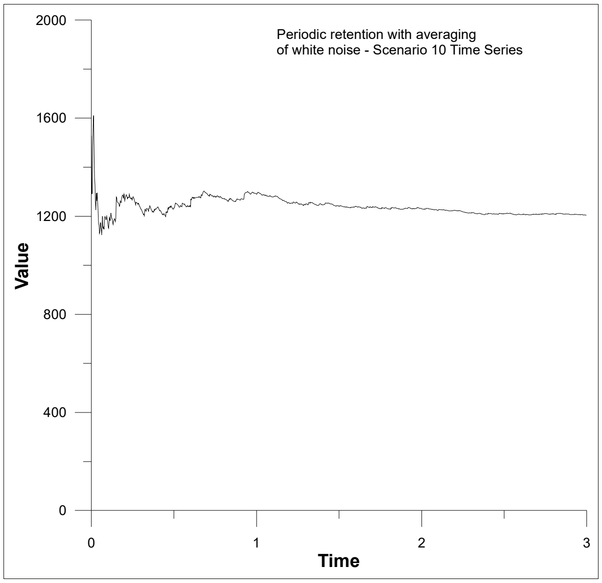

Figure 5-3. The time series for Retention Scenario 10.

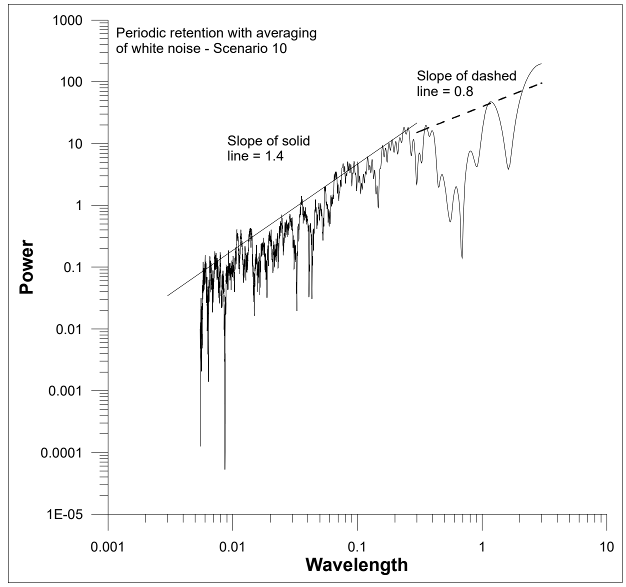

Figure 5-4. The power spectrum for Retention Scenario 10.

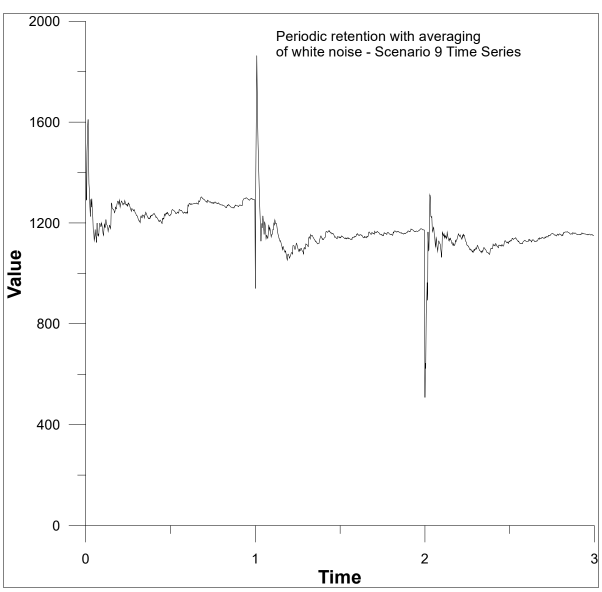

Figure 5-5. The time series for Retention Scenario 9.

