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Preparing for closure—systematic framework for water quality reviews

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Abstract

Water is the golden thread that runs through closure planning considerations and potential for long-term water quality impacts presents one of the main challenges for effective closure of mine sites. The majority of operating mines sites have existing water quality programmes in place to assess and manage such water quality impacts. However, these programmes often developed organically over time in response to specific matters arising at a site. Operational monitoring programmes further typically have a focus on compliance matters, and monitoring data are at times underutilised when it comes to understanding water quality dynamics at a mine site.

In recognition of the above, we have reviewed large water quality datasets forming part of existing monitoring programmes for a range of mines sites (~10 mine sites) in the Pilbara region of Western Australia, with the aim of understanding spatial and temporal trends to support risk management and closure planning. These programmes included compliance monitoring for ground and surface water (water levels and chemistry data) for monitoring as well as production bores and pit water grab sampling data.

The objectives of these reviews included assessing whether the existing surface and groundwater monitoring programmes indicate trends in water quality, to identify the geochemical process controlling such trends and whether the existing monitoring plans are fit to address the overall risk management at closure. The reviews identified gaps/improvements in the programmes and the opportunities to develop closure focussed monitoring programmes that prioritise monitoring locations, specify monitoring parameters and frequency to support long term planning.

The paper outlines a systematic framework for conducting these reviews and how the outcomes of these reviews can lead to the development of adaptive monitoring programmes in support of closure planning.

Keywords: *water quality monitoring, acid and metalliferous drainage, closure planning*

1 Introduction

Potential for long-term water quality impacts presents one of the main challenges for effective closure of mine sites. Water quality impacts at many mine sites are primarily associated with the generation of acid and metalliferous drainage (AMD) from mineral waste (such as reactive waste rock and tailings) as well as reactive rock exposures in open cut or underground mine works and ore stockpiles. Other water quality impacts could include elevated nitrate concentrations from residue of explosives such as ammonium nitrate fuel oil (ANFO) or impacts associated with chemicals used in ancillary services such as petroleum hydrocarbons associated with fuelling facilities or the use of per- and poly fluoro substances (PFAS) associated with firefighting training facilities.

While the majority of operating mines sites have existing monitoring programmes in place to assess and manage water quality impacts, these programmes have often developed organically over time in response to specific matters arising at a site. Operational monitoring programmes further typically have a focus on compliance matters, and monitoring data are at times underutilised when it comes to understanding water quality dynamics at a mine site.

The mining industry is experiencing a shifting paradigm in monitoring, with an increasing focus on planning for closure. There is a recognition that operational monitoring programmes, focussed as they typically are on compliance, may be limited in developing a robust understanding of site water quality dynamics relevant to closure planning (Gemson et al., 2019). Review of the available datasets provides an opportunity to determine the existing knowledge base, identify relevant knowledge gaps for closure planning and to establish the basis of a closure focussed monitoring programme.

This paper presents a systematic framework for conducting reviews of water quality monitoring data. We have applied this framework to monitoring datasets from several iron ore mining sites in the Pilbara, located within Western Australia. The outcomes of these reviews can lead to the development of adaptive monitoring programmes in support of closure planning.

2 Systematic framework for water quality reviews

2.1 Objective

The objective of these reviews is to develop an understanding of spatial and temporal trends in water quality to support risk management and closure planning. Specifically, the review should identify:

- Whether the existing surface and groundwater monitoring programmes indicate trends in water quality associated with mining activities. This would typically include AMD, salinity, potential release of nitrogen compounds associated with ammonium nitrate fuel oil (ANFO) blast residue, and chemicals associated with ancillary services.
- The geochemical processes controlling these trends.
- If current monitoring programmes are fit for managing risk at closure.
- Knowledge gaps in site water quality dynamics.
- Opportunities to close the gaps and to establish the basis of a closure focussed monitoring programme.

2.2 Seven-step framework

To achieve these objectives, this paper proposes a seven-step framework as outlined in Table 1.

Table 1 Seven-step framework to review surface water and groundwater monitoring data

Step	Process	Inputs	Tools	Outputs
1	Initial stakeholder engagement.	Stakeholder knowledge.	Workshops, meetings, interviews, etc.	Expectations. Scope.
2	Establish environmental setting and identify the main site-related sources of deleterious water quality.	Site characterisation studies. Public Environmental Reviews. Environmental Impact Assessments.	Conceptual Site Model (CSM).	SPR model.

