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A probabilistic framework for assessing groundwater remediation at a legacy mine

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Abstract

This study demonstrates the advantages of a probabilistic groundwater flow and transport model over a deterministic approach for evaluating the long-term effectiveness of a mine closure groundwater remediation program. While addressing inherent uncertainties, the model uses chloride as a conservative tracer to predict contaminant migration to down-gradient compliance points under two scenarios: future groundwater extraction based on corrective actions informed by the deterministic model and no action.

An automated three-step workflow is employed:

1. *Regional and site-scale hydrogeological models are constructed using MODFLOW-6.*
2. *Model predictions are refined through iterative ensemble smoothing (PESTPP-IES) by calibrating to historical site data, reducing output uncertainty.*
3. *Calibration-constrained results generate probabilistic groundwater quality predictions at compliance points over 200 years.*

The analysis reveals that planned pumping rates derived from the deterministic model are unlikely to be sustainable due to limitations in aquifer hydraulic properties. The probabilistic model identifies maximum sustainable pumping rates which vary over time, are lower than the planned pumping rates, and assesses groundwater quality sensitivity to pumping variations. While the groundwater extraction program is generally effective in suppressing contaminant concentrations during operation, results indicate concentrations rebound near or above regulatory limits after the extraction program is complete, likely due to residual mass stored in the vadose zone that is released when groundwater levels stabilise.

This work underscores the importance of probabilistic modelling for capturing inherent uncertainties in groundwater remediation predictions. This robust, risk-informed framework enhances mine closure planning at any stage of mining, empowering stakeholders to make informed decisions and improve long-term groundwater resource protection. The probabilistic approach provides a more realistic assessment of potential risks and allows for more effective management strategies compared to traditional deterministic methods.

Keywords: *groundwater modelling, probabilistic analysis, mine remediation*

1 Introduction

Numerical groundwater flow and transport modelling tools used for mine closure decision support have historically utilised deterministic modelling techniques. While deterministic flow and transport techniques can provide important baseline results for conceptualising the hydrogeologic system and comparing groundwater remediation scenario forecasts, they provide no quantification of uncertainty in historical

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anthropogenic stresses (e.g. pumping, mining, etc.) and hydrogeologic processes within the system of interest, thereby leaving estimates of future outcome probabilities unaccounted for. In forecasting mine water management, understanding and planning for system uncertainties can be particularly important for informing remediation and engineering plans, complying with environmental regulations, and/or engaging with external stakeholder groups.

This study adapts a deterministic MODFLOW-6 (MF-6) (Hughes et al. 2017; Langevin et al. 2017) groundwater flow and transport model to a probabilistic uncertainty analysis model that utilises MF-6 and PESTPP-IES (White 2018) at a mine and mill closure project. Historical groundwater contamination at the mill facility occurred during multi-year seepage of mill process fluids from the tailings storage facility (TSF) and the mill overflow basin (OB). Large uncertainties exist in the hydrogeologic conceptual site model due to the presence of high-frequency silt and claystone lenses in the sedimentary aquifer and a thick (30 m; 100 ft) unsaturated zone (Figure 1). Moreover, historical records of mining and milling activities, along with the geochemical concentrations of the seeped mill process fluids, are not well documented.

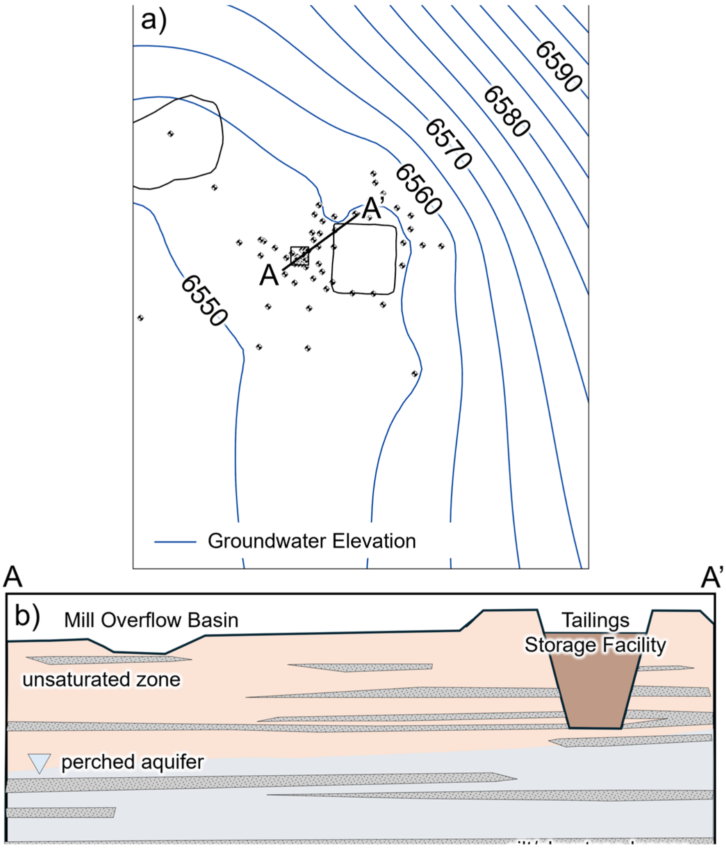


Figure 1 (a) Schematic map showing the regional groundwater gradient, monitoring wells, the mine pit, tailings storage facility (TSF), the mill overflow basin (OB), and cross-section line (A to A'); (b) Schematic cross-section of interbedded sandstone aquifer showing perched aquifer, mill OB, and TSF

Both the deterministic and probabilistic models include a regional and site-scale inset models and historical calibration of estimated mill fluid seepage rates and concentrations, groundwater quality, groundwater heads, and historical pumping. The calibration-constrained regional groundwater flow model informed groundwater heads along the site-scale inset model boundary but is not detailed here for brevity. A previous version of the deterministic model was used to forecast a groundwater remediation program (GRP) and included prescribed pumping rates over a 30-year predictive period. The probabilistic model, implemented several years after the deterministic model, was then used to test the risk-based efficacy of the GRP by forecasting groundwater quality and testing the aquifer's ability to maintain the prescribed pumping rates.

The objectives of adapting the model from deterministic to probabilistic were to inform future data collection efforts needed to better refine the hydrogeological conceptual site model and, by accounting for the aquifer heterogeneity, achieve a better model calibration and thus confidence in model predictions that estimate the effectiveness in remediating mill-impacted groundwater.

The modelling methods described herein focus on the probabilistic groundwater flow and transport model, which utilise chloride as a conservative tracer of mill-impacted groundwater. Transport of other groundwater constituents of concern was considered but those results are not included due to additional complexities of geochemical reactions. Results focus on comparing model calibration between the deterministic and probabilistic approaches, identifying data gaps that could improve site conceptualisation, comparing prescribed pumping between the deterministic and probabilistic models, and the probabilistic results that evaluate the prediction of interest (POI): effectiveness of the GRP by assessing the difference in water quality at one or more down-gradient well/s near the mill boundary over a 200-year predictive period with and without the GRP.

1.1 Site history and setting

The mine and mill site are located in a high desert region. The climate is considered semi-arid with relatively low annual precipitation and a wide range of seasonal temperatures. Summers tend to be dry with an average temperature of 28°C (83°F), while winters are very cold with an average temperature of -1.7°C (29°F). Historical estimates of annual precipitation from DAYMET (Thornton et al. 1997) range from 13–30 cm/year (5–12 in/year) at the site. Regional estimates of groundwater recharge can be up to 1.3 cm/year (0.5 in/year).

The geology at the site is characterised as a massive sedimentary package made up of interbedded and interfingered sandstones, siltstones, and mudstones (Figure 1). The groundwater in the aquifer is semi-confined and perched in some areas at the site due to discontinuous siltstone lenses. Groundwater is generally found 30.5 m (100 ft) below land surface, resulting in a relatively thick unsaturated zone in which historical mill seepage solutes reside. Regional groundwater flows are toward the southwest (Figure 1).

