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Deriving background concentrations of contaminants of potential concern in groundwater: an example from the Ranger uranium mine, Australia

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Abstract

In the absence of pre-mining groundwater quality data, ERM interrogated nearly 220,000 data points in the Ranger uranium mine groundwater database to establish a background dataset for analytes for each hydrolithologic unit (HLU) at the site. These datasets were used to identify if analytes in groundwater were operations related, and therefore contaminants of potential concern (COPCs), and to develop background threshold values (BTVs) to inform groundwater monitoring programs and mine closure activities.

The assessment assumes COPC concentrations from monitored areas comprise both operations-derived and background concentrations. The approach applied allows a site-specific background dataset to be extracted from a dataset obtained from impacted areas at a site; it relies on a weight-of-evidence approach consistent with that described in guidance from the US Navy, Interstate Technology and Regulatory Council and the US Environmental Protection Agency. In this assessment, if analyte concentrations were not related to mining activities (i.e. derived only from background conditions), the analyte was not considered to be a COPC. BTVs were then developed for the background datasets to support decision-making during closure at the site.

Ranger data was compiled and reviewed so as to meet data quality standards. Iterative population partitioning was used to identify breakpoints in each HLU analyte–specific dataset using quantile-quantile (QQ) plots, independent of site-qualifying information. The breakpoint was refined using multiple lines of evidence, including temporal concentration trends, covariance with known site sources, expected source composition, and spatial patterns of impacts. For each analyte within a given HLU, 95/95 upper tolerance limits were used as BTVs for each background dataset. This approach allows background concentrations to be developed for sites where insufficient up-hydraulic gradient background or pre-development data are available, thus capitalising on a site's operational database. This is particularly relevant in mineralised areas where background (naturally occurring) concentrations of metals or other inorganic constituents may be higher than guideline or default trigger values and concentrations.

Keywords: *background threshold values, contaminants of potential concern, quantile-quantile plots, groundwater monitoring programs, mine closure*

1 Introduction

In naturally mineralised regions, understanding background concentrations of inorganic constituents that may ultimately become constituents of potential concern (COPCs) as a result of mining activities is of key importance. Establishing these background concentrations allows appropriate assessment criteria to be established for water quality monitoring and to inform mine closure activities. These assessment criteria recognise that the naturally occurring concentrations of some COPCs in groundwater may be elevated in some areas because of the mineralised geological setting.

Energy Resources of Australia Ltd (ERA) operates the Ranger uranium mine (the 'site') located in the Northern Territory (NT) of Australia. The mine site is located in the Ranger Project Area (RPA) and is progressing towards closure; it is surrounded by, but separate to, Kakadu National Park. The geological and hydrolithologic units (HLUs) within the RPA on which the Ranger mine is located vary across the site and with depth. The varying mineralogy and concentrations of inorganic constituents within the over 20 HLUs at the site are likely to have resulted in different background groundwater quality across the site. In addition to the geological complexity, the Ranger mine has been operational since 1980. Since then, locations at which mining, waste rock and tailings placement, and waste water disposal have occurred have varied. Additionally, the quality of waste water has also changed over the operational life of the mine. Based on these changes, sources of COPCs and specific COPCs through time at the mine are likely to have varied.

The long operational life of the mine and evolving understanding of the HLUs at the site mean that the amount of clearly identifiable background groundwater quality data from groundwater bores within the RPA is limited. Monitoring of groundwater conditions and the construction of bores for groundwater monitoring in the surrounding Kakadu National Park is also limited in order to limit disturbance within the park. This means that background groundwater quality cannot be readily evaluated from bores in locations removed from the RPA footprint.

Background concentrations of COPCs in groundwater had been evaluated by Energy Resources Australia using groundwater data up until 2013. However, since 2011, ERA has expanded the groundwater monitoring bore network and associated groundwater quality dataset at the Ranger mine substantially. Over this period, ERA expanded the groundwater monitoring network, and, in some cases, the analytical suite monitored, to address specific issues and in response to recommendations based on regular reviews of groundwater monitoring data.

This paper presents the approach taken to establish an updated and broader set of background COPC concentrations at the Ranger mine that considers the substantially larger dataset, increased understanding of conditions at the mine, and improvements in data management and assessment technologies. These background values were used to develop background threshold values (BTVs), which in turn are used to inform groundwater monitoring programs and related mine closure activities.

Establishing a background dataset for this site is particularly complex. Commonly, reference locations or upgradient groundwater datasets are used to establish background values to guide closure decisions (e.g. National Environment Protection Council [NEPC] 1999; US Navy 2004); however, this site is surrounded by Kakadu National Park, a world heritage area that has highly sensitive cultural resources, where offsite drilling and sampling is restricted. Consequently, any background data had to be derived from samples collected within the site boundaries. Additionally, groundwater monitoring over the 40-year lifetime of the mine has varied in terms of sampling frequency and hydrogeological and spatial coverage. Over time, the understanding of the site geology has evolved and HLUs have been re-characterised. This has resulted in inconsistencies in the spatial and temporal coverage of data in the different HLUs. These differences in coverage, together with the lack of pre-mining data, make it difficult to extract and validate a site-specific background dataset.

The underlying premise for this assessment was that concentrations of COPCs in samples collected in potentially impacted areas comprise both mining-derived concentrations and background concentrations, in recognition of the migration of solutes in groundwater. In other words, not all concentrations of a COPC in a dataset collected from potentially impacted areas represent impacted conditions – they may relate entirely to background conditions. This premise is used as a basis for 'extracting' a site-specific background dataset from a dataset obtained from impacted areas at a site (e.g. the US Environmental Protection Agency [USEPA] 2014). When analyte concentrations in a sample were derived only from background conditions (i.e. are not related to mining activities), the analyte was not considered to be a COPC.

BTVs were developed for the background concentration to facilitate use of the background datasets in decision-making. BTVs are statistically constructed threshold values that capture the variability in the background dataset and set a reasonable upper concentration limit for samples drawn from an unimpacted bore. Where BTVs could not be developed but background concentrations could be identified, these concentrations were adopted as BTVs.

