FINAL REPORT

Groundwater Modelling for the OGC Waihi Project: Predictive Uncertainty Quantification

Waihi
New Zealand

Prepared for:

OCEANAGOLD

PO Box 190,
Waihi, New Zealand

Prepared by:

INTERA

INTERA Geosciences Pty Ltd
166/580 Hay St
Perth, WA 6000

SEPTEMBER 2024

Executive Summary

Oceana Gold New Zealand Limited (OGNZL) is the owner and operator of the Waihi underground mine, a gold/silver mine, located in the town of Waihi on the North Island of New Zealand. The area around Waihi has been explored and mined for gold and minerals since 1879. Recent exploration projects have identified a gold and silver resource deposit beneath Wharekirauponga, north of Waihi. OGNZL proposes to recover this resource by developing an underground mine with the Wharekirauponga Underground (WUG) as part of the Waihi North Project (WNP).

As part of the consent applications for the WUG, several hydrogeological studies were undertaken, including the development of a numerical groundwater flow model developed by FloSolutions in 2023, with the objective of estimating potential impacts of the WUG on the groundwater environment and mine inflow rates into excavations. In order to assess and quantify the uncertainty associated with these predictions, OGNZL has commissioned INTERA to undertake the uncertainty analysis of the WUG model.

This report's descriptions of the theory, data, approaches, and results are intended for a reader with expertise and experience in predictive uncertainty analysis and decision support modelling. The technical vocabulary and details may be challenging and/or misleading for other readers, who may wish to first familiarize themselves with the technical background. Such readers may find value in the tutorials, webinars, and papers available at the Groundwater Modelling Decision Support Initiative's website, www.gmdsi.org.

The uncertainty analysis works included several updates in the original model setup, including the use of additional groundwater level data collected since the last calibration round, updated model parameterisation using the pilot point method to consider spatial variability of hydrogeological parameters and enable uncertainty analysis, and the development of several stochastic model realizations in agreement with conceptualisation and available monitoring data for assessment of uncertainty of the various predictions.

History-matching, also known as model calibration, was undertaken using the Iterative Ensemble Smoother method implemented by White (2018). Calibration results in general show a good agreement with historical observations, although a few elevated residuals remained and are possibly associated with model defects, such as the presence of small-scale structures that were not explicitly represented in the model.

The simulation of the life-of-mine and recovery periods provided estimates for the various predictions of interest and their associated uncertainty. Simulated drawdown results for 2035 (end-of-mine) show that while drawdowns are significant in the deep portions of the model (near the underground workings), drawdown at water table elevations are relatively small (less than 20 m) for the vast majority of the model domain. Recovery results obtained for 2045 (10 years after end-of-mine) suggest that groundwater levels will recover to near pre-mine levels, with residual drawdowns of up to 2 m at water table depths. Simulated groundwater flows show maximum inflow rates of 38l/s for peak flows at upper 95th percentile, stabilizing to values under 28 l/s from 2029 until end-of-mining.

The completion of this work identified opportunities for improvement in the current model form that can be beneficial for ongoing model development. These improvements include:

- Conversion of the current model form to MODFLOW6, facilitating its integration with uncertainty analysis tools and workflows;
- Conversion of the model to an unstructured grid, to enable local refinement and minimize computing requirements and improve the stability of the model;
- Continuous recalibration of the model as new data becomes available.

Table of Contents

List of Appendices

List of Figures

List of Tables

1. Introduction and background

Oceana Gold New Zealand Limited (OGNZL) is the owner and operator of the Waihi underground mine, a gold/silver mine, located in the town of Waihi on the North Island of New Zealand. The area around Waihi has been explored and mined for gold and minerals since 1879.

Recent exploration projects have identified a gold and silver resource deposit beneath Wharekirauponga, north of Waihi. OGNZL proposes to recover this resource by developing an underground mine with the Wharekirauponga Underground (WUG) project.

The WUG is part of the Waihi North Project (WNP) shown on Figure 1-1 , which aims to integrate with current and approved mining activities at Waihi and extend the life of mine from 2030 to 2038. Other components of the WNP include a new open pit mine (Gladstone Open pit), increased rock and tailings storage and increased processing capacity. A detailed description of the WNP, proposed WUG, declines, ventilation shaft locations and associated infrastructure can be found in section 3 of FloSolutions 2023a.

Hydrogeological investigations including drilling, hydraulic testing, monitoring, conceptual model development and numerical modelling were conducted by FloSolutions between 2021 and 2023 to support consent applications for the WUG. A groundwater effects assessment is required as part of consent and must consider mine inflows, groundwater drawdown, deep recharge, potential effects on shallow groundwater and any potential impacts to streams, waterways, and reductions in baseflow. A numerical groundwater flow model was developed as part of the consent application. The modelling objectives were to evaluate potential impacts of the WUG and inform a groundwater effects assessment of the proposed WUG project.

FloSolutions constructed a 3D numerical groundwater model in MODFLOW-USG (Panday et al 2013), with pre- and post-processing facilitated with Groundwater Vistas, a graphical user interface, used to build, run, and visualise MODFLOW models.

The model was built with a structured (regular) grid with 294 rows and 200 columns varying in size from 35m regionally, to 15m node spacing near the mine. Vertically, there are 38 layers represented in the model, which are each approximately 15m thick. The model has a total of 1,589,359 active nodes.

The numerical model domain spans approximately 4.5km x 5km and covers the entire Wharekirauponga Stream catchment and half of the catchments of adjoining streams (Figure 1-2). The elevation of model top ranges from 43m to 745m and the model base is flat at – 400 m. Conceptual shallow groundwater flow is from the SW to NE (FloSolutions, 2023b).

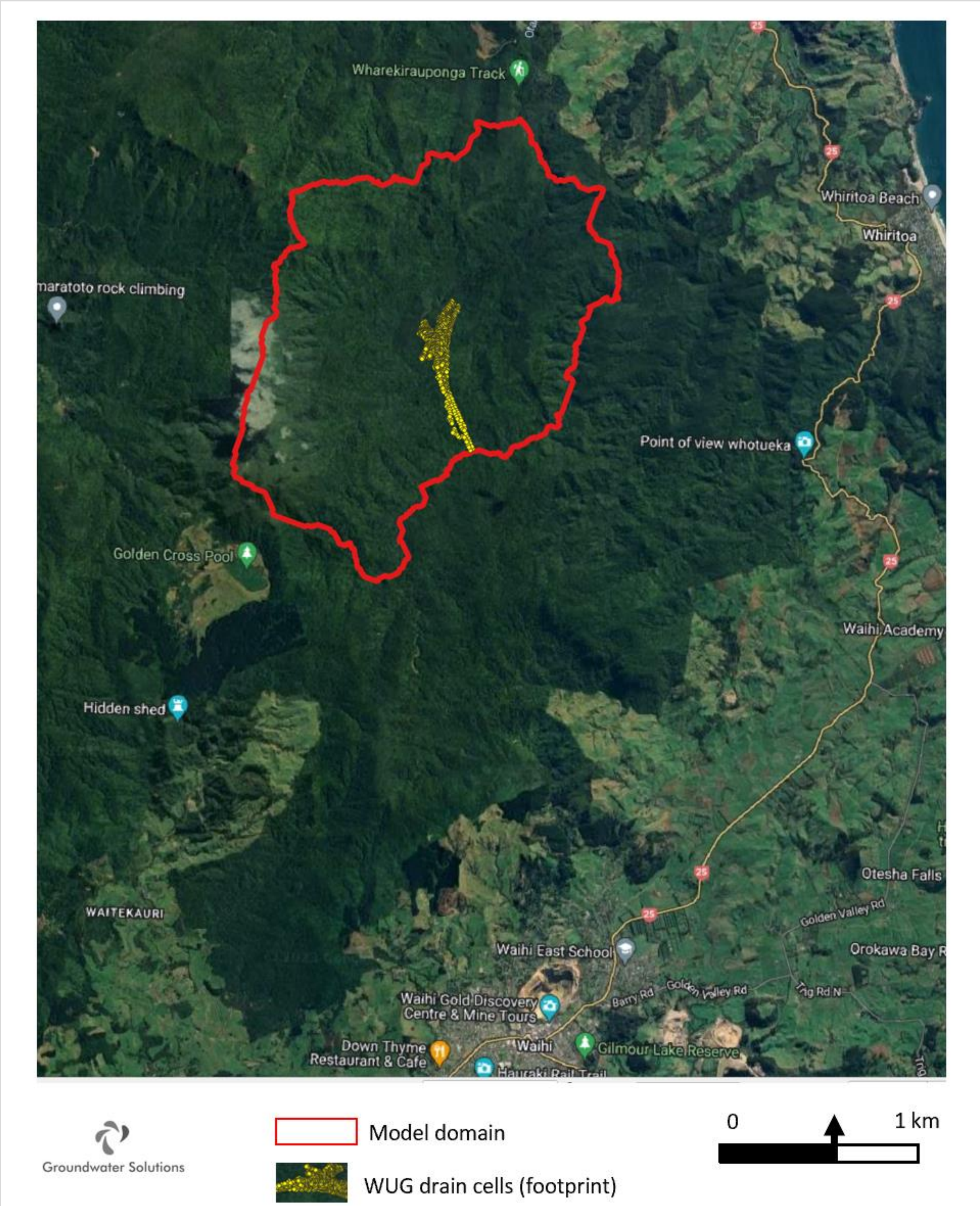

Figure 1-1 - Location of the WUG (mine footprint based on FloSolutions drain configuration).

The model simulation time is divided into four periods (Table 1) with numerical solutions for the steady state, transient calibration, and predictive periods of mine development including recovery.

In the numerical model files, constructed by FloSolutions, each of these four simulation periods was represented in a separate model.

Model boundary conditions were applied to represent the following:

- areal recharge to groundwater across the surface of the model;
- surface water interaction with groundwater using river and drain boundaries;
- groundwater movement out of the model at depth through an interpreted faulted zone using general head boundaries;
- and the act of mine dewatering using drain boundaries (Figure 1-3).

The conceptual model of hydrogeological units developed by FloSolutions (2023a) was used to assign 23 unique hydrostratigraphic zones (HSU zones) across the model domain (Figure 1-2) and apply hydraulic conductivity and storage parameters.

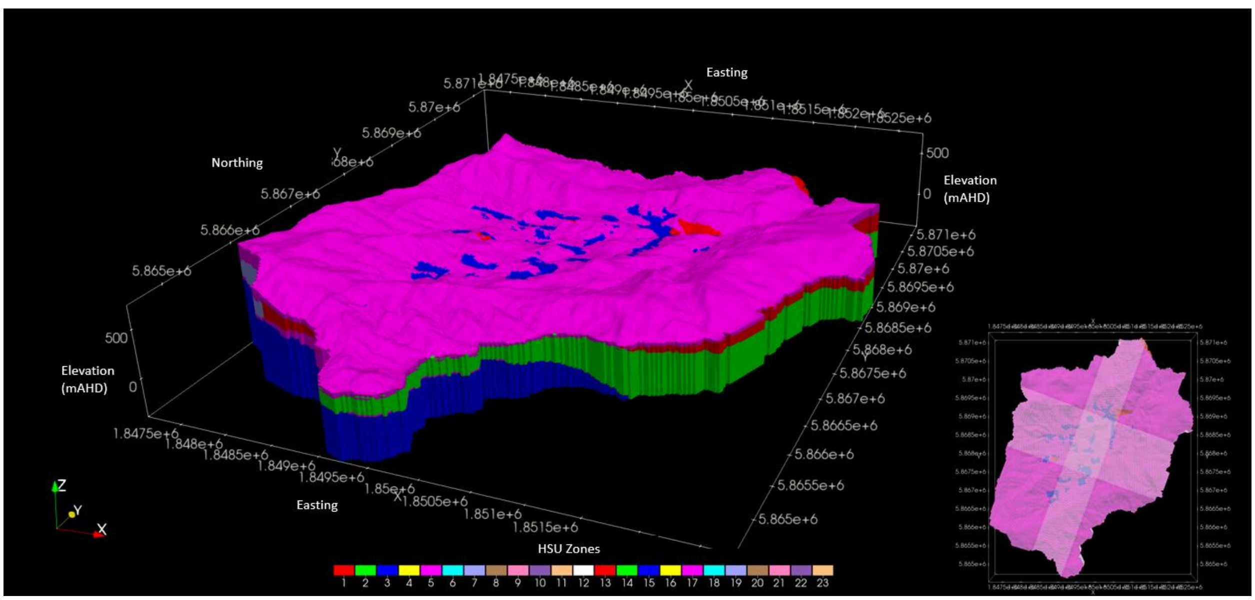

Figure 1-2 - Model domain and spatial discretization.