The mine and mill operations ceased in the 1980s and have since been operating toward closure under the regulatory remediation program to achieve pre-mining groundwater quality. In the early 1990s, the mine and mill owners discovered multi-year seeps of mill process water from the TSF and the mill OB. Figure 2 shows the 2023 estimates of groundwater chloride concentrations, which represents a conservative tracer of groundwater impacted from the TSF and mill OB seepages. The TSF GRP, consisting of four pumping wells, and the mill OB GRP, consisting of three pumping wells, began shortly after the discovery of mill process water seepages. The GRP appears to be improving the extent of the chloride plume to a lesser extent at the mill OB than the TSF (Figure 2).

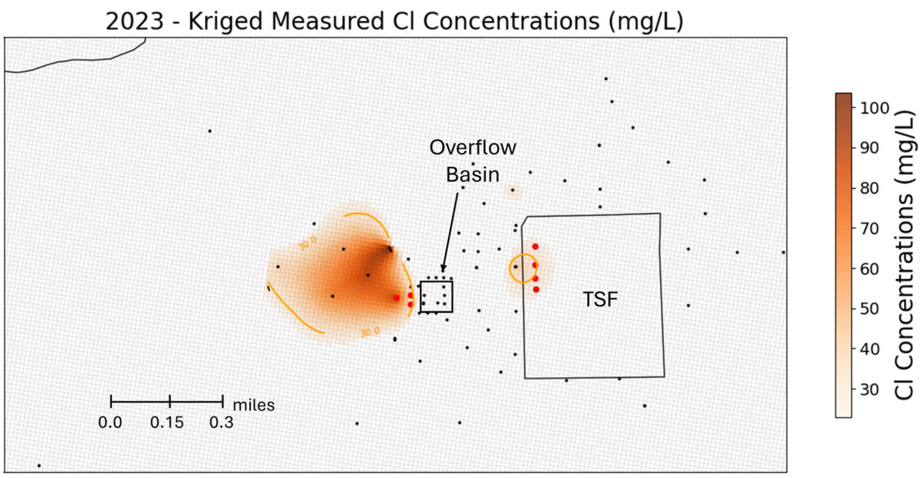


Figure 2 Map of interpolated 2023 chloride concentrations and groundwater remediation program pumping wells (red circles)

2 Modelling approach

2.1 Deterministic (base) model

The site-scale inset deterministic groundwater models were implemented to align with the hydrogeologic conceptual site models. While the deterministic model was historically used to provide initial estimates of pumping for the GRP, it is used in this study as the base model for the probabilistic modelling approach. The deterministic ('base') model setup is detailed below, and calibration results are presented in Section 3.

2.1.1 Inset groundwater flow and transport model

The inset model was developed with the primary objective of simulating groundwater flow and the mass transport of seepage originating from TSF and mill OB sources that have impacted groundwater. This model also accounted for both historical and future GRP. Representing site-scale processes, the inset flow and transport model utilised a rectangular grid (Figure 3) consisting of two layers, 400 rows, and 440 columns, encompassing approximately 32 Mm^2. The grid cells within the inset model were uniformly spaced at 15 × 15 m (roughly 50 × 50 ft). Vertically, the model was discretised into two layers representing the upper 180 m (approximately 600 ft) of the aquifer. Layer 1 has a thickness of 46 m (150 ft), comprising approximately 15 m (50 ft) of saturated material and 30.5 m (100 ft) of unsaturated material, while Layer 2 is 137 m (450 ft) thick and entirely saturated.

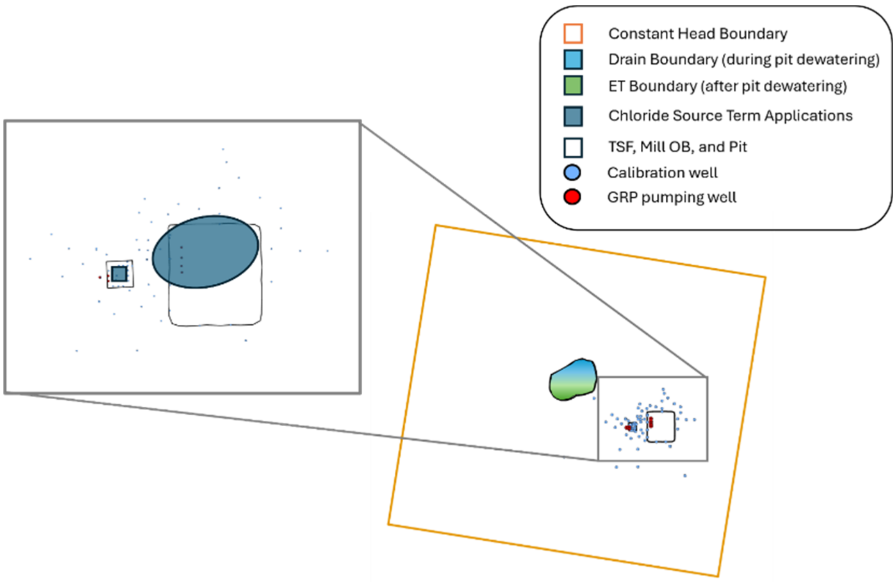


Figure 3 Inset groundwater flow model domain showing calibration targets and boundary conditions

Hydraulic conditions within the inset model were constrained by several boundary conditions and hydraulic properties. A transient history-matching period, spanning from the early 1970s to present day, was applied to simulate historical pit dewatering and GRP pumping, and to calibrate the model against groundwater heads, groundwater flows, and water quality data. A recharge boundary condition was implemented, assuming 1% of transient historical precipitation across the inset model domain. Head-dependent boundary conditions were applied along the perimeter of the inset model domain. Calibrated, time-varying heads were mapped onto the inset model grid from the regional model cells for both the historical and predictive periods. A transient drain boundary condition was applied to the pit to simulate dewatering during the mining period, from the 1970s to the early 1980s, with water levels linearly declining from the estimated pre-mine watertable elevation to the present-day pit water elevation. An evaporation boundary condition was applied to the pit water surface from the early 1980s through the predictive period, representing an evaporation rate of approximately 127 cm/yr (50 in/year), based on historical water balance estimates for the site.

To simulate the effects of the vadose zone on water and contaminant migration, the unsaturated zone flow (UZF) and unsaturated zone transport (UZT) MF6 packages were applied to the upper 30.5 m (100 ft) of the model. The UZF and UZT packages were specifically used to simulate chloride contamination originating from the TSF and mill OB sources, as representing the unsaturated zone was crucial for accurately estimating the timing and duration of contaminant concentrations in the saturated zone. Chloride source terms were applied to the TSF and mill OB areas based on historical estimates of mill fluid release areas, with an assumed aquifer background chloride concentration of 23 mg/L based on historical reporting. Historical estimates of GRP pumping, along with prescribed predictive pumping scenarios, were also incorporated into the model. Finally, aquifer hydraulic conductivity and storage values were applied based on historical site data and/or literature values for similar hydrogeologic settings.

2.2 Probabilistic model

Understanding future groundwater flow and contaminant movement requires considering how past mining activities have influenced current conditions. Several uncertainties surrounding historical events, however, exist. First, records over several decades indicating billions of gallons of groundwater extracted from the 1970s to early 1980s, and additional hundreds of millions from GRP wells, vary in completeness and reliability. Second, historical monitoring well data, crucial for model calibration, may contain errors or bias. Finally, estimates of contaminant timing, magnitude, and composition from the TSF and mill OB highlight significant uncertainty in historical impacts on groundwater quality.

Unlike past deterministic models that provided a single future prediction for GRP pumping needs, probabilistic models assess pumping effectiveness by updating parameters to better represent flow and transport processes. This approach uses uncertainty analysis (UA) within a risk-informed framework to interpret model predictions by estimating probabilities, rather than a single outcome.

The UA uses a Monte Carlo method to generate probable model inputs and integrates a Bayesian framework to refine these inputs with historical groundwater observations. This involves defining model inputs as random variables with probability distribution functions (PDFs), randomly sampling these PDFs to create equally probable scenarios, and using these scenarios in a predictive model to generate a distribution of predictions. The Bayesian framework updates initial parameter distributions (priors) based on how well initial predictions match observations (likelihood), resulting in updated distributions (posteriors) consistent with available data.