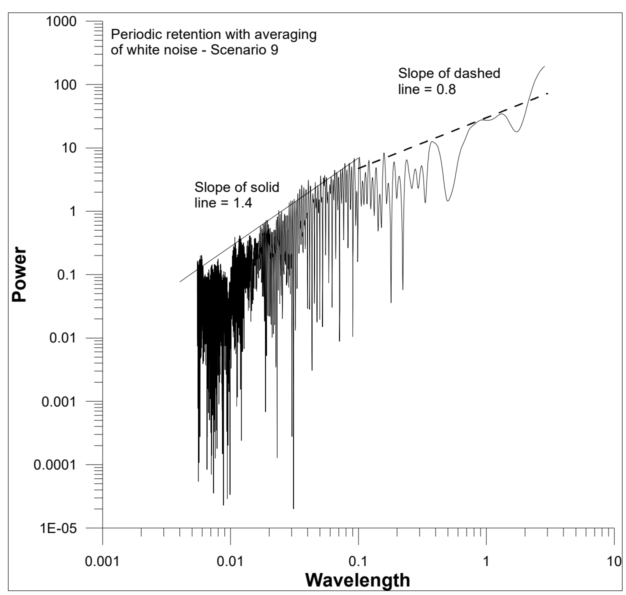

Figure 5-6. The power spectrum for Retention Scenario 9.

Scenario 9 was similar to Scenario 10, but the pond was instantaneously emptied at the end of each year and the averaging was started again. This increased the variability in the time series at the beginning of each year (Figure 5-5) compared with Scenario 10 (Figure 5-3).

The power spectrum for Scenario 9 had about the same spectral slopes as Scenario 10 (Figure 5-6). However, the wavelength at which the slope changed fell from 0.3 yrs to 0.1 yrs.

Scenario 1 simulated a pond with a retention time of 25 days throughout most of each year. However, during a 40-day period in spring, the pond filled quickly so it held only three days of flow for four consecutive periods and then held seven days of flow for four consecutive periods. This resulted in a time series that showed much less daily variability (Figure 5-7), compared with the less-attenuated and non-retained daily input (Figure 5-1). Nevertheless, during the high flows (less retention) in spring, large and variable peaks of high concentrations from the input still appeared.

The power spectrum corresponding to Figure 5-7 for Scenario 1 showed:

- a spectral slope of $\alpha \sim 1.0$ (Figure 5-8);
- a step-down in spectral power around a wavelength of 0.4 yrs, coinciding with the notable spectral peak in the input (Figure 5-2); and
- the reestablishment of $\alpha \sim 1.0$ at longer wavelengths.

This slope of $\alpha \sim 1.0$ is notably different from that of the non-retained input at $\alpha \sim 0.0$ (Figure 5-2) and if the full retained water at $\alpha \sim 1.4$ and 0.8 (Figures 5-4 and 5-6). Furthermore, it approaches a 1-over-f slope, but does not reach the continuity criterion of two or more orders of magnitude in wavelength (Section 5.3 of Morin, 2016a). Nevertheless, it suggests 1-over-f slopes for water chemistry may not necessarily require self-organization of many factors.

Scenario 4 was mostly a test of the algorithm for spectral analysis. Scenario 4 was a mixture of Scenario 0 for Years 1 and 3, and Scenario 1 for Year 2 (Table 5-1). As a result, the time series showed no periodicity (not shown), and the power spectrum was close to that in Figure 5-2 (white noise). Thus, allowing white noise to pass through unattenuated for some annual periods can yield white noise for the entire spectrum of a Scenario. As Scenario 3 shows below, a similar result is obtained when white noise passes through unattenuated even for one season each year.

Scenario 5 was similar to Scenario 1 including spring flows and retention, but non-spring flows were much lower so that the pond could hold 100 days of flow rather than 25 days of flow. The time series of Scenario 5 showed the smoothing effect of the longer non-spring retention (Figure 5-9 vs. Figure 5-7).

Moreover, Scenario 5's power spectrum (Figure 5-10 vs. Figure 5-8) was distinctly different above a wavelength of 0.04 yrs due to the longer non-spring retention. Below 0.04 yrs, the spectral slope was slightly higher at $\alpha \sim 1.1$, compared with $\alpha \sim 1.0$. Above 0.04 yrs, the longer retention caused the $\alpha \sim 1.0$ slope to split into two overlapping slopes: $\alpha \sim 0.8$ (somewhat similar to $\alpha \sim 1.0$) and white noise with $\alpha \sim 0$. Thus, the overlapping slopes at longer wavelengths arose from the longer non-spring retention and not from changes in high-flow, low-retention spring flows.

