HOW LONG IS LONG ENOUGH?
ROBUST TIMEFRAMES FOR RECLAMATION MONITORING

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ABSTRACT

Post closure monitoring is a common requirement for mines worldwide. Following completion of closure activities, monitoring is undertaken to document and evaluate the effectiveness of closure activities in meeting closure objectives and success criteria. Monitoring is carried out with a focus on elements that remain post-closure, and on areas where there is an expectation or risk of impacts. Effective management of reclamation risk requires a deliberate approach to understanding, assessing, and responding to potential impacts at a site-specific level. What is the best approach in determining monitoring timeframes to reduce uncertainty in reclamation performance? Monitoring periods are often pre-prescribed by regulations or left to proponents to determine. Monitoring timeframes need to be defensible but are largely an exercise in addressing perceived risk from regulators or stakeholder groups. Typically, the greater the perceived risk and potential uncertainty, the longer the monitoring period stipulated by regulators. Risk defined without process forms the crux of the problem in setting realistic monitoring periods. A deeper understanding of potential perceived risks with respect to specific potential failure modes is therefore required. Monitoring periods should be determined based on temporal scales of the mechanisms and processes involved in potential failure modes to address and constrain variability of parameters measured. Climate is frequently the most influencing factor for reclamation performance, largely manifested through getting the "right" water balance to interact with the materials and vegetation specified in the future land use. It forms the "uncontrollable" variable in the success equation that carries with it the greatest risk to closure designs. In this paper, two case studies are presented, one from Northern Alberta, the other from Australia with vastly different climates but similar water related closure objectives. Empirical Mode Decomposition is one such tool used to help define meaningful monitoring periods for these sites.

Key Words: Reclamation, Monitoring, Criteria, Relinquishment, Closure, Water Quality.

INTRODUCTION

Post closure monitoring is often used to evaluate effectiveness of closure activities at meeting agreed closure objectives and success criteria. Closure monitoring is required to ensure the commitments and license requirements made, and design intentions planned in reclamation and closure plans come to be realized in the timeframes proposed.

Closure and reclamation of mine landscapes largely follows an engineering process through which aspirational returning land use closure visons will dictate closure objectives and the subsequent design criteria. Engineering designs are developed to provide the fundamental building blocks for landscape restoration, reclamation, rehabilitation. Therefore, post closure monitoring should be thought of as an engineering tool to compare the measured field performance against the expected stated performance and design criteria. The issue with trying to resolve closure monitoring timeframes has to do with the timeframes of the site-specific controls on the processes and mechanisms.

Closure practitioners become focused on monitoring for outcomes rather than leading indicators. No better example of this exists than long term water quality monitoring. Water quality is the outcome of numerous 'upstream' processes. While it is intended to assess the performance of mine waste storage facilities such as mine rock storage facilities (MRSFs) and tailings storage facilities (TSFs), water quality measured at a regulatory compliance station can be considered a lagging indicator of success, rather than a leading indicator of performance. A leading indicator is any measurable or observable variable of interest that predicts a change or movement in another data series, process, trend, or other phenomenon of interest before it occurs. A lagging indicator is an observable or measurable factor that changes sometime after the variable with which it is correlated changes. Lagging indicators confirm trends and changes in trends. Regulators also frequently rely on lagging performance indicators like water quality.

Reclamation ecologists and biologists have grappled with similar monitoring difficulties for decades. The practices have evolved from solely productivity based measured of a particular vegetation or wildlife species as the key success criteria, to one of capability and function. Capability and productivity are closely and theoretically linked, that capability means a potential productivity, and that it is different for different land uses. Capability gives a better understanding of land use. Productivity can be used as a measure to confirm capability has been met but caution is required not to measure productivity at the expense of ecosystem function (e.g., fertilized forests are productive but perhaps not sustainable). Productivity can be separated from capability but productivity will still be used as a measure. Ecosystem functions can be defined by the ecological processes that control the fluxes of energy, nutrients and organic matter within the ecosystem to maintain terrestrial life.

