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Improving probabilistic predictions of post-closure groundwater solute loads for Ranger uranium mine

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Abstract

Groundwater transport of mine-derived solutes to surface waters and the resulting concentrations after closure of the Ranger mine in the Northern Territory, Australia, are important to stakeholders and Energy Resources of Australia (ERA). In 2020 at ERA's request and in consultation with stakeholders, INTERA Incorporated developed source terms for 20 constituents of potential concern (COPCs) and conducted a site-wide groundwater uncertainty analysis (GW UA) to estimate the predictive uncertainty in peak COPC loads from groundwater to surface waters. History matching to thousands of head observations constrained uncertainty in hydraulic parameters. Available data informed uncertain future COPC concentrations from each source. The GW UA's many equally probable predictions of COPC loads became inputs to a surface water model that predicted COPC concentrations in receptor creeks, all supporting ERA's Pit 3 backfill application.

In 2023 INTERA updated source terms and ran a Pit 3-specific UA to support an updated pit backfilling application. This Pit 3 UA focused on pit COPC sources, especially expressed tailings porewater, called pit tailings flux (PTF), which was the primary driver for peak total magnesium loading in the 2021 GW UA. After ERA revised its reclamation plan to reduce the PTF volume, INTERA changed the UA workflow to allow uncertainty in PTF volume and location that had been fixed in 2021. Source concentration probability distribution functions were updated to incorporate new information. The Pit 3 UA applied a Bayesian approach to produce hundreds of equally likely predictions of COPC loads to nearby Magela Creek. Stakeholder input was received throughout implementation.

The 2023 results showed a much smaller mean and variance in peak total magnesium loading to Magela Creek than the 2021 results. New information helped constrain the previous input uncertainty, leading to a decrease in predictive uncertainty in the peak load compared to 2021 even though the PTF volume and extent were treated as uncertain.

Keywords: *groundwater flow and solute transport model, uncertainty, mine closure, tailings, waste rock, probabilistic prediction*

1 Introduction: Ranger mine closure, risk and modelling

After ceasing production at the former Ranger uranium mine in 2021, Energy Resources of Australia (ERA) continues to be focused on mine rehabilitation and closure in compliance with environmental and cultural protection requirements. The mine and the more extensive Ranger Project Area (RPA) are located near Jabiru in Australia's Northern Territory, separate from and surrounded by Kakadu National Park (Figure 1) on the traditional lands of the Mirarr people.

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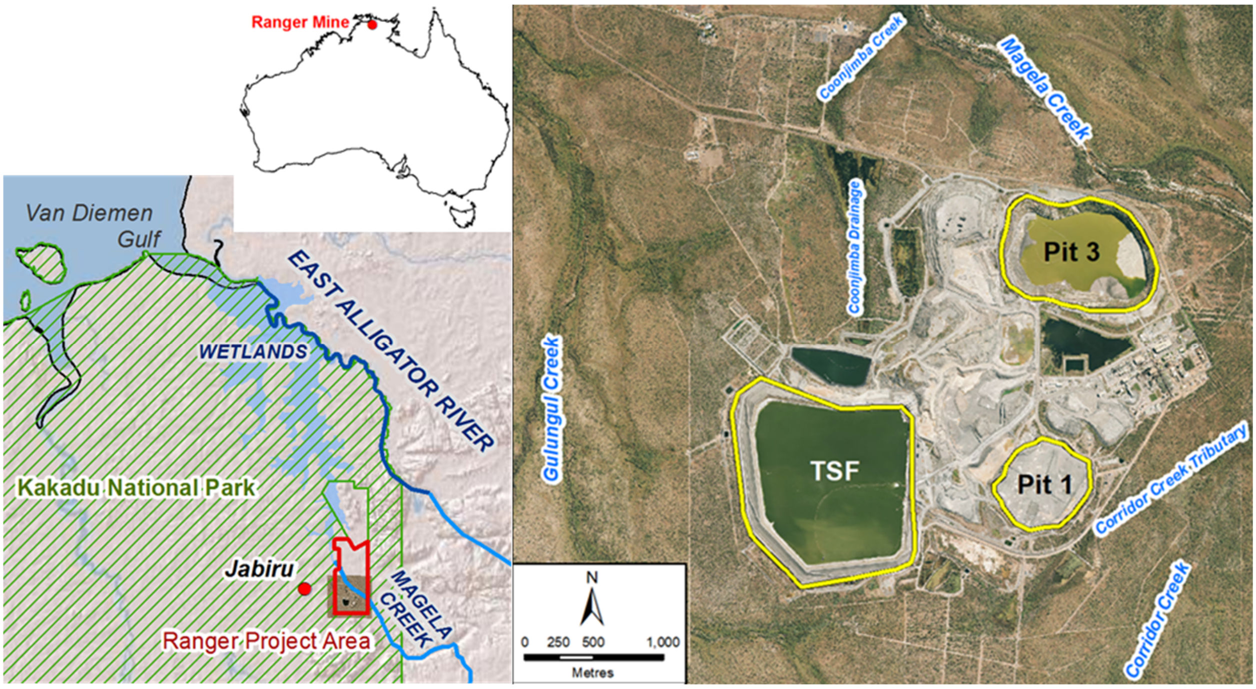

Figure 1 Ranger Project Area location, creeks and mine features (TSF = tailings storage facility)

The environmental requirements (ERs) are the Commonwealth of Australia's environmental protection conditions under which ERA operated and is now rehabilitating and closing the former Ranger mine. At the date of this paper, the ERs are attached to the Section 41 Authority issued under the *Atomic Energy Act* (Commonwealth of Australia 1953). Implementation of these ERs is carried out by legislation and instruments of the Northern Territory Government and through the Ranger Authorisation, the most recent of which is Authorisation 0108-18. The ERs consist of primary environmental objectives related to environmental protection and rehabilitation, and secondary environmental objectives related to water and air quality; radiological protection; management of hazardous substances, wastes, excavated material and tailings; blasting; rehabilitation; and soil, vegetation and fauna protection.

The primary environmental protection objectives include maintaining the world heritage attributes of Kakadu National Park and the ecosystem health of the Ramsar Convention (1971) wetlands, and protecting the health of the regional community and the natural biological diversity of aquatic and terrestrial ecosystems of the Alligator Rivers Region. The primary rehabilitation objective is to rehabilitate the RPA to an environment similar to the adjacent areas of Kakadu National Park. In relation to the management of the final disposal of tailings, the secondary objectives provide (among other conditions) that the tailings are physically isolated from the environment for at least 10,000 years.

At Ranger, closure-related risk is in part driven by the ERs for creek surface waters. The Office of the Supervising Scientist (OSS) has established guidance values or standards for concentrations of constituents of potential concern (COPCs) in creek and billabong surface waters. Closure risk can therefore depend on the probability of COPC concentrations in surface water exceeding thresholds. This risk is in turn partly driven by the uncertainty in groundwater (GW) COPC mass that will be discharged to the creeks after mine closure. Probabilistic predictions show future outcomes and their probabilities, which allows the risk to be managed more effectively than deterministic predictions, which lack probabilities. Estimating the predictive uncertainty in COPC loads to surface waters produces many equally likely predictions, so it also gives the probability of predicted outcomes.

To support ERA's 2021 application for final backfill of Pit 3, INTERA Incorporated (INTERA) conducted GW modelling to provide probabilistic predictions of transport from mine site sources and COPC mass loading to Magela, Corridor, Coonjimba and Gulungul Creeks (Figure 1) during the 10,000 years following mine closure. INTERA's calibration-constrained GW uncertainty analysis (GW UA) (2021 Ranger site-wide UA), implemented with review and input from ERA, estimated the predictive uncertainty in peak and long-term COPC loads to the receptor creeks from 15 different mine sources (INTERA 2021). Groundwater solute loads for magnesium (Mg) and 19 other COPCs were required for four individual groundwater sheds (GWsheds) and all GWsheds combined (delineated by dark blue lines in Figure 2). COPC loads at selected probability values became inputs to a surface water model that predicted surface water COPC concentrations to assess potential impacts (Water Solutions 2020, 2021).