Notably, the spectrum for Scenario 1 displayed a step-down in spectral power around a wavelength around 0.4 yrs, whereas the spectrum for Scenario 5 displayed a break in slope around 0.04 yrs. Based on Scenarios 6, 7, and 8 discussed below, this order-of-magnitude decrease in wavelength and the change from step-down to slope break is due to the increased non-spring retention intervals.

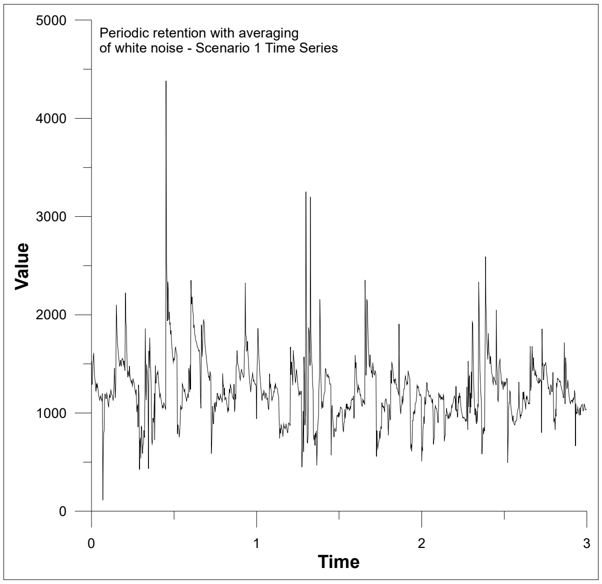

Figure 5-7. The time series for Retention Scenario 1.

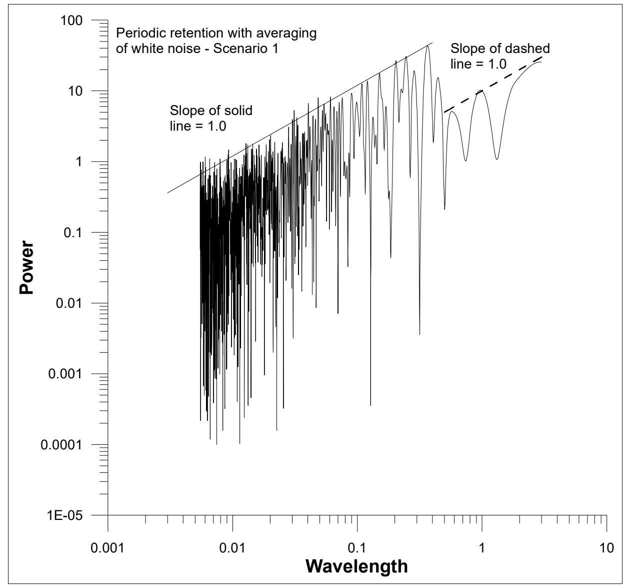

Figure 5-8. The power spectrum for Retention Scenario 1.

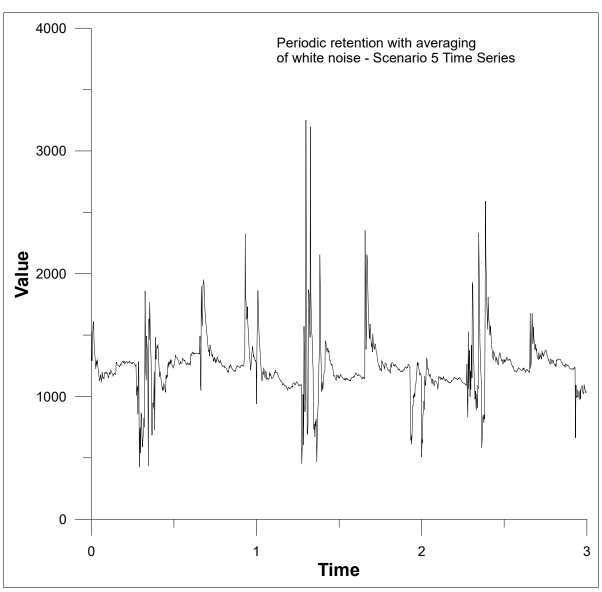

Figure 5-9. The time series for Retention Scenario 5.