Step	Process	Inputs	Tools	Outputs
3	Collate the sources of monitoring data.	In-house database management software.	Spreadsheets, code packages (VBA, Python), etc.	Collated data table.
4	Consolidate the data.	Collated data table.	Spreadsheets, code packages (VBA, Python), etc.	Consolidated dataset (draft).
5	Review data quality.	Consolidated dataset (draft).	QA measures, QC samples TDS-EC ratio, Alkalinity-pH congruence, Charge Balance Error (CBE), Anomalous values.	Consolidated dataset (final).
6	Exploratory data review: Criteria exceedances Statistical overview Initial assessment of spatial and temporal trends	Consolidated dataset (final).	Screening against assessment criteria. Statistical software packages. Graphical analysis methods.	Confirmation of COPCs and exceedances. Boxplots. Histograms. Scatterplots. Initial spatial and temporal trend reviews.
7	Detailed data review: Spatial and temporal variation. Geochemical processes. Background data assessment. Data gap assessment.	Consolidated dataset (final). Insights from exploratory data review.	Statistical software packages. Graphical analysis methods. Hydrogeochemical software packages.	Spatial and temporal trend reviews. Processes affecting water quality. Background data populations. Data gaps in monitoring programmes.

Combined, the outcomes of these seven steps can be applied to inform the development of a closure-focussed water quality monitoring programme. The steps of this framework are described in further detail below. Selected examples are presented based on application of this framework to the authors experience of more than a dozen iron ore mine sites in the Pilbara.

2.2.1 Initial stakeholder engagement

Stakeholder engagement provides critical intelligence regarding mine site monitoring programmes and the data collected by those programmes. The tools for this step consist of the broad range of consultation approaches such as interviews, meetings, workshops, etc. Themes to discuss in these interactions include:

- Confirmation of the intended outcome of the monitoring data review. Generally, closure teams and site personnel recognise that the review is the start of an iterative process to obtaining and improving closure-focussed data.
- Regulatory requirements for monitoring, including commitments that have been made in terms of closure monitoring and post-closure land use. Where no specific regulatory requirements are in place, following direction provided in guidance documents such as the GARD Guide (INAP, 2014) and MEND guidance (MEND, 1990) would assist with alignment with industry practice.
- Available studies and characterisation data to support the development of a conceptual site model (CSM).
- Recognised sources of water quality impacts.
- Sources and format of monitoring data.
- Sampling procedures applied by monitoring teams.
- Recognised data quality issues, if any.

2.2.2 Identify the main sources of site-related deleterious water quality

The tool to apply in this step is the CSM relevant to identified closure risks. A CSM is developed from site knowledge and characterisation data. Typically, these would be contained in documents developed to obtain and maintain mining authorisation such as environmental impact reports, geological and hydrogeology characterisation reports, waste characterisation studies, regulatory compliance reports, and mine closure plans. In our jurisdiction (Western Australia) these documents include annual and triennial aquifer reviews (AARs and TARs) and public environmental reviews (PERs).

Based on the CSM, a site-specific source-pathway-receptor (SPR) model can be developed. The SPR model identifies the sources of deleterious water quality, the pathways along which the chemical(s) are mobilised, and the human and ecological receptors that may be at risk from chemical exposure. This approach is widely applied in closure and environmental management and there are several national and state guidelines that may apply (e.g., Assessment and Management of Contaminated Sites for Western Australia (DWER, 2021) and the National Environment Protection (Assessment of Site Contamination) Measure (NEPC, 1999)). Potential SPR linkages to consider are presented in Figure 1.