Table 1 - Temporal discretization used by the numerical model.

Stress period	Stress period duration	Description
Steady state model		
1	Long Term Equilibrium	Steady state: develops initial pre-development conditions in response to modelled hydraulic parameters and boundary conditions.
Transient calibration model		
2 – 54	Monthly	Calibration period from December 2018 to March 2023, simulates groundwater response to time varying recharge, river and drain boundary conditions representing variations in precipitation and surface water stage.
Predictive model		
55 - 79	6 Monthly	Represents proposed underground mining at WUG from January 2023 to January 2035
Recovery		
80	40 years	Represents groundwater recovery from end of mining in 2035 to 2075

A detailed description of the model build and hydrogeological conceptualisation can be found in FloSolutions 2023b and is beyond the scope of this document.

Consent applications to develop an underground mine and associated infrastructure at WUG were submitted to Waikato Regional Council in June 2022. Groundwater Solutions Pty. Ltd. (GS) was sub-contracted by INTERA to conduct a review and update of the numerical groundwater modelling. The modelling review and updated methodology applied a calibration constrained predictive uncertainty analysis to update the model calibration, and better quantify the uncertainty of the model predictions.

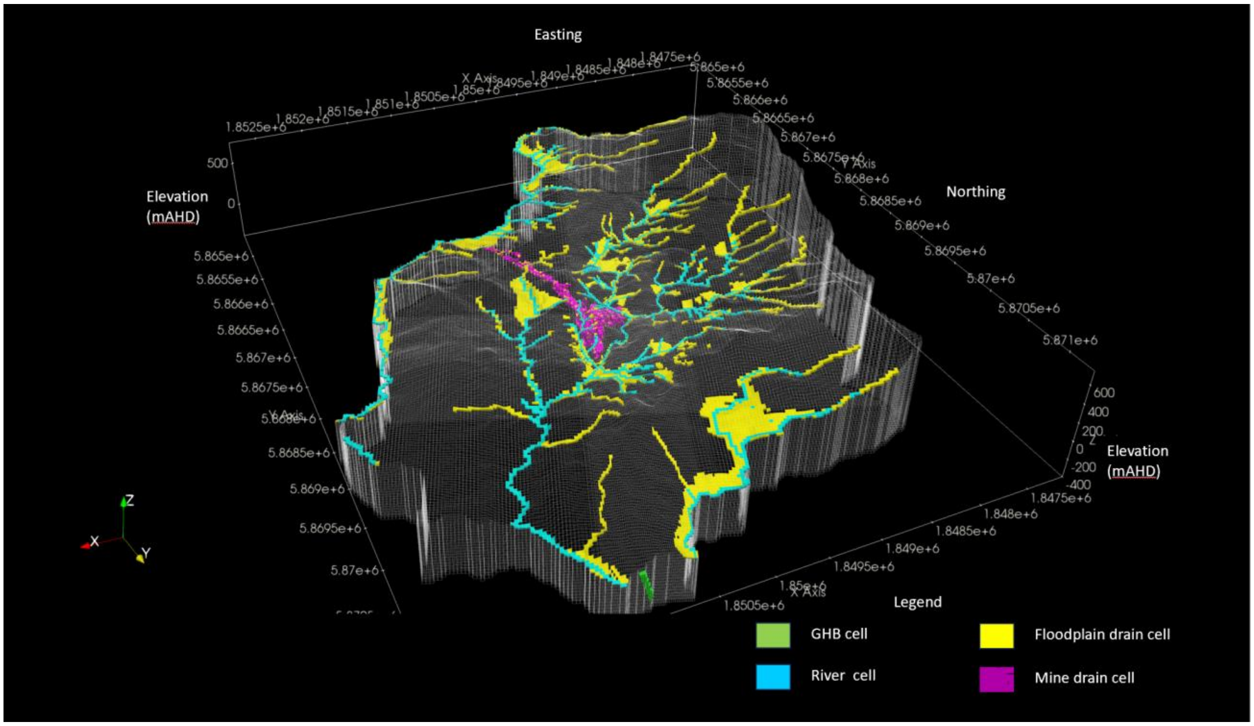

Figure 1-3 - Boundary conditions of predictive model showing drain cells (yellow), river boundaries (blue), general head boundary cells (green) and drain cells representing mining at WUG (pink).

2. Modelling objectives and Scope of work

The numerical groundwater modelling described in this report was designed to predict:

- Potential baseflow reductions to surface water due to WUG development;
- Potential drawdown impact to groundwater due to WUG development;
- Mine inflow rates into excavations;
- Post mining recovery level.

Additionally, a quantitative assessment of the predictive model uncertainty was required to allow risk-based decision-making. This involved updating the modelling conducted by FloSolutions including the following tasks:

- Update model parameterisation using the pilot point method to consider spatial variability in hydraulic parameters and areal groundwater recharge across zones.
- Review, revise and process the model calibration targets to calibrate to observed differences in steady state hydraulic head, first observed hydraulic head measurements at monitoring

locations with timeseries observations, and changes or drawdown from the first hydraulic head observation.

- A steady state model calibration and parameter uncertainty analysis using the iterative ensemble smother (IES) method. This step generated multiple alternative model parameter sets that all produced predictions that matched the observation data (within acceptable error).
- Construct an updated predictive model that combines the steady state and transient calibration models with predictive simulation of project development and a forty-year recovery period.

All modelling was conducted in accordance with principles and guidance outlined in the Australian Groundwater Modelling Guidelines (Barnett et al, 2012). However, the guiding principle of the project that defined the approach was based on recent documentation detailing best practice for groundwater modelling within a risk-based framework (Peeters and Middlemis, 2023).

This approach focuses on the inherently uncertain prediction of interest, and views the modelling process as a method of using observation data and a conceptual model to reduce the predictive uncertainty. The Australian groundwater modelling guidelines propose a qualitative class-based system to assess the groundwater model and associated predictive capability based on numerous metrics. This project follows the updated modelling guidance and focuses on the predictions of interest and the capability to provide predictions with quantitative uncertainty analysis. This allows probabilistic, risk-based decisions to be made on operational and environmental factors.

3. Model calibration

Calibration involves an iterative process of adjusting hydrogeological parameters, subject to conceptualisation constraints, so that the simulated output matches the historical observations within acceptable error. It is conducted to improve confidence in the predictions generated by the model. However, groundwater models cannot predict exactly what will happen in the future, only what likely won't happen. A crucial role of models in the decision-making process is to assess the likelihood of various scenarios occurring (Doherty 2011). Consequently, to evaluate the range of potential inflow volumes, drawdown magnitudes and recovery curves, model predictive uncertainty analysis was conducted during the calibration and uncertainty analysis process. The calibration process included use of PESTPP-IES (White et al 2020), an open-source implementation of the ensemble-smoother form of the Gauss-Levenberg-Marquardt algorithm for computationally efficient history-matching (White, 2018). The iterative ensemble smoother method used by PESTPP-IES is an approximation method used to solve the inverse problem during calibration. Ensemble methods start with a group or "ensemble" of parameter realisations and the model is run with each parameter realisation. The Jacobian matrix (sensitivity matrix between model parameters and simulated observations) is approximated based on average values of simulated observations and parameters across the entire ensemble of realisations. Unlike earlier versions of PEST, where the Jacobian was calculated and required the model to be run once for each parameter, PESTPP-IES only requires as many model runs as there are parameter realisations. Consequently, PESTPP-IES is considerably more computationally efficient than previous versions of PEST when using large numbers of parameters and has the added advantage that calibration and uncertainty analysis are conducted simultaneously. This greater efficiency allows for higher model parameterisation so that more information can be extracted from the observation dataset. PESTPP-IES is a stochastic calibration where many realisations converge upon the parameter set yielding the best fit between measured and simulated observations, while keeping in agreement with hydrogeological conceptualisation.

3.1 Parameterisation

All adjustable hydrogeological model parameters, as set in FloSolutions (2023a), were included in the model calibration. These included the most sensitive parameters relevant to the predictions of interest, such as horizontal hydraulic conductivity, vertical hydraulic conductivity anisotropy, specific storage, specific yield, and recharge. Initial model parameters were divided into 23 HSU zones for hydraulic parameters and 8 recharge zones to represent the conceptual hydro-stratigraphic model as defined in FloSolutions 2023a. Model parameterisation was updated to use the pilot point method to apply a spatially variable field to parameter zones that can better reflect the heterogeneity and uncertainty that is inherent in groundwater systems (Tonkin and Doherty, 2009). Pilot points are sets of point locations where model properties (parameter values) are specified. The pilot point method of parameterisation enables definition of spatially variable parameter fields across model domains with far fewer parameters than mesh elements, and regular spaced parameter values can be applied to a mesh with irregular refinement.

Pilot points allow hydraulic properties to assume spatially variable values within the model domain, by defining plausible parameter value ranges which are then interpolated across the entire model domain using a geostatistical technique called kriging. Parameter values defined at pilot point locations were interpolated onto the model grid using PLPROC Software (Doherty, 2015b). A regular 3D grid of points with 200m lateral spacing and 100m vertical spacing was defined across the full model domain, and a refined grid of 50m lateral and vertical spaced points were used in the local area of the project. To capture the narrow, continuous, and high permeability Edmonds fault zone in the conceptual model, additional pilot points were added along this feature (Figure 3-1). Pilot point locations for hydraulic property parameters are shown in Figure 3-1 and Figure 3-2. The parameter initial values and ranges are listed in Table 2.