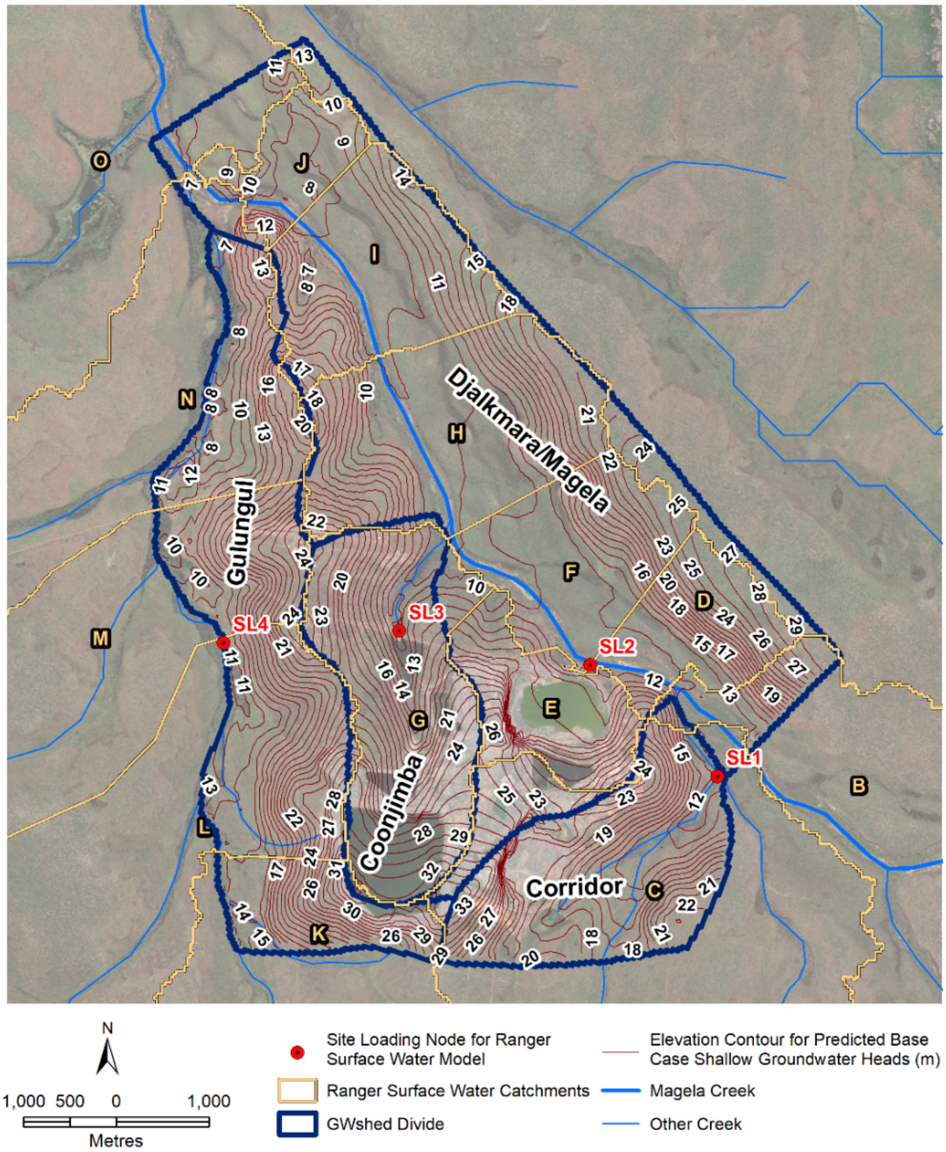

Figure 2 **Groundwater shed and surface water catchments and site-loading nodes in the Water Solutions (2020) surface water model from the 2021 Ranger groundwater uncertainty analysis**

To support ERA's 2023 resubmission of the Pit 3 Backfill Application, INTERA completed a new UA, called the Pit 3 UA, focused on COPC loads from only Pit 3 sources to the creeks (INTERA 2023). INTERA updated Ranger source terms with recently acquired data, added more uncertainty parameters and converted the predictive model to the United States Geological Survey's recent MODFLOW 6 (Langevin et al. 2017, 2022) codes, all with stakeholder review and comment. The resulting annual peak and long-term COPC loads were used as inputs to a surface water model to predict COPC concentrations in surface water. This paper describes the methods, data and results for the Ranger 2021 site-wide UA (Study 1) and the 2023 Pit 3 UA (Study 2). It then compares their results to show how incorporating the new information gained after Study 1 reduced the predictive uncertainty in Mg loading to surface water receptors and likely decreased post-closure risk for COPCs entering surface waters.

2 Uncertainty analysis definition and methodology

Uncertainty analysis is a set of formal methods to quantify the uncertainty or probability associated with model predictions that are to be used to support risk-informed decisions. These methods rely on a framework based on Bayes' theorem to make predictions or decisions from initial estimates or updated estimates of the uncertain values of a system state or feature (Benjamin & Cornell 1970; Freeze et al. 1990; Watermark Numerical Computing 2015). The Bayesian framework offers a robust way to effectively inform risk-focused decisions using GW models even with the well-known uncertainties in hydrogeologic properties and driving forces, including data sparsity, spatial heterogeneity and difficulties in scaling measurements. UA also directly addresses the inherent non-uniqueness of numerical model calibration in which most GW models can be equally well calibrated by a large number of different sets of parameter values, yet each parameter set can potentially give a different predicted outcome.

The Bayesian UA framework for decision support modelling, like that used for Ranger, is based on more than 20 years of scientific research, practical applications and development of open-source software tools. Much of the work has been supported by the Groundwater Modelling Decision Support Initiative (GMDSI) in Australia and the United States Geological Survey. Interested readers can find a wide range of useful publications, webinars, tutorials and case studies at https://gmdsi.org.

A calibration-constrained UA seeks to estimate the uncertainty in GW model predictions using information gained from site-specific observations (Watermark Numerical Computing 2015). In the UA framework, GW model parameters are defined to represent or reflect uncertainty in the model inputs. Observations about the modelled system and Bayes' theorem are used to update (and, where possible, decrease) the initial parameter uncertainty so as to produce uncertain predictions that are consistent with observations. Initial estimates of uncertainty in model parameters that are derived from expert knowledge (information that is known before the model is even constructed) are called prior probability distribution functions (PDFs) in Bayes' theorem. Using observations of the modelled system (e.g. historical heads, fluxes, concentrations), random samples from the prior parameter PDFs are constrained through the history matching or calibration process to include only parameter values that give predictions consistent with the observation data. These sets of updated parameter values represent the posterior PDFs in Bayes' theorem because they have assimilated or been constrained by the information in the history matching data.

Model predictions can be made with random samples from the prior parameter PDFs, giving prior predictions that reflect maximum parameter uncertainty, or with random samples from the posterior PDFs, giving posterior predictions that are much more likely to be consistent with observations. Predictions made with prior parameters are an estimate of the maximum uncertainty in the prediction of interest, uninformed by the system's behaviour. In many GW modelling applications, including post-closure flow and transport at Ranger, the predictive uncertainty depends on both the uncertainty in posterior parameters, which were informed or adjusted during history matching, and the uncertainty in prior parameters that were uninformed by history matching. Examples of the latter at Ranger include concentrations for post-closure source terms, future GW recharge and waste rock hydraulic properties.

