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# Environmental Monitoring of Water Quality and Flow Has Fallen Behind at Minesites

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## Summary

More than a thousand non-mining journal publications show that water quality and flow in surface waters and groundwaters are dynamic and variable. When measured over extended periods, high-frequency data have revealed fractal patterns. Mathematically, this means that water quality and flow can be variable on all time scales, even seconds and shorter. In a general sense, this is not surprising because each liter or each milliliter can carry a different number of mg/L of each natural element and human-made compound. To justify high-frequency monitoring of these dynamic environmental conditions, Kirchner et al. (2004) explained:

> "Imagine trying to understand a Beethoven symphony if one could only hear one note every minute or two! That is what we are trying to do when we infer the hydrochemical functioning of a catchment from weekly or monthly grab samples. Or imagine trying to understand a symphony from a high-fidelity recording of just one of its crashing crescendos."

However, high-frequency monitoring of water quality and flow at minesites has fallen behind and is lagging the high-frequency monitoring at non-mining sites. No longer are there good technical or financial reasons for avoiding high-frequency monitoring at minesites, which can begin for a few thousands of dollars. And there are excellent reasons for high frequency, like monitoring reality at a site and avoiding environmentally dangerous misinterpretations due to low-frequency monitoring of highly dynamic environmental systems. It is now time for environmental monitoring at minesites to catch up to the rest of the world.

## 1. Non-Mining High-Frequency Monitoring

In 2004, Kirchner et al. (2004) released a milestone paper entitled, *The fine structure of water-quality dynamics: the (high-frequency) wave of the future*. It is important to see that this publication is about high-frequency "water-quality dynamics", which has also been a focus of MDAG research for decades.

Kirchner et al. (2004) begin and end with:

> "Science is often driven forward by the emergence of new measurements. Whenever one makes observations at a scale, precision, or frequency that was previously unattainable, one is almost guaranteed to learn something new and interesting."

> "Imagine trying to understand a Beethoven symphony if one could only hear one note every minute or two! That is what we are trying to do when we infer the hydrochemical functioning

> of a catchment from weekly or monthly grab samples. Or imagine trying to understand a symphony from a high-fidelity recording of just one of its crashing crescendos. That is what we are trying to do when we analyse high-frequency samples of an individual storm event. Continuous high-frequency monitoring of catchment hydrochemistry will require significant resources and tenacity. In our view, however, what we stand to learn is well worth the effort. If we want to understand the full symphony of catchment hydrochemical behaviour, then we need to be able to hear every note."

This led to many additional studies by Professor Kirchner and his colleagues, including Kirchner et al., (2000, 2001, and 2004); Kirchner (2003, 2005, 2009, 2016a, 2016b); Feng et al. (2004); Aubert et al. (2013); Kirchner and Neal (2013); Benettin et al. (0215); Godsey et al. (2010); Rode et al. (2016); Bieroza et al. (2023).

Bieroza et al. (2023) confirmed that the annual number of peer-reviewed publications on high-frequency monitoring increased ten-fold, from roughly 20 per year to 230 per year between 2004 and 2021 (see Figure 1 below).