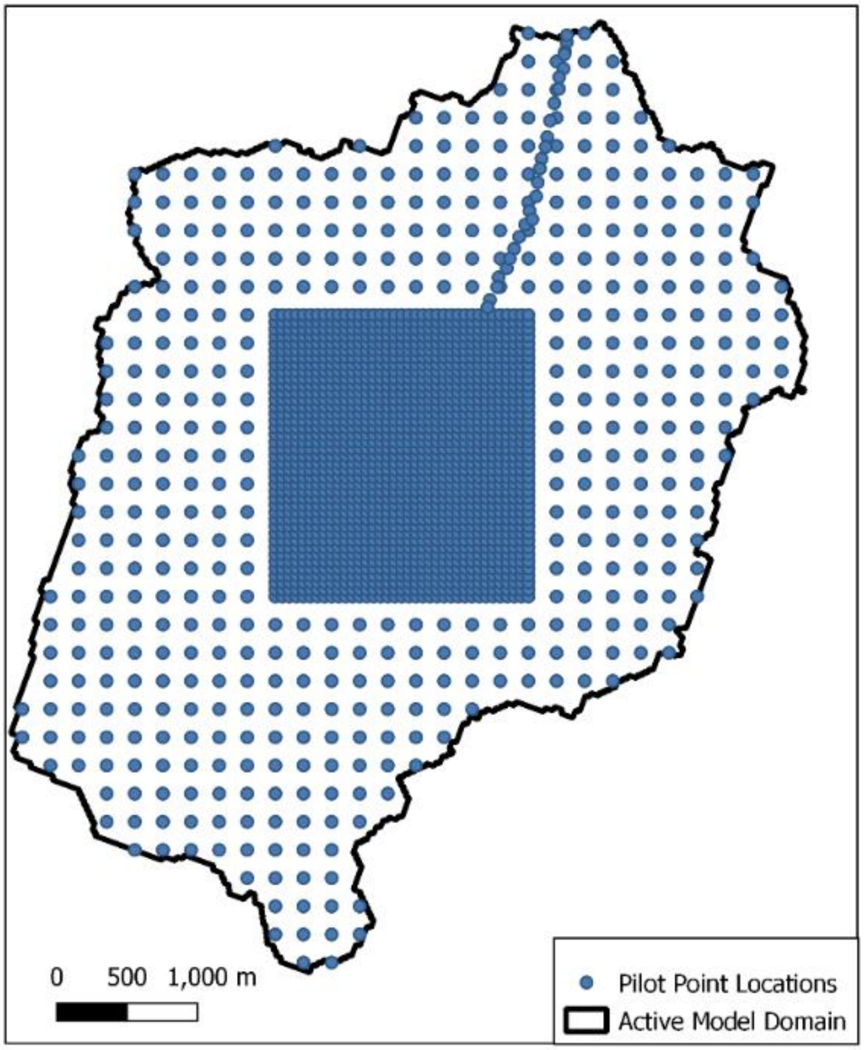

Figure 3-1 - Plan view of pilot point locations.

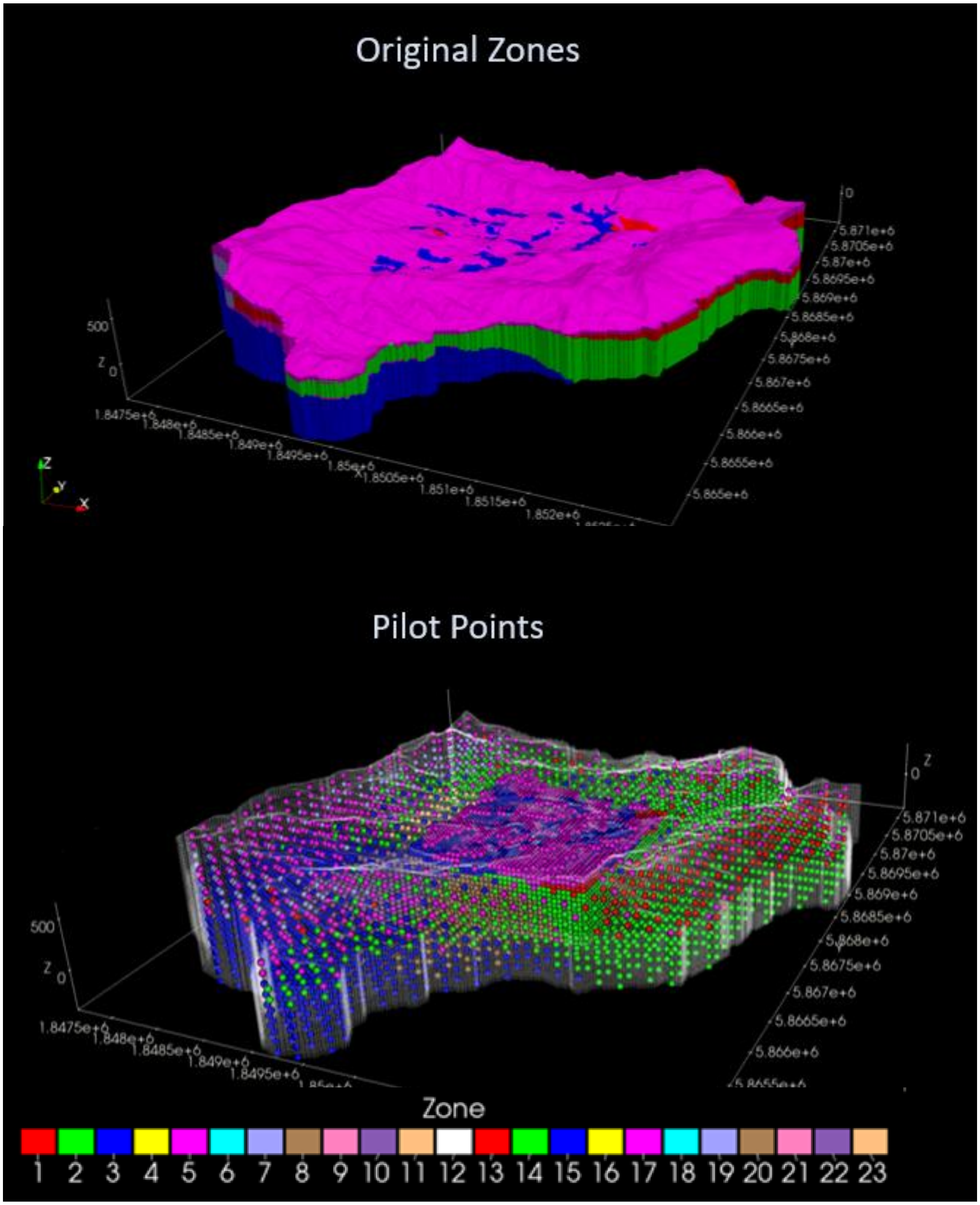

Figure 3-2 - 3D view of pilot point locations.

Table 2 - Initial hydraulic parameter values and bounds.

HSU Zone	Hydro stratigraphy	Horizontal Hydraulic Conductivity (m/s)			Vertical Hydraulic Conductivity Anisotropy (Hk/Vk)			Specific storage (1/m)			Specific Yield(%)		
		Initial value	Minimum	Maximum	Initial value	Minimum	Maximum	Initial value	Minimum	Maximum	Initial value	Minimum	Maximum
1	Post Mineral Andesite Cover	2.1E-07	4.2E-09	1.1E-05	5.0E+00	1.0E+00	5.0E+01	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	1.0E+01
2	Rhyolite Volcaniclastics	1.0E-09	1.0E-10	5.0E-08	1.0E+01	1.0E+00	1.0E+02	5.0E-06	1.0E-06	1.0E-05	4.0E+00	1.0E+00	7.0E+00
3	Western Deep Andesite Flow	5.0E-10	1.0E-10	2.5E-08	2.5E+00	1.0E+00	2.5E+01	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	5.0E+00
4	Dyke	5.0E-10	1.0E-10	2.5E-08	1.0E+00	1.0E+00	1.0E+01	5.0E-06	1.0E-06	1.0E-05	1.5E+00	1.0E+00	5.0E+00
5	Weathered Zone	1.5E-06	3.0E-08	7.5E-05	1.8E-01	1.0E-01	1.0E+01	1.0E-05	1.0E-06	1.0E-05	8.0E+00	1.0E+00	1.5E+01
6	T-Stream Vein	7.8E-07	1.6E-08	3.9E-05	4.9E+01	1.0E+00	5.0E+02	5.0E-06	1.0E-06	1.0E-05	3.5E+00	1.0E+00	1.0E+01
7	South Colluvium	5.0E-10	1.0E-10	2.5E-08	3.3E+00	1.0E+00	5.0E+01	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	5.0E+00
8	Eastern Rhyolite Intrusive Dome	2.1E-08	4.2E-10	1.1E-06	1.6E+00	1.0E+00	5.0E+01	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	5.0E+00
9	North Rhyolite Flow Dome	1.0E-07	2.0E-09	5.0E-06	4.0E+02	1.0E+01	7.0E+02	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	5.0E+00
10	South Rhyolite Flow Dome	5.0E-10	1.0E-10	2.5E-08	1.0E+00	1.0E+00	1.0E+01	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	5.0E+00
11	Western Rhyolite Dome	5.0E-10	1.0E-10	2.5E-08	7.3E+00	1.0E+00	5.0E+01	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	5.0E+00
12	EG_I	4.8E-07	9.6E-09	2.4E-05	5.0E+01	1.0E-01	1.0E+02	5.0E-06	1.0E-06	1.0E-05	3.5E+00	1.0E+00	8.0E+00
13	EG_2	1.3E-08	2.6E-10	6.5E-07	1.7E+00	1.0E-01	5.0E+01	5.0E-06	1.0E-06	1.0E-05	3.5E+00	1.0E+00	8.0E+00
14	EG_3	1.0E-05	2.0E-07	5.0E-04	4.8E+01	1.0E-01	1.0E+02	5.0E-06	1.0E-06	1.0E-05	3.5E+00	1.0E+00	8.0E+00
15	Alteration Zone	1.1E-08	2.2E-10	5.5E-07	7.3E+00	1.0E-01	5.0E+01	5.0E-06	1.0E-06	1.0E-05	3.0E+00	1.0E+00	8.0E+00
16	contact zone	5.0E-08	1.0E-09	2.5E-06	1.0E+00	1.0E-01	1.0E+01	5.0E-06	1.0E-06	1.0E-05	3.0E+00	1.0E+00	8.0E+00
17	Med-Depth Andesite Flow	5.0E-10	1.0E-10	2.5E-08	2.5E+00	1.0E+00	2.5E+01	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	5.0E+00
18	South Edmonds	2.0E-05	4.0E-07	2.0E-04	3.0E+02	1.0E-01	5.0E+02	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	8.0E+00
19	North Edmonds	3.0E-05	6.0E-07	3.0E-04	3.0E+02	1.0E-01	5.0E+02	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	8.0E+00
20	Hihger K Rhyolite Volc	1.2E-08	2.4E-10	6.0E-07	1.0E+01	1.0E+00	1.0E+02	5.0E-06	1.0E-06	1.0E-05	6.0E+00	1.0E+00	8.0E+00
21	Upper_EG_3	1.0E-10	2.0E-11	5.0E-09	4.8E-01	1.0E-01	1.0E+01	5.0E-06	1.0E-06	1.0E-05	3.5E+00	1.0E+00	8.0E+00
22	Upper_South Edmonds	2.0E-10	1.0E-10	1.0E-08	5.4E-01	1.0E-01	1.0E+01	5.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	8.0E+00
23	Upper_North Edmonds	3.0E-10	1.0E-10	1.5E-08	8.1E-01	1.0E-01	1.0E+01	1.0E-06	1.0E-06	1.0E-05	2.0E+00	1.0E+00	8.0E+00

3.1.1 Recharge parameters

Eight recharge zones were defined based predominantly on topography (elevation threshold levels) and the presence of an altered clay zone in the centre of the domain (Table 3). Further information is provided in section 4.3.3.2 of FloSolutions 2023b. A monthly timeseries multiplier was applied to the steady state recharge parameters for the transient calibration simulation and the steady state values were applied for the predictive simulations. To update the parameterisation to better reflect the uncertainty in recharge, a regular 200m grid of pilot points was defined across the model domain with initial values and bounds based on the original zones. Recharge multipliers in the transient calibration period were adopted from the FloSolutions modelling (FloSolutions, 2023b). Recharge pilot point locations and the original zones are shown in the table below with initial values and bounds listed in Table 1.

Table 3 - Initial recharge parameter values and bounds.