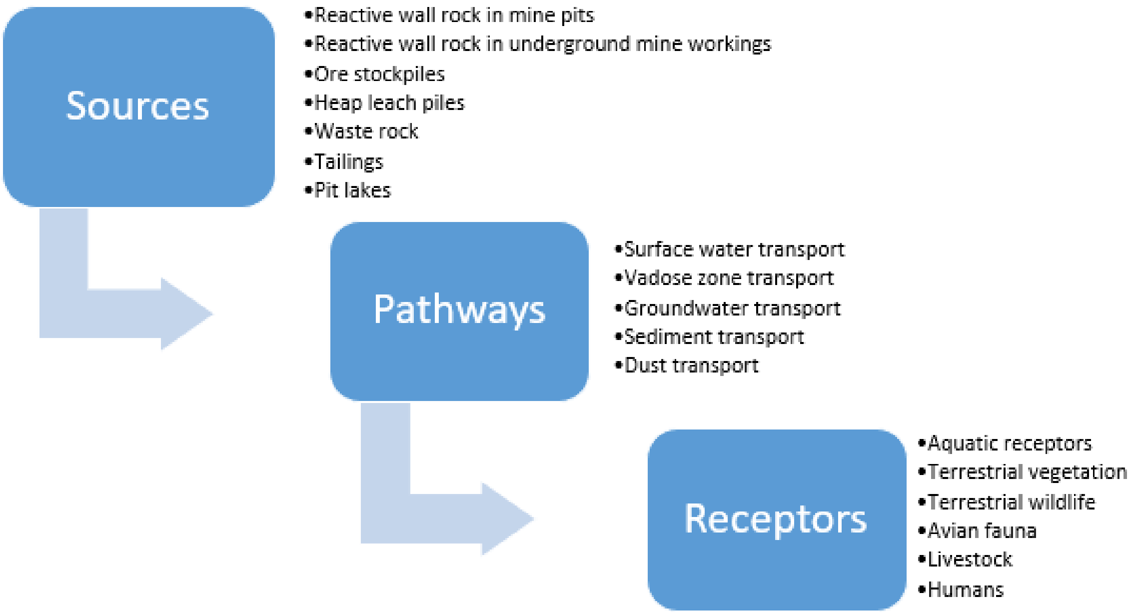

Figure 1 SPR model to guide monitoring data review

2.2.3 Collate the data

At this stage, the focus is on generating spreadsheet tables that merge the different datasets. To assist in this process, metadata fields are added to the collated dataset indicating the data source. There is relatively little value in reviewing water chemistry data if the location of the samples is not known. Therefore, an important aspect of this step is to confirm that every monitoring location has spatial coordinates.

Responsibility for environmental data collection can rest with several different teams. Frequently the management and performance of these teams are affected by different drivers. This can lead to multiple datasets from different groups of monitoring locations, different time periods, and different analytical parameters. Frequently, they may be accessed using different software packages resulting in data stored in different formats. However, the monitoring sites and data recorded in these datasets may overlap. We have found that internal access to data sources increases the potential for obtaining larger, complete datasets. It also increases the efficiency of access. Nevertheless, our experience indicates that the time and effort expended during this step can be considerable and should not be underestimated when planning a monitoring data review project.

Stakeholder engagement is an important part of this step. Intelligence gained during the initial stakeholder engagement can yield good dividends. However, it is also important to share the outcome of the data collation process with stakeholders to obtain consensus on the scope of the data before the technical work of interpreting the data gets underway. One output of the data collation process would be a summary of data collection over time (Figure 2) which provides a high-level overview of sampling effort that can be correlated with the mine development and operational activities at a site.

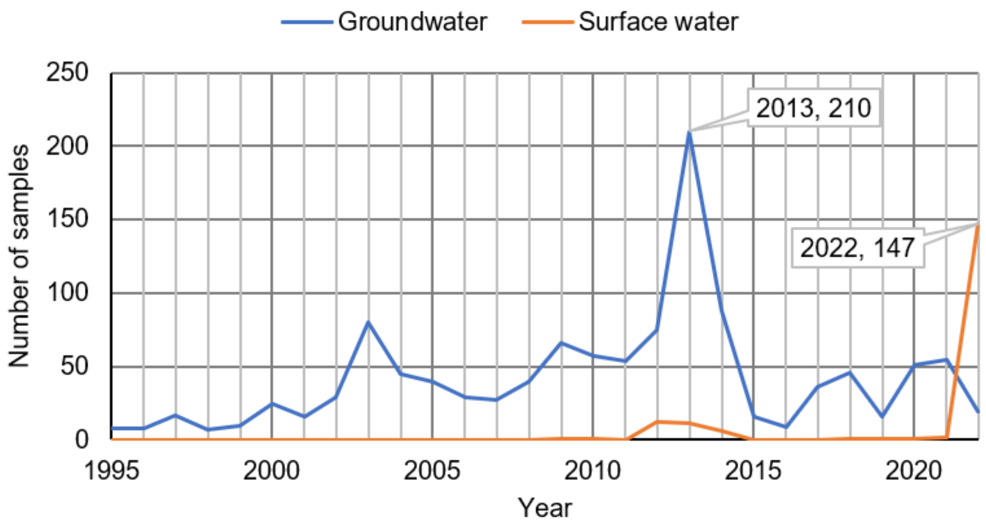

Figure 2 Example of summary of water quality samples collected over time at a Pilbara mine site

The final output of this step is a table of collated data. A typical configuration would have each row of the table representing a water sample. Individual columns would represent fields of sample metadata (for example, geospatial coordinates, date of collection, location description, source database, analytical laboratory, etc.) and fields for water quality parameters (for example, pH, bicarbonate alkalinity, nitrate, selenium, etc.).

2.2.4 Consolidate the data

After collation, the merged dataset will include fields from different data sources that contain values for the same water quality parameters, often in different units. In this consolidation step, the fields that can be correlated are combined under a single field name. This requires confirmation of concentration units and conversion if necessary.

The collated dataset may also contain parameters which have little relevance to the water quality review. For example, reactive silica is relevant to bulk water supplies that may be subject to treatment or tracer studies. However, it is not helpful in assessing potential ecological impact. There may also be fields that contain little or no data. The consolidation process considers these parameters and fields and potential justification for their removal. It can be helpful to engage stakeholders in this process to obtain consensus on removal and alleviate potential concerns regarding loss of data.