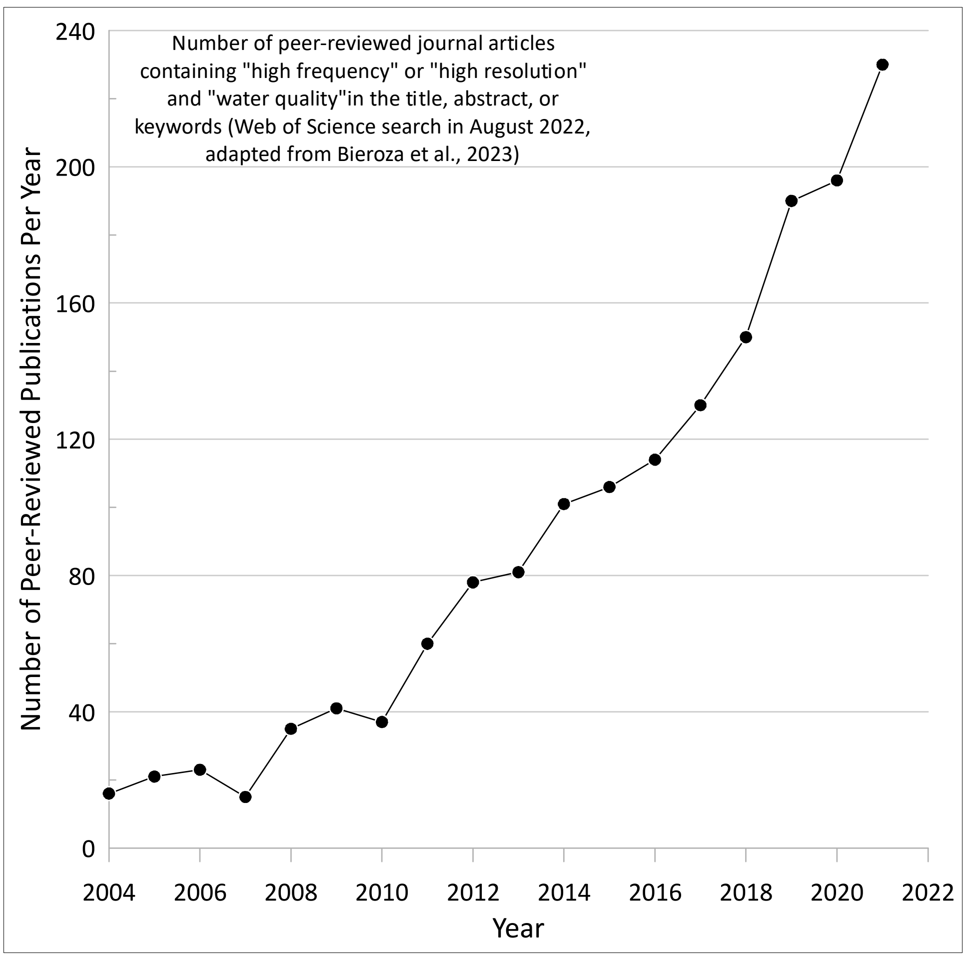


**Figure 1. Number of peer-reviewed journal articles containing "high frequency" or "high resolution" and "water quality"in the title, abstract, or keywords; Web of Science search in August 2022; adapted from Bieroza et al. (2023).**

Bieroza et al. (2023) added:

> "High-frequency water quality measurements have generated new insights into the 'fine structure of water quality dynamics'. Measurements at a similar temporal resolution as many hydrological and biogeochemical process rates, previously obscured by low-frequency or sporadic high-frequency sampling, have revolutionized our understanding of catchment and stream processes that shape water quality."

With some bragging, and justifiably so, Rode et al. (2016) stated:

> "Just over a decade ago, Kirchner et al. [2004] envisioned the hydrologic sciences being transformed by the increased availability of stream chemistry measurements at time scales commensurate with hydrologic forcing.... At the same time, ecologists were recognizing the transformative potential of sensors that allow ecosystem processes to be measured at time and space scales that match relevant physical, chemical and biological drivers.... The vision of Kirchner et al. [2004] has been realized, in part, with significant progress in estimating solute residence times in watersheds, but it is the converging vision across hydrological, biogeochemical, biological, and ecological disciplines that highlights the significant intellectual payoff from new sensor technologies in watershed and stream science. Now streamwater chemistry data are available every hour, or even every minute across a broad range of analytes, and commensurate biological data are available at fortnightly to daily intervals for sustained periods greater than one year. These advances allow the study of multiple solutes at subdaily intervals, not just single solute time series, and enable interpretations and hypothesis testing of ideas around river biogeochemistry, biology and ecology, in addition to catchment signals. These novel measurements have revealed complex temporal dynamics that were obscured by traditional sampling frequencies and have enabled new insights into the inner-workings of watersheds and streams."

von Freyberg et al. (2017) gave a detailed technical example of high-frequency monitoring of water quality and the stable isotopes of $^{18}O$ and $^{2}H$:

> "This paper presents the first field hydrology application of Picarro's Continuous Water Sampler (CWS), which was coupled to a L2130-i wavelength-scanned cavity ring-down spectrometer to measure $\delta^{18}O$ and $\delta^{2}H$ in stream water and precipitation at a temporal resolution of 30 min. We combined this real-time isotope analysis system with a dual-channel ion chromatograph for the synchronous analysis of major cations and anions.... our 1-month field experiment demonstrates the marked short-term variability of several natural tracers in a small, highly dynamic watershed. The hydrograph separation exercise clearly showed that long-term, high-frequency isotopic and chemical analyses are essential for capturing the 'unusual but informative' events that shed light on catchment storage and flow processes. We further showed that the right timing for capturing peak event-water contributions can easily be missed with conventional grab sampling strategies at time intervals longer than 3 h, resulting in an underestimation of the event-water fraction. In addition, the relative timing of the isotopic and chemical responses was highly variable, demonstrating the challenge of capturing the right moments with episodic snapshot campaigns or long-term monitoring with daily, weekly, or even monthly sampling intervals."