The probabilistic models use MF-6 (Hughes et al. 2017; Langevin et al. 2017) for flow and transport, and the UA employs the iterative ensemble smoother (IES) capability of PESTPP (PESTPP-IES). PESTPP is a suite of tools for scalable and highly parameterised inversion with environmental models (Welter et al. 2012, 2015; White 2018), with its PESTPP-IES capability being a relatively new technique for nonlinear UA (White 2018). Unlike traditional PEST (Doherty 2015), PESTPP-IES approximates the Jacobian matrix using model runs for each realisation of uncertain parameters.

INTERA's UA workflows are fully reproducible using Python scripts and pyEMU (White et al. 2016); a Python framework for building, running, and postprocessing PESTPP analyses. The flow and transport models incorporate packages representing hydrological processes, aligning with the current site model. Model updates are scripted in Python using FloPy (Bakker et al. 2016), and PyPESTUtils processes model outputs for comparison with observed measurements in PESTPP-IES. The specific packages used in the inset groundwater flow and transport models are detailed in subsequent sections.

2.2.1 Steps for implementing the groundwater uncertainty analysis workflow

The POI is to evaluate the effectiveness of the GRP by assessing the difference in chloride concentrations at one or more down-gradient well/s over a 200-year predictive period with and without the GRP. To assess the POI, the following sets of tasks were completed for the probabilistic UA flow and transport model (Figure 4):

1. Start with the deterministic inset groundwater flow and transport model.
2. Define input parameter (prior) PDFs using relevant compiled information, or professional judgment where information is not available. These include, but are not limited, to hydraulic conductivity, storage, porosity, recharge, and chloride source term concentrations and seepage rates.
3. Run the history-matching model hundreds of times with randomly sampled prior parameter PDFs (Step 2).
4. Parameters will be updated to posterior parameter PDFs, which are informed through each history-matching model run (Step 3).
5. Use calibration-constrained posterior parameter PDFs (Step 4) to run predictive model runs forward in time. Assess predictive uncertainty in achieving chloride concentrations at specified location/s.

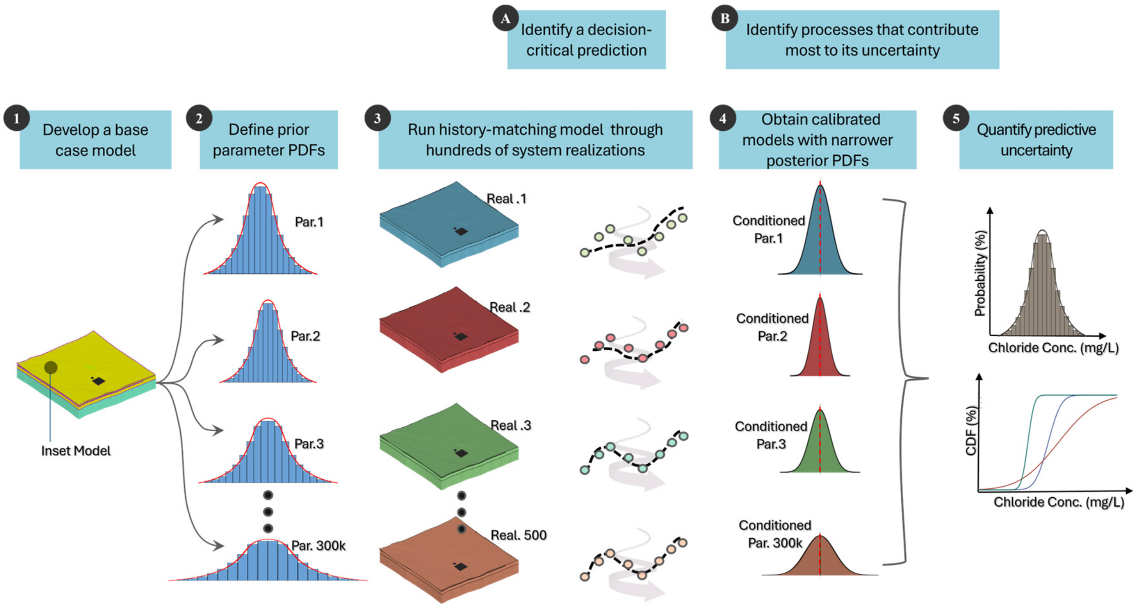


Figure 4 Schematic of MF-6 and PESTPP-IES workflow

2.2.2 Inset uncertainty analysis groundwater flow and transport model

The site-scale inset UA groundwater flow and transport model was used to represent the uncertainty in the local hydrogeologic conceptual site model. Predictive uncertainty was determined by first setting the uncertainty in several flow and transport model input parameters. Inset model parameters that were varied included head-dependent boundary conditions (CHD BCs) set along the inset model domain boundary. For each CHD cell, the mean head value was randomly sampled from the regional UA model posterior realisations. Spatially varying recharge was allowed to vary between 0.025 and 8% of annual precipitation. Hydraulic conductivity, storage parameters, porosity, and dispersivity (horizontal, transverse, and vertical) varied spatially throughout the model domain using layer and pilot point parameters. An example of how aquifer hydraulic conductivity (K) values are spatially varied using layer-scale and pilot points is depicted in Figure 5. Chloride source term concentrations for the TSF and mill OB were based on historical reports from the site and were allowed to vary between 20 and 200% of the initial estimates. Historical pre-mining data from the site indicate natural background chloride concentrations. Based on the available data, a constant background concentration of 23 mg/L was applied. Model parameters that were not allowed to vary in the inset UA included historical and predictive GRP pumping, and pit water evaporation.

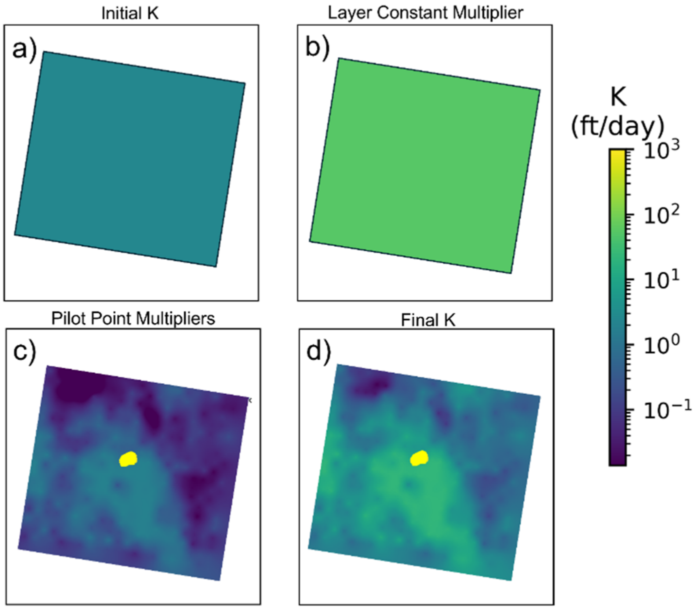


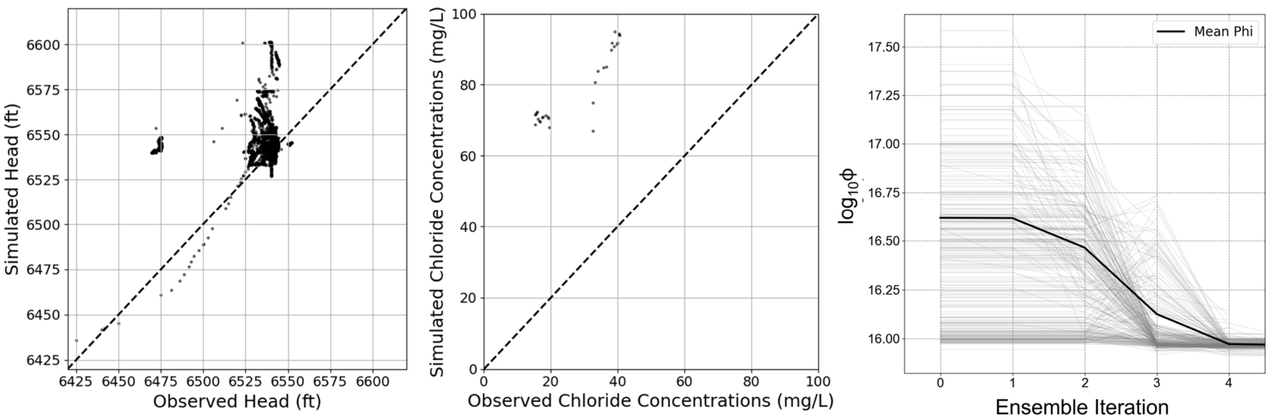
Figure 5 Example of multi-scale parameter approach for uncertainty in hydraulic conductivity (K) field using large-scale (layer) and intermediate-scale (pilot point) multipliers