Productivity used to be a regulatory goal but that goal shifted in the early 1980s to embrace the concept of capability as early as 1985 by the Alberta Land Conservation and Reclamation Council. Productivity is dominantly an agricultural concept, though it is also important for commercial forestry. It is a less useful goal when evaluating natural systems, and is particularly subject to manipulation (e.g., fertilization). For example, in the past, the number of elk or stems per hectare were thresholds historically set for success. Reclamation practitioners quickly realized those measures may still be achieved, yet still have a reclamation project that will not continue to be successful overtime. Therefore, the focus shifted to land capability, equivalent capabilities, with self-sustaining requirements, to more closely mimic reference sites. With the emphasis on self-sustaining ecosystems, a deeper investigation was required to understand what initiates and sustains ecosystems.

Ecologists understood that there were physical, chemical, and biological building blocks – indicative of underlying processes - that must occur for ecosystems to be self-sustaining. For example, the physical properties of the material such as soil texture, must retain adequate water for plant use, and that plants and soils must interact to ensure nutrient cycling occurs. Functionality-based indicators recognize the interconnectedness of the system, and thus provide leading indicators of ecosystem performance. Leading indicators provide the opportunity for adaptive management if the system is not functioning as intended.

Reclamation ecologists have also demonstrated the utility of function-based performance indicators. For example, it is not necessary to wait 80-100 years for climax conifer trees to grow to demonstrate success. Function based performance indicators are now at the forefront for monitoring. Interdisciplinary teams now evaluate water and carbon fluxes on reclaimed mine sites against reference sites impacted through other disturbance agents (i.e., forest harvest and fire). Monitoring metrics now typically include vegetation characteristics, soil properties, and water and carbon fluxes on reclamation and reference sites equipped with eddy-covariance, climate, and soils instrumentation as leading practice. The central premise of this research is that plant water use, and carbon assimilation are indicators of ecosystem health and success, and that studying the rate, timing and magnitude of these processes can provide a mechanistic understanding of whether reclamation sites are functioning in a similar manner to non-mined ecosystems. (Straker et. al., 2019).

So how may we expand the learnings from ecological reclamation monitoring and adapt them to engineering and geoscience disciplines? How can we develop meaningful leading indicators for water quality success?

METHODOLOGY

Closure Planning Design Process:

Clear reclamation certification criteria for mines are important. Criteria influence the work requirements, processes, and timelines for certification. Criteria provide certainty for the industry because operators and reclamation practitioners understand expectations. Transparency for all stakeholders is improved because it is clear on what criteria certification decisions will be based. Meeting criteria provides confidence that reclamation objectives, in turn, are being met.

For the purpose of this paper, key terms relevant to the discussion are adapted per Poscente and Charette, 2011 (Figure 1) as:

- Closure Vision/ Returning Land Use Goal: The result or outcome toward which effort is directed.
- Objective: A purpose toward which a reclamation effort is directed.
- Criteria: (plural) A category of conditions or processes by which the achievement of a reclamation objective is assessed. A Criterion (singular) is characterized by one or more related indicators that are used to determine success or to assess change over time.
- Indicator: An attribute that can be measured or described and used to evaluate if a criterion has been met.
- Measure: A qualitative or quantitative aspect of an indicator; a variable that can be measured (quantified) or described (qualitatively) and demonstrates either a trend in an indicator or whether a specific standard was met.
- Method: A description of a way, technique, process or procedure for attaining a measure.
- Standard: A definite rule established by authority. Environmental standards often take the form of prescribed numerical values that must be met.

Though Methods and Standards will not be discussed herein, they will form an important future discussion as it applies to leading indicators for water quality monitoring.

Designing or beginning the closure process with "the end in mind" is a practical approach to mine reclamation. The aspirational closure vision or targeted returning land use(s) provide a directional focus to the design process. Closure objectives generally remain consistent across most mine sites with slight deviations in only specialized cases. Objectives such as "safe", "chemically stable", "physically stable" "Non-Polluting" are common.