Nearly ten years ago, van Geer et al. (2016) summarized high-frequency monitoring primarily in the European Union and focused on nutrients in surface waters and groundwaters. The title of their paper, as the overview of a special issue of publications in Hydrology and Earth System Sciences was: *High-resolution monitoring of nutrients in groundwater and surface waters: process understanding, quantification of loads and concentrations, and management applications*.
Here are some quotations from their overview:

> "... we present a new assessment of the objectives behind high-frequency monitoring as classified into three main groups: (i) improved understanding of the underlying hydrological, chemical, and biological processes (PU); (ii) quantification of true nutrient concentrations and loads (Q); and (iii) operational management, including evaluation of the effects of mitigation measures (M)."
>
> "To satisfy the increasing demand for knowledge and information on the dynamic behaviour of nutrients, the past 10–15 years have seen a rapid development of observation devices and technologies for high-resolution monitoring of nutrients and other solutes and isotopes at affordable cost, encouraging researchers, and other stakeholders to perform studies in experimental as well as operational settings. Thus, vast amounts of research data have been collected on various water quality variables, allowing the study of relevant biogeochemical processes and enabling comparisons between the results obtained by the use of different monitoring devices."
>
> "The scale at which information is required is termed 'information scale'.... The following three temporal scales are considered:
>
> - short-scale dynamics and extreme events (minutes to weeks);
> - seasonal and annual patterns (months to several years);
> - longer-term behaviour and trends (years to decades)."
>
> "High-frequency data will in the future assist in achieving a better understanding about in-stream processes such as nitrogen and phosphorus assimilation, sedimentation, and resuspension processes. Moreover, water quality models will be challenged when calibrated against high-frequency data, which in turn will force models to be more dynamic (run at lower time steps) and improve their internal process descriptions."

From the viewpoint of regulatory management of water, Rozemeijer and van der Velde (2014) stated:

> "Considering the large temporal variability in surface water quality is essential for adequate water quality policy and management. Neglecting these dynamics may easily lead to decreased effectiveness of measures to improve water quality and to inefficient water quality monitoring. The objective of this paper is to summarise our understanding of temporal variability in surface water and upper groundwater quality and to discuss the consequences and opportunities for regional water quality monitoring. In regional monitoring networks, measurement frequencies are typically too low to capture the short-term temporal variations in solute concentrations. This causes large uncertainty in the assessment of (trends in) average concentrations and contaminant loads."

Rozemeijer and van der Velde included a graphical example of errors in average values, variability, and trends due to low-frequency monitoring of the dynamic reality of water quality (see Figure 2 below). Other examples are Figures 5 and 6 of Morin (2025b).