3 Results

3.1 Inset model calibrations

Model calibration against historical groundwater head and/or concentration data is crucial for ensuring the accuracy and reliability of model predictions but can also serve as a valuable test of the hydrogeologic conceptual site model. For this complex mine closure site, achieving satisfactory calibration is inherently difficult for both deterministic and probabilistic approaches due to considerable uncertainties. These uncertainties stem from the spatial variability in local-scale hydraulic properties, the poorly constrained historical pumping regimes (including GRP pumping and pit dewatering), and the unknown characteristics and timing of multi-year mill fluid seepages.

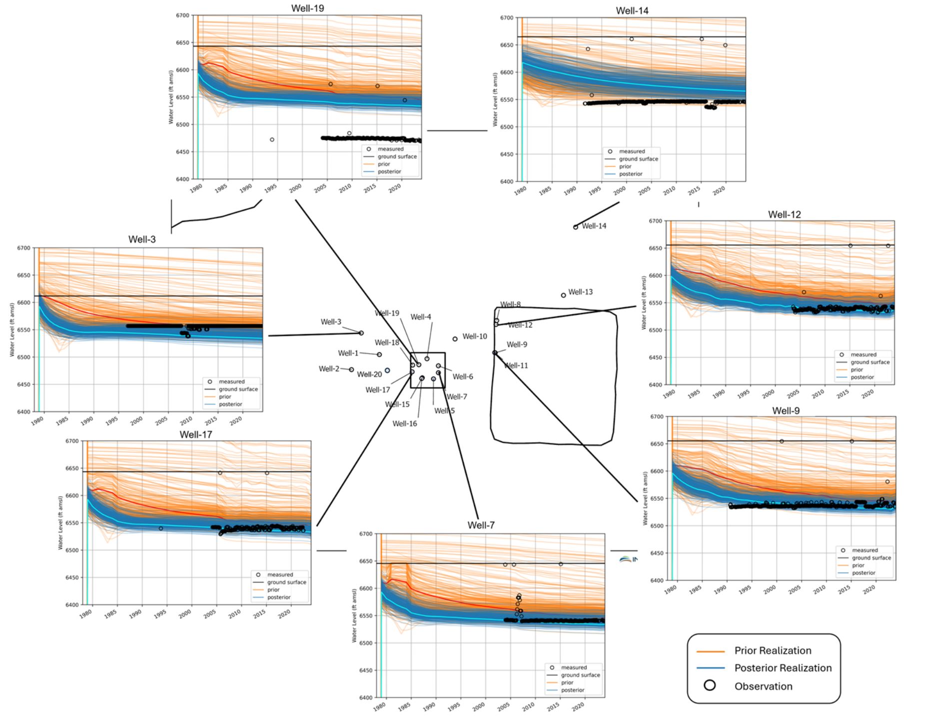
Model simplifications of local-scale controls are critical for achieving a computationally efficient model that maintains accuracy with the conceptual site model. Even with significant simplification of groundwater flow and transport controls, deterministic modelling at this complex site has yielded a limited degree of calibration against historical groundwater head and chloride concentration data (Figure 6). This difficulty in achieving a strong match underscores the limitations of a single parameter set in representing a system characterised by substantial and interacting uncertainties. Consequently, the resulting deterministic model, despite best efforts, likely fails to capture the full range of plausible system behaviors and may lead to overly narrow and potentially unreliable predictions of future conditions. The resulting calibration highlights the need for the probabilistic UA approach that can explicitly account for these uncertainties.



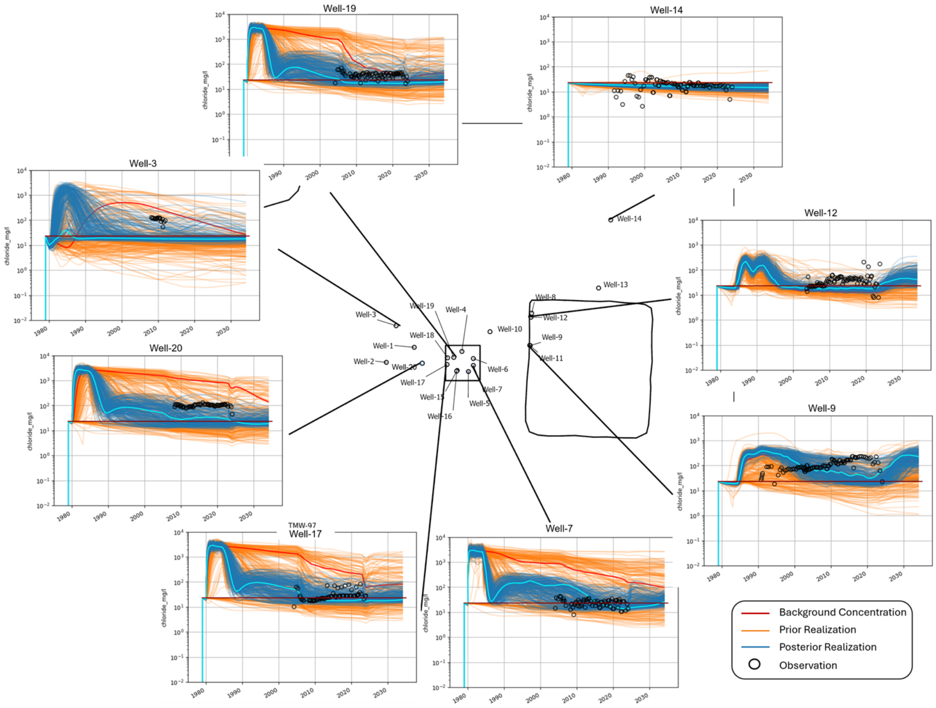
(a) (b) (c)

Figure 6 1:1 plots showing deterministic model simulated versus measured (a) groundwater heads and (b) chloride concentrations for inset base-case model calibration targets; (c) Probabilistic model reduction in phi from running PESTPP-IES for the inset history matching model

The deterministic ('base') model, in conjunction with hundreds of additional model runs, underwent calibration by utilising parameter estimation techniques (i.e. PESTPP-IES) informed by prior PDFs and historical groundwater head and chloride concentration data. Employing uncertainty analysis techniques, probabilistic calibration explores the plausible range of model parameters and their influence on simulated groundwater heads, moving beyond a single 'best fit' to assess model reliability and the potential variability in predictions. The PESTPP-IES workflow (Section 2) initiates this process by running the MF-6 groundwater flow model hundreds of times, randomly sampling input parameters from defined prior PDFs. During each history-matching model run, parameters are iteratively adjusted or 'upgraded' based on the agreement between simulations and observed historical data. These upgraded ('posterior') parameter sets aim to converge towards values that better reproduce the observations. Alongside parameter adjustments, PESTPP-IES records the corresponding objective function (phi), representing the sum of squared weighted residuals across all observations and quantifying the overall goodness of fit for each model realisation. As demonstrated in Figure 7, phi generally decreases with each PESTPP-IES iteration due to the utilisation of these upgraded parameter sets. As anticipated, the initial ('prior') phi values (zero value on Figure 7) and parameter contributions are relatively high due to the absence of history-matching-driven parameter upgrades. Subsequent iterations (one through three) show clear incremental improvements in phi. The improvement in model fit and decrease in model uncertainty between the prior and (iteration four) posterior ensembles is evident in the simulated hydrographs (Figure 7a). The inset groundwater flow model appears to be well calibrated by the posterior ensemble. The inset transport models encompass many of the historical chloride observations but some measured chloride concentrations (Figure 7b) show clear evidence of undefined local-scale influences on mill-related fluid transport and disagreement with a site-wide constant background concentration (e.g. Well-3, Well-11, Well-12, Well-20). The discrepancies between simulated and observed chloride concentrations reveal areas with data gaps and suggest a potential need to refine the site's conceptual understanding. Despite these mismatches, the inset flow and transport model remains a valuable tool for evaluating groundwater remediation program effectiveness, as it offers further insight into predictive groundwater flows and fluxes that influence plume migration. The results of the inset model flow and transport calibration are further discussed in Section 4.