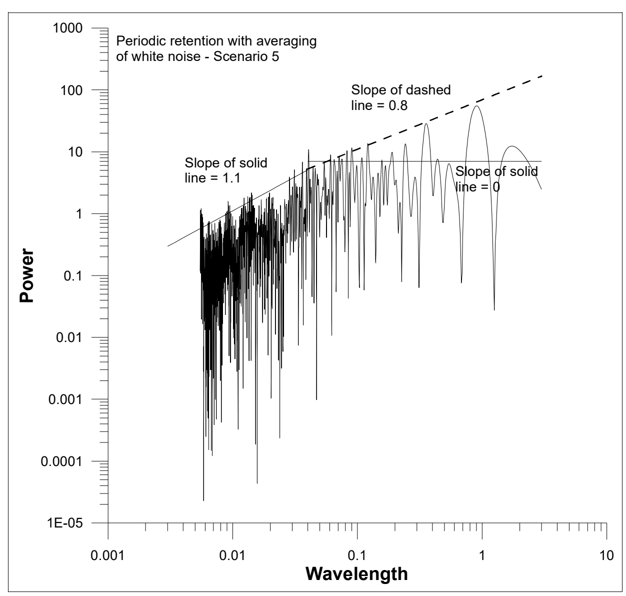

Figure 5-10. The power spectrum for Retention Scenario 5.

As Scenario 5 above and Scenario 3 below show, near-continuous consecutive periods of retention, even when variable in length, are needed throughout each annual period to avoid white noise. This is consistent with Scenarios 9 and 10 above.

Two overlapping slopes, with one generally being white noise as found with Scenario 5, was attributed to relatively large ponds with substantial retention in Case Study 2 of Morin (2016a). That observation is consistent with Scenario 5 here. Also, that Case Study 2 included a sampling location near the toe of waste rock, where the two overlapping spectral slopes suggested an "upstream", internal pond hidden within the waste-rock pile.

Scenario 3 had the same non-spring retention interval of 100 days as Scenario 5 (Table 5-1). However, the spring retentions differed markedly. Scenario 5 (and 1) simulated a 40-day series of 3-day and 7-day retention intervals, and Scenario 3 simulated very high spring flows with no retention for 60 days. The lack of spring retention in Scenario 3 meant that white noise passed through the pond unattenuated and unfiltered for 60 days.

Compared with Scenario 5 (Figure 5-9), the time series for Scenario 3 showed higher variability in spring concentrations and less variability at other times (Figure 5-11). The corresponding power spectrum for Scenario 3 revealed a general, near-white spectral slope of α ~ 0.1 across the range of wavelengths (Figure 5-12), much whiter than two of the three slopes from Scenario 5.

The second, overlapping slope of α ~ 0.8 at longer wavelengths (> 0.04 yrs) in Scenario 5 (Figure 5-10) was missing from Scenario 3 (Figure 5-12). This showed the second, steeper slope at longer wavelengths in Scenario 5 arose, in part, from the series of short retention intervals during spring. Furthermore, the loss of both slopes close to α ~ 1.0 from Scenario 5 showed that some retention, however variable, is needed at least every season to avoid nearly unattenuated white spectral slopes in ponds. However, as Scenarios 7 and 8 show below, shorter periods of no retention, like seven days annually, do not substantially reduce spectral slopes towards white noise. Between these two extremes, Scenario 2 suggests 30 days annually of no retention has an intermediate effect, yielding a spectral slope around α ~ 0.6.