The output of this step is a draft consolidated dataset comprising the combined water quality data for samples collected from the various site monitoring programmes.

2.2.5 Review data quality

The level of quality assurance (QA) and quality control (QC) in mine site water chemistry monitoring is variable over time and location. Many mining companies have sample collection and analysis procedures but the extent to which these are understood and implemented by monitoring teams varies. Thus, the QA aspect of monitoring is difficult to establish. It can be difficult, if not impossible, to determine what field procedures were applied to samples collected years ago. For example, whether monitoring bores were purged prior to sampling, sampled using low-flow techniques, or whether no-purge grab samples were taken. Therefore, the water chemistry review is generally limited to data QC. That is, assessing the internal consistency of the data as an indicator of its reliability in representing the chemistry of the water samples.

Our review framework includes six control elements:

- Identifying known data quality issues from stakeholder consultation (and consideration of QA measures as available and verifiable).
- Consideration of the results of QC samples such as blind duplicate and equipment rinsate samples.
- Assessing mass derived total dissolved solids (TDS) – electrical conductivity (EC) ratios.
- Consistency between reported alkalinity (total, carbonate, bicarbonate, and hydroxide alkalinity) and pH values.
- Evaluating charge balance error (CBE) as a standard indicator of data quality (Murray & Wade, 1996).
- Identifying anomalously low or high concentrations for analytes when considering temporal trends.

An example of a systematic data quality issue, identified through assessment of TDS-EC ratios is illustrated below. Initial stakeholder engagement indicated that EC data had been entered into a monitoring database using the wrong units. This was readily identified as two separate populations by comparing to TDS concentrations (Figure 3). The erroneous data were clearly outside of the expected ratio range of 0.55 to 0.75 (Hem, 1985) and necessary unit corrections could be made.

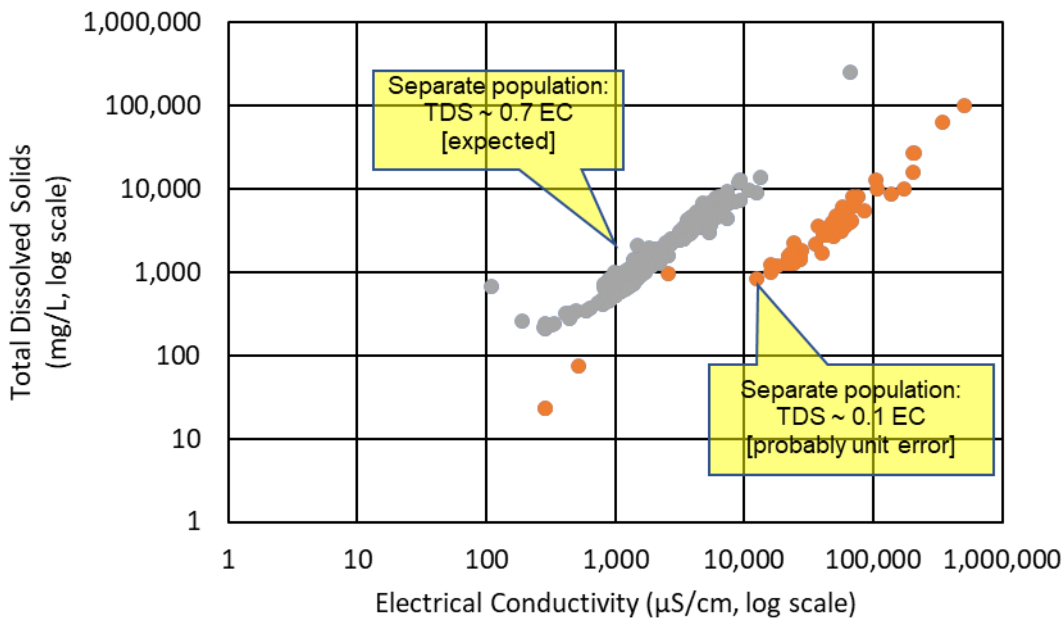

Figure 3 Two populations identified by comparing EC and TDS in monitoring dataset

2.2.6 Exploratory data review

The exploratory data review provides the opportunity to confirm key constituents of potential concern (COPCs), to assess the data distribution of those COPCs and other parameters informing water quality, and to gain an initial understanding of spatial and temporal trends in water quality.