(a)

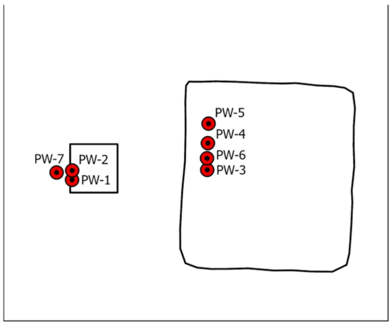


(b)

Figure 7 Observed (black), prior (orange), and posterior (blue) (a) heads and (b) chloride concentrations for select inset calibration targets

3.2 Future effectiveness of groundwater remediation program

Groundwater extraction wells under prescribed GRP pumping rates are planned to remediate mill-impacted groundwater at the mine and mill closure site. Figure 8 shows the placement of proposed GRP pumping well configuration along with future rates, which propose to use four TSF extraction wells for 30 years and three mill OB extraction wells for 10 years. The prediction of interest to assess the GRP effectiveness is evaluated using probabilistic chloride values that are generated by running the calibrated posterior ensemble 200 years in the future using two pumping scenarios: no future pumping (no action) and GRP pumping. To evaluate the GRP effectiveness, INTERA defined monitoring well points of compliance (POC) both cross-gradient and down-gradient from the TSF and mill OB ('GRP evaluation wells') to assess future chloride concentrations relative to background concentrations. Moreover, INTERA assessed the spatial distribution of future chloride concentration probabilities of exceeding background concentrations.



Extraction Well Id	Area	Phase 1: Average Flow Rate Year 0 – 10 (gpm)	*Phase 2: Average Flow Rate Year 10-20 (gpm)	Phase 3: Average Flow Rate Year 20 - 30 (gpm)
PW-01	Mill OB	0.6	0.0	0.0
PW-02	Mill OB	0.2	0.0	0.0
PW-07	Mill OB	0.2	0.0	0.0
PW-03	TSF	0.6	0.9	1.2
PW-04	TSF	0.6	0.9	1.2
PW-05	TSF	0.4	0.4	0.0
PW-06	TSF	0.6	0.9	0.9
Totals		3.3	3.3	3.3

(a) (b)

Figure 8 Groundwater remediation program pumping well (a) locations and (b) predictive pumping rates

3.2.1 Predictive chloride transport at points of compliance

Predictive model results suggest that approved GRP pumping rates, based on the deterministic model, may not be sustainable for the planned duration of pumping. Figure 9 depicts the estimated total GRP pumping rate until the end of the 30-year predictive period. At present day, the estimated attainable pumping rate of 2.5 L/s (40 gpm) on average is less than the approved rate of 3.2 L/s (52 gpm). While this difference shows uncertainty in the exact estimation of attainable pumping, the probabilistic model suggests with high probability that attainable pumping rates will decrease in the future. Notably, the consolidation of GRP pumping to the TSF area restricts the total attainable pumping rate by 0.7 L/s (10 gpm) (i.e. the estimated total drops from approximately 2 L/s to approximately 1.3 L/s on average). The estimated pumping remains at 1.1 to 1.3 L/s (17 to 20 gpm) for the remainder of the GRP, indicating near steady-state conditions. Importantly, this result does not consider the possibility of lowering pumps below their current elevation to maintain higher pumping rates.

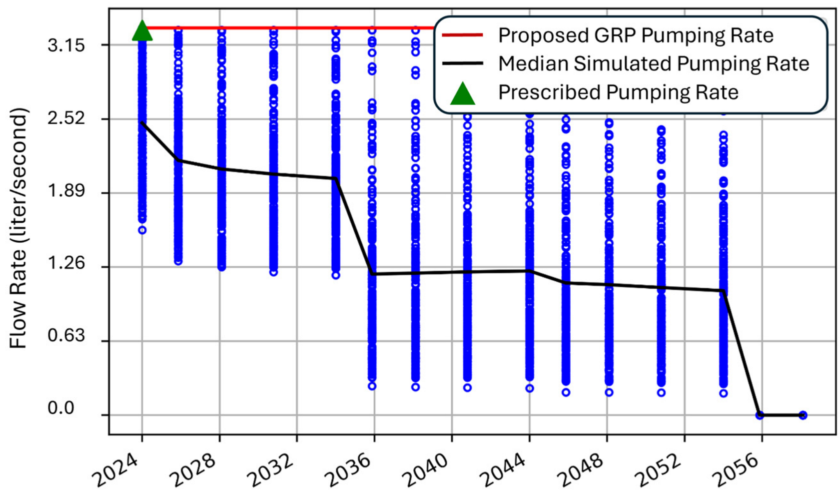


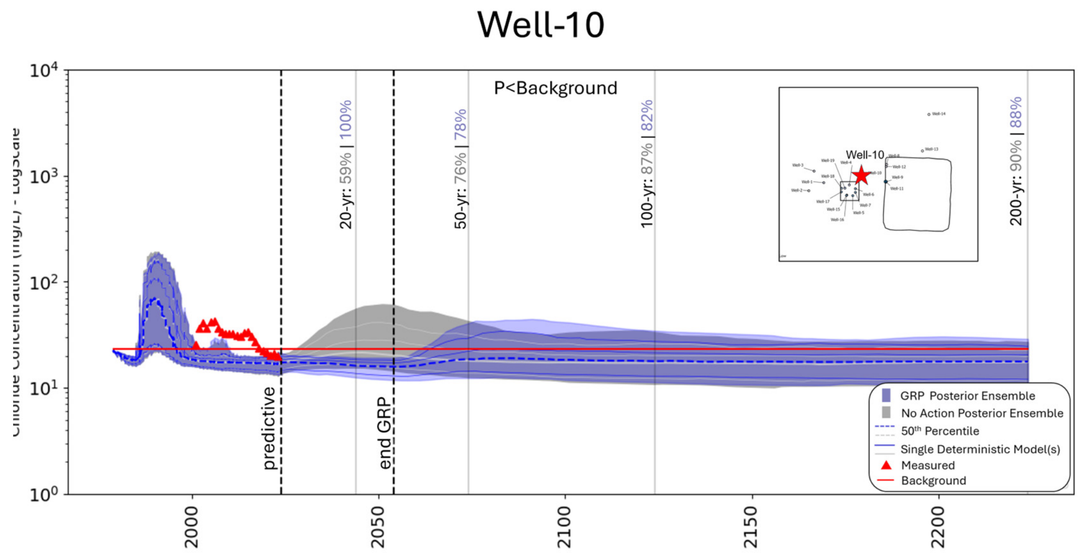
Figure 9 Planned versus estimated groundwater remediation program (GRP) pumping rates. Time series of total GRP pumping comparing the planned GRP pumping rates (red line) with the mean GRP pumping rates observed in the model ensembles (black line) and pumping rates for all ensemble members (blue circles)

Using no action and variable-rate GRP pumping scenarios, predictive chloride values are assessed at the GRP evaluation wells. Figure 10a depicts the model predictions for future chloride concentrations at Well-10. The left side of the plot is a schematic site map depicting the mill OB and the TSF, monitoring wells, and a red star locating the monitoring well that corresponds to the time series. The time series shows the posterior ensemble (purple overlying grey) and the observation data for the historical period (1970s through present day), followed by the calibration-constrained posterior predictions for the no action (grey) and GRP (purple) pumping scenarios. Single lines are used to depict examples of single deterministic model runs within the no action and GRP ensembles. Two annotated vertical dashed-black lines are used to mark the start of the predictive period (2024) and the end of predictive pumping (2054). Four annotated vertical dashed-grey lines are used to depict the probability of meeting background chloride concentrations (23 mg/L) under the no action (grey) and GRP (purple) scenarios at 20, 50, 100, and 200 years into the future.