A UA randomly samples values for each parameter, ensuring that they span a wide range of parameter uncertainty to create multiple parameter sets called realisations. Each realisation contains one randomly sampled value for each parameter needed to run the predictive model. Each set of parameter realisations is called an ensemble and generates an ensemble of predictions. All parameters of interest are varied simultaneously in a UA and the resulting predictions are used to calculate the probability of the outcome. The risk associated with a given outcome is a function of the outcome's probability.

3 Study 1: The 2021 Ranger site-wide uncertainty analysis

The 2021 Ranger site-wide GW UA was a comprehensive calibration-constrained investigation that estimated the site-wide GW COPC loads and their predictive uncertainty to Magela Creek and its tributaries from Ranger mine sources over a government-mandated 10,000-year post-closure assessment period. INTERA calibrated the hydraulic properties and boundary conditions with more than 10,000 head observations and applied the null space Monte Carlo method (Tonkin & Doherty 2009; Watermark Numerical Computing 2015) to make 983 equally likely predictions of post-closure Mg loads to give the peak and 10,000-year loads for all 20 COPCs (INTERA 2021). ERA and the OSS gave reviews and input during the Ranger GW UA development. The COPC loads from all sources across the Ranger site were handed over for use in a predictive surface water model (Water Solutions 2021) to estimate COPC concentrations in receptor creeks.

3.1 Groundwater flow and transport model

The Ranger site-wide numerical GW model was constructed to encompass all COPC sources, surface water receptors, key hydrolithologic units (HLUs) and potential transport pathways from sources to receptors. Based on the deterministic 2019 Ranger site-wide flow model (INTERA 2019), the 2021 site-wide UA model comprises a history matching model to simulate transient flow during Ranger's 40 years of mining and a predictive model to simulate both flow and solute transport during the 10,000 years after closure. GW flow was simulated using the MODFLOW-NWT (Niswonger et al. 2011) code and solute transport with the MT3D-USGS code (Bedekar et al. 2016). The model domain covers about 29 square kilometres (Figure 2) and vertically spans nearly 800 metres to accommodate the dense Pit 3 brine COPC source and deep transport pathways. The finite difference model grid is discretised into 30 by 30 m cells in the horizontal plane and 19 layers as a balance between model run time and the spatial resolution of COPC sources, receptors and transport pathways. HLU hydraulic properties were assigned by intersecting the grid with a geological model's 3D HLU volumes. Properties were assumed to be uniform within each HLU volume. The history matching model's simulation period encompasses a pre-mining, steady state period and the mining period through 2019, which is far longer than in any previous Ranger calibrated flow model, and time-varying stresses and hydraulic properties. The predictive model simulated transient solute transport for 300 years using steady state heads that represent average long-term flow conditions.

The history matching GW flow model was set up to incorporate the major stresses applied to the Ranger GW flow system at Pit 1, Pit 3 and the former TSF (Figure 1). After moving all tailings to Pit 3 and cleaning the TSF, it became the Ranger water dam in 2022 (Paulka et al. 2023). Mining of Pit 1, associated pumping of a dewatering bore and mining of Pit 3 caused very large head decreases in adjacent HLUs over many years. Partial backfilling locally raised the heads in the pits in relatively short times. For about 40 years, process water storage in the former TSF applied a head increase of several tens of metres over the TSF footprint. Even so, GW recharge, evapotranspiration, and GW-surface water exchanges drove the largest fluxes into and out of the model domain in both history matching and predictive models.

3.2 Site-wide uncertainty analysis approach

The 2021 site-wide UA produced many equally likely predictions of interest made using random samples of prior and posterior parameters (Figure 3). INTERA created an initial set of calibrated model parameters by updating the INTERA (2019) site-wide GW flow model that simulated the 40-year mining period (step 1 in Figure 3). INTERA and stakeholders collaboratively developed prior parameter PDFs to define an initial estimate of the ranges in parameter values (step 2 in Figure 3). For example, the prior PDF for the hydraulic conductivity (K) of the shallow weathered Cahill HLU, one of most important HLUs for shallow GW transport, was developed by setting the mean equal to the initial calibrated value and using site-specific data to set the variance (Figures 4a to 4c). Stochastic realisations of input prior parameters were created by drawing random samples from the prior PDFs (steps 2 and 3 in Figure 3). The randomly sampled prior values for the shallow weathered Cahill HLU's K span three orders of magnitude (Figure 4d). The prior parameter realisations were then subjected to a null space linear projection operation to condition their values on historical observations, yielding posterior realisations that provide good matches to the head data used for flow calibration (step 4 in Figure 3). The posterior values for many parameters were strongly constrained by information in the calibration data (e.g. K values in Figure 4e), whereas the constraining effects were moderate for some parameters and minimal for others (INTERA 2021).

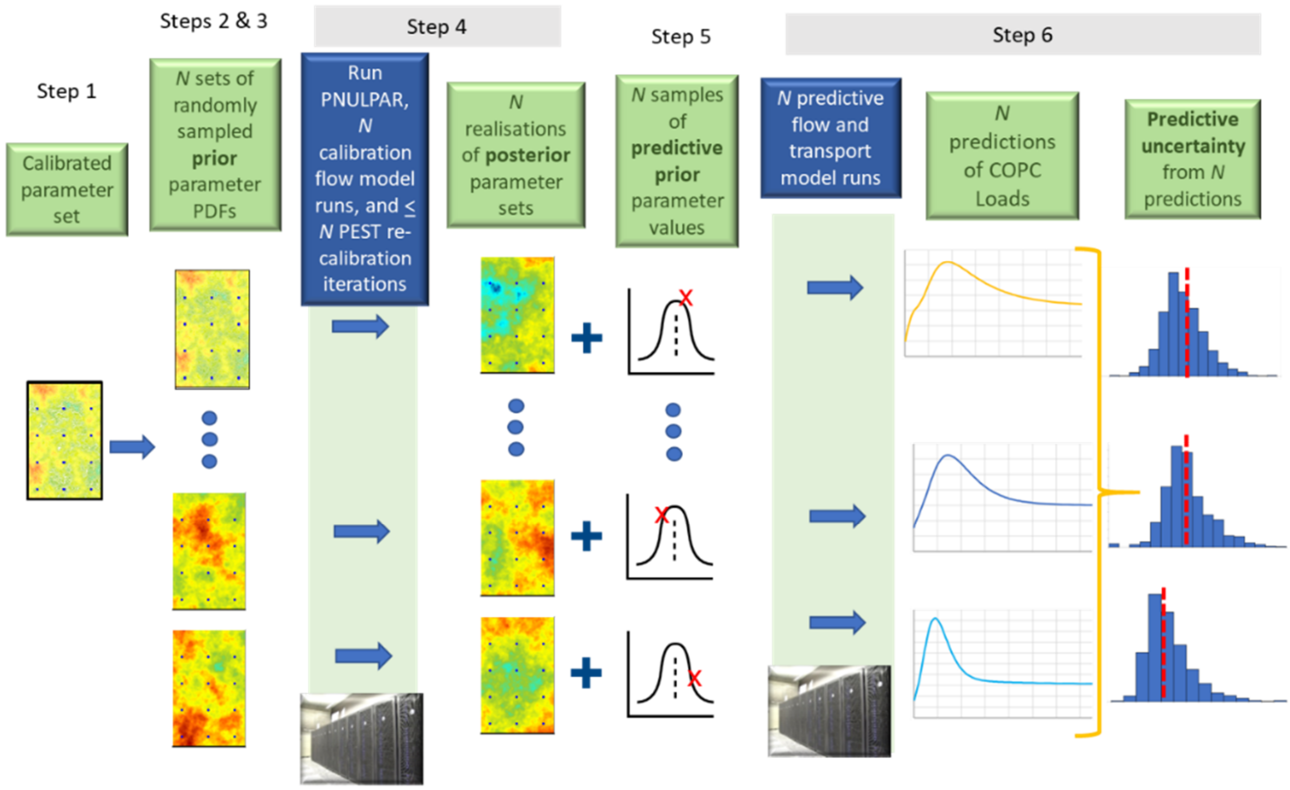

Figure 3 2021 site-wide uncertainty analysis process for magnesium peak total load