Zone	Recharge (m/d)	Maximum	Minimum
2	7.00E-04	1.40E-03	7.00E-05
3	7.00E-04	1.40E-03	7.00E-05
4	1.00E-07	2.00E-07	1.00E-08
5	4.00E-06	8.00E-06	4.00E-07
6	8.00E-05	5.00E-04	1.60E-06
7	3.00E-04	6.00E-04	3.00E-05
8	7.00E-04	1.40E-03	1.40E-05
9	3.00E-04	1.00E-03	6.00E-06

The pilot point parameterisation for hydraulic properties and recharge resulted in 94,872 unique parameters that were considered in the model calibration and predictive uncertainty analysis.

3.2 Observation data

Vibrating wire piezometer and groundwater level data from 2018 to 2023 was provided by OGNZL. A review of the provided data found that some of piezometer data lacked reference levels and there was ambiguity about measurement location, so to expedite the scope of work the targets in the provided model files were adopted as the calibration dataset, which also required the application of weightings in some cases during the calibration process (see more details later).

3.3 Calibration targets

Targets in the provided steady state and transient calibration models were reviewed and compared to initial model simulated values. Targets developed by FloSolutions included estimated steady-state average water levels at 48 unique locations and a time series of hydraulic head with earliest measurements in 2018 and latest in 2023 at 29 locations. Several observation locations had transient target values that were significantly inconsistent with initial simulations using the model zones and parameter values documented in FloSolutions 2023b. In these situations, the estimated steady-state levels were replaced by the first head measurement of each borehole.

Calibration target processing included calculating the differences between all unique steady state hydraulic head targets. Additionally, the differences between transient observations and the first observed value after the estimated steady state target were calculated at all locations with time series observations. Model calibration to differences in observations provides additional information to the calibration process and can better inform predictions of interest (Doherty, 2015a).

Observation locations with uncertain observations and or potential errors were given a lower weight in the calibration and omitted from the calculation of head difference targets.

Estimated surface water baseflow provided four additional calibration targets that were simulated by extracting the total flux out of river and drain boundary conditions representing surface water upstream from the monitoring location where the estimated baseflow was available.

Total model calibration targets included:

- 44 steady state hydraulic head targets,
- 4 steady-state, estimated average river baseflow targets,
- 946 steady state, hydraulic head difference targets,

Steady state head and baseflow targets used in the calibration are listed in Appendix A.

3.4 Steady state calibration

Given that the transient groundwater level showed little variation and response to processes that could inform the model parameters, the initial model calibration effort was focused on only the steady state simulation of long-term equilibrium groundwater flow. Adjustable parameters were log-transformed to increase optimisation efficiency. Optimum parameter values were constrained to lie between specified upper and lower bounds, which were based on available field data and literature values. An ensemble of 300 alternative initial (prior) parameter sets were generated based on random values drawn from Gaussian distributions defined by the hydraulic conductivity and recharge parameter bounds listed in Table 2 and Table 3. One parameter realization called the 'base parameter set' had initial values assigned from the starting parameters in the FloSolutions model provided, listed as initial values in Table 2 and Table 3.

The calibration process iteratively minimizes an objective function that is made up of the weighted sum of squared differences between observations and the equivalent model simulations. The calibration ran through five iterations. Plots of the model fit to observation data are shown in Figure 3-3. The base realization, shown in blue, is the result of what would be traditionally referred to as the 'calibrated model' while the ensemble results (in grey) represent the remaining uncertainty after calibration. Ideally the range of the ensemble should cover the 1:1 line of best fit dashed black line) and reduce in range as parameters are informed by observations.

The model fit with steady state head observation data is improved from the FloSolutions result, however there are observation locations that have remaining residuals (Figure 3-5), in particular in multi-level locations (such as WKP05D), where massive vertical head differences (over 70m) are observed between the different monitoring levels.

Calibration performance was statistically quantified using SRMS error given as a percentage:

$$SRMS = \frac{100}{\Delta h}\sqrt{\frac{1}{n}\sum_{i=1}^{n}[W_i(z_{hi} - h_i)]^2}$$

where:

- ***Δh*** is the range of measured observations
- ***n*** is the number of measurements in the calibration dataset
- W_i is the statistical weighting (unitless) applied to measurement ***i***
- h_i is the measured value of observation ***i***.
- z_{hi} is the modelled result equivalent to observation ***i***

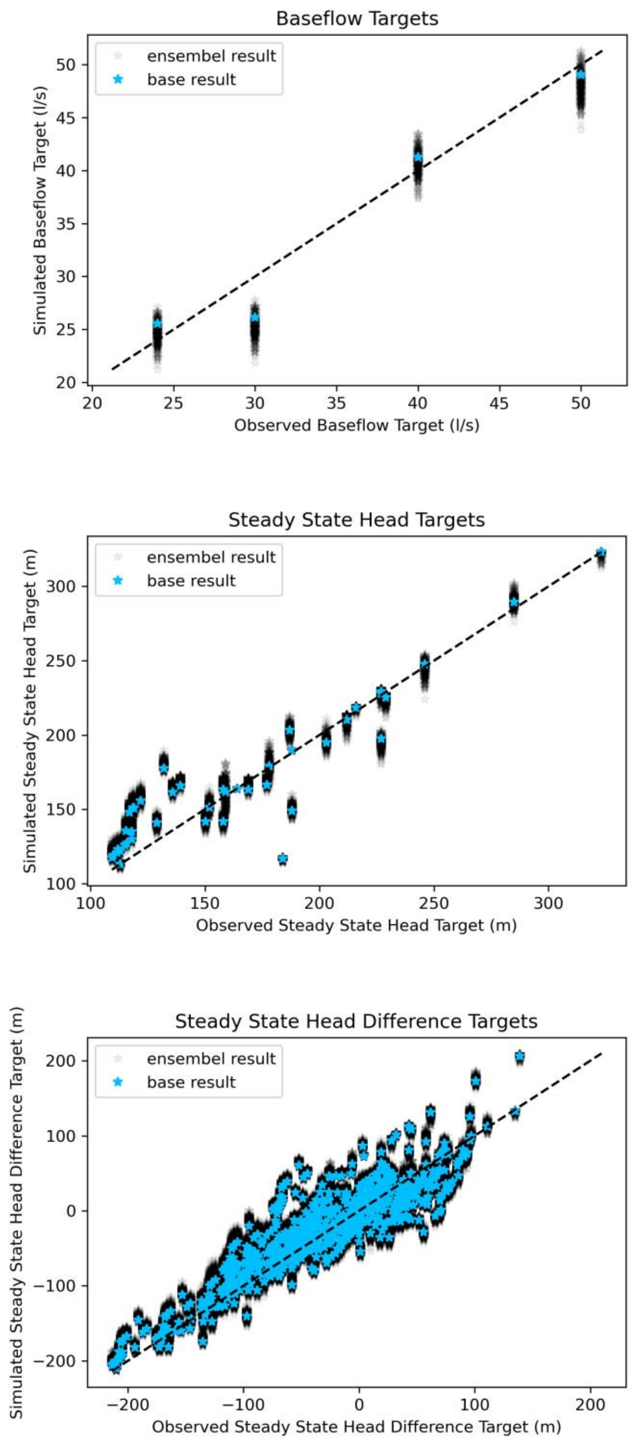

Figure 3-3 – Summary of calibration results.

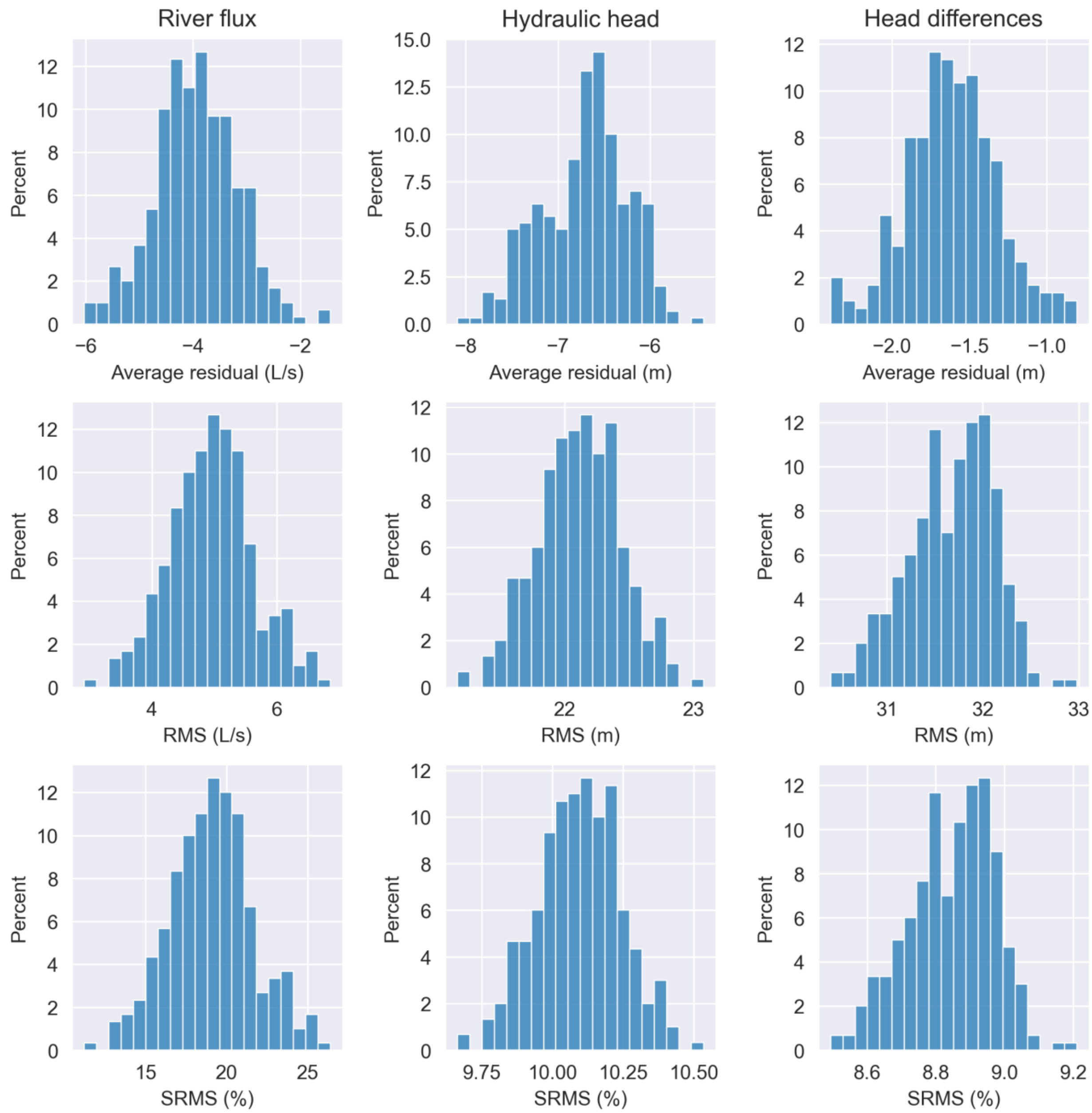

Figure 3-4 – Calibration histograms for all realizations, grouped by observation type and calibration metric.