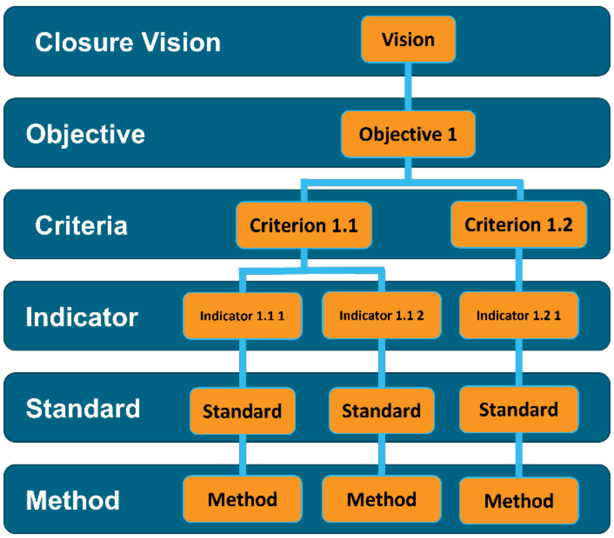

Figure 1- Hierarchy for the development of closure criteria and indicators. (Adapted from Poscente, M., and Charette, T. 2011)

Challenges to Select Water Quality Criteria for Mine Rock Storage Facility (MRSFs)

In the context of closure objectives for mine rock storage facility design, water quality criteria most commonly means non-polluting from a water quality perspective at various receptors. "Non-polluting" criteria are often already pre-established water quality jurisdiction guidelines. Sometimes, water quality criteria are established on a site-by-site basis due to a sensitivity of a nearby receptor, other times, they are established in the context of regional water quality frameworks.

The typical approach in developing design criteria for mine waste facilities is to work backwards from the receptor through the pathway, to the source, to determine the sources contribution criteria. The issue with this approach is these source term and receptor water quality targets are still largely lagging indicators of performance.

Closure practitioners become focused on monitoring for the outcome, rather than focusing on what must first occur for the outcome to occur. Especially for water quality, lagging indicators are often selected as they are most easily translated to already pre-established regulatory guidelines. Although identifying lagging indicators for selecting performance criteria is relatively easy and already established, greater effort is required to establish temporal robustness of the closure designs (i.e., MRSFs, TSFs, etc).

Mine Rock Storage Facility Variability Considerations

Due to the temporal scales of the process and mechanisms involved with metalliferous/ acid rock drainage (ML/ARD) generation and mobilization, waiting for lagging indicators to be achieved may often take decades. Wetting up and draining down of pore water in MRSFs can take decades or centuries. These timeframes occur beyond the adaptive management phases of closure. When expected performance is not achieved, there are few options (though much more costly) remaining to mitigate issues.

Furthermore, spatial scales are also exceptionally large when considering MRSFs. The facilities can span several hundreds of hectares and contain hundreds of millions of tons of rock. The waste materials contained in the facilities are also highly variable based on the lithology of the mining blocks, the mining practices over time, and natural weathering of the materials. Due to both the temporal and spatial scales, uncertainty in performance indicators of these facilities can be massive. Water quality measured at a receptor is inherently a composite of all source term variability, which makes it a practical approach to try and constrain this variability. However, this monitoring approach cannot resolve what portions of a facility are contributing to a greater proportion of the metal or acidity load. Due to the nature of the composite sampling, a seepage sample collected from the base of the facility represents an 'average' condition for the facility as a whole. Spatially variability within the facility is considered homogeneous based on the samples location. There is no way of applying targeted adaptive management spatially within the facility in this way. In this context, monitoring water quality nearly into perpetuity becomes a distinct possibility.

LEADING APPROACH FOR WATER QUALITY CRITERIA

The prolonged timeframes for the internal MRSF processes to occur implies monitoring of indicative water quality should occur until the processes either reach steady state or drop below levels (threshold approach) in the monitoring. As a result, monitoring timeframe for mine closure is constrained by the slowest expected process or mechanism as part of a design. An alternate approach to effectively manage reclamation risk is understanding, assessing, and responding to design specific failure modes. The preferred approach would be assessing closure and reclamation designs using leading indicators of performance, rather than the conventional lagging indicators of performance that results in exceptionally long monitoring periods.

A Functionality Based Approach

Reclamation ecologists recognized the value to moving from a productivity measure to a focus on monitoring based on functionality when returning landuse expectations are well defined. The same value and approach can be applied to water quality monitoring, such that it can be based on leading indicators of performance, with the potential for shorter monitoring periods, the ability to leverage adaptive management during operations and address regulatory uncertainty in long term predictions.

To develop leading indicators of performance for water quality, it is necessary to understand how ML/ARD is formed and mobilized. It is this functionality-based approach of understanding how a system operates that will allow for the development of leading indicators of performance for the engineered design.