Confirmation of COPCs include screening water quality data against relevant assessment criteria. If developed for a site, this would include screening against site specific trigger values (SSTVs) that take into account baseline/background water chemistry data. Where SSTVs are unavailable, water chemistry data are screened against default assessment criteria. The selected assessment criteria need to take into consideration the SPR framework for the area being monitored, associated environmental values / beneficial uses identified and the long term mine closure goals including post-closure land use. Identification of parameters exceeding these criteria can assist with the prioritisation of COPCs carried through to the detailed data assessment.

In addition to considering exceedances of water quality assessment criteria, the identification of COPCs should also consider available mineral waste geochemical characterisation data (such as leachate testing) as well as the nature of other sources of contaminants (which may not have yet been tested for in water samples at the time of review).

The assessment of data distribution includes the use of statistical and graphical tools. These tools can elucidate important patterns in the data sets, and examples of typical data visualization tools used for this purpose are shown in Figure 4.

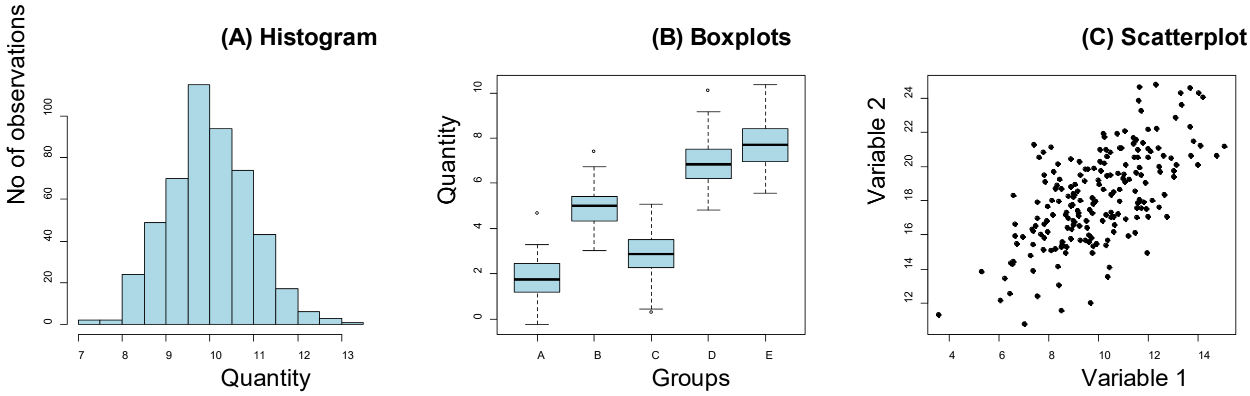

Figure 4 Data visualisation tools (Gemson et al., 2019)

An example of the application of box plots to assess different data populations at an iron ore mine in the Pilbara is shown in Figure 5. In this case, water hardness (in mg/L as $CaCO_3$ equivalents) show clearly different population distributions between two different aquifers at the site, informing the application of different hardness modification factors for the assessment criteria of the elements cadmium, chromium, nickel, lead and zinc (ANZG, 2018).

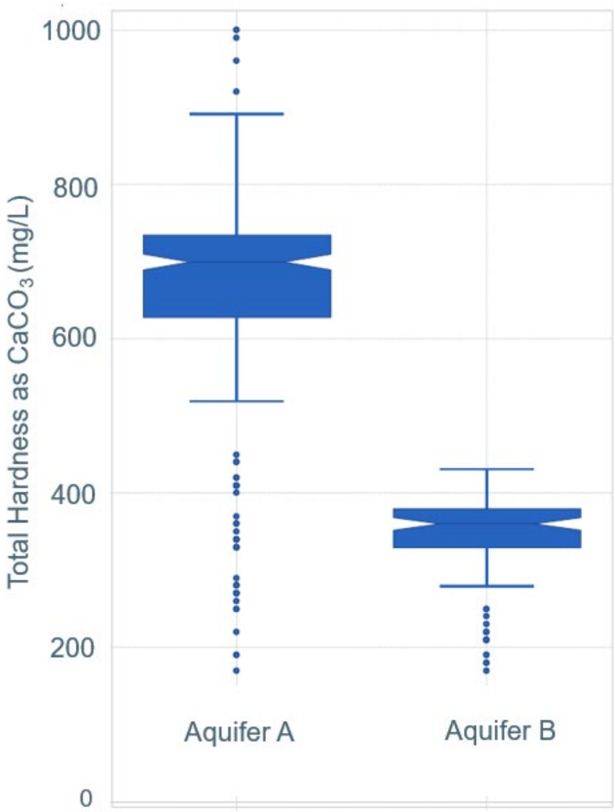

Figure 5 Box plots showing differentiation in hardness (as $CaCO_3$) distributions between two aquifers

The initial review of spatial trends will identify priority areas spatially. While this may include monitoring locations close to sources of deleterious water quality, it could equally pertain to locations along pathways or at receptor point monitoring locations. Initial review of temporal trends depends on the amount of temporal data available to evaluate the statistical significance of trends. The nature of the trends, including indicators of seasonal variation will influence the appropriateness of specific methods such as the Mann-Kendall or Mann-Whitney test for trend significance.