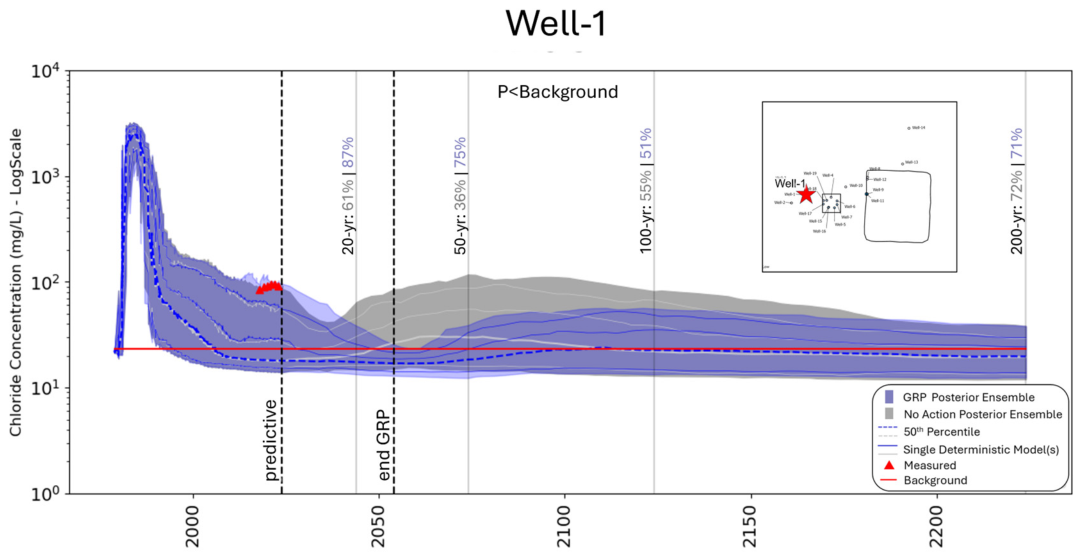
TSF cross-gradient GRP evaluation Well-10 (Figure 10a) shows measured chloride concentrations above background. Predictive concentrations for this well show that chloride concentrations appear to be suppressed by GRP pumping. Although the magnitudes vary from well to well, a notable increase in simulated solute concentrations is observed once GRP pumping is terminated in both the no action (year 2024) and GRP (year 2054) pumping scenarios. These simulated increases may be due to a relatively long residence time of solute mass in the vadose zone slowly releasing to the saturated zone, and/or watertable rebound releasing trapped mass in the vadose zone after GRP pumping terminates. Under the GRP pumping scenario, the estimated probability of chloride meeting background concentrations in this cross-gradient TSF POC well at 20 years (GRP pumping), and 50, 100, and 200 years (after GRP pumping) is 100, 78, 82, and 88%, respectively. Under the no action scenario, the probability of chloride meeting background concentrations at 20, 50, 100, and 200 years (after GRP pumping) is 59, 76, 87, and 90%, respectively. The relatively high 50-year probability of the no action scenario meeting background chloride concentrations (76%) compared to the GRP pumping scenario (78%) may be due to the introduction of additional mass stored in the vadose zone entering the saturated zone upon watertable rebound in the GRP pumping scenario.

The mill OB cross-gradient GRP evaluation Well-1 (Figure 10b) generally shows elevated historical chloride concentrations. Predictive concentrations for this well show current and future (2024 to 2034) GRP pumping has minor impacts in decreasing the median chloride concentrations (purple line). The termination of GRP pumping in the no action scenario in the present day, the termination of mill OB GRP pumping in 10 years (year 2034), and the termination of TSF GRP pumping in 30 years (year 2054) correspond to notable rebounds in chloride concentrations at these cross-gradient locations.

Similar to the TSF area, the increases in simulated chloride concentrations following the termination of pumping may be due to continued solute loading to the saturated zone through one or both of the following processes: a relatively long residence time of solute mass in the vadose zone slowly releasing to the saturated zone, and/or watertable rebound releasing trapped mass in the vadose zone after GRP pumping terminates. While the range in predictive risk for chloride exceedances (reported below) may explain the potential transport pathways of chloride, such results should be taken with caution due to the general under-estimation of simulated chloride concentrations for Well-1. Under the GRP pumping scenario, the probability of meeting background chloride concentrations in mill OB GRP evaluation wells at 20 years (GRP pumping), and 50, 100, and 200 years (after GRP pumping) is 87, 75, 51, and 71%, respectively. The predictive probability of meeting the background chloride concentrations in the mill OB GRP evaluation wells under the no action scenario at 20, 50, 100, and 200 years (after GRP pumping) is 61, 36, 55, and 71%, respectively.



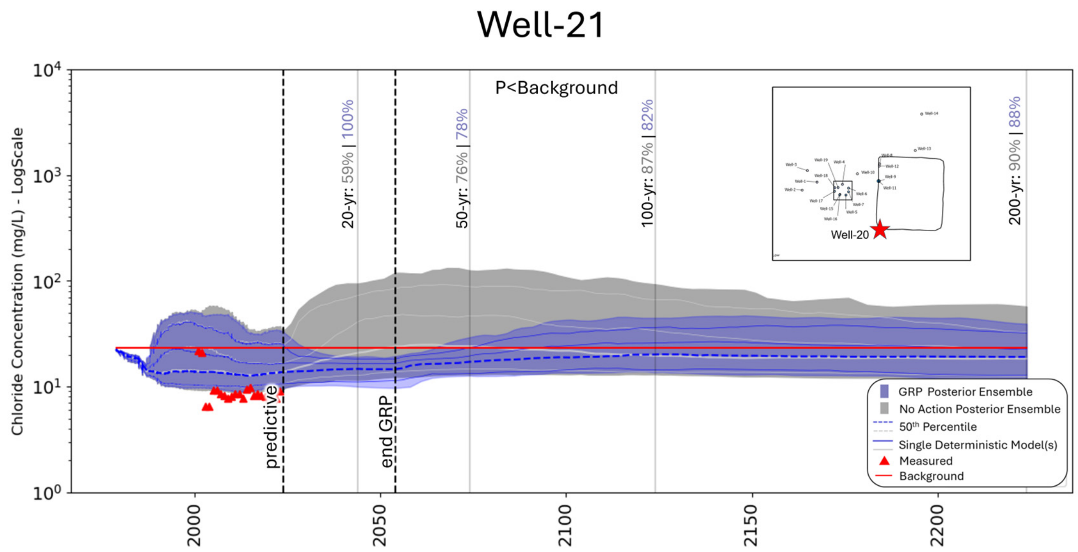
(a)



(b)

Figure 10 Predictive probability chloride concentrations for cross-gradient points of compliance monitoring wells at (a) tailings storage facility Well-10 and (b) mill overflow basin Well-1

The TSF and mill OB down-gradient GRP evaluation wells Well-21 (Figure 11a) and Well-22 (Figure 11b), respectively, show chloride observations below the background, potentially indicating little to no impact from historical releases in these areas, and/or that seepage has been mitigated by historical GRP pumping. Simulated chloride concentrations are generally higher than those observed, which may be due to the local variations in background chloride concentrations that fall below the simulated background value of 23 mg/L. In the flow and transport model, background groundwater was assumed to be uniformly equal to chloride background concentrations. Thus, predictive results that indicate an increase in down-gradient solute concentrations as GRP pumping decreases may be biased due to this assumption.