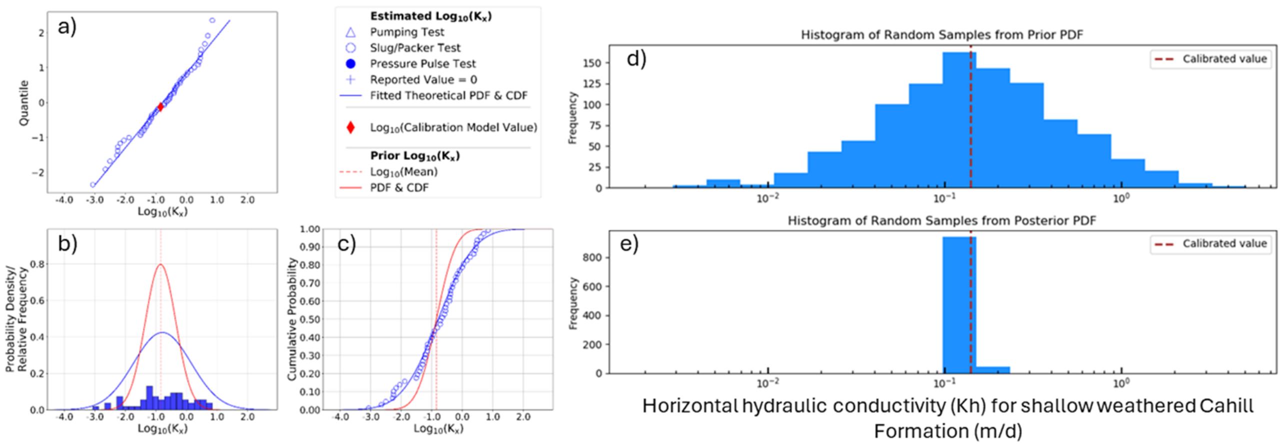

Figure 4 Site data and prior and posterior probability distribution functions (PDFs) for the horizontal hydraulic conductivity of shallow weathered Cahill hydrolithologic units: (a) quantile-quantile plot of site data; (b) histogram of data with prior PDF; (c) cumulative distribution functions of data and prior PDF; (d) histogram of 983 random samples from prior PDF; (e) histogram of 983 posterior PDF samples after history matching

Each posterior realisation was augmented with random samples of prior parameters present only in the post-closure predictive flow and transport model (step 5 in Figure 3) and then run in the 2021 site-wide UA post-closure predictive model to produce many equally likely predictions of Mg total loads to creeks (step 6 in Figure 3). The resulting predictions of Mg loads honoured both the 40 years of site-specific calibration data and expert knowledge about the Ranger site. The predictive uncertainty in the Mg total loads was estimated using histograms and cumulative distribution functions (CDFs) (step 6 in Figure 3), from which values were selected for surface water modelling.

3.3 Site-wide uncertainty analysis results

The total Mg load from all GWsheds for each of the 983 predictions reaches a maximum value (i.e. peak load) within the first 70 years and decreases to a more-or-less steady, smaller value during the following 230 years (Figure 5a). An example of a horsetail plot, Figure 5a graphically depicts the variability of the predictive total Mg load over time resulting from the uncertainty in predictive parameter values, particularly the greater variability in load magnitude during the first several decades and the far smaller variability during the last 230 years. Early time peaks and smaller steady loads at late times were also observed in the results for the individual GWsheds. Peak loads are largest for all GWsheds and progressively smaller for the individual Magela, Coonjimba, Corridor and Gulungul GWsheds (Figure 5b). Peak Mg loads to the Magela GWshed are a little smaller in magnitude than the peak total Mg loads, whereas peak loads to the other GWsheds are much smaller than those to the Magela GWshed (Figure 5b).

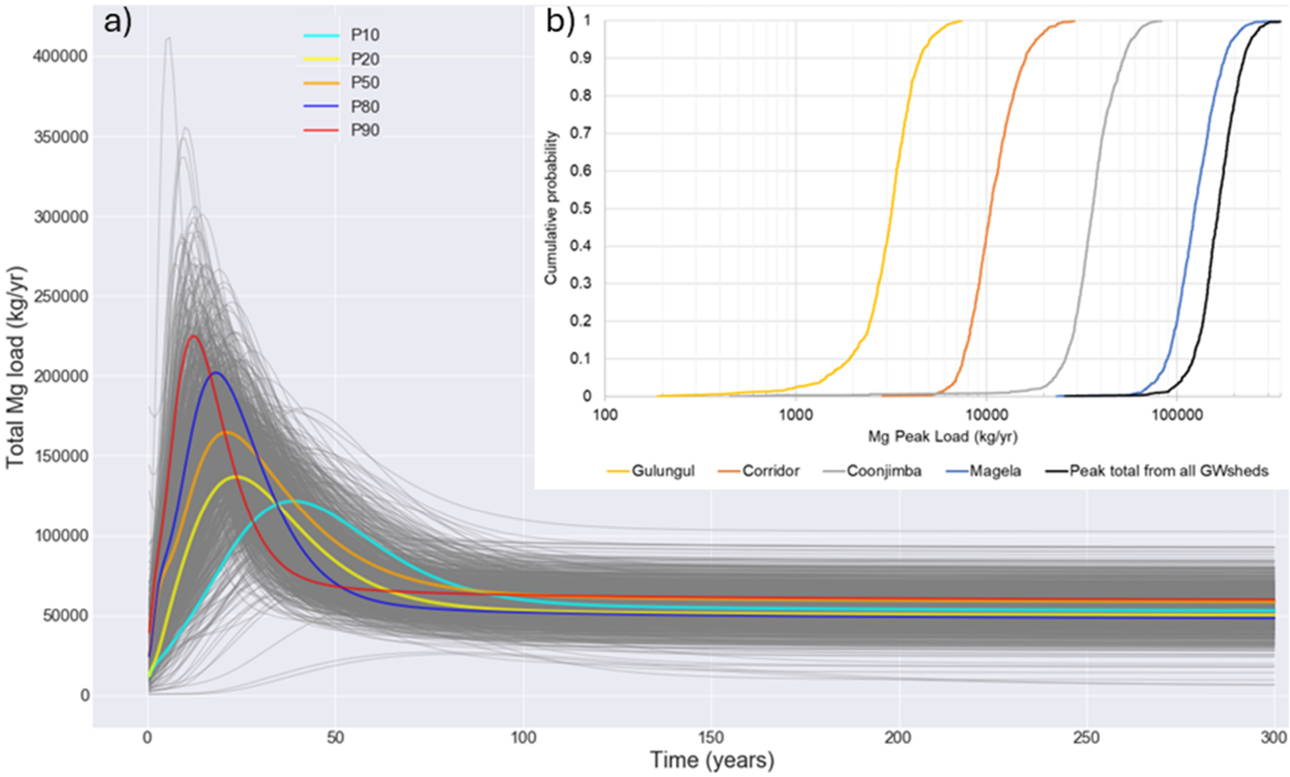

Figure 5 Selected results from the 2021 site-wide uncertainty analysis: (a) horsetail plot of total magnesium (Mg) load from all 983 predictive realisations, with coloured lines showing realisations corresponding to selected probability values; (b) empirical cumulative distribution functions of peak Mg loads for individual and combined groundwater sheds

Pit 3 sources drive the peak Mg loads for the Magela GWshed and all GWsheds. Pit 3 sources comprise the pit tailings flux (PTF) that is expressed during tailings consolidation and not removed prior to closure, tailings leaching, saturated waste rock backfill and leaching from vadose zone waste rock (VZ WR leachate). At the P50 probability level, the Pit 3 PTF Mg source is by far the largest contributor to peak total loads because the maximum PTF load is far larger than the next largest Mg contributors, the TSF plume and the VZ WR leachate source (Figure 6). The latter is the largest Mg source after the peak. Contributions from the Pit 1 sources, high-density sludge (HDS), the processing plant area plume, the retention pond 2 plume and saturated waste rock are minor donors to the peak total load (Figure 6).