2.2.7 Detailed water quality review

Key sub-tasks include detailed assessment of spatial and temporal variation in water quality, identification of geochemical processes controlling water quality, identifying background populations for key COPCs (if supported by the available data), as well as identifying data gaps in the monitoring programme.

2.2.7.1 Assessment of spatial and temporal variation

The assessment of spatial trends focus on spatial variation in water chemistry in relation to sources, pathways, receptors and includes the three-dimensional dynamic associated with aquifer frameworks. Contours of chemical concentration may be deceptive to show spatial variation given the multiplicity of sources and pathways on mine sites. Post maps showing monitoring locations with pre-determined ranges of chemical concentration can be useful to highlight areas of concern in relation to the catchment setting, potential sources, pathways, and receptors.

Temporal trends are assessed graphically and through use of statistical methods to identify the statistical significance of temporal trends (Fu & Wang, 2012). Parameters assessed are generally those associated with the main sources of deleterious water quality as well as general indicators of potential AMD impacts such as sulfate, alkalinity, and pH. These can show developing impacts such as increasing sulfate concentrations in groundwater downgradient of backfilled pits containing potentially acid-forming (PAF) material (Figure 6). In this example the temporal trend, as evaluated through the Mann Kendal non-parametric method, has a P value of <0.01 (indicating a statistically significant trend at a 99% confidence level).

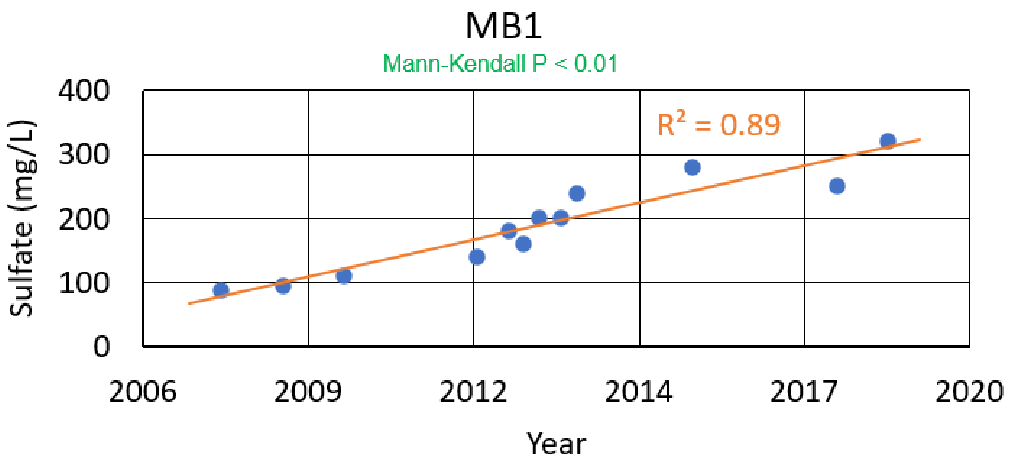

Figure 6 Temporal trend assessment using the Mann-Kendall method

2.2.7.2 Identify potential processes controlling water chemistry

Our framework is directed at data trends and features that are indicative of AMD including acidic drainage, neutral metalliferous drainage, and/or saline drainage. This includes trends in bulk chemistry parameters such as alkalinity and TDS as well as individual parameters such as sulfate, trace metal, and metalloid concentrations.

Graphical methods to identify these processes are common. For example, a Piper plot identifies samples based on the relative proportions of major ions. This can be used to characterise water from different aquifers or sources, identify cation exchange, and the influence of AMD. In the example shown in Figure 7, linear trends in monitoring bore data indicate increasing proportion of sulfate (SO_4) from an AMD source. In this case, the AMD source was Mount McRae Shale material exposed in the pit walls. Mount McRae Shale is generally recognised as PAF in iron ore deposits associated with the Brockman Iron Formation. The pit sump monitoring samples maintained a relatively consistent water quality over time, suggesting the McRae exposures were localised, mainly affecting water quality at monitoring bore MB4.