2 Regulatory context and technical guidance

The Ranger uranium mine is governed by both Commonwealth and NT legislation and regulations (Energy Resources Australia Ltd 2018). The Ranger Authorisation is the key instrument that governs operations at the mine; it was revised in 2018 to take into account the Ranger Mine Closure Plan, and to incorporate changes to reporting and operational matters and other monitoring requirements. In addition to the specific authorisation, groundwater monitoring at the site is conducted with consideration of the National Environment Protection Measure (NEPC 1999). This presents a framework for assessment that considers the source pathway receptor (SPR) model. The assessment of background concentrations presented here considers current and former site activities, HLUs, and surface water catchments within this SPR framework.

In order to identify and qualify the potential extent of environmental impact to groundwater from mining-related activities, the natural or background conditions of groundwater need to be understood so that concentrations of COPCs measured in groundwater at the site can be compared to those that may occur under natural conditions. This recognises that the naturally occurring concentrations of some COPCs in groundwater may be elevated in some areas because of the mineralised geological setting. Establishing background COPC concentrations also informs the requirement to ensure that, in accordance with the Ranger Authorisation, environmental impacts within the RPA are as low as reasonably achievable during operation, and during and after rehabilitation.

Specific schedules of the ASC NEPM (NEPC 1999) make reference to the need to consider background concentrations and refer the reader to the South Australia Environmental Protection Authority (EPA) (2008) document for further guidance. The South Australia EPA (2008) has been superseded and is not directly applicable to the Ranger mine that is in the NT; however, it describes general approaches to determine background concentrations for a site. The South Australia EPA (2008) guidance references USEPA guidance documents on the conceptual and statistical approach to the development of groundwater background datasets. Because of the extensive and well-establish protocols associated with the USEPA guidance documents, the approach developed here adheres closely to that guidance, including methods described in US Environmental Protection Agency (USEPA) (2002, 2006, 2009, 2015).

In order to establish background concentrations of COPCs at the RPA, these guidance documents were relied upon to apply industry standard approaches to the establishment and use of background groundwater datasets. In general, these guidance documents acknowledge that there is no 'one-size-fits-all' solution; however, there is general agreement that the derivation of background concentrations should include a weight-of-evidence approach that considers the site history, the hydrogeological, geological, and geochemical conditions of the site, and graphical representations of the data through space and time.

3 Dataset inventory and quality review

The USEPA (1991) has guidelines for evaluating the usability of historical and compiled datasets for risk assessments. The usability assessment considers the completeness, comparability, representativeness, precision and accuracy of the dataset. Applying the data usability framework was helpful in this study as the dataset was being used for something other than its original purpose and has data that spans four decades, based on a groundwater monitoring network that has changed substantially through time. Consistent with the USEPA approach, the dataset was assessed for completeness, comparability, representativeness, precision, and accuracy.

The curated site dataset included a total of 241,300 records. A range of filters were applied to a separate database to arrive at the starting dataset for the background evaluation that considered the usability of the data. Three HLUs representing shallow weathered, deep weathered and shallow bedrock in the same geological formation were the most data rich, both in terms of the number of results and in terms of the coverage across the COPCs. Most of these results were due to the expansion of the groundwater monitoring network and program from 2011, particularly around the tailings storage facility. Several HLUs have relatively few bores and are generally data poor, typically representing shallow sands or localised formations.

A data-screening step was established after the data usability step, which established minimum data requirements for the number of bores (represents spatial coverage), number of results per bore (represents temporal coverage) and detection rates (concentrations above the analytical detection limit) required in order to advance datasets to the full background evaluation. Where it was considered appropriate based on site knowledge, proxy background values were selected for some of the HLUs and for several analytes with insufficient data completeness for further background evaluation. A review of data with respect to comparability indicates that, at least for the last decade, field-sampling protocols and analytical protocols remained consistent. A detailed review of metals in terms of whether or not they would have been filtered prior to analysis was conducted in order to assess data comparability, and a unit harmonisation step was carried out to ensure that all data were reported in consistent units to allow comparability.

Representativeness refers to the extent to which the data appropriately characterise the area of interest. The bores at the site have been assigned an HLU designation based on the current conceptual understanding of the hydrogeology and geology of the site and only bores screening a single HLU were included. These assignments allow for background concentrations of analytes within each HLU to be characterised separately and ultimately allow COPCs to be identified for each HLU. Using the methodology described in Section 4, the background evaluation specifically identified and removed impacted samples from the background dataset so that the remaining samples were representative of background conditions for each HLU.

Given its age, the database and document record are not complete with respect to a data-precision review and quality assurance/quality control (QA/QC) sample collection and lab analysis. However, information associated with more recent data collection is more complete, consistent with NEPM guidance. Given the long time frame over which groundwater quality data was collected and the record of QA/QC sample collection through time, the precision and accuracy of the data was assumed to have been evaluated at the time of collection and is considered to be within allowable limits.

Overall, through this review of the dataset, nothing was found in the comparability, representativeness, precision or accuracy of the data that interfered with the overall usability of the dataset. Gaps in the historical record for some HLUs were handled by using professional judgement and considering the application of proxy values for BTVs. The uncertainties associated with the usability of the dataset for this scope of work were also assessed.

Summary statistics were calculated on the dataset to characterise the main features, as noted above. As part of this assessment, the number of samples above and below the detection limit (DL) was visualised in stacked bar plots, as shown in Figure 1.