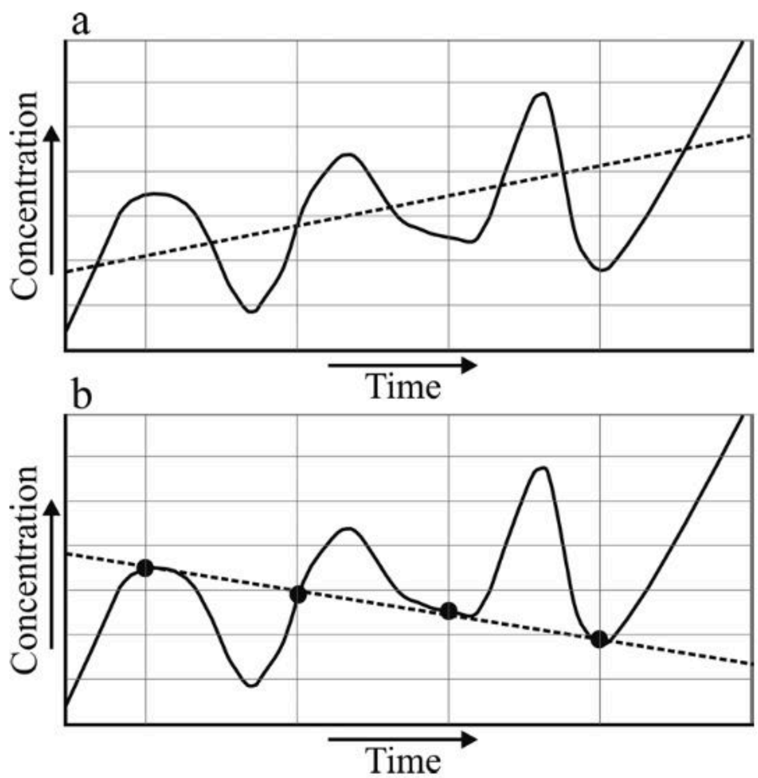


**Fig. 3.** Hypothetical example of an upward trend in solute concentrations **(a)**, which is misinterpreted as a downward trend due to the uncertainty which is involved in low-frequency measurements **(b).**

**Figure 2. An example of errors in averages, variabilties, and trends caused by low-frequency monitoring of a dynamic system like water quality and flow (from Rozemeijer and van der Velde, 2014).**

Here are a few of more than a thousand publications on high-frequency environmental monitoring, some with quoted excerpts.

Jung et al. (2020): Benchmarking inference methods for water quality monitoring and status classification.

Wade et al. (2012): "This paper introduces new insights into the hydrochemical functioning of lowland river systems using field-based spectrophotometric and electrode technologies. The streamwater concentrations of nitrogen species and phosphorus fractions were measured at hourly intervals on a continuous basis at two contrasting sites on tributaries of the River Thames - one draining a rural catchment, the River Enborne, and one draining a more urban system, The Cut."

Halliday et al. (2015): High-frequency water quality monitoring in an urban catchment: hydrochemical dynamics, primary production and implications for the Water Framework Directive.

Burns et al. (2019): "the comprehensive nature of sensor records has allowed unprecedented insight to how $NO_3^-$ concentrations change during events and on a diel basis as a function of seasonal and climatic variation. These advances have resulted in improved conceptual models of many systems with unprecedented detail on seasonality. With heightened concern about the effects of climate change, sensor-based investigations are poised to inform knowledge of how changes in the frequency and intensity of extreme hydrologic events and drought-wet cycles affect the watershed N cycle."

Yu et al. (2021): Drivers of nitrogen and phosphorus dynamics in a groundwater-fed urban catchment revealed by high-frequency monitoring.

McDowell et al. (2024): "Detecting change in water quality is key to providing evidence of progress towards meeting water quality objectives. A key measure for detecting change is statistical power. Here we calculate statistical power for all regularly (monthly) monitored streams in New Zealand.... years. While >95% of all monitored sites had suicient power and samples to detect change in nutrients and clarity over 20 years, on average, sampling frequency would have to double to detect changes in *E. coli*. Furthermore, to detect changes in 5 years, sampling for clarity, dissolved reactive phosphorus and *E. coli* would have to increase up to fivefold. The cost of sampling was predicted to increase 5.3 and 4.1 times for 5 and 20 years, respectively.... Our study has important implications for investment decisions involving balancing the need for intensively sampled sites where changes in water quality occur rapidly versus other sites which provide long-term time series."

Table S1 of Supporting Information in McDowell et al. discusses about a dozen emerging technologies including available sampling frequencies, advantages, disadvantages, and examples.

All this work, in more than a thousand non-mining journal publications, confirms that water quality and flow in surface waters and groundwaters are normally dynamic and variable. When measured over extended periods, high-frequency data have revealed fractal patterns. Mathematically, this means that water quality and flow can be variable on all time scales, even seconds and shorter. In a general sense, this is not surprising because each liter or each milliliter can carry a different number of mg/L of each natural element and human-made compound. As Kirchner et al. (2004) explained:

> "Imagine trying to understand a Beethoven symphony if one could only hear one note every minute or two! That is what we are trying to do when we infer the hydrochemical functioning of a catchment from weekly or monthly grab samples. Or imagine trying to understand a symphony from a high-fidelity recording of just one of its crashing crescendos."

Thus, high-frequency monitoring is necessary to properly understand local water quality and flow and thus to safely protect the surrounding environment.

## 2. Examples Among Many of a Few Current High-Frequency Sensors for Water Quality and Flow

For a few to several thousand of dollars, there now are commercially available, in situ, submersible sensors that record various water-quality and flow/water-level parameters at high frequencies. The sensor readings are stored in onboard dataloggers, optionally with on-demand transmission by wifi or cell-phone networks, with internal batteries lasting up to several years.