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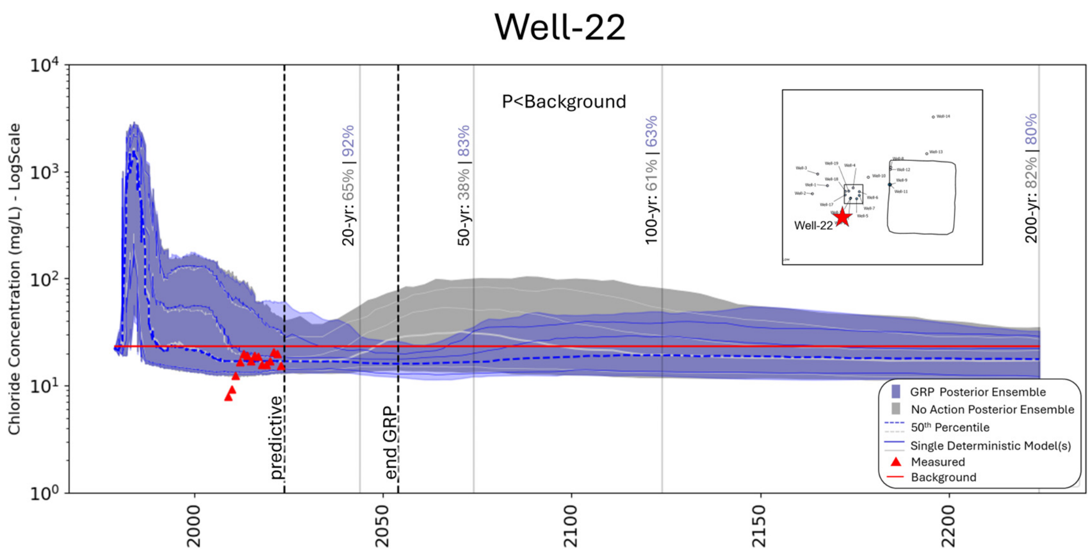


(b)

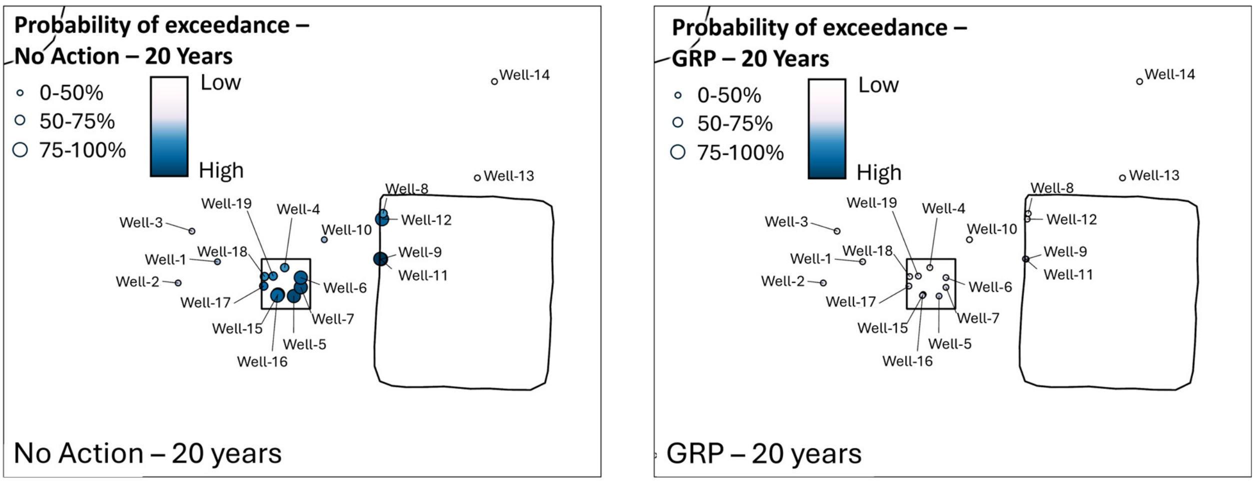
Figure 11 Predictive probability chloride concentrations for down-gradient points of compliance monitoring wells at (a) tailings storage facility Well-21 and (b) mill overflow basin Well-22

3.3 Probabilistic spatial distributions

GRP pumping is currently working to remove mill-derived constituents in groundwater from groundwater extraction wells. Suppressed and/or decreases in chloride concentrations are indicative of plume mass being removed, as evidenced by both historically measured (e.g. Figure 7) and simulated (Figures 10 and 11) chloride concentrations. The spatial distribution showing the simulated probability of chloride concentrations exceeding background concentrations at 20, 50, 100, and 200 years in the future demonstrates the conservative migration of mill-impacted groundwater. Figure 12 depicts the 20-year (year 2044) impacts of the no action and future GRP pumping scenarios, which runs for 30 years, on chloride concentrations. The no action scenario exhibits significantly higher probabilities of exceeding chloride background concentrations compared to the GRP pumping scenario. In particular, the simulated risk of exceeding chloride background at 20 years into the no action scenario is pronounced closer to the OB and TSF sources, while the GRP pumping scenario demonstrates relatively low risk near these sources.

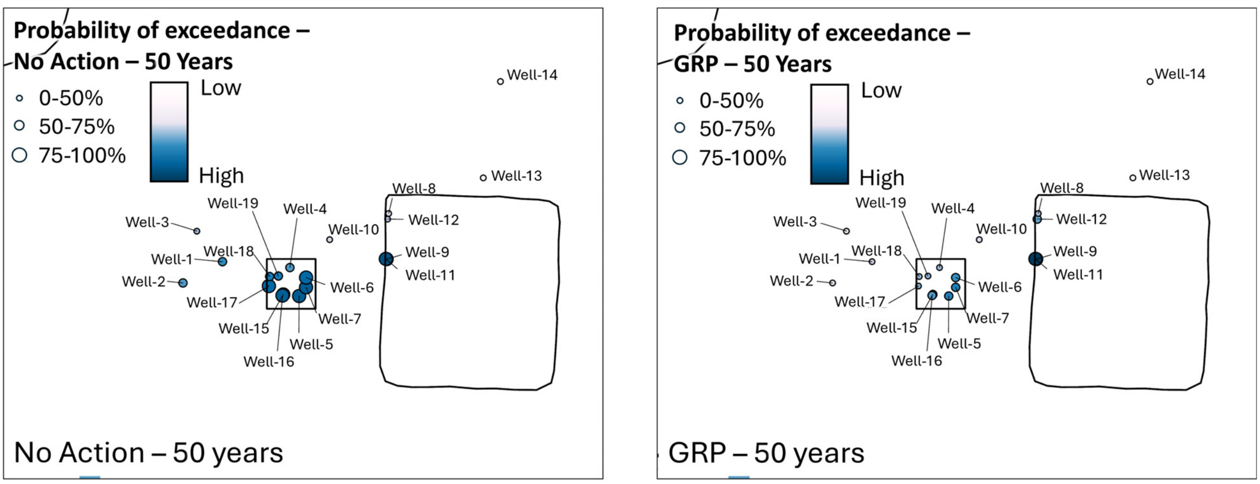
By 50 years (year 2074), the revised GRP pumping program has concluded, leading to a notable increase in the simulated risk of exceeding chloride background concentrations near the mill OB and TSF sources (Figure 13). At 50 years, the no action scenario maintains a relatively high risk of exceeding background chloride concentrations near these sources but also exhibits an elevated risk of exceeding chloride background concentrations towards the open pit (e.g. Well-1, Well-2, and Well-3) compared no action at 20 years and to the GRP pumping scenario at 50 years. Over the longer term, by 100 years (year 2124) and 200 years (year 2224; Figures 14 and 15, respectively), the probability of exceeding chloride background becomes comparable between the no action and GRP pumping scenarios.