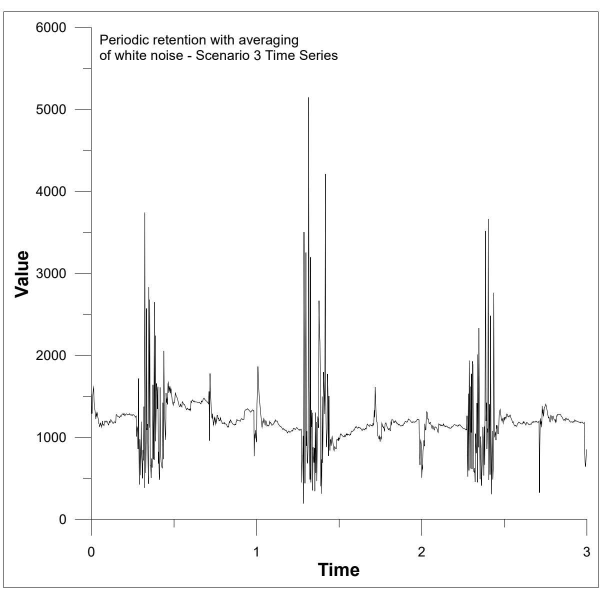

Figure 5-11. The time series for Retention Scenario 3.

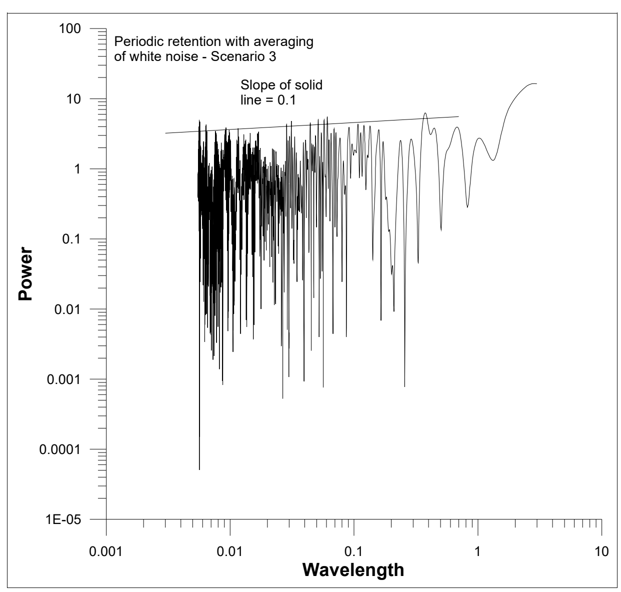

Figure 5-12. The power spectrum for Retention Scenario 3.

Scenarios 6, 7, and 8 were variations on Scenario 1, where retention times for winter, summer, and fall were all relatively short on 25-day intervals (Table 5-1), except Scenario 8 that included a very-high-flow 7-day interval of no retention in the fall. These are in contrast to Scenarios 3 and 5 discussed above which had 100-day non-spring intervals of retention. The primary differences among Scenarios 1, 6, 7, and 8 thus lie in the spring retention schedule, with some scenarios having very high flows with intervals of no retention up to seven days long.

The comparison of Scenarios 1 (Figures 5-7 and 5-8), 6, 7, and 8 (Figures 5-13 through 5-18) revealed the following.

1) Because Scenarios 6, 7, and 8 had short intervals of no retention in spring, small portions of the input of white noise passed through unattenuated, unfiltered, and unaveraged. This resulted in the appearance of a third spectral slope, of white noise ($\alpha \sim 0$), at wavelengths shorter than 0.015 yrs (5.5 days). This passing of unfiltered short-wavelength white noise was seen in Case Study 1 of Morin (2016a). In that Case Study, at wavelengths below 9-26 hours, high-frequency monitoring of waste-rock drainage in a ditch detected rapid plug flow through internal coarse-rock channels.

2) The primary (longest) spectral slope of $\alpha \sim 1.0$ in Scenario 1 was unchanged in Scenarios 6 and 7. However, Scenario 8 produced a slightly reduced, whitened slope of $\alpha \sim 0.9$ compared with Scenario 7. The only difference between Scenarios 7 and 8 was that Scenario 8 included white-noise variability and peak concentrations passing through the pond, with no retention, for 7 days each fall. Thus, unlike Scenarios 0 and 3, this shorter period of no retention only slightly whitened the spectral slope and did not reduce it almost to $\alpha \sim 0$.