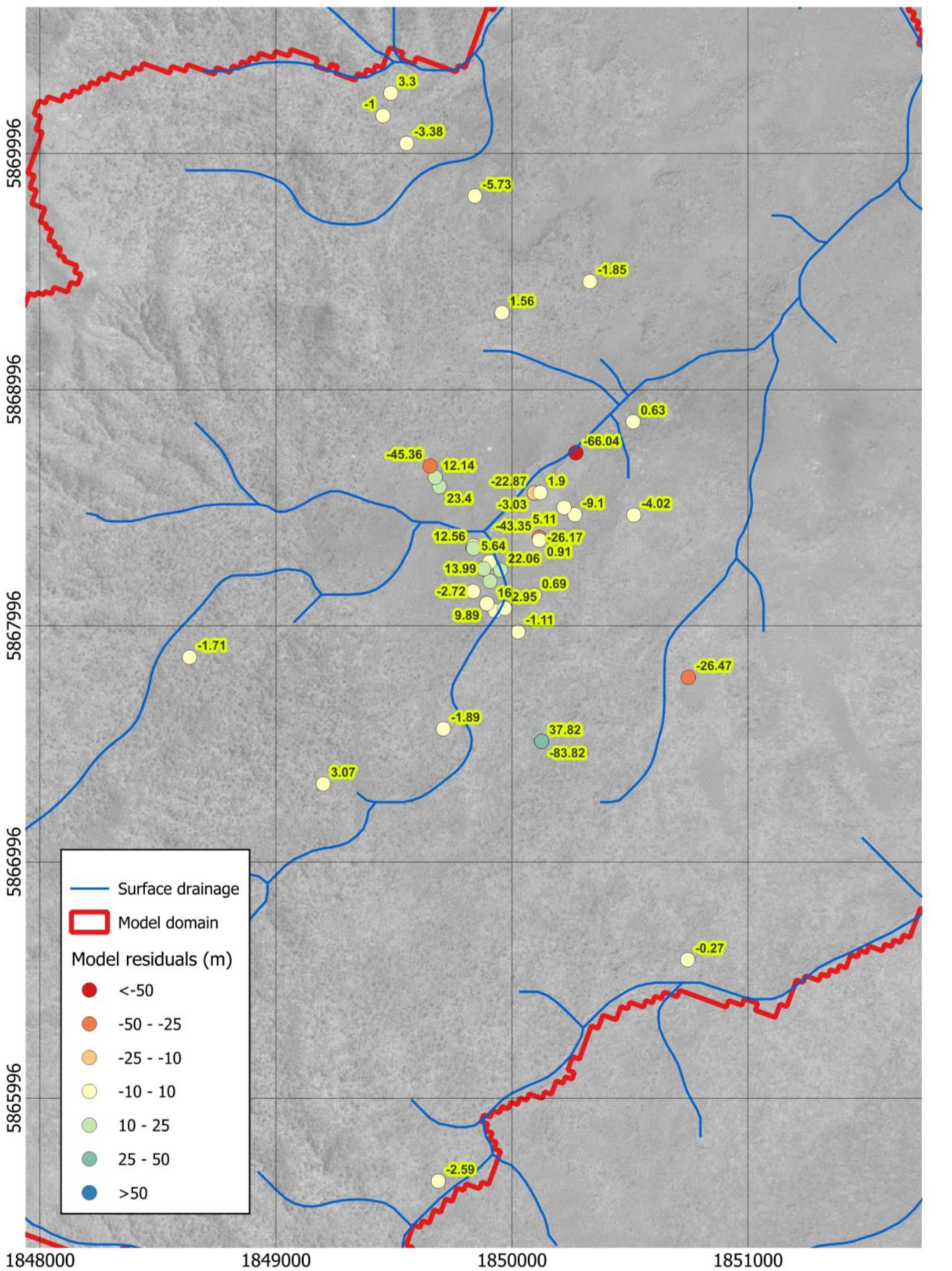

Figure 3-5 – Distribution of pre-mine simulated mean head residuals.

Details of the calibration statistics for the base parameter set are listed in Table 4. There is a large range in observed hydraulic head values, and subsequently, head difference observations, due to the topographic relief of the model domain. There are some residual discrepancies between simulated results and corresponding observations in in both hydraulic head and head difference observation groups. The inability of the calibration process to further reduce model residuals and the fact that some observations do not have an ensemble range that spans the 1:1 line of best fit in either the initial prior, or calibrated iteration 5 results in Figure 3-3, suggests that results may be influenced by data and model defects (i.e., inability of the numerical models to fully represent the true groundwater system). Calibration data error (value and location), and aspects of the model that are inconsistent with the true groundwater system can both result in an inability to match observation data even with highly parameterised approaches. It is likely that localized faulting and fractures will have a large influence on the groundwater flow system, and significant uncertainty in the location and extent of smaller scale fractures across the model domain remains. The reduction in observation residuals between the initial simulations and the resulting IES iteration 5 ensemble shows that the updated parameters were informed by the calibration process and, at this stage of model development and observation data analysis, form the best available input parameters for predictive simulations.

Table 4 - IES iteration 5 - base realization calibration statistics.

Metric	Steady state heads (m)	Head differences (m)	River Flux (l/s)
SRMS	10.0	8.7	13.2
RMS	21.9	31.0	3.4
Minimum residual	-20.5	-104.7	-1.0
Maximum residual	74.7	105.2	6.6
Average residual	7.5	2.4	1.9
Measurement range	219.1	358.1	26

Despite the limited data coverage of hydraulic heads and surface water fluxes, the model calibration enabled a considerable reduction in parameter uncertainty. This can be observed by calculating the reduction in parameter uncertainty (which is the ratio between standard deviation of pre- and post-calibration parameter values, as displayed in Figure 3-6), and by directly comparing pre- and post-calibration distributions on a parameter basis (displayed for selected parameters on Figure 3-7). These plots show a significant reduction in uncertainty, occurring (as expected) mostly in pilot points located near observation points.

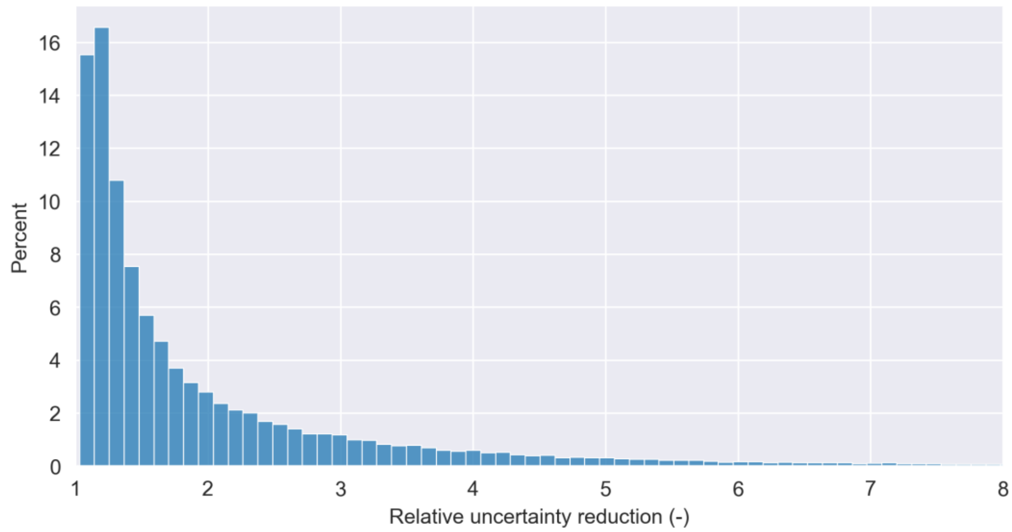

Figure 3-6 - Histogram of parameter uncertainty reductions (pre- / post-calibration standard deviations) for all parameters.

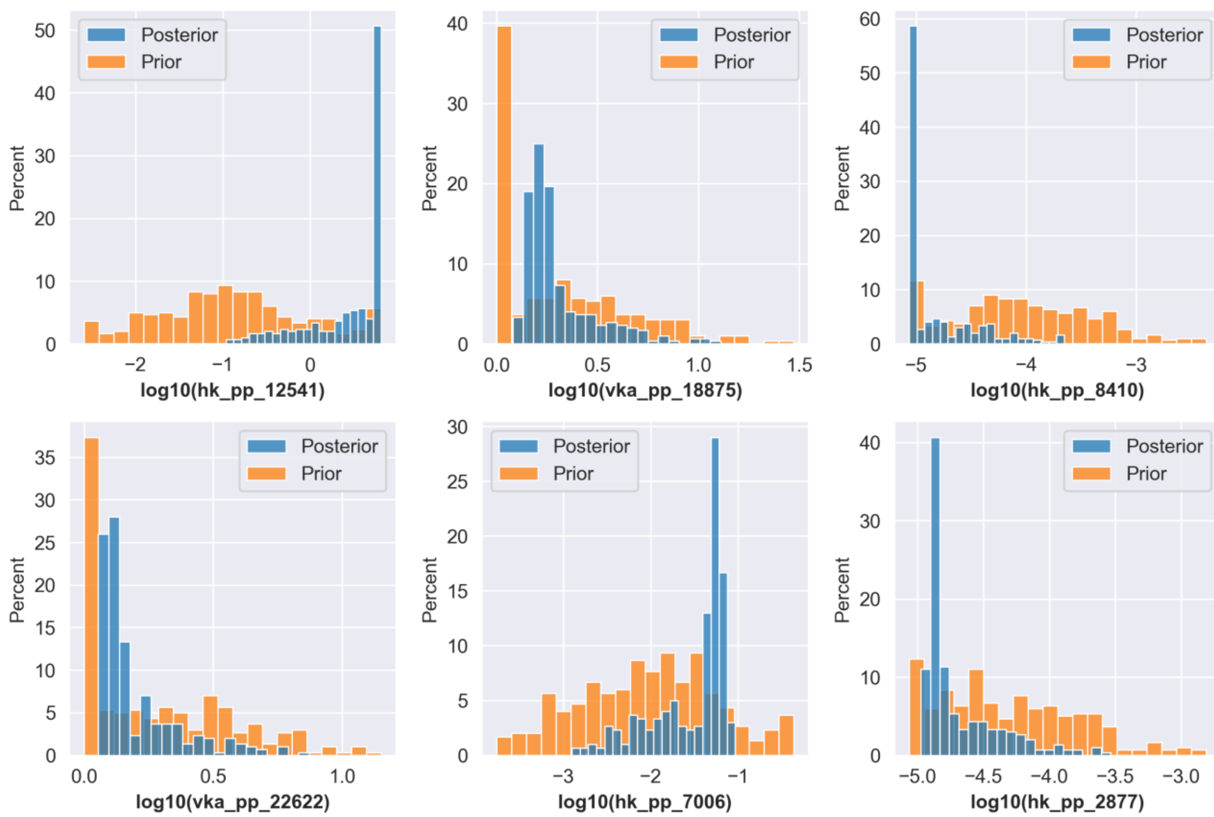

Figure 3-7 - Comparison of pre- and post- calibration values for selected parameters (hk – horizontal hydraulic conductivity in m/d, vka – vertical anisotropy Kh/Kv).

4. Predictive modelling

A transient predictive model was formed by merging the provided model files to simulate the four phases listed in Table 1 in a single simulation including:

- steady state simulation of background groundwater conditions,
- transient simulation of groundwater response to time varying recharge and river boundaries through the timespan of transient observation data collection (2018-2023),
- transient simulation of project development from 2023 to 2035, and
- groundwater recovery for 40 years after project development (2035 to 2075).