Current examples of relatively inexpensive in situ sensors include Solinst submersible 5 LTC which monitors water level, water temperature, and water electrical conductivity in surface waters and groundwaters:

https://www.solinst.com/products/dataloggers-and-telemetry/3001-levelogger-series/ltc-le

velogger/datasheet.php
It measures and records these values at high frequencies of up to minutes and stores them in an onboard data logger with batteries lasting for up to several years. This costs a few thousand dollars.

Additional water-quality parameters can be measured at high frequency with more expensive sensors like YSI EXO, but at the expense of lower battery life and length of submersibility:
https://www.ysi.com/exo

These examples of many currently available sensors confirm that there are no longer good technical or financial reasons for avoiding high-frequency monitoring at minesites. And there are excellent reasons for high frequency, like monitoring reality at a site and avoiding environmentally dangerous misinterpretations due to low-frequency monitoring of highly dynamic environmental systems.

## 3. Where is the High-Frequency Monitoring of Water Quality and Flow at Minesites?

The preceding sections of this MDAG Case Study might give the impression that high-frequency monitoring of surface-water and groundwater quality and flow is as common at minesites as at many non-mining sites, but this is wrong. There are only few minesites around the world with an extended record of high-frequency monitoring (discussed in Morin, 2019, 2018a, and 2016). Thus, high-frequency monitoring at minesites is in an early "primitive" stage lagging far behind non-mining monitoring discussed above and shown in Figure 1 above.

It is puzzling why this is the case. Perhaps it is because many regulatory approvals and permits require monitoring on annually, quarterly, or monthly bases without realizing the misunderstandings, errors, and environmental risks this low-frequency monitoring can lead to. In this case, regulatory-driven monitoring fails in its primary objective to protect the surrounding environment and humans.

This primitive, low-frequency approach to minesite monitoring has been criticized by some for decades. For example, I have told the story of the "Lucky Mine and the Unlucky Mine" based on real events. The Lucky Mine collects grab samples of drainage once a month, but by coincidence has never collected one during the short-term maximum annual concentration (similar to Figure 2 above). The Unlucky Mine happened to collect one monthly sample during the annual maximum concentration, and panic ensued. The analytical laboratory was asked to repeat the analysis, and it confirmed a high concentration. The mining company suspected contamination during collection or analysis. The laboratory blamed the mining company and vice versa. Another sample was collected weeks after the annual maximum. Of course, the concentration in this later sample was much lower, and the former true-maximum analysis was dismissed as anomalous and incorrect.

I can assure through personal experience that the story of the "Lucky Mine and the Unlucky Mine" continues to occur even in 2025. This is not a reliable and environmentally safe way to monitor. Undetected short-term variations in water quality can represent serious problems or even destruction of environmental quality and life depending on factors like intensity, severity, duration, and species-level bioavailability and toxicity (e.g., Morin, 2017c and 2025a). These cannot be explained or understood by low-frequency sampling or by sampling in hindsight.

Nevertheless, there have been a few minesites that have monitored at several locations at high frequencies for up to years. Some pre-2010 mining-related examples of high-frequency monitoring include the following.

At one site (Morin et al., 1995a, 1994, and 1993) with monitoring of flow as often as every 15 minutes and of water quality as often as every four hours:

> "This information led to the ability to delineate the optimum frequency of monitoring and the maximum short-term concentrations that are not detected during monitoring.... This work has shown that drainage concentrations behave like climatic and hydrologic events with, for example, one-hour peak values over one-year and multiple-year periods.... This knowledge plays a role in predictions of future drainage chemistry...."

This showed statistically that lower-frequency monitoring would have resulted in errors up to about one order of magnitude in annual-average and annual-maximum concentrations (see also Figures 11 to 16 in Morin, 2015).

As an aside, high-frequency monitoring can also be important spatially. For example, the pH of solid-phase samples of mine rock can show significant high-frequency (short-distance) variability (Morin and Hutt, 2001b).

At a tropical gold minesite in Indonesia (van der Linden, 1994a and b; Firth and van der Linden, 1997; Case Study 6.2-1 in Morin and Hutt, 1997 and 2001a), highly variable precipitation over short periods required high-frequency monitoring at several locations. In Bayak Stream receiving the minesite drainage, pH could vary by two pH units within a 24-hour period accompanied by changes in metal concentrations up to a factor of 10.