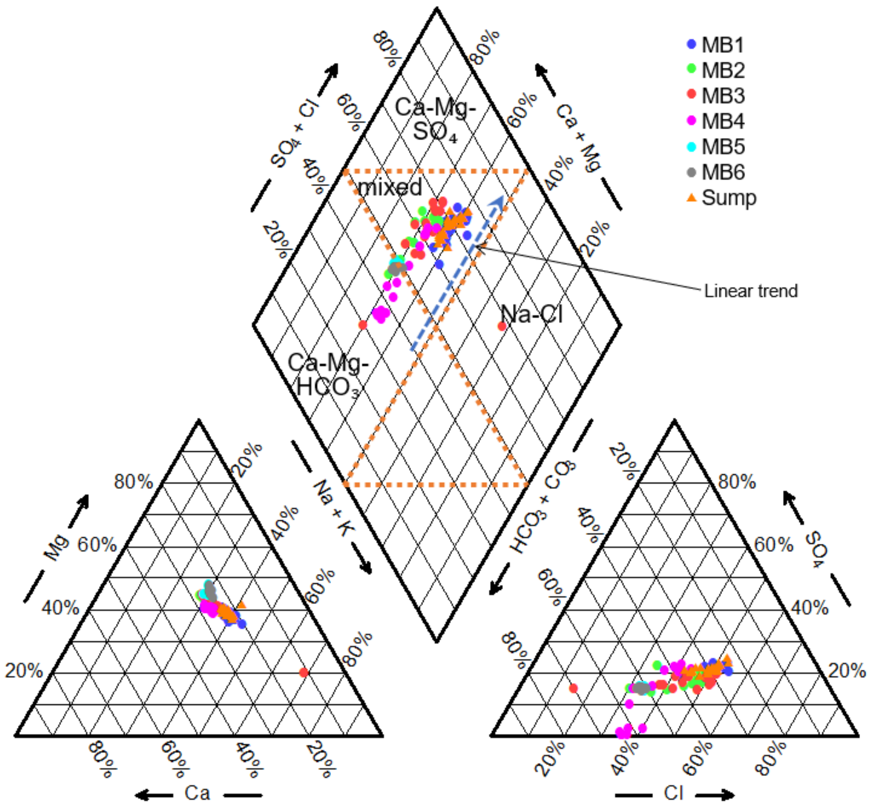

Figure 7 Piper plot example

2.2.7.3 Assessing background populations

In naturally mineralised regions, an understanding of background concentrations of inorganic constituents is of key importance for the identification of mine impact and the consideration of SSTVs for water quality monitoring.

The evaluation of background COPC concentrations is generally based on data from monitoring locations that are up-hydraulic gradient of mine features with the potential to impact on water quality, and/or on pre-mining baseline data. Background data available from these sources may however be lacking, especially at mine sites that have been operating for decades (with operations starting prior to a requirement or expectation that baseline conditions needed to be established prior to mining) and where the landscape setting of the mine site has limited the availability of up-hydraulic gradient bores.

Where background data from these sources are lacking, one can extract a background dataset that presents background concentrations of COPCs from a site wide water quality monitoring dataset. This effectively entails identifying sampling locations that are free of mine influence. There are multiple advantages of extracting a site-wide background dataset from a pooled dataset including; 1) this dataset being more representative of site-wide background geochemical and hydrogeological conditions than a limited background dataset of off-site locations, and 2) the extracted background dataset typically being much larger in size than traditional background datasets collected from off-site locations and the larger background dataset therefore better addressing variability in background concentrations (Singh, 2014). Such an assessment should include multiple lines of evidence to identify groundwater data representative of background conditions through the combined use of graphical and statistical tools.

These tools include the use of quantile-quantile (Q-Q) plots to identify different populations in a dataset, with the presence of discontinuities (or breaks) on a normal Q-Q plot suggesting the presence of multiple populations (Singh, 2014). An example Q-Q plot is presented in Figure 8, with data below the identified break point being indicative of background nitrate concentrations on a Pilbara iron ore site.