The process of sulfide oxidation and formation of ML/ARD has been discussed and referenced well in the literature and only a summary is presented here. Sulfide minerals in ore deposits are formed under reducing conditions in the absence of oxygen. When exposed to atmospheric oxygen or oxygenated waters due to mining, mineral processing, excavation, or other earthmoving processes, sulfide minerals can become unstable and oxidize (Figure *2*). The reactions shown are schematically represented and may not represent the exact mechanisms, but the illustration represents a useful visual aid for discussing pyrite oxidation as an evolutionary process.

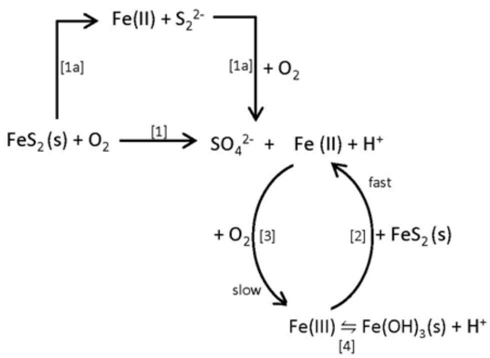

Figure 2- Model for the Oxidation of Pyrite (Stumm and Morgan, 1981).

This reaction can occur both abiotically and biotically (i.e., facilitated through microorganisms). In addition to direct oxidation, pyrite can also be dissolved and then oxidized. Under most circumstances, atmospheric oxygen acts as the oxidant. Oxygen dissolved in water can also result in pyrite oxidation but due to its limited solubility in water, this process is much less prominent.

Addressing Risk though Engineering Failure Modes

As part of mine closure and reclamation design, engineering tools such as Failure Modes and Effects Analysis are often completed. A Failure Modes and Effects Analysis (FMEA) is a systematic, proactive method for evaluating a process to identify where and how it might fail. The failure is also assessed to determine the relative impact of different failures, to identify the parts of the process that are most in need of change. The FMEA includes elements of risk and uncertainty as communication tools for scrutinizing an asset such as an MRSF that has already been constructed or a design yet to be built. The focus of the FMEA is on the individual process and mechanisms of the system, and how they interact to better understand failure modes.

In the context of an engineering design for a cover system or a mine rock storage facility constructed using engineered layers for gas management, an FMEA will understand at which critical thresholds the design fails to meet its intent (source term water quality). Components of the engineered design such as the engineered gas management layer will have air permeabilities specified, to achieve significant retardation of oxygen resupply to the acid producing material. Failure modes tell us the key indicators that may lead to a design failure, but conversely, under what conditions the design is expected to succeed. Failure modes should be used as a starting basis for the formation of key leading indicators of performance for water quality.

Key failure modes in the context of ML/ARD generation from MRSFs may be, but are not limited to:

- Mine rock pyrite content greater than expected leading to additional acidity being produced.
- Oxygen ingress into MRSF is greater than expected to sustain oxidation reactions.
- Net percolation of infiltrating water causes mobilization of oxidation products from the MRSF to the receiving environment.

Failure modes speak to fundamental mechanisms and process of the design, as well as site-specific controls on these mechanisms. In the case of MRSF water quality, (ML/ARD generation and mobilization) oxygen is required for the oxidation process to occur, and net percolation is required for metal and acidity loads to be mobilized as seepage. In the absence of either of those two components, ML/ARD seepage does not occur. Developing a monitoring program that monitors net percolation and oxygen results in a program that can be deployed in operations, before closure, while providing valuable information and has the potential to be adaptively managed rather than waiting for water quality monitoring of seepage.