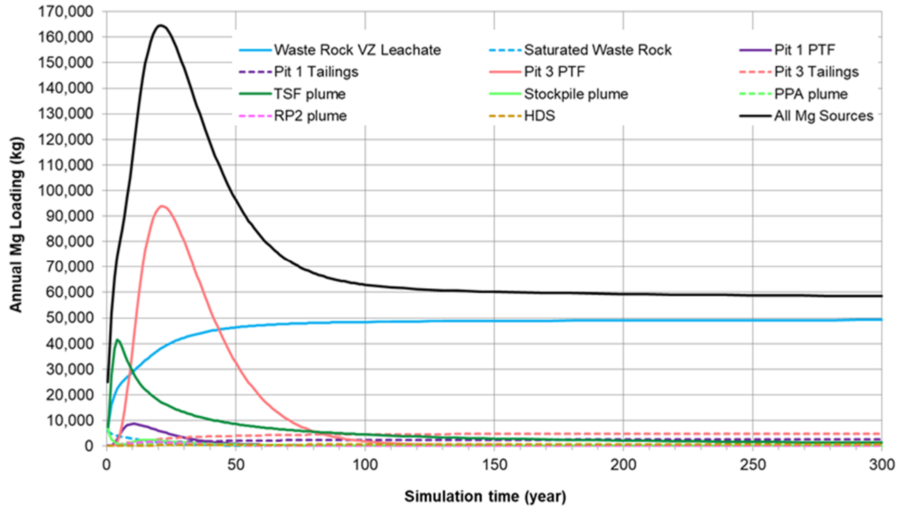

Figure 6 2021 site-wide uncertainty analysis P50 loads from individual magnesium (Mg) sources over time for Mg load to all groundwater sheds

The peak loads from all GWsheds for other COPCs were calculated from a combination of scaling the Mg loads by source concentration and plume loading simulations. The other COPCs include aluminium (Al), calcium (Ca), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), nitrate nitrogen (NO3-N), lead (Pb), total phosphorus (P-total), polonium-210 (Po210), radium-226 (Ra226), selenium (Se), sulphate (SO4), total ammonia nitrogen (TAN), uranium (U), vanadium (V) and zinc (Zn). Peak loads from all GWsheds to creek receptors for all COPCs vary by orders of magnitude from COPC to COPC, with only SO4 having loads larger than Mg (Figure 7). The range between the P05 and P95 loads are typically less than an order of magnitude.

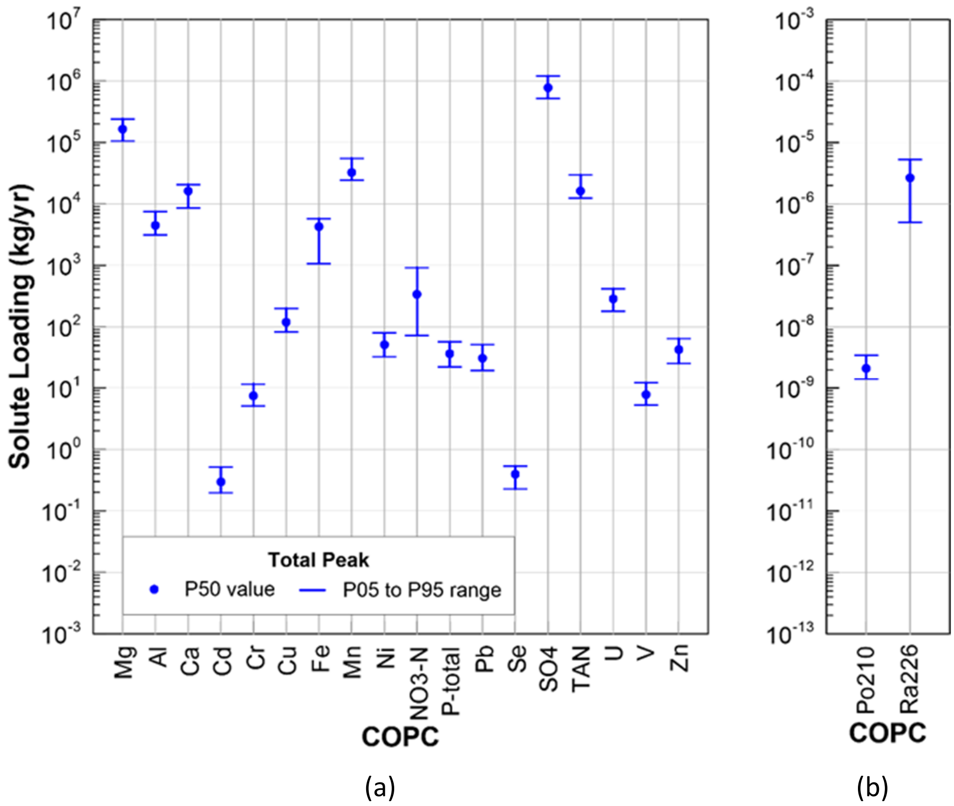

Figure 7 Peak total loads from all groundwater sheds for all constituents of potential concerns showing P05, P50 and P95 values for non-radionuclide constituents of potential concern (a) and radionuclide COPC (b) from the 2021 Ranger site-wide uncertainty analysis

In summary, the 2021 Ranger site-wide UA provided robust predictions of post-closure COPC loads to creek receptors by defining and incorporating parameter uncertainty. Pit 3 sources drive the peak Mg loads for the Magela GWshed and all GWsheds. These load values were derived from 983 equiprobable realisations that combine calibration-constrained posterior parameters with random samples of prior predictive parameters. This means that the 983 predictions of interest were made with 983 equally well-calibrated sets of parameters, many of which had values that ranged randomly across multiple orders of magnitude.

4 Study 2: The 2023 Ranger Pit 3 uncertainty analysis

The uncertainty analysis for the 2023 update to the Pit 3 Application was based on the 2021 site-wide UA but only simulated COPC loads from Pit 3 sources for three reasons. Firstly, updated predictions of loading from Pit 3 were needed because significant changes had been made to several Pit 3 source terms since the 2021 site-wide UA. Secondly, there had been no changes in the conceptualisations of the other mine site sources since the site-wide UA and, as such, there was no need to reassess loading from these sources at this time. Thirdly, several OSS comments on the original Pit 3 Application were related to the inability to extract loading from Pit 3 sources only from the 2021 site-wide UA results.

The prediction of interest for the Pit 3 UA is the solute loading from the Magela GWshed to Magela Creek from Pit 3 sources for all 20 COPCs at the time of the peak and in 10,000 years. The 2023 Pit 3 UA predictions incorporate new information and reclamation decisions that became available after Study 1's completion.

4.1 Updates to the predictive flow and transport model and prior probability distribution functions

To estimate COPC loads from only Pit 3 sources to the creeks, INTERA updated the 2021 site-wide UA with new information and revised the predictive flow and transport model accordingly (INTERA 2023). Pit 3 sources comprise the tailings, PTF, VZ-WR, saturated zone waste rock (SZ-WR), and high density sludge (HDS) found in the pit. The major new features of the Pit 3 UA follow.