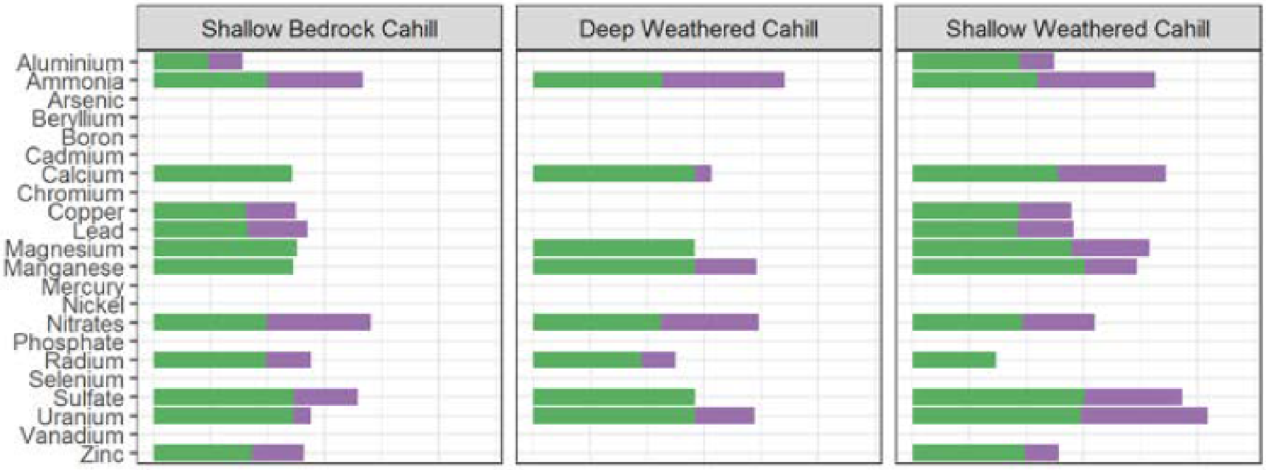

Figure 1 A subset of the key characteristics of the dataset. Number of samples per analyte per HLU (green plus purple) and number of samples with concentrations below the laboratory detection limit (purple). This was repeated for each analyte listed for each of the 17 HLUs for which data points were available

4 Methodological approach

In addition to site-related concentrations, background-level concentrations of analytes, including COPCs, may be present in every groundwater dataset (e.g. USEPA 2014). For example, even though samples at a site may be collected after the onset of site activities, monitoring bores may be sufficiently far from sources, and/or data collected sufficiently early that analyte concentrations still represent background conditions. Based on this understanding, not all concentrations of a COPC observed in a dataset collected from potentially affected areas represent impacted conditions (Department of Toxic Substances Control [DTSC] 1997; USEPA 2014; US Navy 2004). For the Ranger mine, this understanding has been used to extract a site-specific background dataset from a larger, pooled, site investigation dataset. Given the temporally and spatially extensive groundwater monitoring record at the Ranger mine, background analyte concentrations are considered likely to be represented with the groundwater quality dataset for the site.

The following sections describe the conceptual approach and decision framework for extracting background from the site dataset. The statistical and graphical methodology is also explained as it applies to decision-making. Unless otherwise specified, all statistics and data visualisations were produced using the statistical computing software R (R Core Team 2019) and Rmarkdown (Allaire et al. 2020).

4.1 Decision frameworks

A decision framework was developed to create an unbiased, rigorous, and consistent approach to extract HLU-specific background concentrations from datasets for all HLUs and analytes. Early development of the decision framework helped to maximise evidence-based and minimise opinion-based decision-making in the final background determinations. To further improve the objectivity of this approach, decisions on background were based on the evidence in the current dataset, and initial background values were developed independent of previous work on site-specific background concentrations for the site and, initially, without the involvement of authors familiar with the site.

The methodological approach for establishing the site-specific background dataset comprised three phases, as described below. Consistent with the conceptual site model (CSM), a background dataset for each inorganic analyte was developed on an HLU-by-HLU basis. However, not all analytes that were considered in the development of the background dataset were necessarily COPCs. Following the background evaluation, an objective approach was used to identify COPCs and to 'off-ramp' other analytes that showed no evidence of being related to mine activities. The HLU-specific background dataset for each analyte was then used to develop BTVs against which groundwater data can be assessed to evaluate whether COPC concentrations are background or are impacted by site activities.

4.1.1 Phase 1: framework for determining data sufficiency

The dataset was assessed in terms of its usability for the specific purpose of this assessment, and whether it was sufficiently complete to meet the objectives. Initially, data completeness, both in terms of whether the dataset has sufficient sample size to meet minimum statistical requirements and also in terms of its spatial and temporal coverage (i.e. its completeness), was assessed. Then analytes and HLUs with high proportions of concentrations below DL were excluded. These types of datasets are referred to as 'highly censored' datasets, and background concentrations were assessed separately.

4.1.2 Phase 2: framework for developing background for datasets with insufficient data

The data that failed Phase 1, the data-screening step, was excluded from the extraction of background for the following reasons: too few bores (i.e. fewer than five bores per HLU); too few samples (i.e. fewer than 20 samples per analyte, per HLU); 100 percent censored (i.e. all reported concentrations were below DLs); or low frequency of detects.

In the case of too few bores (insufficient spatial coverage), or too few samples (too few data points for statistical analysis), consideration was given as to whether BTVs for analytes from other HLUs could be applied as proxies to the HLUs with insufficient spatial or temporal coverage. Where the dataset for an analyte within an HLU passed the data sufficiency test, the dataset was then assessed for the amount of data reported as not detected (ND). Where all reported concentrations of a specific analyte were below the DL, these analytes were not considered to be COPCs in that HLU. Where the analyte had low detection rates (i.e. greater than 40 percent NDs) the DLs were assessed to determine a DL that could be used as an adopted background value. For these analytes, concentrations above the DL were initially assumed to be from site impacts.

Datasets for analytes within HLUs that passed both the temporal and spatial sufficiency tests and the tests for censored data were then progressed to further background assessment (Phase 3).