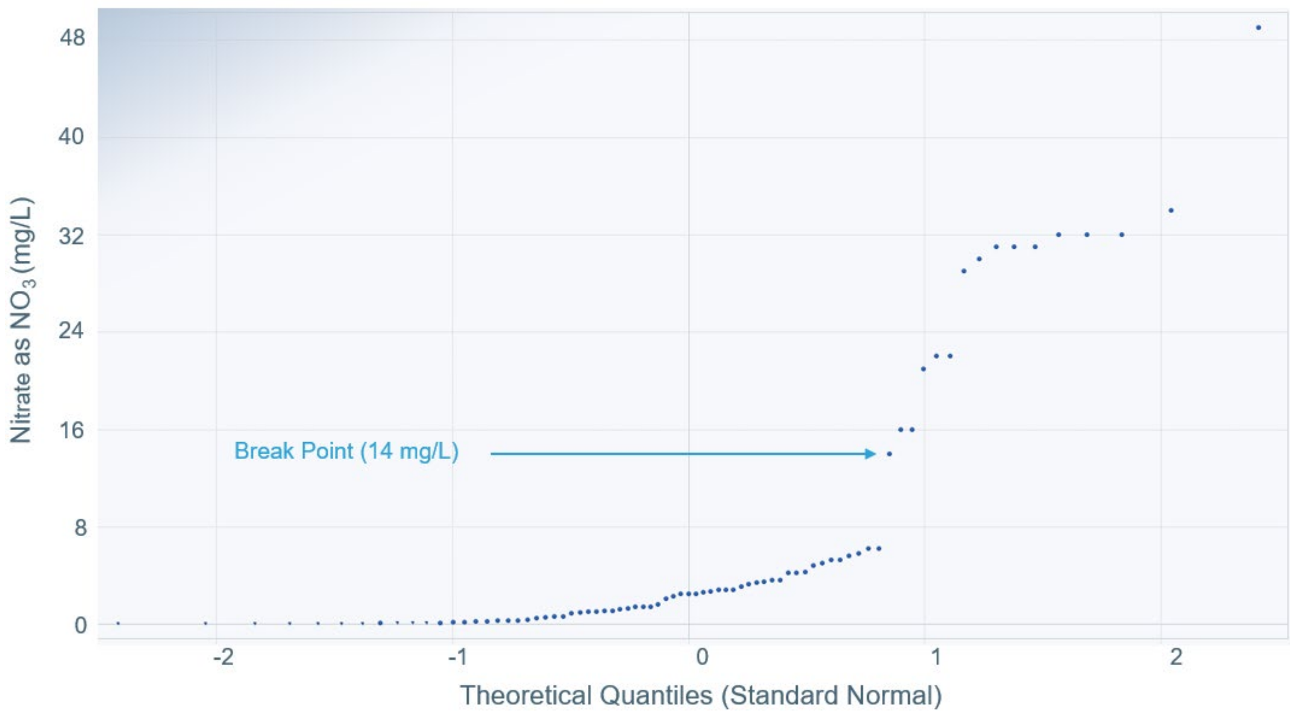

Figure 8 Q-Q plot showing breakpoint in support of identifying background population

2.2.7.4 Identifying data gaps in monitoring

The review provides the basis for the identification of data gaps in the monitoring programme from a closure perspective. This includes 1) potential gaps in spatial coverage of monitoring locations (both in terms of a two-dimensional plan view of the site but also in terms of the three-dimensional understanding of the aquifer framework which may include multiple hydrostratigraphic units), 2) completeness of analytical suites and 3) sampling frequency. Once data gaps have been identified and the materiality of the gaps assessed, the knowledge of these gaps can be incorporated into the development of a closure focussed monitoring programme.

3 Incorporating outputs into adaptive water quality monitoring programmes

The insights gained through the systematic water quality review, both in terms of the existing knowledge base as well as gaps identified, provides the basis for the development of adaptive water quality monitoring programmes that include consideration of closure planning. The data “picture” presented by the review will have gaps that lack sufficient resolution. These knowledge gaps might include:

- Areas for which there is no data (and which may represent sources, pathways, or receptors in the SPR model).
- Monitoring locations from which samples have been collected at irregular intervals.
- Trends (temporal and/or spatial) in water quality parameters for which the drivers are not clear.
- Lack of data from which to determine site-specific background concentrations.

In addition to these knowledge gaps, information gathered on the current monitoring programmes is reviewed to assesses fitness for purpose. This includes quality assurance aspects such as:

- Review of the sampling locations associated with the existing programme.
- Review of sampling methods and sampling frequency of the existing programme.
- Review of the field parameters and laboratory analysis associated with the existing programme.

A broader context applied is whether the monitoring programme is focussed on supporting closure planning and, in the future, able to demonstrate whether closure water quality criteria are being met. This includes considerations such as those described in Gemson et al (2019):

- Confirmation of COPCs.
- Reference/background concentrations of COPCs.
- Appropriate assessment criteria.
- Source-pathway-receptor framework.
- Regulatory requirements.
- Borehole construction.
- Sampling frequency.

Lastly, and frequently overlooked, is the adaptive component of a monitoring programme. This requires regular scheduled and auditable reviews of monitoring data. These reviews should not just be directed at identifying environmental impacts and regulatory compliance. They should also consider whether the monitoring programme, as applied at the time of review, is able to meet its objectives. This may require a revision of monitoring locations, installation of new monitoring bores, updates to field sampling procedures and analytical suites, and similar systemic factors.

4 Conclusion

Review of existing surface and groundwater datasets provide an opportunity to develop a knowledge base for closure focussed monitoring, while also providing the basis to identify existing data gaps relevant to a closure focussed monitoring programme. Undertaking these reviews in a systematic fashion, as outlined in this paper, facilitates the identification of spatial and temporal trends in water quality, geochemical processes controlling trends, gaps in the monitoring programme and opportunities to address the gaps to support long term closure planning.

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