New consolidation modelling results led to updates to the volumes, K and effective porosity for coarse, fine, and mixed tailings in Pit 3 (Figure 8). The volume of the higher-K coarse tailings in the Pit 3 UA is about 16% larger than that in the 2021 site-wide UA.

COPC concentrations for several Pit 3 source terms were updated with recently acquired data. For example, new Mg concentration data for leachate from the VZ WR from bore TLFOB5 in the trial landform and data from stockpile bores, scaled to have roughly the same residence time as the final landform, were used to update the prior PDF for this source term (Figure 9).

ERA determined that closure activities could significantly reduce the PTF volume in the waste rock backfill overlying Pit 3 tailings from the conservative value of 350 million litres assumed in the site-wide UA. Pit 3 PTF was the largest contributor to 2021 peak Mg loads. Given the uncertainties in the contact between tailings and waste rock and in the feasibility of extracting all PTF prior to final closure, ERA and INTERA decided to treat the PTF volume and its placement in overlying waste rock as uncertain parameters. The mean PTF volume was estimated to be 65 ML, with P05 and P95 volumes of 37 and 110 ML, respectively. PTF placement in the waste rock was also a function of the random effective porosity of the waste rock (Figure 10).

Recent information from ERA showed that the HDS mass placed in Pit 3 tailings is about 12,000 metric tonnes, much less than the roughly 37,000 metric tonnes assumed for the site-wide UA.

To take advantage of improvements in modelling capabilities, numerical stability and faster run times, INTERA converted the predictive flow and transport model to MODFLOW 6 (Langevin et al. 2017, 2022).

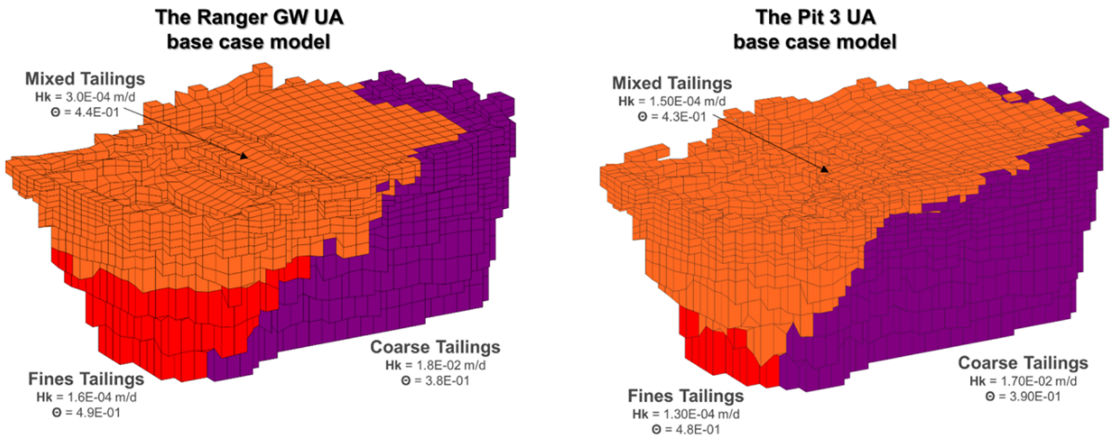

Figure 8 **Comparison of the gridding and mean parameter values for the Pit 3 tailings in the 2021 site-wide uncertainty analysis (UA) and 2023 Pit 3 UA**

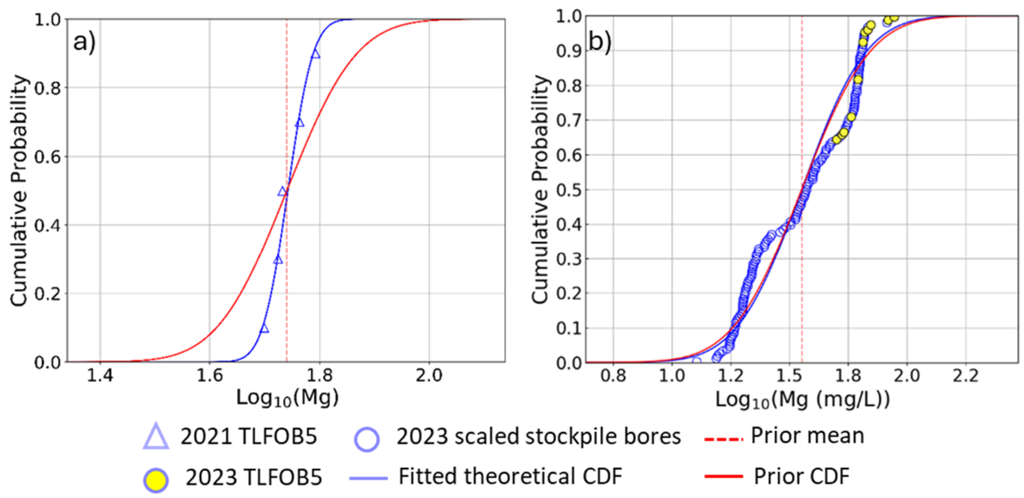

Figure 9 **Magnesium concentration data and cumulative distribution functions for the vadose zone waste rock leachate source term prior parameter: (a) 2021 site-wide uncertainty analysis (UA); (b) 2023 Pit 3 UA**

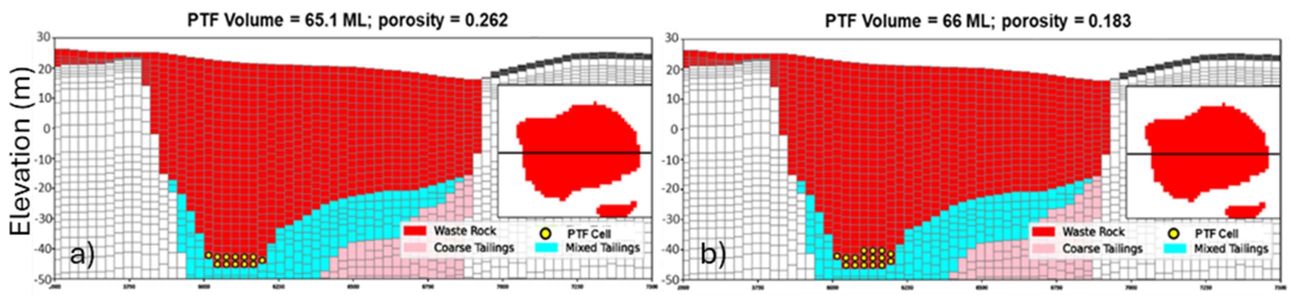

Figure 10 **Example pit tailings flux (PFT) source term location for two realisations with similar randomly sampled PTF volumes but different randomly sampled waste rock porosity values from 2023 Pit 3 uncertainty analysis**

4.2 Pit 3 uncertainty analysis workflow and approach

INTERA constructed a scripted workflow for the Pit 3 UA based on the open-source software tools PESTPP, FloPy, pyEMU, PESTPP-SWP and HTCondor. FloPy (Bakker et al. 2016) was used to automatically develop different MODFLOW 6 model packages. PESTPP is a suite of tools designed to conduct scalable and highly parameterised inversion with environmental models (Welter et al. 2015; White et al. 2021b). The Pit 3 UA workflow is fully reproducible through its use of pyEMU (White et al. 2016a), a Python framework for building inputs, running, and post processing the outputs of PEST and PESTPP UAs. Reproducible workflows, while requiring more effort up front, save significant time when changes inevitably need to be made to parameter values and/or bounds, or to other elements of the modelling workflow. HTCondor software automates computationally intensive workloads/simulations by managing and distributing model runs over a number of computational nodes and returning the outputs to the head node (https://htcondor.org). PESTPP-SWP is a PESTPP tool that runs an environmental model using a predefined set of parameter fields and records the values of model outputs calculated using these parameter fields (White et al. 2021).