4.1.3 Phase 3: framework for extracting and establishing background using weight of evidence

For sites without an established background dataset from upgradient, reference areas or regional data, population partitioning methods can be used to extract background concentrations from datasets. At the Ranger mine, this approach was applied to extract background concentrations for analytes from individual HLUs that had passed the tests for data sufficiency and censored data. Similar to the data sufficiency decision framework, a decision framework was established to promote the objectivity and repeatability of the process to extract and establish site-specific background concentrations for each analyte within an HLU (Phase 3). At a high level, this decision framework comprised two stages:

- Statistical population partitioning: use of standard statistical population partitioning methods to identify a breakpoint in the data that initially partitions (separates) the data into two groups: below the breakpoint (prospective site-specific background) and above the breakpoint (potentially site impacted).
- Validation of breakpoints: validation, or, where necessary, refinement of the breakpoint using site knowledge applied to temporal, spatial, and geochemical lines of evidence.

The first stage used statistical quantile-quantile (QQ) plots to partition the HLU-analyte data. This was conducted strictly in accordance with standard statistical population partitioning methods and guidance (DTSC 1997; USEPA 2014) and did not involve any site knowledge.

Consistent with guidance, the second-stage validation of breakpoints involved evaluating the following lines of evidence to justify the location of the breakpoint:

- Time series lines of evidence (i.e. scatterplots of concentrations versus time).
- Geochemical and indicators of mine release lines of evidence (i.e. relationships between analytes, known indicators of mine impact, and other geochemical parameters).
- Geospatial lines of evidence (i.e. maps showing locations relative to potential sources).

None of these lines of evidence alone provides sufficient evidence to justify a site-specific background dataset. Instead, they were considered together to provide validation by integrating multiple lines (or weight of evidence). In order to arrive at a final, robust background dataset, multiple rounds of iteration occurred. Within the population partitioning stage, QQ plots were analysed and regenerated iteratively to find breakpoints. These breakpoints were further refined through iterative review of the additional lines of evidence relative to the selected breakpoint. This back and forth helped the team 'test' different breakpoints, selecting the one with the strongest support across all lines of evidence. Ultimately, the data above the breakpoint was considered impacted by site activities and the data below the breakpoint was considered to represent background conditions.

4.1.3.1 Stage 1: statistical population partitioning with QQ plots

Guidance (e.g. USEPA 2014; US Navy 2004) recognises the population partitioning method as a tool for identifying background concentrations from a site investigation dataset. Population partitioning is especially amenable to sites with naturally occurring constituents of interest, such as metals in groundwater (USEPA 2014). The population partitioning methodology relies on iterative implementation of QQ plots for each analyte in each HLU. For this exercise, all bores within an HLU were pooled in order to derive a single background dataset per analyte and HLU.

For assessment of background concentrations at the Ranger mine, QQ plots for a specific analyte were constructed using data from a single HLU. Once a breakpoint was identified, data above the breakpoint were removed from the dataset and the smaller dataset was replotted. The removal of the data above the breakpoint and the replotting of the data below the breakpoint on a re-scaled axis allowed breakpoints in the lower concentration ranges to be revealed. This process continued iteratively until no further breakpoints or discontinuities were observed in the data. The data that remained were considered the prospective background dataset, consistent with guidance (e.g. USEPA 2014; US Navy 2004).

Because environmental data is often lognormally distributed, QQ plots were constructed for untransformed and in-transformed (i.e. natural log transformed data) data using the car package in R (version 3.0). Both plots were used in the population partitioning approach used in this assessment to help see data anomalies that might have been masked in one of the transformations. To facilitate decision-making, a tool was created to automate the repeated visualisation of the QQ plots. A reactive dashboard called a Shiny App (Chang et al. 2018) was built to allow the user to enter different breakpoints and immediately see the impact on the resulting QQ plot. Breakpoints were successively lowered until no additional breaks were obvious in the normal or log-transformed space.

While the iterative QQ plot methodology is a powerful tool for population partitioning, the methodology assumes that the locations with the lowest concentrations are representative of background (i.e. unimpacted) concentrations and that the range in background concentrations is fully represented by the data below the breakpoint. A consequence of these limitations is that the background concentration, and subsequently the BTV, may be set too low and/or not capture the full range of natural variability of the analyte in the environmental setting. In general, this limitation is considered acceptable because it creates bias in the BTV that is environmentally protective.

When data from multiple bores within an HLU are pooled for a QQ plot evaluation, there is an increased chance that the background dataset could have multiple inflection points and/or non-delimiting inflection points. US Navy (2004) cautions that multiple natural subpopulations created by variation in physical characteristics can yield segmented QQ plots with multiple inflection points. In these instances, the lowest inflection point will not represent the upper bound of the background concentration range and the BTV could be underestimated. Using QQ plots on an HLU-by-HLU basis for the Ranger mine groundwater dataset is intended to minimise multiple 'breakpoints' that are due to natural variability in geological and hydrogeological characteristics. Additionally, the multiple lines of evidence in the next phase of the evaluation were developed to safeguard against these errors; they serve as an important validation step of the breakpoints determined from the QQ plots.

4.1.3.2 Stage 2: validation based on weight of evidence

Although QQ plots are a useful aid to identifying multiple populations, they should be used in conjunction with other analyses to verify visual findings and establish a background dataset (USEPA 2002; US Navy 2004). In the first stage, breakpoints were identified using minimal site knowledge. In this second stage, the breakpoints from the QQ plots were tested and ultimately validated by applying current understanding of the site along several lines of evidence. These lines of evidence were considered collectively to develop a weight-of-evidence basis to challenge, and ultimately validate, the breakpoint identified in each QQ plot. The lines of evidence examined the prospective background data temporally, timing versus site activities, site geochemistry, and location relative to site activities and history. In some cases, the lines of evidence suggested that adjustments should be made to the initial QQ plot breakpoint. In this way, data characteristics such as covariation with other variables (e.g. time and source concentration) and site knowledge were incorporated into the lines of evidence to iteratively refine the breakpoint on the QQ plots and finalise the background dataset.