In both predictive scenarios, the greatest risks of mill-impacted groundwater entering the aquifer persists near the mill OB and TSF sources once GRP pumping ceases, likely due to the long residences time of mass in the unsaturated zone and/or fine-grained lenses interrupting vertical transport. Without alternative GRP pumping configurations, the simulated groundwater chloride concentrations suggest that mill impacts to groundwater may persist over the long-term (e.g. more than 50 years).



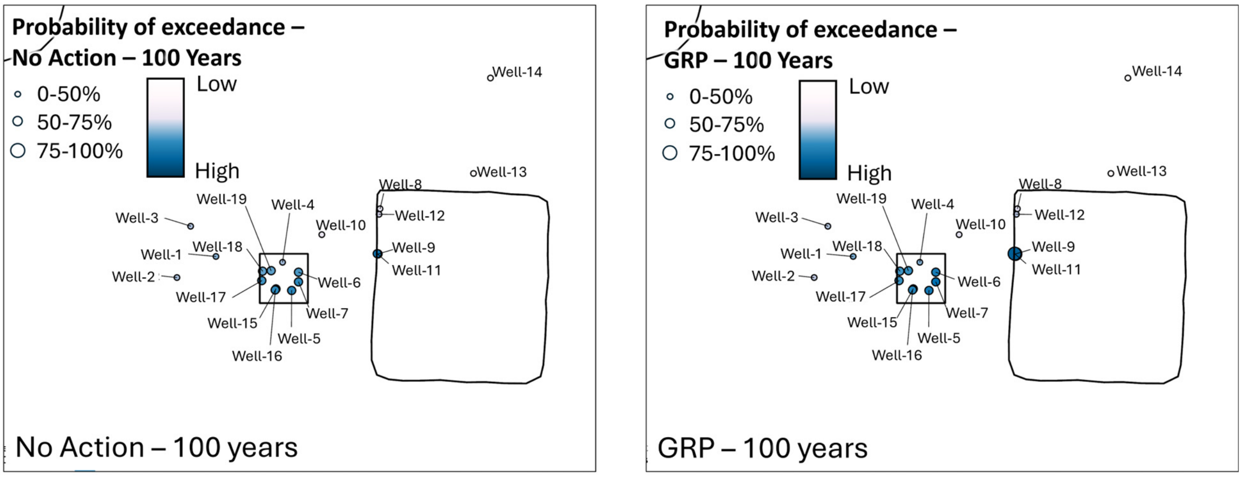
(a) (b)

Figure 12 Map displaying 20-year predictive probabilities of meeting chloride background concentrations under (a) no action and (b) GRP predictive pumping scenarios



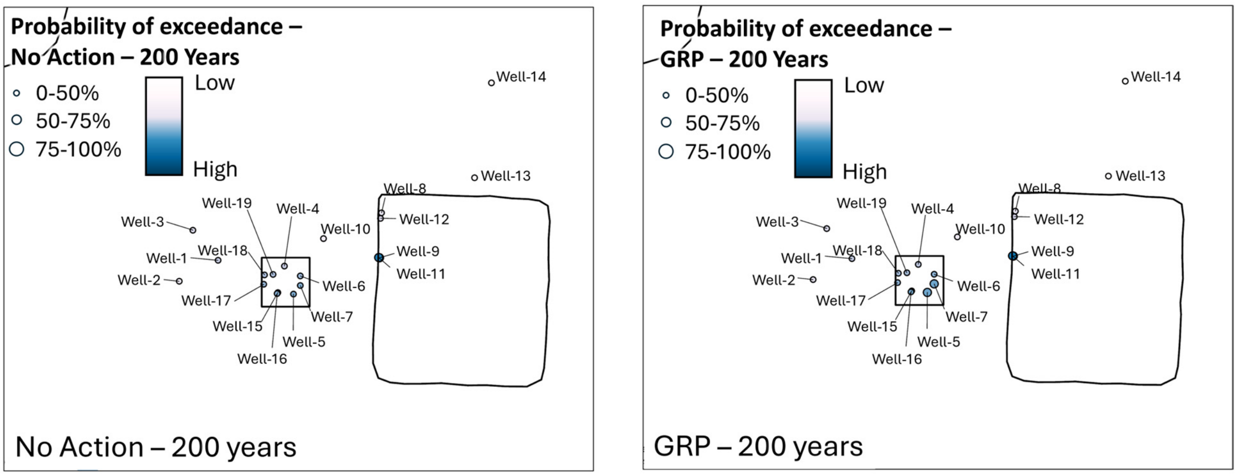
(a) (b)

Figure 13 Map displaying 50-year predictive probabilities of meeting chloride background concentrations under (a) no action and (b) GRP predictive pumping scenarios



(a) (b)

Figure 14 Map displaying 100-year predictive probabilities of meeting chloride background concentrations under (a) no action and (b) GRP predictive pumping scenarios



(a) (b)

Figure 15 Map displaying 200-year predictive probabilities of meeting chloride background concentrations under (a) no action and (b) GRP predictive pumping scenarios

4 Discussion and conclusion

At complex mine and mill closure sites with uncertain historical data, relying solely on deterministic modelling for groundwater remediation poses risks. Probabilistic modelling offers significant advantages by explicitly incorporating uncertainty, providing a more realistic representation of the system and quantifying the reliability of the GRP pumping efficacy, unlike deterministic models that offer a single, potentially misleading prediction. This approach also identifies key parameters influencing model outputs, strategically guiding future data collection. By exploring a range of plausible conditions, probabilistic modelling evaluates different conceptual site model interpretations and provides a distribution of potential GRP outcomes, enabling more robust, uncertainty-aware closure plans.

Given the absence of uniform quantitative standards for model calibration (Anderson & Woessner 1992), statistical methods and professional judgment remain essential for assessing model confidence relative to prediction goals. While calibration to site-specific data is crucial for reducing uncertainty and improving prediction reliability, expert judgment is vital to avoid the influence of questionable data or overfitting local-scale processes. It should be emphasised here that calibration, in its abstract meaning, extends beyond merely matching site measurements. Calibration also involves approximating the dominant flow and transport dynamics that govern the prediction of interest (i.e. GRP sufficiently lowering contaminant concentrations at compliance points), which the calibrated realisations (including unsaturated zone impacts) are considered to sufficiently capture for supporting the primary objective of this analysis. Additionally, if the silt or claystone lenses within the unsaturated zone exert any influence on the transport processes, they would likely induce greater dispersion to the contaminant plumes by introducing local heterogeneities in the velocity field. This would, in turn, lead to reduced contaminant concentrations at down-gradient points of compliance compared to those predicted by the calibrated model realisations. Hence, the predicted concentrations by these realisations represent the most conservative response from the system against the existing sources under the known site conditions, which is essential for assessing the performance of the remediation program (the main objective of this study).

Despite current limitations in local-scale transport calibration, the probabilistic approach provides valuable insights into future GRP efficacy and informs crucial next steps for data collection and conceptual model refinement. The probabilistic modelling identified important data gaps such as local-scale unsaturated zone influences (silt/claystone lenses), historical seepage volumes and concentrations, and background chloride concentrations. Future efforts should address these data gaps to reduce predictive uncertainty. The model also suggests the planned deterministic-derived pumping rates may be unsustainable, indicating lower, variable sustainable rates. While the GRP suppresses chloride during operation, a significant probability of rebound after cessation highlights the importance of vadose zone contributions and potential inadequacy of the current well configuration for long-term compliance.

In conclusion, this study demonstrates the superior value of probabilistic groundwater modelling over deterministic methods for assessing GRP effectiveness at complex mine closure sites. By incorporating and quantifying uncertainties, it provides a more realistic and informative evaluation, revealing potential risks like unsustainable pumping rates and post-pumping contaminant rebound due to vadose zone influences. Calibration challenges underscore the need for further investigation into local-scale processes to refine the conceptual site model. Ultimately, the probabilistic approach supports more informed and robust decision-making for long-term groundwater protection, emphasising the iterative nature of conceptual model development and the critical role of uncertainty analysis in remediation planning.

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