The steady state simulation of groundwater flow does not include storage parameters so the steady state calibration provides no information on appropriate storage parameter values. Initial realizations of storage parameters were generated from Gaussian distributions defined by the parameter bounds defined in Table 2 and combined with the hydraulic conductivity and recharge parameter ensemble that resulted from the steady state calibration. An ensemble of 150 parameter realizations informed by the steady state calibration was used in the predictive uncertainty analysis. Model predictions followed the results documented in FloSolutions 2023b, and included:

- Predicted changes in hydraulic head at the same times and locations as the transient model calibration data.
- Predicted hydraulic head at all observation locations listed in Appendix A over the 2023-2075 simulation of project development and recovery.
- Predicted groundwater baseflow to 9 watersheds over the transient calibration and predictive period 2018-2075
- Predicted mine inflow during the 2023-2035 span of simulated project development.
- Predicted groundwater drawdown across the model domain in the uppermost saturated layer at: 2035 end of mining, 2045, 2055 and 2075 (10,20 and 40 years of recovery)

4.1 Groundwater levels

The transient observation dataset was processed into drawdown calibration observations by taking the difference between the first observed hydraulic head value after the estimated 2018 steady state target and all subsequent transient hydraulic head observations. Plots of the observed changes in hydraulic head from first observation time over the 2018-2023 period are shown in Appendix B. The recharge parameterisation in model calibration included spatially variable static recharge at pilot points. For the transient simulation of the calibration period, the time varying multipliers on recharge at each monthly stress period between 2018 and 2023 in the provided FloSolutions model files were adopted. At many locations there was correlation between the observed and simulated changes in hydraulic head even if the magnitude of the changes differs. At several observation locations the model simulations have larger magnitude simulated changes in hydraulic head than observed, this discrepancy could be due to:

- Storage parameters being too low,

- Hydraulic conductivity parameters being too low, or
- Model defects related to input recharge multiplier timeseries and the fact that evapotranspiration was not explicitly modelled.

4.2 Drawdown at observation points

Hydrographs displaying simulated hydraulic heads over the predictive timespan of 2023 through project development to 2035 and 40 years of recovery to 2075 are shown in Appendix C. Deep observation locations near mine drain cells (e.g. WKP11D_D) show significant predicted changes in hydraulic head (> 100m).

Predictive drawdowns at shallow observation locations (e.g. SAT1-SAT14 and Warm Spring) suggest that magnitude over life of mine will be small, with hydraulic heads at 2035 positioning within the span of predicted pre-mine hydraulic heads produced by the ensemble of parameter sets. This is related to the fact that drawdown will propagate differently over depth (see section 4.5).

4.3 Groundwater baseflows

Groundwater interaction with surface water was simulated using river and drain boundaries in the top layer of the model. River boundaries have specified water levels and can simulate flux both into and out of the model (loosing and gaining reaches, respectively) while drain boundaries only simulate flux out of the model and are more suitable for smaller ephemeral (losing) streams and riverbanks. Groundwater fluxes were aggregated in 2 different zones sets as follows:

- Original zone set (displayed in Figure 4-1), as presented in the FloSolutions report; and
- A new zoning breakdown (displayed in Appendix D), which was provided to Oceana Gold for further surface water catchment studies.

The total flux out of the river and drain boundaries within each zone was recorded during the pre- and end-of-mining (2035) periods (Figure 4-2 and Figure 4-3).

Comparison of these flows show that largest flow reductions from aquifer into river boundaries are observed in zones 6,7, 8, and 9. For the drain boundaries, largest reductions from pre-mine to end-of-mine are observed in zones 7, 8 and 10.

To illustrate the changes in baseflows over the entire simulated period, time series for baseflows of each watershed zone are provided in Appendix D. In those plots, it can be observed that simulated fluxes approach initial pre-mine levels by 2075 (end of simulation).

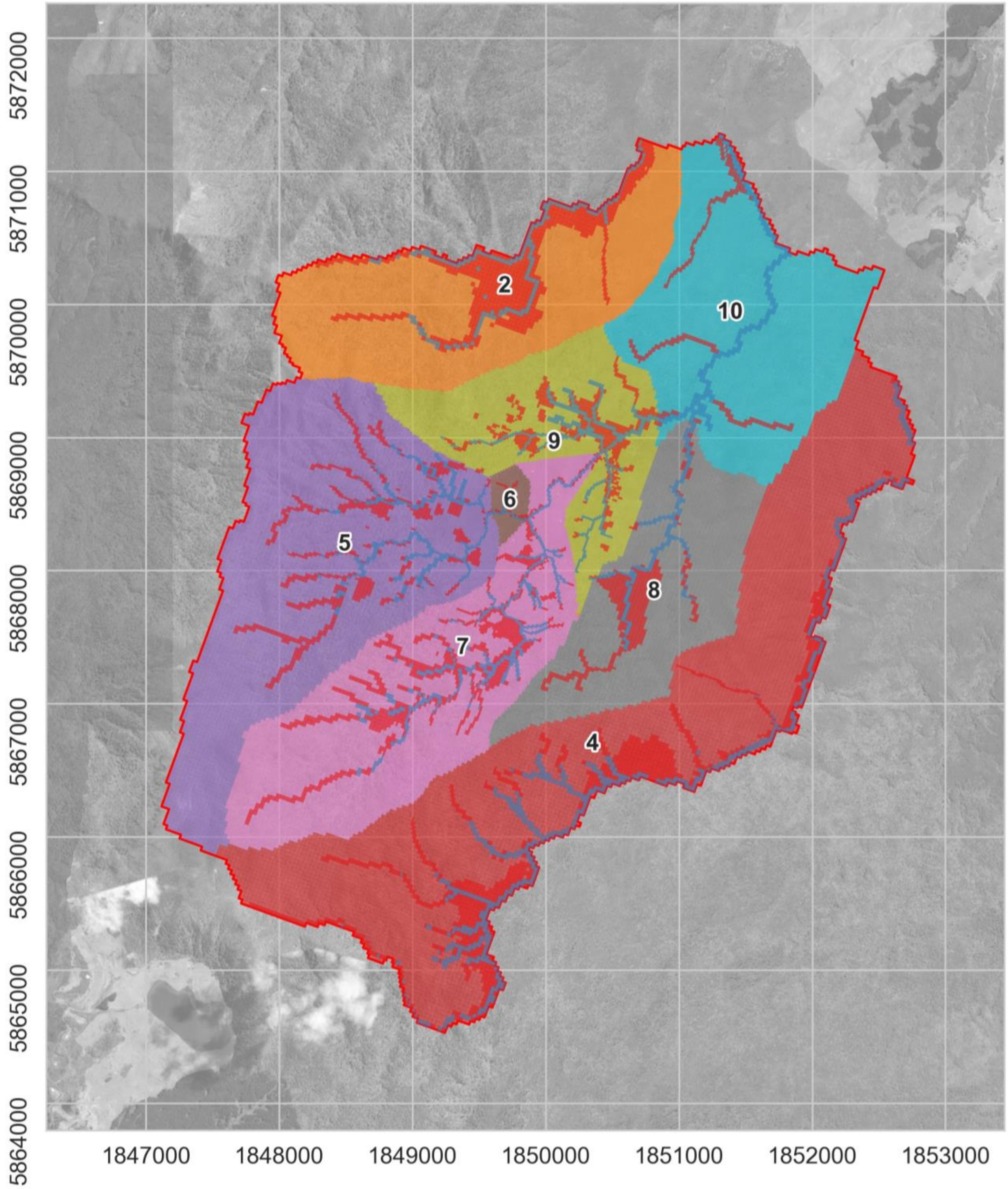

Figure 4-1 - Surface water zones and boundary conditions (red cells – drain boundaries, blue cells – river boundaries).

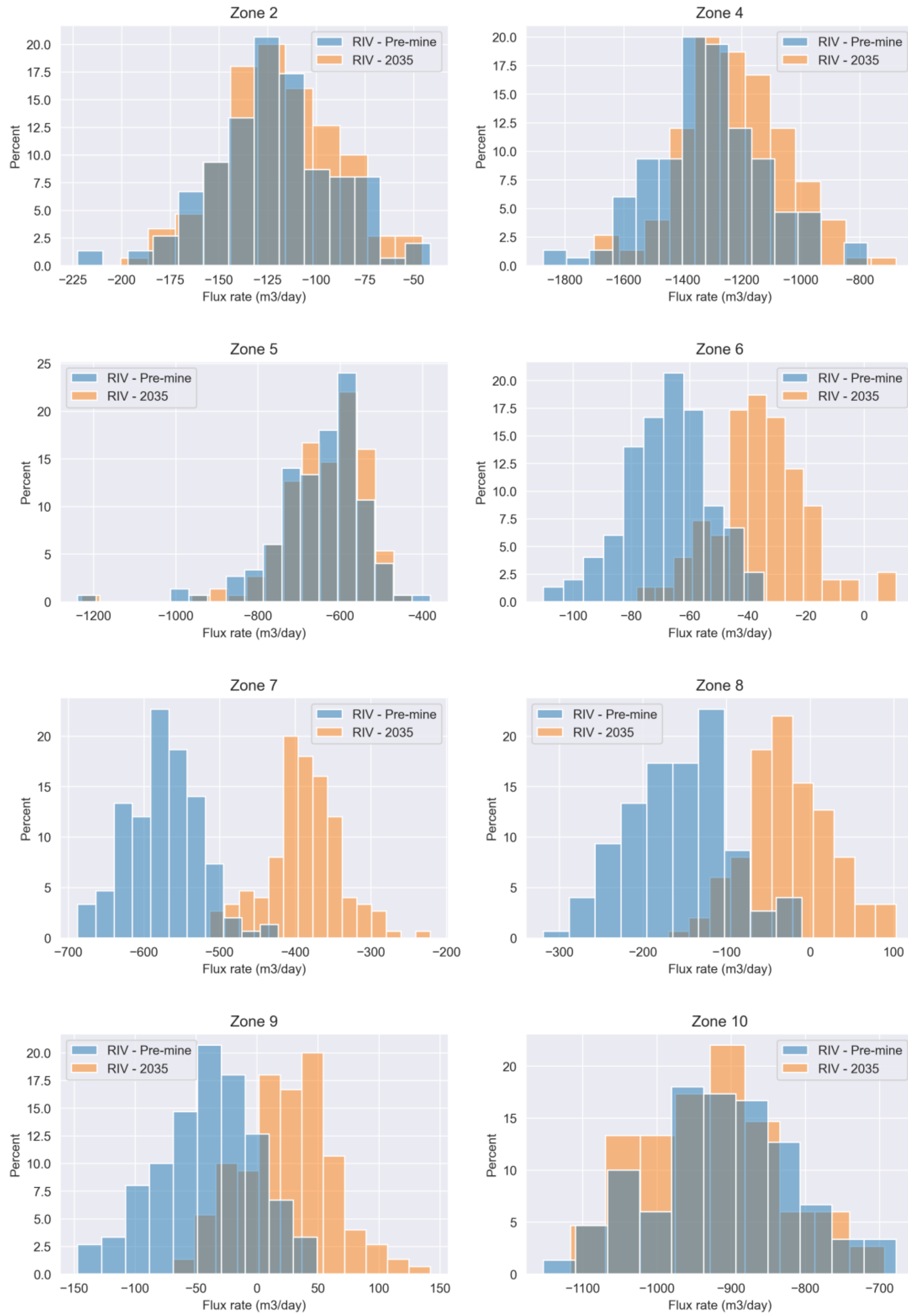

Figure 4-2 – Simulated river boundary water fluxes pre- and post-mining[1].

[1] Negative fluxes mean flow from model cells into the river boundaries.