The Study 2 modelling approach takes the parameter realisations from the 2021 site-wide UA predictive model, makes changes to several prior values for parameters that are present only in the predictive model updated for the Pit 3 UA, and then runs the updated realisations to estimate the predictive uncertainty (Figure 11). The posterior parameter values created by the null space linear projection operation and calibration run during the 2021 site-wide UA (step 4 in Figure 3) remain unchanged, and so were used to partially construct the Pit 3 UA predictive model's prior ensemble (step 1a in Figure 11). A majority of the predictive prior parameters in the site-wide UA were left unchanged for the Pit 3 UA. Data and information acquired since the 2021 site-wide UA were used to update tailings volumes and properties, PTF volume and COPC concentrations for some Pit 3 source terms, all of which are present only in the predictive model (step 1b in Figure 11). The resulting predictive parameter realisations were run in the Pit 3 UA post-closure flow and transport model for each of the five sources (step 2 in Figure 11), and the predicted water and solute fluxes were post processed to estimate the peak and 10,000-year loads (steps 3 through 5 in Figure 11).

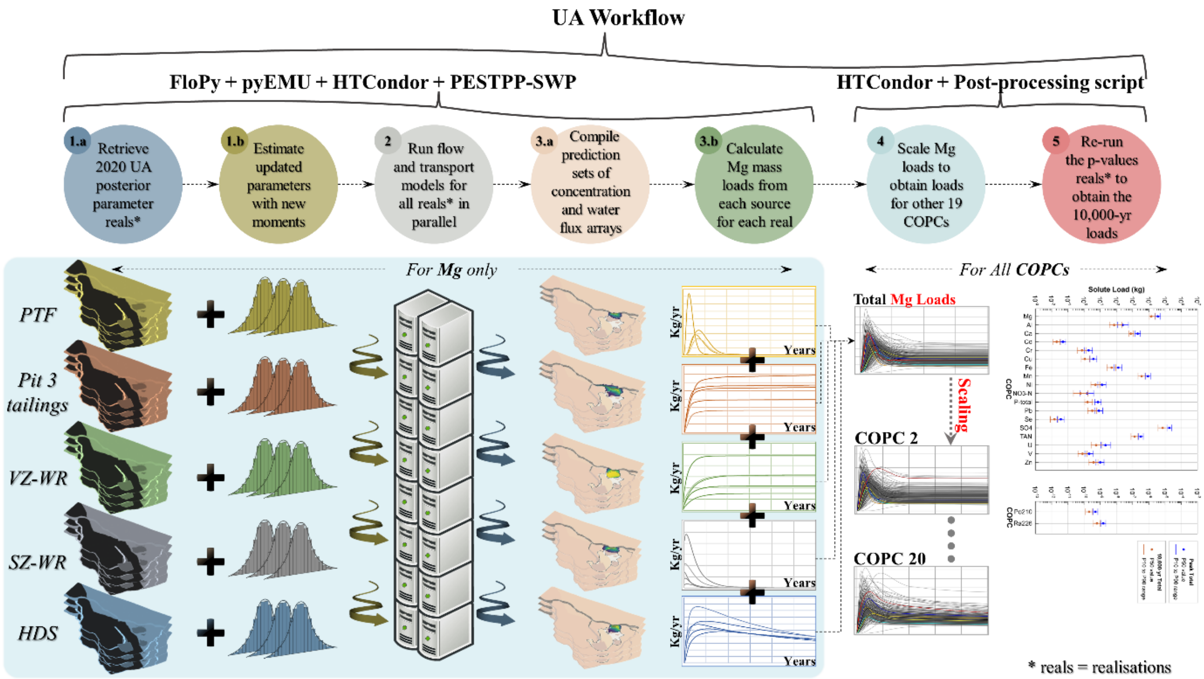

Figure 11 Pit 3 uncertainty analysis workflow steps and processes

4.3 Pit 3 uncertainty analysis results

The primary source contributing to the peak total load for Mg is the Pit 3 PTF (Figure 12), like the 2021 site-wide UA. The Mg peak load from the Magela GWshed at the P50 probability level is about 35,000 kilograms per year (kg/yr), whereas it was about 124,000 kg/yr in the 2021 site-wide UA that included sources outside Pit 3 (compare Figures 5b and 12). The total loads are similar from about 100 to 300 years because the PTF source term is negligible then, having been flushed out and discharged to Magela Creek within the first 50 years (Figure 12). After 100 years, the main sources contributing to the total load are Pit 3 tailings, VZ

WR leachate and HDS (Figure 12). Compared to the 2021 Magela GWshed peak loads, Pit 3 UA peak loads from the Magela GWshed are smaller for all other COPCs except radium (Figure 13).

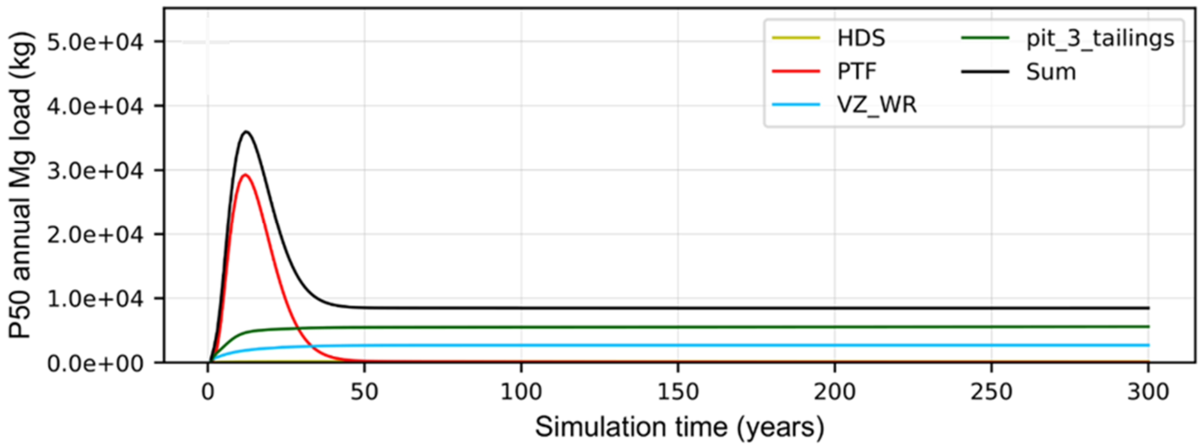

Figure 12 Magnesium (Mg) loads from individual Pit 3 sources to Magela Creek over time for the posterior realisation giving the P50 peak total Mg load from 2023 Pit 3 uncertainty analysis