5 Data screening and results

The first decision framework was applied to screen the data for its spatial completeness, temporal completeness, and degree of analytical censoring so that all datasets advancing to the background evaluation met the minimum data requirements for graphical and statistical evaluation. Seventy total HLU and analyte datasets (representing a total of eight HLUs) met all data-screening requirements and therefore proceeded to background evaluation. Nine HLUs had no analytes that passed the data-screening requirements, and therefore these HLUs, in their entirety, did not proceed to background evaluation. Several analytes had insufficient detects, or insufficient data in all HLUs, and therefore these analytes did not proceed to background evaluation in their entirety. For those HLUs with too few bores screened solely within the HLU, to allow further assessment of background concentrations, the geological and hydrogeological settings of each HLU were compared against adjacent, and/or other geologically equivalent, data-rich HLUs. This was done to identify whether the background concentration results from the data-rich background datasets could be applied to HLUs with insufficient bores. In those cases, BTVs developed for analytes in data-rich HLUs were substituted as proxy values for the data-deficient HLUs.

Site-specific background concentrations could not be assessed for several analytes within data-rich HLUs due to no data available, insufficient samples analysed, or an insufficient number of bores sampled (as discussed above). Results for metals analyses including aluminium, arsenic, beryllium, boron, cadmium, chromium, copper, lead, mercury, nickel, selenium, vanadium, and zinc were reported for several HLUs, as were ammonia and nitrate. Consequently, background datasets were developed for these analytes in several HLUs. The long-recognised COPCs of uranium, radium, magnesium, manganese, and sulfate were analysed in bores from each HLU. For each of the HLUs that progressed through to the background evaluations, there were sufficient samples of each of these analytes to evaluate background concentrations.

If HLUs had sufficient bores, and there were sufficient analytes for each of those HLUs, the analytes progressed to the test for censored data (i.e. >40 percent of concentrations below DLs). Consistent with the decision framework, evaluation of background concentrations could not be completed for an individual analyte where less than 60 percent of the results were reported above the DL. Depending on the HLU, the analytes with concentrations below DLs that met this criterion were ammonia and nitrates, and metals including beryllium, cadmium, chromium, copper, lead, mercury, selenium and vanadium. In each of these cases, and consistent with the decision framework, and also for cases where 100 percent of results reported for an analyte were ND (for an HLU and analyte with a sufficient number of bores and samples), the DL was considered to be representative of background conditions. Since DLs have changed over the long monitoring history at the site, a DL, typically the lower, and/or more recent detection limited, was adopted.

6 Results of background evaluation

6.1 Results by HLU

The results of the background evaluation were reported for each analyte by HLU. For each HLU, results were compiled in interactive html dashboards. The layout of the dashboards was the same for all HLUs and included the staged methodology presented above.

QQ plots were presented in the dashboard to show the breakpoint determination (Figure 2). The QQ plots represented the final breakpoint, showing the background dataset (brown) and impacted data points. The dashboards also illustrated supporting information in terms of lines of evidence, including time series data by HLU by analyte (Figure 3) and time series data by bore for all analytes (Figure 4).

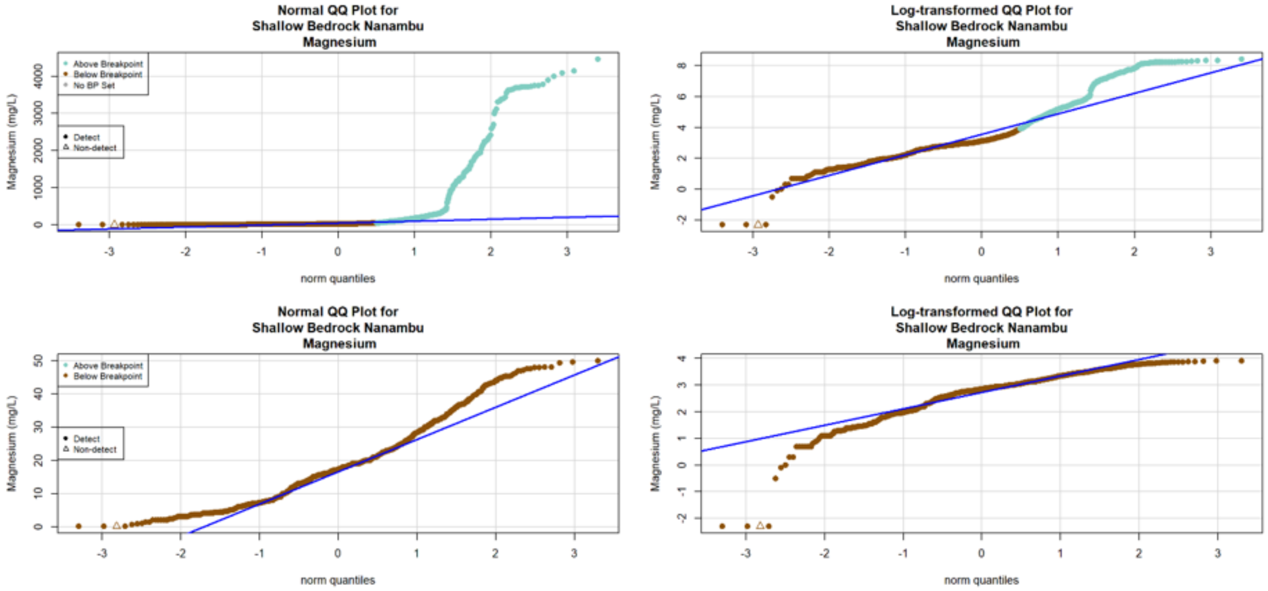

Figure 2 QQ plot for sulfate in a single HLU showing normal and log-transformed data. Brown is below breakpoint (zoomed in on lower plots); turquoise represents above breakpoint (site impacted), shown only in the upper plots