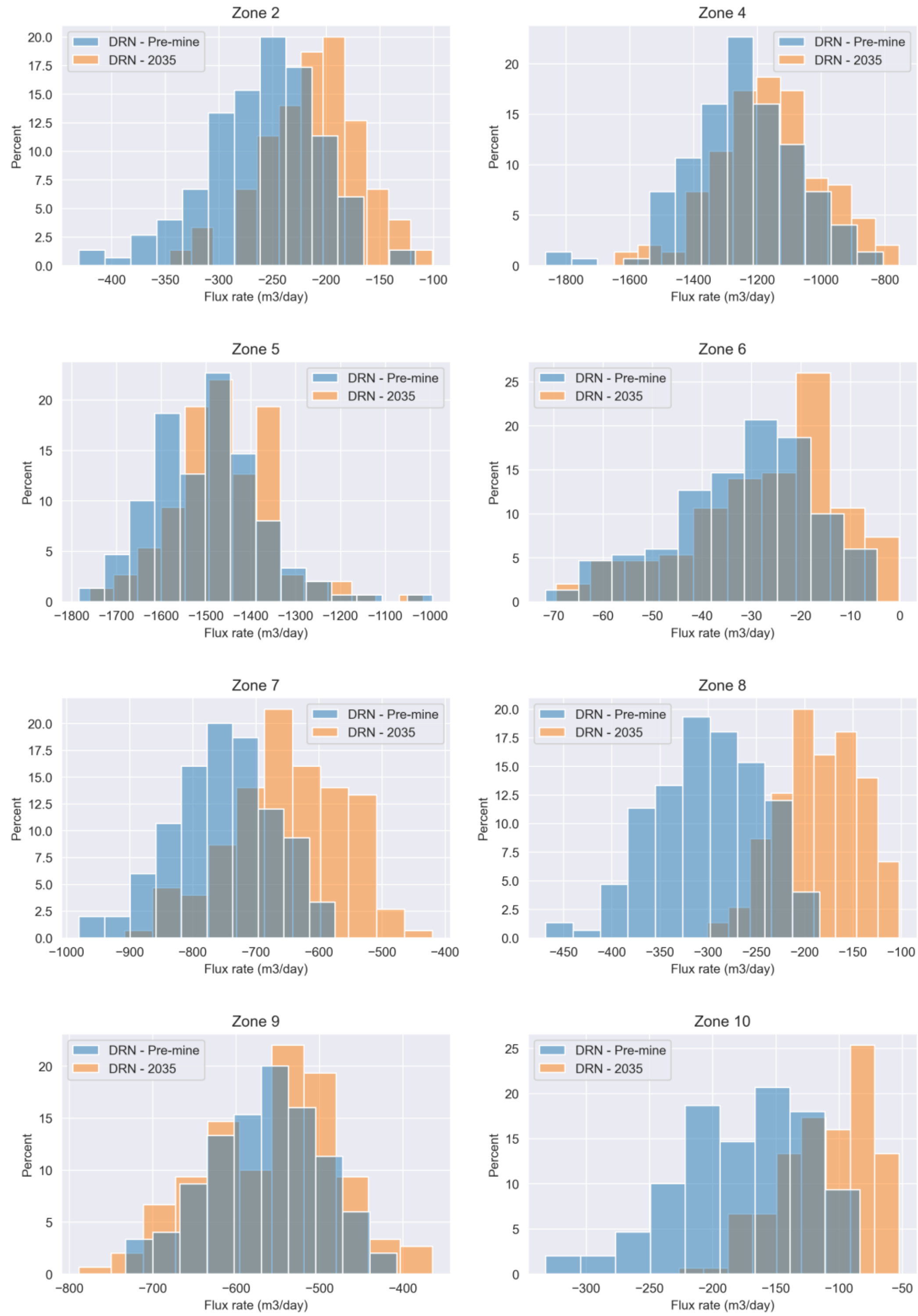

Figure 4-3 – Simulated drain boundary water fluxes pre- and post-mining[2].

[2] Negative fluxes mean flow from model cells into the drain boundaries.

4.4 Groundwater fluxes into the mine

Groundwater fluxes into drain boundaries representing mine development were processed into time weighted averages over the six-month stress periods. Predicted flux is shown in Figure 4-4, with the base shown in blue and the ensemble members in grey. The maximum predicted inflow rate at any time in the simulation was 34 l/s for the base parameter set. Simulated maximum inflow rate from the ensemble of alternative parameter sets had a mean value of 34 l/s and a and an upper 95th percentile value of 38 l/s.

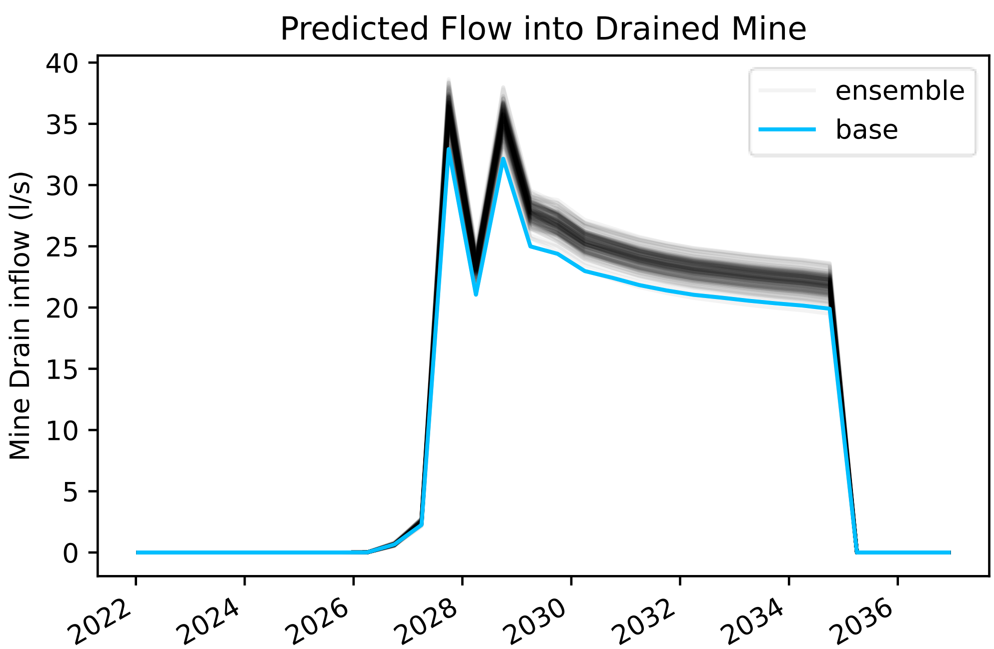

Figure 4-4 - Predicted flux rates into the mine.

4.5 Spatial drawdown

Estimated water table elevation was calculated from the 3D distribution of hydraulic head recovery by extracting the hydraulic head in the uppermost saturated cell at each unique spatial location. Water table elevations were calculated at the initial steady state, 2035 end of mine development, 10,20, and 40 years into post mining. The mean steady state water table and water table drawdown in 2035, 2045, 2055, and 2075 are shown in Figure 4-5 to Figure 4-9, while upper and lower 95th percentiles are provided in Appendix E. These time snapshots equate to:

- 2035 – end of mining period;
- 2045 – 10 years post-mining;
- 2055 – 20 years post-mining; and
- 2075 – 40 years post-mining.

The steady state water table contours overall mimic the topography, with two small exceptions near the coordinates 5867000S,1849000E where two localized zones present elevated hydraulic heads, likely associated with a combination of high recharge and low hydraulic conductivity, as well as the fact that evapotranspiration boundaries were not explicitly assigned to the model.

The 2035 drawdown contours show distinct areas with drawdown greater than 200m, and sharp changes to areas with significantly less drawdown. These differences are likely due to the development of perched saturated water tables (resulting from faster drawdown propagation at depth) above mine drains in some areas and desaturation of all cells above mine drains in other areas. To illustrate this, cross sections displaying simulated drawdown contours and zero-pressure isolines (representing the interface between saturated and unsaturated zones) are displayed in Figure 4-10 and Figure 4-11.

Within 10 years of recovery, the maximum drawdown is less than 20m and a full recovery to initial steady state water levels is achieved by the end of the 40-year recovery simulation. Lastly the predictive results indicate some small drawdowns in the northeastern edge of the model for the years 2055 and 2075, and are artifacts related to small numerical errors, since they are clearly disconnected from drawdowns induced by the mine boundary conditions.

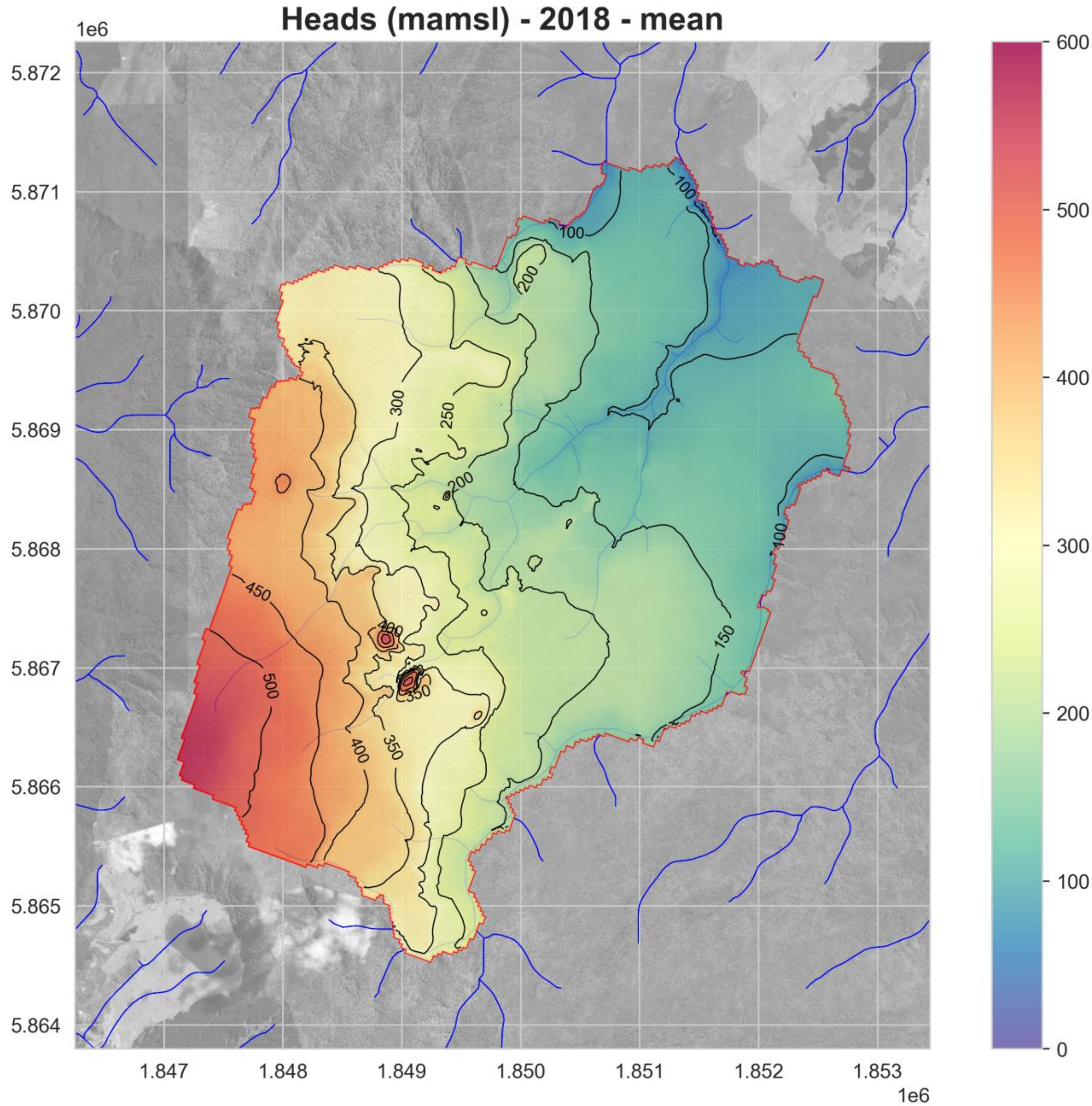

Figure 4-5 - Simulated mean steady state (pre-mine) water table.