<u>Assessing Robustness</u>

In ecological reclamation science, robustness and resilience are two terms often used to describe the ability of an ecosystem to maintain its normal patterns or rebound from external forces. For ecosystems, examples include maintaining or recovering to normal nutrient cycling and biomass production after being subjected to external stressors such as drought. Ecological resilience is a useful concept where there is significant risk of ecosystems losing their ability to exhibit recovery such that they wind themselves towards an undesirable state. The desirable state is often the next state in a succession trajectory. However, the indicators of ecosystem health and success of these reclaimed ecosystems such as plant water use and carbon assimilation, studying the rate, timing and magnitude of these processes can provide a mechanistic understanding of whether reclamation sites are functioning in a similar manner to non-mined ecosystems. (Straker et. al., 2019). In assessing the robustness of the ecosystems, the stressors must be assessed within a range of variability. Often, the primary external stressor will be climate and its components (e.g., mean precipitation, max and min temperatures, etc.). Sensitivity or Monte Carlo Analysis are tools often used to test a variable over a wide range of input parameters (O'Kane, 2011). The question becomes, what range of variability must be tested to ensure the design is sufficiently robust to meet its intent?

For determining the range of variability required to assess long-term MRSF performance of our leading indicators, climate is the ultimate governor of MRSF performance at a mine site. While certain design parameters can be adjusted to certain degrees, the climate at a site cannot be controlled. Therefore, it is imperative that the designer fully understands the possible dominant climate at a site. However, all too often a simple average of climate parameters is applied as an input into the models used during the cover system design process. Not only does an average value of precipitation or air temperature result in an unrealistic generalization of site conditions, but it also fails to account for the cycles of variation that are inherent within all climate signals. Failure to examine the scales of variability within a climate dataset necessarily results in a spurious simplification of what is an extraordinarily complex system. Furthermore, cycles of variation should be what forms the basis for determining monitoring periods of the leading indicators of performance, as they often exhibit the largest range of variability and external stress to a design. Being confident the leading indicators of performance meet the design intent over the expected range of variability should form the basis for providing sufficient robustness in the system.

Alberta Canada Case Study-Monitoring Duration

Numerical models should assess designs over the range of variability of climate that can reasonably be expected to occur over the facilities design life. If the design life is intended to be 100 years for example, assessment of the dominant climate cycles that can be expected to occur in this timeframe should occur.

The methods presented by Tallon et. al 2015 for understanding cover system performance in Fort McMurray Alberta determined climate is the ultimate determinant of performance. Typical cover system design efforts apply average climate values as model inputs, resulting in an over-simplification of what is inherently a complex system. The authors demonstrated a novel technique for separating the inherent scales of variability within a given climate signal. Long term (1908-2012) air temperature and precipitation data from Fort McMurray, Canada were used. Air temperature averaged 0.3°C, while the long-term average precipitation was 412 mm. A moving average revealed a long-term warming trend of 0.03°C yr^{-1}.

Determination of the cumulative departure from the mean for precipitation showed qualitatively periods where the annual average values departed substantially from the mean, suggesting the presence of wet and dry climate cycles. Both techniques operated under the assumption of data stationarity, or the assumption of a constant mean and variance, which does not incorporate small scale cycles and long-term trends. Empirical mode decomposition (EMD) was then used as a means of dealing with a non-linear, non-stationary dataset. The EMD technique worked directly in the time domain to separate out the scales of variability inherent in the input signal, as well as to determine the contribution to the total measurement variance of each inherent scale. Air temperature was found to be dominated by the annual scale of variation, accounting for 76% of the total variance. However, the EMD technique was also able to identify a long-term warming trend, while also uncovering high frequency variations from five to seventeen days (Figure *3*). Precipitation had a more even contribution of high, medium, and low frequency cycles of variation. A major contribution to the total variance of the precipitation signal was at the 3- and 7-year scales, which are postulated to correspond to El Niño / La Niña cycles, and the Pacific Decadal Oscillation, respectively.