3) The slope at the longest wavelengths, after the step-down of spectral power at 0.4 yrs, increased slightly from $\alpha \sim 1.0$ to 1.1-1.3. The step-down at 0.4 yrs did not vary in these scenarios, but was reduced to 0.04 yrs in Scenario 5, indicating the non-spring retention interval significantly affected the wavelength of the step-down.

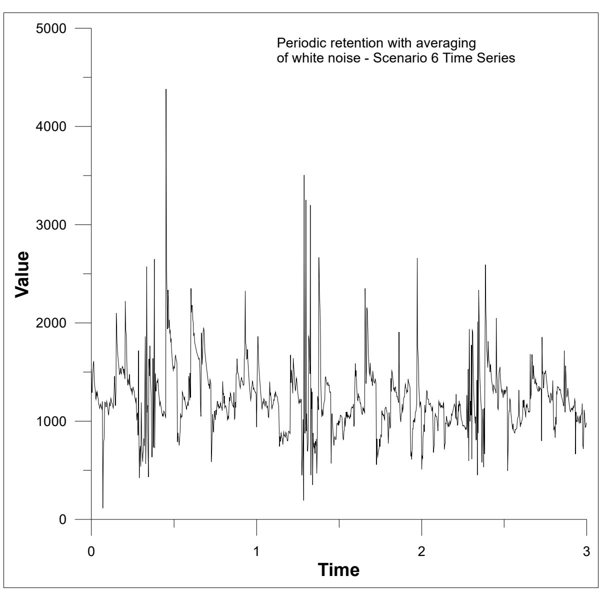

Figure 5-13. The time series for Retention Scenario 6.

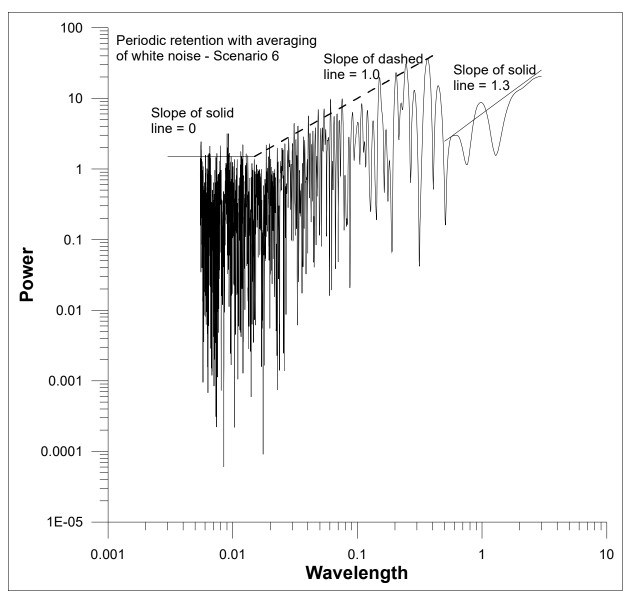

Figure 5-13. The power spectrum for Retention Scenario 6.

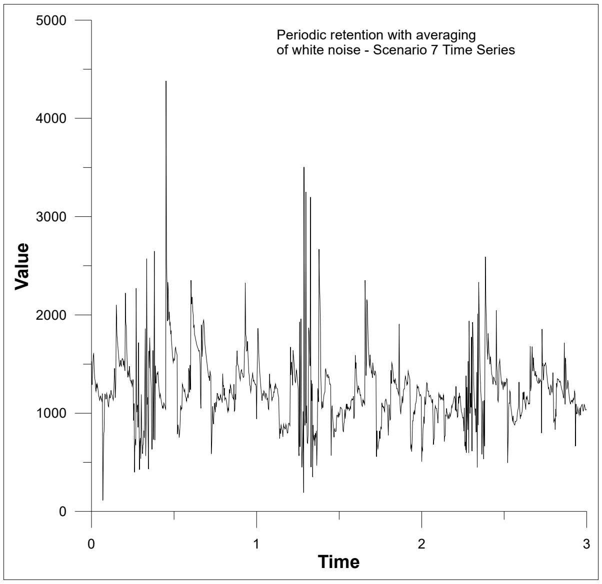

Figure 5-15. The time series for Retention Scenario 7.