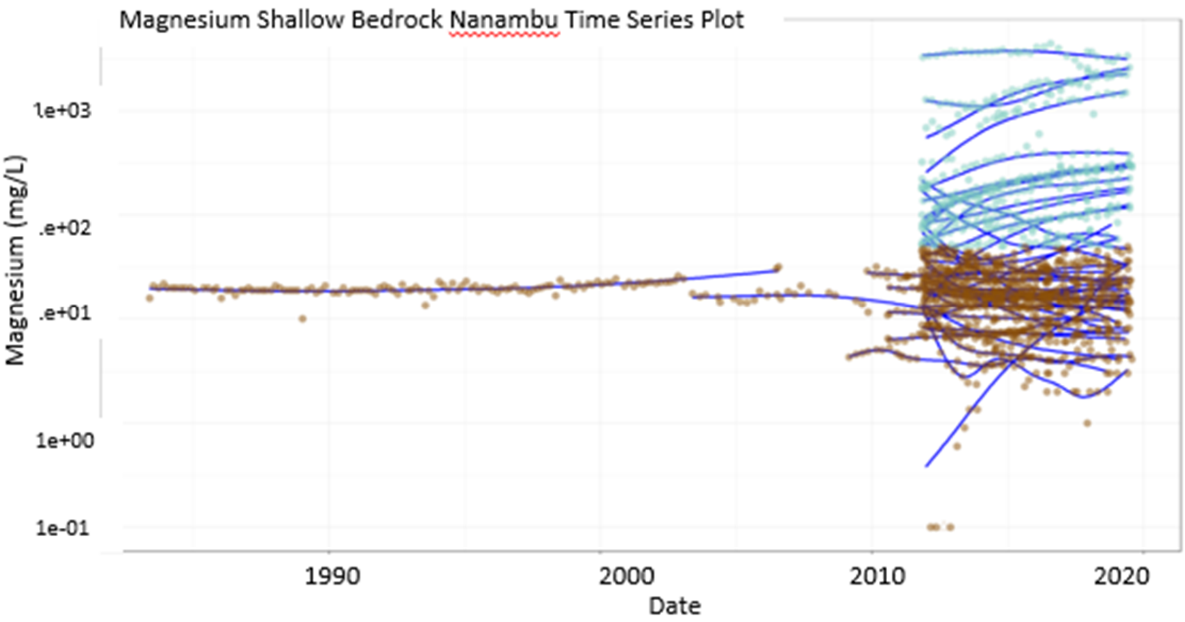

Figure 3 Concentration versus time for a single analyte in a single HLU. Brown is dataset below breakpoint; turquoise represents dataset above breakpoint

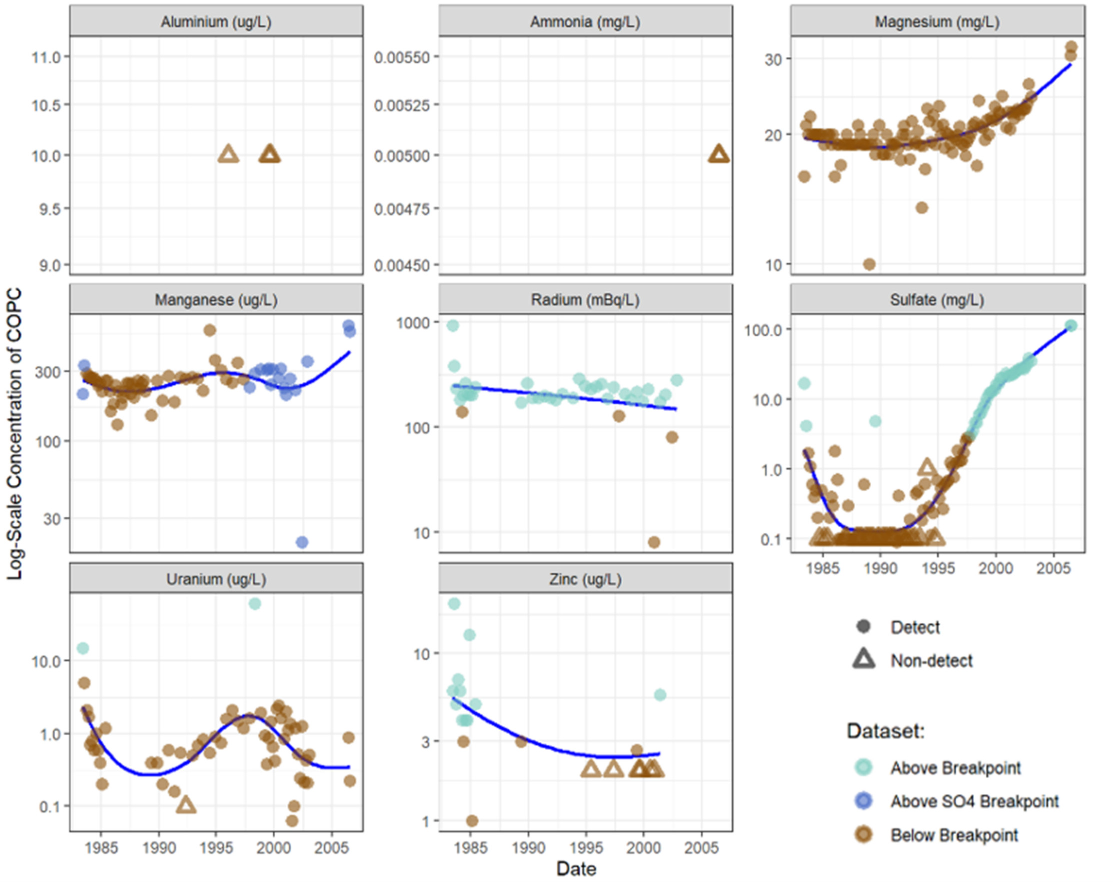

Figure 4 Concentration versus time for each analyte in a single bore. Brown is dataset below breakpoint; turquoise represents dataset above breakpoint, blue represents data above sulfate breakpoint

Other lines of evidence that were plotted on the dashboards included sulfate versus analyte boxplots (Figure 5) and geochemistry plots.