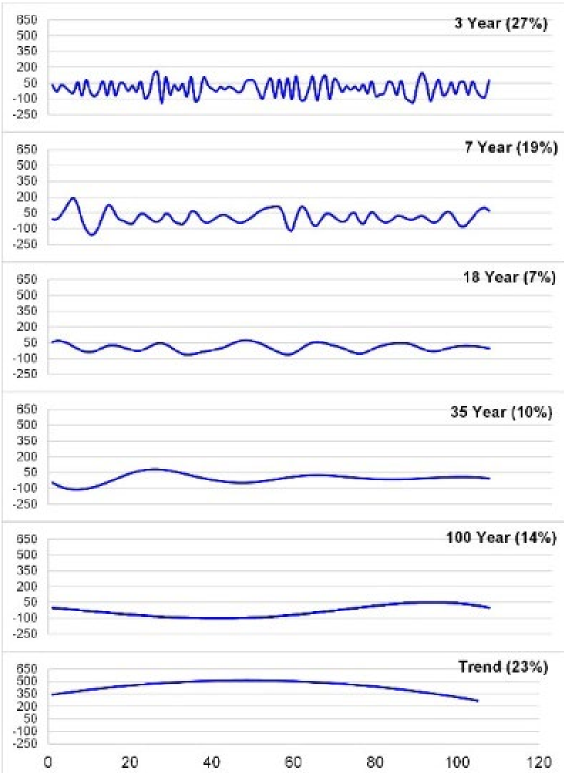

Figure 3- Temporal scales of variation intrinsic within the 1924 to 2012 Fort McMurray air temperature record. Y axis represents scales contribution to the total signal, X axis represents total number of years.

These findings highlight the importance of understanding where within the major climate cycles one is. More specifically, for a monitoring program, how to appropriately place monitoring results in the context of the monitoring record. If monitoring results for total seepage volumes begin to trend lower for example, comparing the results against the temporals scales of variation can better help explain results, especially in highlighting what might be expected when wetting cycles such as La Niña begin to dominate the climate signal.

Australia Case Study- Monitoring Frequency

Closure and reclamation planning for mine waste having the potential to generate ML/ARD requires rigorous management to mitigate or minimize the effect on the receiving environment. Cover systems are an accepted prevention and control alternative and have been successfully used at numerous sites around the world for ML/ARD management. The two principal objectives of a cover system are to control the ingress of oxygen to underlying reactive mine wastes or to control infiltration of meteoric waters to the underlying waste. There are two primary disadvantages to cover systems for mine waste: cost and the risk with respect to long-term performance (Yanful et al. 2006).

Full-scale cover system performance is often evaluated by water quality analyses of seepage discharged from the waste storage facility. This approach empirically defines a waste storage facility through monitoring of its cumulative effect at the base. Although there are several merits to this approach, monitoring of the cumulative effect at the base of the waste storage facility has two major disadvantages.

The first is, it may take tens if not hundreds of years before a considerable change is measured inside or downstream of the waste storage facility due to processes such as drain-down effects, complete oxidation of sulfide minerals, and mixing with groundwater. Secondly, without added forms of monitoring, there will not be enough information to explain the results if they do not meet expectations. The understanding for measured water quality at the base of a waste storage facility requires some fundamental parameters, including precipitation, runoff, soil water storage change, etc. Therefore, this monitoring approach on its own does not supply enough information for understanding and predicting performance of a cover system placed on the waste storage facility to mitigate ML/ARD.

O'Kane (2011) demonstrated, using the Mt. Whaleback Mine in Western Australia as a case study, that the Hilbert-Huang transform technique (part of the same EMD employed in the previous case study) could be used to analyze water content variability with time. The author showed water flow mechanisms in a field cover test plot (TP#1) and the response of sensor measured water content to precipitation events at the various depths for over 12 years using high frequency (hourly) measurement. The Hilbert-Huang transform provided a promising analysis approach to assist in designing an appropriate full scale cover system performance monitoring system, as well for interpreting data from point scale measurements and their validity in demonstrating macro scale performance. Therefore, not only were temporal monitoring frequencies refined around specific processes, but indications of spatial variability were also better understood for a monitoring program. The monitoring frequency (scale) for obtaining sufficient data, which is associated with spatial instrumentation and temporal data acquisition, must be understood to deploy a cost-effective monitoring system. Monitoring length will always be dependent of type of indicator and will be site specific. Detailed monitoring such as that outline in the case study allows for a more comprehensive understanding of the on-site water flow dynamics (process and mechanisms) which in turn provides data-based evidence for how long the monitoring may take. Guidance exists for monitoring key activities, scales and objectives for cover system development in the INAP Global Cover System Guidance Manual (INAP, 2017) (adapted from McKenna et al., 2011 and after Barbour, 2014). Without a data based defined monitoring period, monitoring plans are in contrast, unsupported, proposing timeframes which do not capture adequate variability in the measurement or require superfluously long monitoring.