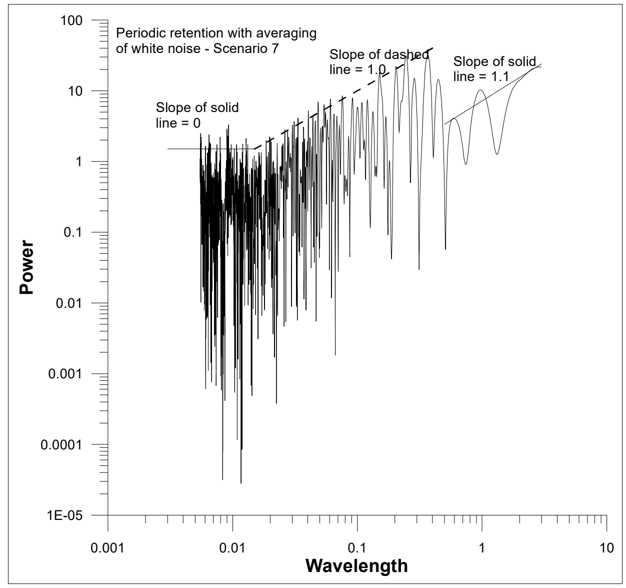

Figure 5-16. The power spectrum for Retention Scenario 7.

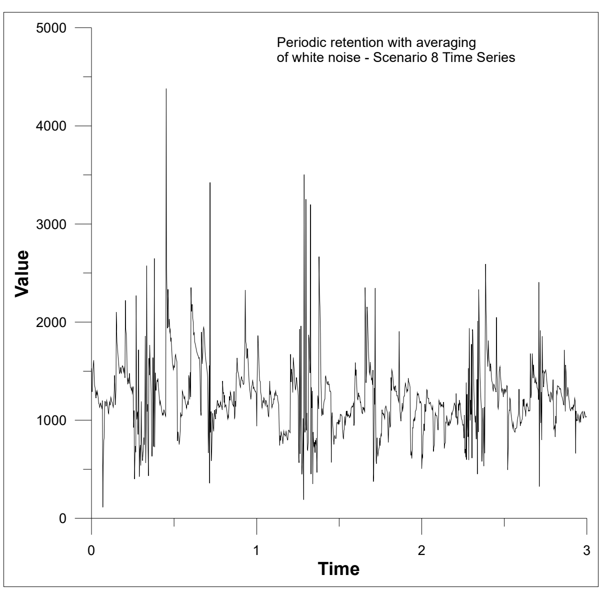

Figure 5-17. The time series for Retention Scenario 8.

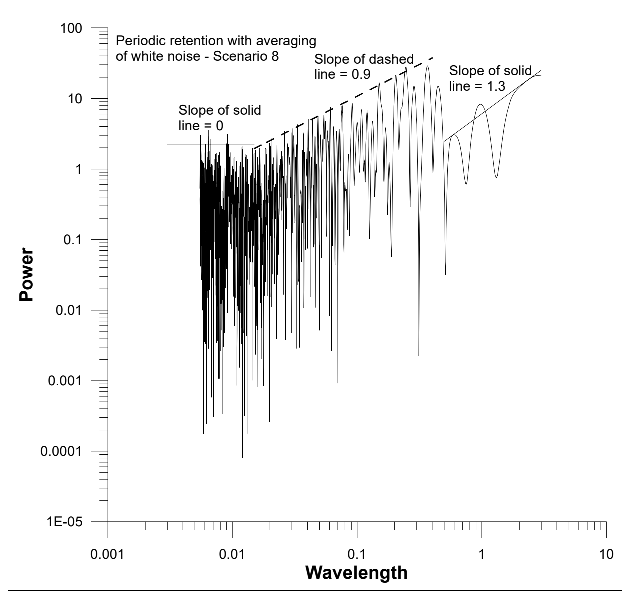

Figure 5-18. The power spectrum for Retention Scenario 8.