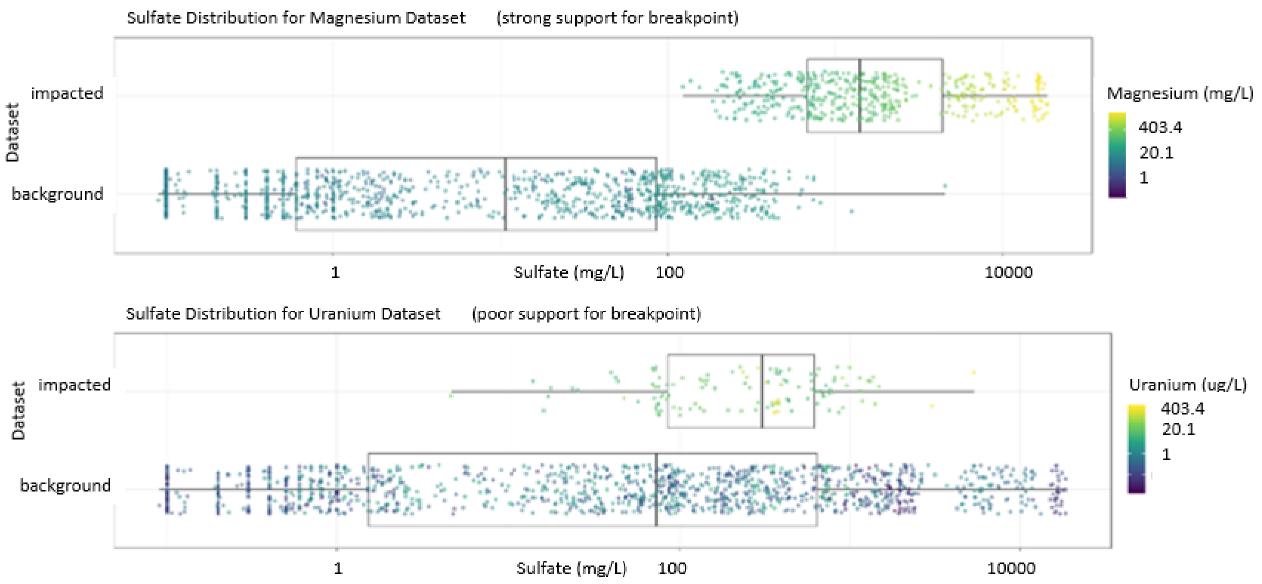

Figure 5 Example boxplots showing analyte concentration versus sulfate concentration

Summary statistics were shown on another screen of the dashboards, together with maps of spatial impacts (Figure 6) and the proportion of analytes above the breakpoint for each sample in each bore.

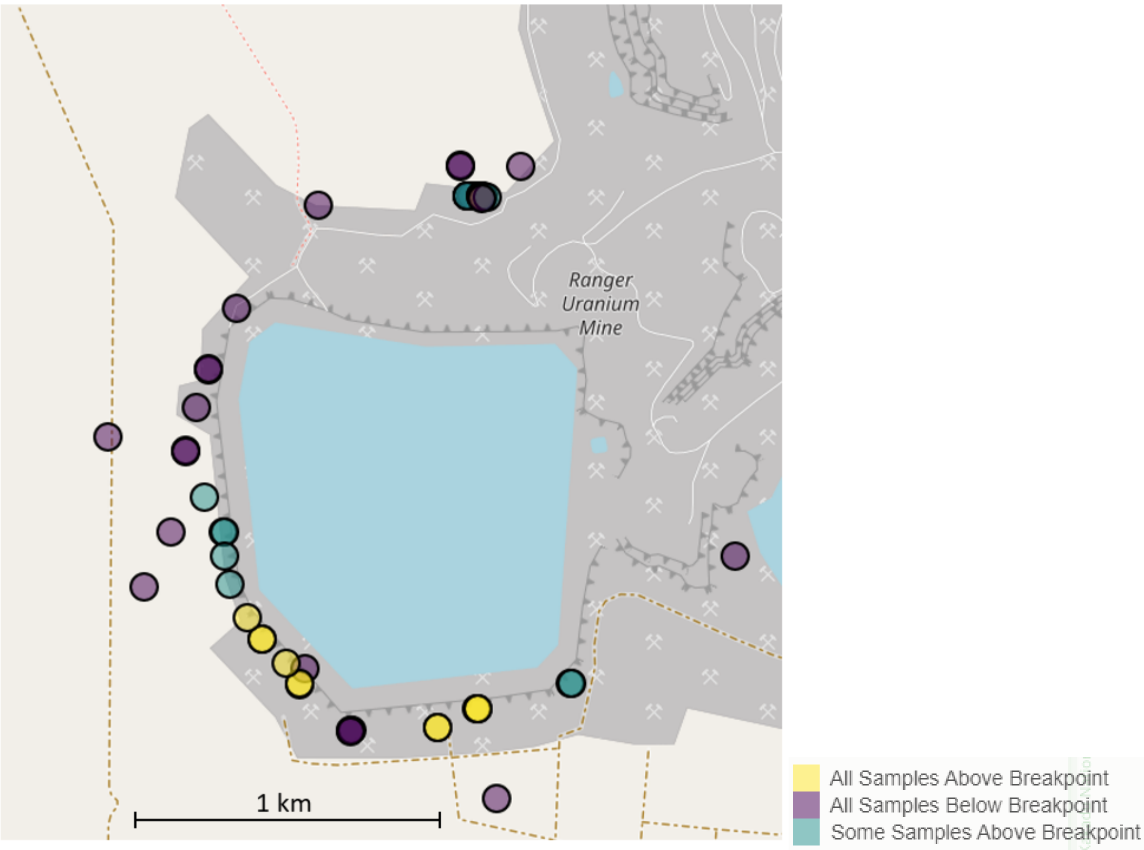

Figure 6 Example map showing analyte concentration versus location relative to breakpoint

6.2 Identification of COPCs

The background evaluation confirmed that, with the exception of radium in some HLUs, the primary COPCs at the site (magnesium, manganese, radium, sulfate and uranium) should remain as COPCs in all HLUs. Where sufficient data was available to conduct the background evaluation, ammonia was always identified as a

COPC. Data availability limited the development of background datasets for nitrate and some metals in some HLUs; however, aluminium and nickel were identified as COPCs for each HLU that could be assessed. Zinc, arsenic, boron and nitrate were identified as COPCs in specific HLUs. The data assessment indicated that copper, lead and vanadium were not COPCs in any HLU. For analytes and HLUs where a high proportion of concentrations were below the DL, determination of an analyte as a COPC was dependent on comparison with concentrations of the primary COPCs in the same bore. For HLUs with insufficient data for analysis, COPCs and associated BTVs were adopted where proxy values were considered reasonable.