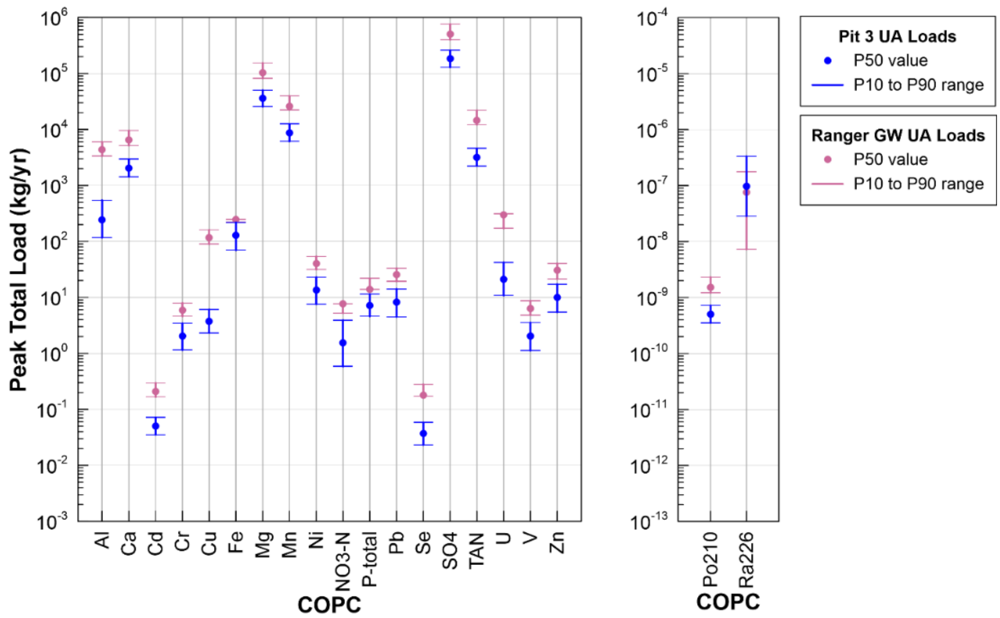

Figure 13 Comparison of peak total load from the Pit 3 uncertainty analysis (UA) and the 2021 site-wide UA for all constituents of potential concern

The individual effects on the prediction of interest from the new source term information is apparent from comparison of the 2021 site-wide UA and 2023 Pit 3 UA annual Mg loads at the P50 probability level (Figure 14). The increased volume of the relatively permeable coarse tailings for the 2023 Pit 3 UA caused a roughly 20% increase in tailings water flux, which raised the maximum tailings Mg load by about 22% from the 2021 maximum load (Figure 14a). After adjusting the 2021 Magela GWshed Mg loads to account for sources outside Pit 3, the updated prior PDF for Mg concentrations in the VZ WR leachate source term led to a 2023 maximum Mg load that is smaller than the 2021 load (Figure 14b). Even though the 2023 PTF volume was about 19% of the 2021 volume, the 2023 peak Mg load is about one third of the 2021 peak load, likely offset by the increased flux through coarse tailings (Figure 14c). Annual Mg loads from the SZ-WR differed by very small amounts (Figure 14d), whereas the new HDS information led to a smaller Mg mass than in 2021 (Figure 14e). The P50 peak from all 2023 Pit 3 sources is about 35% of that from 2021 (Figure 14f).

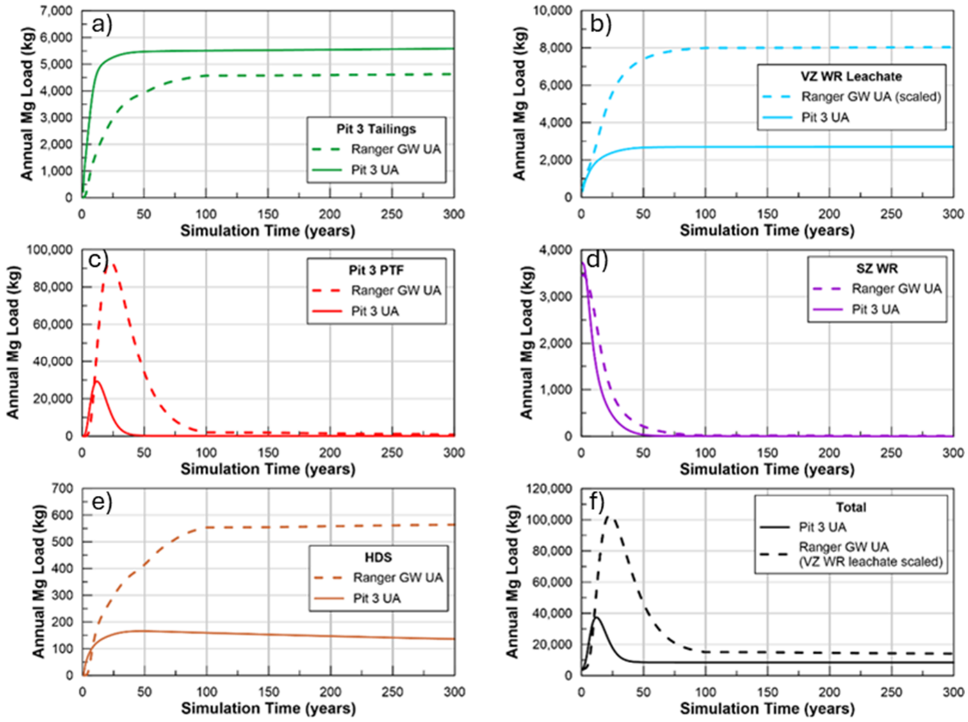

Figure 14 Magnesium loading by the Pit 3 source for the 2021 site-wide uncertainty analysis (UA) and 2023 Pit 3 UA P50 realisations

Comparing all predictions of the 2023 peak Mg loads from Magela GWshed with 2021 UA predictions for the Magela GWshed, after rescaling the differences from sources outside Pit 3, reveals the 2023 UA results have a lower mean and far smaller predictive uncertainty (Figure 15). Consistent with Figure 14f, the mean peak Mg load for the 2023 UA, estimated by the highest orange bar in Figure 15, is roughly 35% of the 2021 mean, estimated by the highest blue bar in Figure 15. The uncertainty in the 2023 predictions, as represented by the spread of all predictions (orange bars in Figure 15), was far smaller than the 2021 predictive uncertainty (blue bars in Figure 15). The incorporation of new information and updates to the prior parameters in the predictive model shifted the mean lower and reduced the predictive uncertainty.

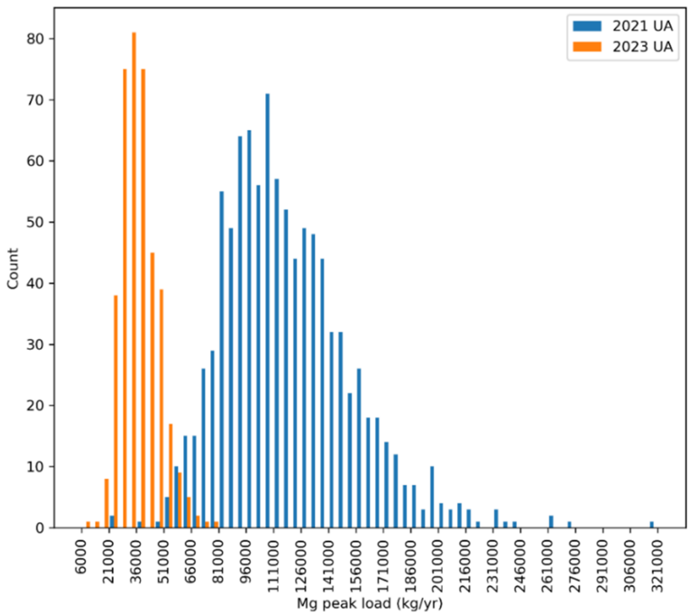

Figure 15 Histogram of all predicted magnesium peak total loads from the Magela groundwater shed for the 2023 Pit 3 uncertainty analysis (UA) and the 2023 site-wide UA (rescaled to Pit 3 sources only)

5 Conclusion

The 2023 Pit 3 UA (Study 2) results yielded smaller peak total Mg loads from the Magela GWshed to Magela Creek than the 2021 site-wide UA (Study 1) results from Pit 3 sources and much smaller predictive uncertainty compared to the 2021 predictions. Updating the prior predictive parameters with new information yielded a smaller range of peak Mg loads compared to Study 1. Incorporation of the new information (after Study 1) likely reduced the risk to surface water from post-closure Mg loads because smaller loads will lead to smaller surface water concentrations. ERA is continuing to improve modelling inputs that may alter the predicted groundwater loads reported in this paper and predicted surface water concentrations.

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