6. Conclusion

This MDAG case study examined how water-retention structures like ponds, lakes, and aquitards affect power spectra (in the frequency-wavelength domain) of inflowing waters. These structures were collectively called "ponds" here for simplicity.

For simulation of inflows into well-mixed ponds, power spectra confirmed that selected random normal Gaussian, and random lognormal Gaussian, daily time series were generally random, with white spectral slopes around $\alpha \sim 0$, with minor periodicity. In all cases, summations of the time series simulating pond retention resulted in red power spectra with slopes of $\alpha \sim 2.0$. Furthermore, spectral analysis of summations of these already-summed series still produced only red slopes.

Therefore, retention of drainage can redden a spectral slope from its initial value to $\alpha \sim 2.0$. However, this does not mean the reddening has to result exactly in $\alpha = 2.0$ under real environmental conditions.

Real, more complex, full-scale examples of precipitation, flow, and 1-over-f aqueous concentrations showed the following.

- When the time series had a power spectrum close to white noise, the retained spectra (based on summation) displayed reddened slopes, but in one case only to $\alpha \sim 1.6$. Further retention of the retained values did not change the spectral slope.
- Retention of real, full-scale examples of 1-over-f ($\alpha \sim 1$) slopes caused two spectral slopes to appear: white noise ($\alpha \sim 0$) at shorter wavelengths and reddened slopes up to $\alpha \sim 2.0$ at longer wavelengths.
- A more complex full-scale example included red noise at intermediate wavelengths, and generally white noise at shorter and longer wavelengths. The retained results were (1) the red slope remained red, (2) the longer-wavelength white noise became red, but (3) the short-wavelength white noise remained white.

In contrast to summation that applies to parameters like flow volume, averaging applies to geochemical concentrations and loadings. A suite of Scenarios simulated geochemical retention (averaging) of lognormal white-noise inflow values, with each Scenario differing by the length of time that periodic inflows were retained (attenuated) or not retained (no attenuation) in a pond.

Long-term retention and averaging of geochemical white noise, when the retention interval between emptying the pond was at least one year, produced reddened spectral slopes. The slopes were $\alpha \sim 1.4$ at shorter wavelengths, and $\alpha \sim 0.8$ at longer wavelengths. When retention was less than one year, more complex results were obtained.

For one Scenario with a sequence of short-term retentions in spring and 25-day retention intervals during other seasons, the spectral slope was $\alpha \sim 1.0$. This suggests 1-over-f slopes for water chemistry may not necessarily require self-organization of many factors.

For another Scenario, longer non-spring retention intervals with no changes in high-flow, low-retention spring flows produced two overlapping spectral slopes ($\alpha \sim 0$ and 0.8) at longer wavelengths. Such overlapping slopes were documented for relatively large water-retaining ponds in Case Study 2 of Morin (2016a), and one sampling location suggested the presence of an "upstream", internal pond hidden within the waste-rock pile.

Comparisons of various Scenarios led to the following additional observations.

- The change from spectral-power step-down to slope break was due to the increased non-spring retention intervals, which also decreased the wavelength at which the break occurred.

- Near-continuous consecutive periods of retention, even when variable in length, were needed throughout each annual period to avoid overall white noise. Furthermore, some retention, however long, was needed at least every season to avoid nearly unattenuated white spectral slopes in ponds. However, a period of 7 days each year with no retention did not substantially reduce spectral slopes towards white noise, but a non-retention period of 30 days annually caused an intermediate whitening of the slope.

- Short intervals of no retention in spring resulted in the appearance of a third spectral slope, of white noise ($\alpha \sim 0$), at wavelengths shorter than 0.015 yrs (5.5 days). This passing of unfiltered short-wavelength white noise was reported in Case Study 1 of Morin (2016a). In that Case Study, at wavelengths below 9-26 hours, high-frequency monitoring of waste-rock drainage in a ditch detected rapid plug flow through internal coarse-rock channels.

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