6.3 Uncertainty analysis

Throughout this assessment, uncertainties, which are associated with every step of analysis, were identified and evaluated to provide an indication of the extent that the site-specific background dataset may either overestimate or underestimate background concentrations. The uncertainty evaluation considered the data source itself, the statistical assumptions and validation, and the use of the background dataset. The uncertainty evaluation did not identify material inconsistencies in the data or the approach that would need to be considered when using the resulting BTVs to assess monitoring results and inform site closure decisions.

7 Development of BTVs

For this assessment, where sufficient data was available, the background dataset developed was used to develop a BTV for each analyte and HLU, even when an analyte was not considered to be a COPC. The BTVs that were developed for COPCs allow comparison of site to background conditions. Additionally they are simple to use in practice; site concentrations are compared to the BTV and if one or more measurements exceed the BTV, the location is potentially impacted. If the site is free of impacts, the majority of measured concentrations should fall below the BTV.

Each dataset that advanced through to the full statistical background evaluation had sufficient sample sizes and detection rates for development of a calculated, statistically based BTV. The upper tolerance limit (UTL) method was selected for BTV calculations for these datasets. UTLs provide a robust estimate of BTVs and can also be applied with minimal statistical consultation and without the need for frequent adjustments and recalculations. Consistent with guidance (USEPA 2015), UTLs for this assessment were calculated for each analyte and each HLU using the 95/95 UTL. This corresponds to the 95th upper confidence level on the 95th percentile (also known as the population coverage) from the background dataset. Hence, for any single observation at or below the 'true' background level, this observation should infrequently (less than five percent of the time) exceed the UTL. For groundwater at the Ranger mine, BTVs were also developed for data that did not progress to the further background assessment, as described above.

8 Summary and conclusion

This evaluation has refined the COPC list and identified the background dataset, established site-specific background datasets where minimum data criteria were met, and established BTVs for COPCs in groundwater at the Ranger mine. The BTVs and background dataset will be critical for establishing appropriate assessment criteria for groundwater quality monitoring and will help to guide closure decisions at the site.

The geological and hydrogeological conditions across the site vary laterally and with depth, resulting in the definition of a large number of HLUs at the site. This results in different background groundwater quality across the site depending on location. Considering the updates to the site CSM, including identification of more HLUs, and the major expansion of the bore network and analytical database since 2011, a re-evaluation of background concentrations was merited. Background values had to be extracted from the site investigation dataset itself due to the limited offsite extent of some HLUs and restrictions for offsite sample collection given that the mine site is surrounded by, but is separate to, Kakadu National Park. Regional and reference values for similar hydrogeological settings are not available to inform closure of the Ranger mine.

Extraction of a background dataset from a larger site investigation dataset has support from various guidance documents. Consistent with many guidance documents, a combination of a population partitioning approach followed by a weight-of-evidence evaluation was implemented for the Ranger mine. To that end, nearly a quarter of a million records from the Ranger site database were compiled and reviewed in the background assessment database to ensure that the data met the data quality and usability standards. Although some HLUs and analytes had limited spatial and/or temporal coverage, 64 HLU-analyte combinations across eight HLUs were able to undergo a full background evaluation.

A robust and objective approach was taken to extract background values from the dataset. A data-screening framework was developed to off-ramp HLUs and analytes that did not meet the minimum data requirements for the further background evaluation. Where supported, surrogate background values were developed for those HLUs and analytes. For HLUs and analytes with sufficient data, the dataset was progressed to the full background evaluation. First, an iterative population partitioning approach was used to identify a breakpoint in the data using QQ plots. This initial determination was made independently of site-qualifying information. The breakpoint was then refined based on the data characteristics, with consideration of site history, sources and known impacts. As discussed above, refining the breakpoint was an iterative process that initially was based on selection of the inflection point by the data team. Then the site knowledgeable team then worked with the data team to challenge and test the inflection point by considering temporal trends in concentrations, covariance with known site sources, and spatial patterns in impacts. This iterative process continued until a breakpoint was found that was supported by multiple lines of evidence.

The initial dataset included a broader suite of analytes than considered previously, and the lines of evidence were used to refine the COPC list for each HLU based on evidence of impacts in the data. Primary COPCs (uranium, radium, magnesium, manganese, and sulfate) were all retained; however, the background radium datasets did not indicate that radium was a COPC in several HLUs. Ammonia, nitrate, and several metals were retained as COPCs on an HLU-by-HLU basis. However, several other metals did not show evidence of impacts and were ultimately removed from the COPC list. BTVs were developed for each HLU. In the case of too few bores or data points for assessment, a surrogate BTV was established based on proxy HLUs. BTVs were developed for all analytes with sufficient data, even in the case that the analyte was not a COPC.

This background evaluation has refined the COPCs for the site, established background datasets for HLUs and analytes, and calculated BTVs for analytes and COPCs on an HLU-by-HLU basis. The BTVs were established using an objective decision framework that was established a priori and supported a defined, transparent and repeatable process across analytes and HLUs. The results were supported by multiple forms of validation that help to provide a high level of confidence in the conclusions. The approach allowed the data to dictate what background was and then supported this with multiple lines of evidence and site knowledge. The statistical methodology used to establish the background dataset and develop the supporting lines of evidence is well established and presented in multiple international guidance documents. The uncertainty evaluation did not identify material inconsistencies in the data or the approach that would need to be considered when using the resulting BTVs to inform site closure decisions.

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