DISCUSSION AND CONCLUSIONS

Similar functionality monitoring frameworks exist for selecting meaningful leading indicators in other fields such as ecological reclamation. Although this paper is not meant to be a discussion on ecological monitoring, ecological monitoring was highlighted to identify previously established monitoring approaches that could be adopted and adapted for geo-environmental field. The leading indicators for water quality are already understood and well documented in the geo-environmental field of study, sulfide oxidation, water percolation being examples of indicators for water quality. In addition to a monitoring approach that focusses on the functionality of the system, tools currently exist for identifying appropriate monitoring periods and frequencies for these indicators as highlighted in the case studies above. The use of these adapted frameworks and methods such as EDM and the Hilbert-Huang transform technique within EDM, will allow mine closure and reclamation experts to develop more meaningful design criteria with appropriate monitoring periods using a risk-based approach.

A risk-based approach should be used together with the functionality monitoring because it allows residual risk management and adaptive management to occur, leading to more favorable outcomes for the environment and closure practitioners. Furthermore, monitoring, and subsequent study of the leading indicators of water quality performance will allow for learnings from other sites to inform future design work across the industry (Figure 4).

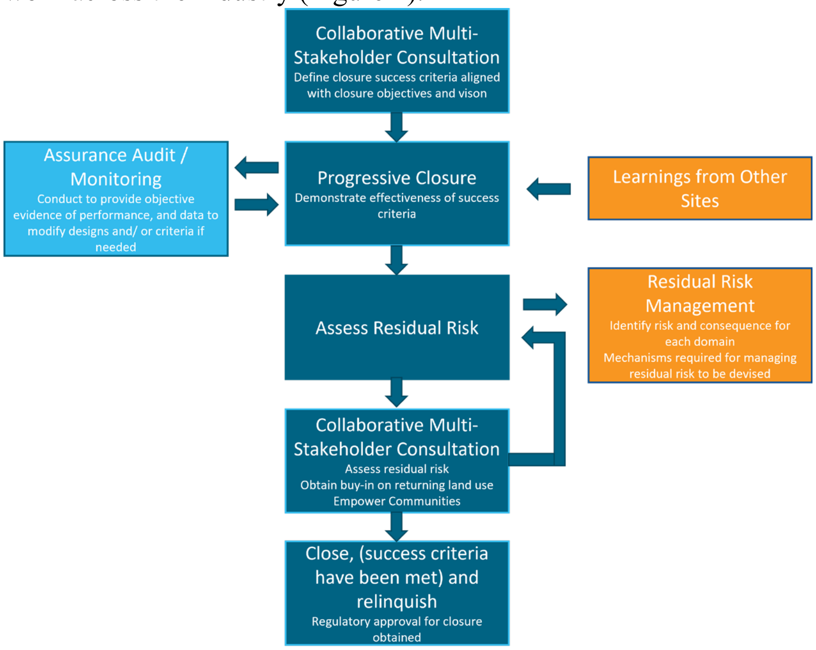

Figure 4- Development of success criteria for mine closure.

By identifying and monitoring leading performance indicators related to mine closure, such the physico-chemical indicators for water quality, data will be derived sooner in the closure timeframe. Using methods such as those highlighted in this paper, those results can be placed in the appropriate climate / performance regime, to provide better context and understanding of the results. Inclusion of these external influences to the performance aids in further isolating (multivariate analysis) the leading indicators contribution to the outcome, which leads to the ability to directly influence how the system functions through adaptive management.

One of the earliest warning systems miners employed to detect the presence of toxic gases and the potential for large scale explosions in a mine used canaries. The combination of the bird's rapid breathing rate, small size and high metabolism made it highly responsive to dangerous gases, especially carbon monoxide (Alberta, 2022). The signal a canary provided would give miners enough time to escape or put on respirators. Eventually, the monitoring approach was advanced, a special type of birdcage with ventilation holes was developed. Although these early miners may not have contextualized the monitoring method of key leading indicators at the time, they were indeed pioneering a monitoring approach we seek to expand on today for long term water quality monitoring. Much like the canaries, pore gas sampling and oxygen sensors employed within MRSFs can provide early indicators of large potential harm to come in the form of ML/ARD. By taking a first principles approach to monitoring key processes and mechanisms, closure practitioners may be afforded the time to escape long term ML/ARD liabilities by develop mitigation strategies that will see us avoid these consequences.

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