Nimick et al. (2010, 2007, 2003), Shope et al. (2006), and Cánovas et al. (2010) reported on daily "diel cycling" of water quality in streams and channels draining minesites. These daily fluctuations were possibly attributable to local variations in (1) upstream metal loadings, (2) stream flow, (3) biological uptake, (4) precipitation/dissolution, (5) adsorption/desorption, and/or (6) photosynthesis-induced pH changes. However, common larger-scale explanations of the variability (Morin, 2019 and 2020) were not considered.

Morin (2017a and 2017b) provided the following observations for a mine-waste-rock pile tens of meters in height. These would not be known without high-frequency monitoring. These could be incorrectly interpreted through lower-frequency monitoring and, in fact, some are contrary to common beliefs about waste rock.

- The onset of significant rapid outflow through tens of meters of waste rock began within hours of substantial precipitation and infiltration, with outflow increasing quickly by a factor of two or more and sometimes persisting for only 15-60 minutes. For prominent one-day peaks of precipitation, up to 75% of the volume of precipitation passed through the local waste rock in less than a day or two.

- Overall, 25-50% of total annual precipitation passed through the waste rock as highly variable rapid flow. The remainder drained more slowly, within days to weeks during wetter seasons and within weeks to months during drier seasons.

- After the drier summer months, 0.085-0.188 m of precipitation was initially needed before rapid flow began. This meant less than 1% of the waste rock had to be "wetted up" and/or saturated before rapid flow was observed. There was generally little additional retention of water through the remainder of a hydrologic year, and the "wetting up" water was eventually lost during drier seasons. This repeated yearly.

-With high-frequency flow measurements, short periods of about two weeks were identified during which flow rates significantly and consistently oscillated on a daily cycle. The hourly flows reached minimum values around or just after midnight, and peaked around noon or just after noon each day. The cause of these brief periods of oscillation is not well understood.

- At both the downstream and upstream monitoring stations, selected time series spanning days to weeks showed no geochemical responses attributable to 1:1 dilution by flow, even during substantial peaks of flow. The lack of 1:1 inverse correlation has also been documented at other minesites, and even in non-mining-related catchments. This should raise alarms about a standard predictive technique for minesite-drainage chemistry, which assumes a 1:1 inverse correlation by dividing an estimated geochemical loading by an estimated flow to predict a full-scale concentration.

- During storms at this minesite, daily outflows at the stations often increased sharply by 400-900%. However, at the same time, aqueous concentrations of some parameters decreased by no more than 35% and often showed little correlation with flow or pH. Other elements actually increased substantially in concentration (the opposite of dilution) during peak diluting flows, when pH decreased as flow increased. This highlighted how quickly the infiltration could accumulate chemical constituents during the hours it passed through the waste rock. Overall, trends in aqueous concentrations differed among elements and parameters, among the selected time periods, and before and after brief significant changes in pH.

Interestingly, the few detailed cases of extended high-frequency monitoring of water quality and water flow at minesites have shown that statistical tests typically used to interpret such data are not applicable. Morin (2020 and 2018b) point out:

> "Where sufficient high-frequency long-term monitoring data are available, the flow rates and the aqueous concentrations of minesite drainages are found to be not simple or steady; they are not stochastic, but also not deterministic; and they are not random or chaotic. They display periodicity in complex ways. Morin and Hutt (2001) pessimistically emphasized,
>
> > 'this regularity reflects the summation of the effects of all other (countless) physical, chemical, and biological processes operating at a minesite.... It may involve so many processes that the explanation may never be known.'"

As a result, common statistical tests do not reliably apply to and characterize minesite-drainage flows and chemistry (e.g., Morin, 2025b). Thus, we may be mostly limited to complex machine-learning techniques (Ma et al., 2021 and 2020; Morin, 2021).

In summary, high-frequency monitoring of water quality and flow at minesites has fallen behind and is lagging the high-frequency monitoring at non-mining sites. No longer are there good technical or financial reasons for avoiding high-frequency monitoring at minesites, which can start for a few thousands dollars. And there are excellent reasons for high frequency, like monitoring reality at a site and avoiding environmentally dangerous misinterpretations due to low-frequency monitoring of highly dynamic environmental systems. It is now time for environmental monitoring at minesites to catch up to the rest of the world.

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