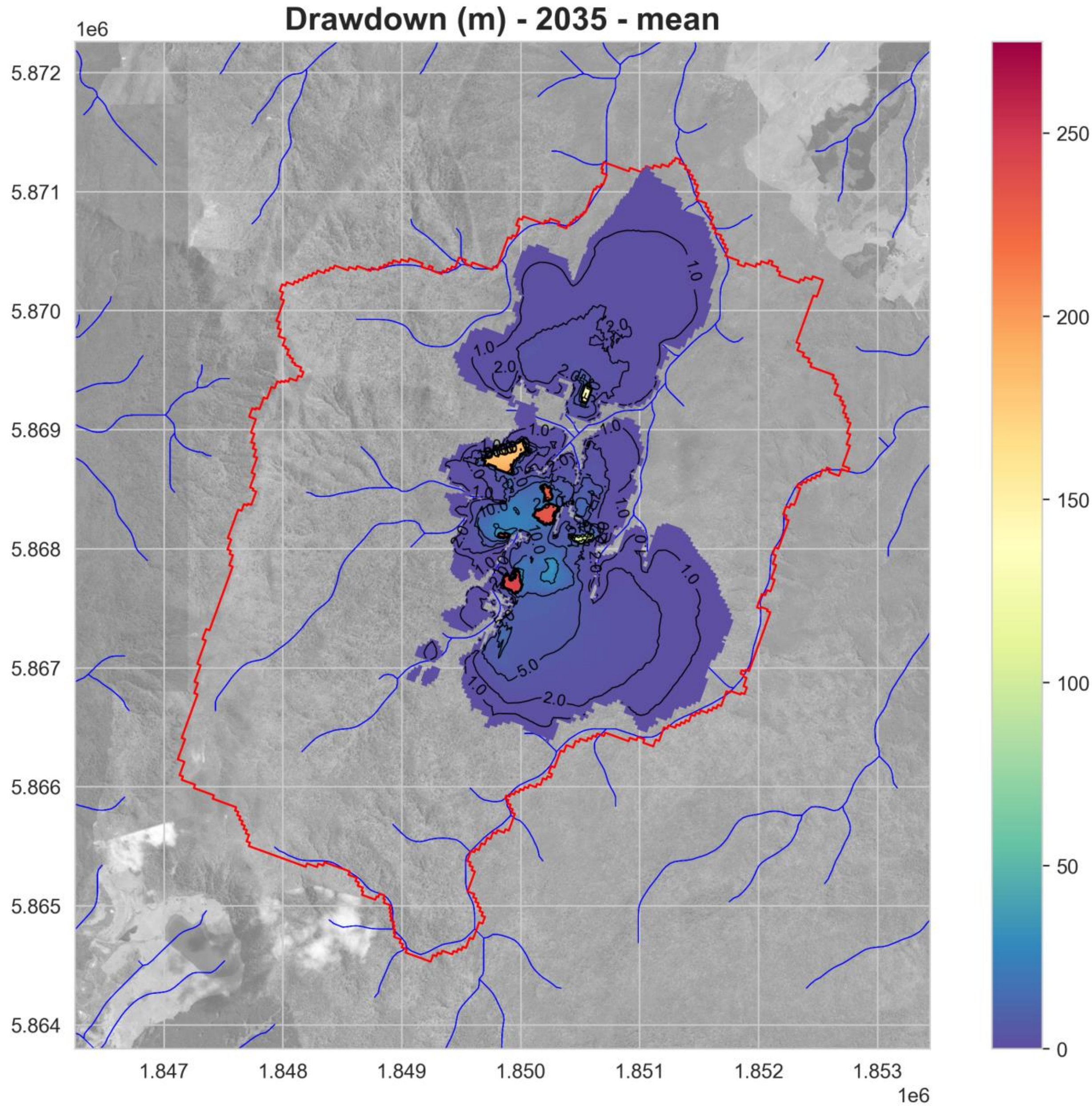

Figure 4-6 - Simulated mean 2035 (end of mining) drawdown.

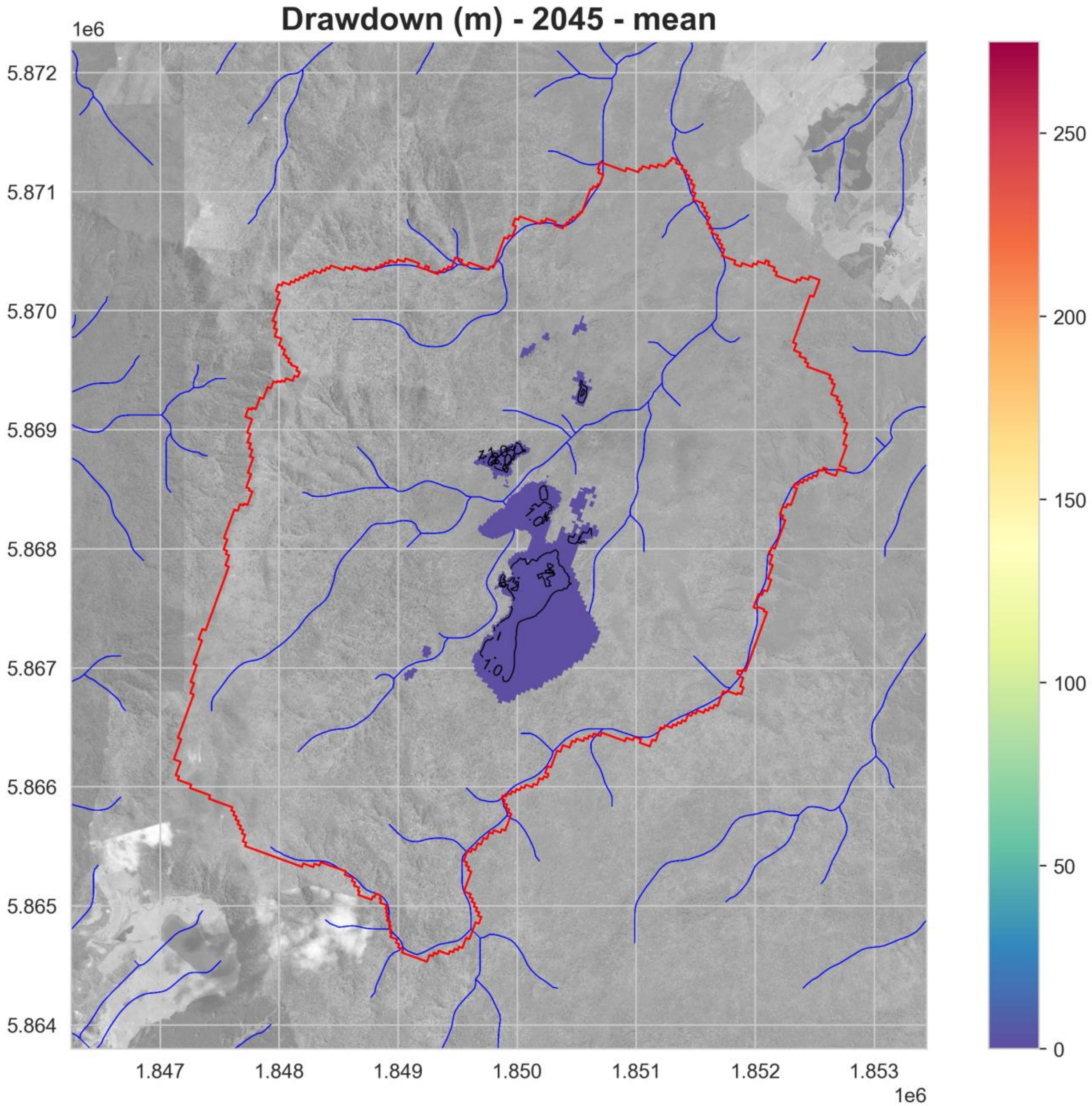

Figure 4-7 - Simulated mean 2045 (10 years post-mining) drawdown.

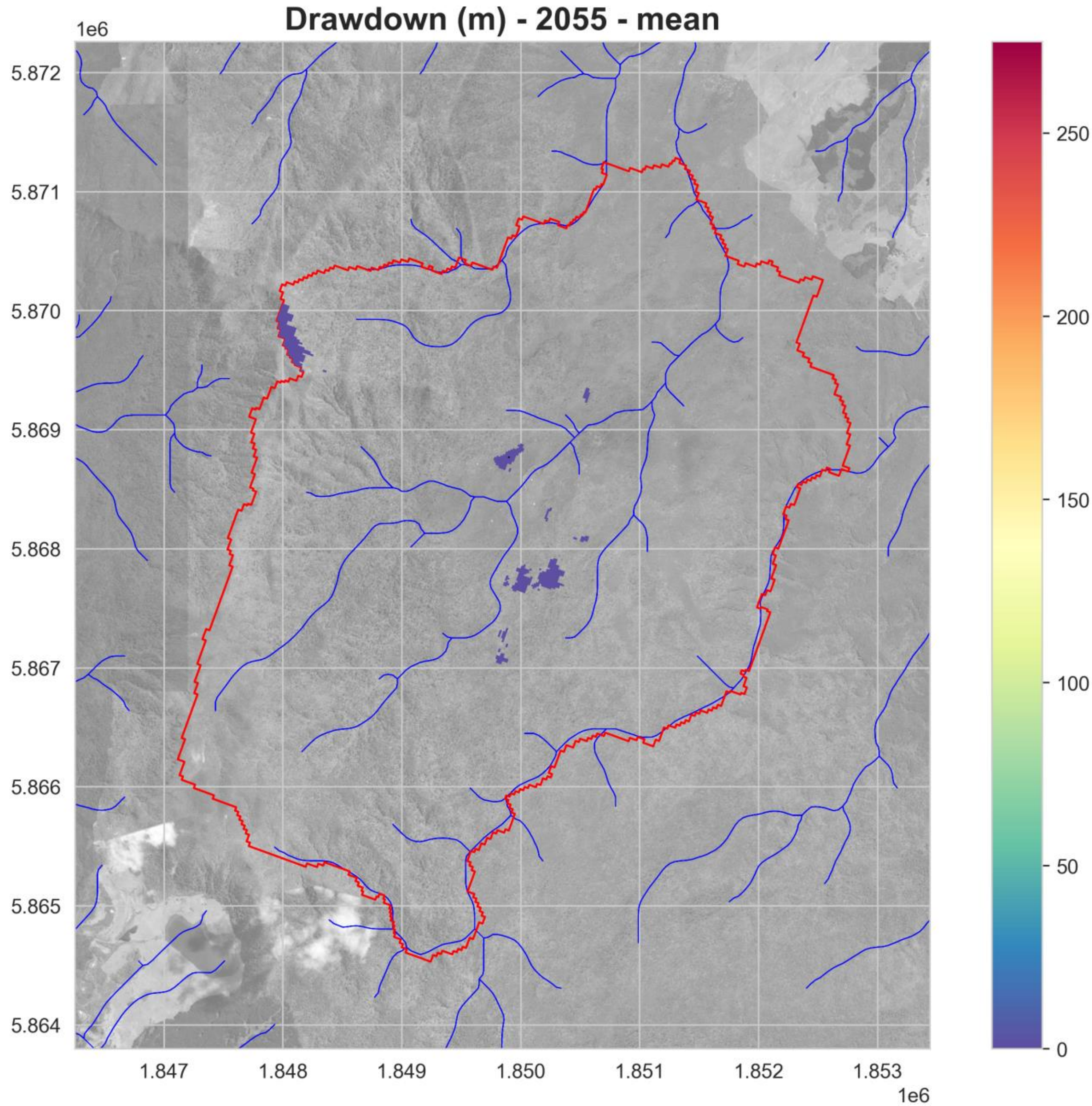

Figure 4-8 - Simulated mean 2055 (20 years post-mining) drawdown.

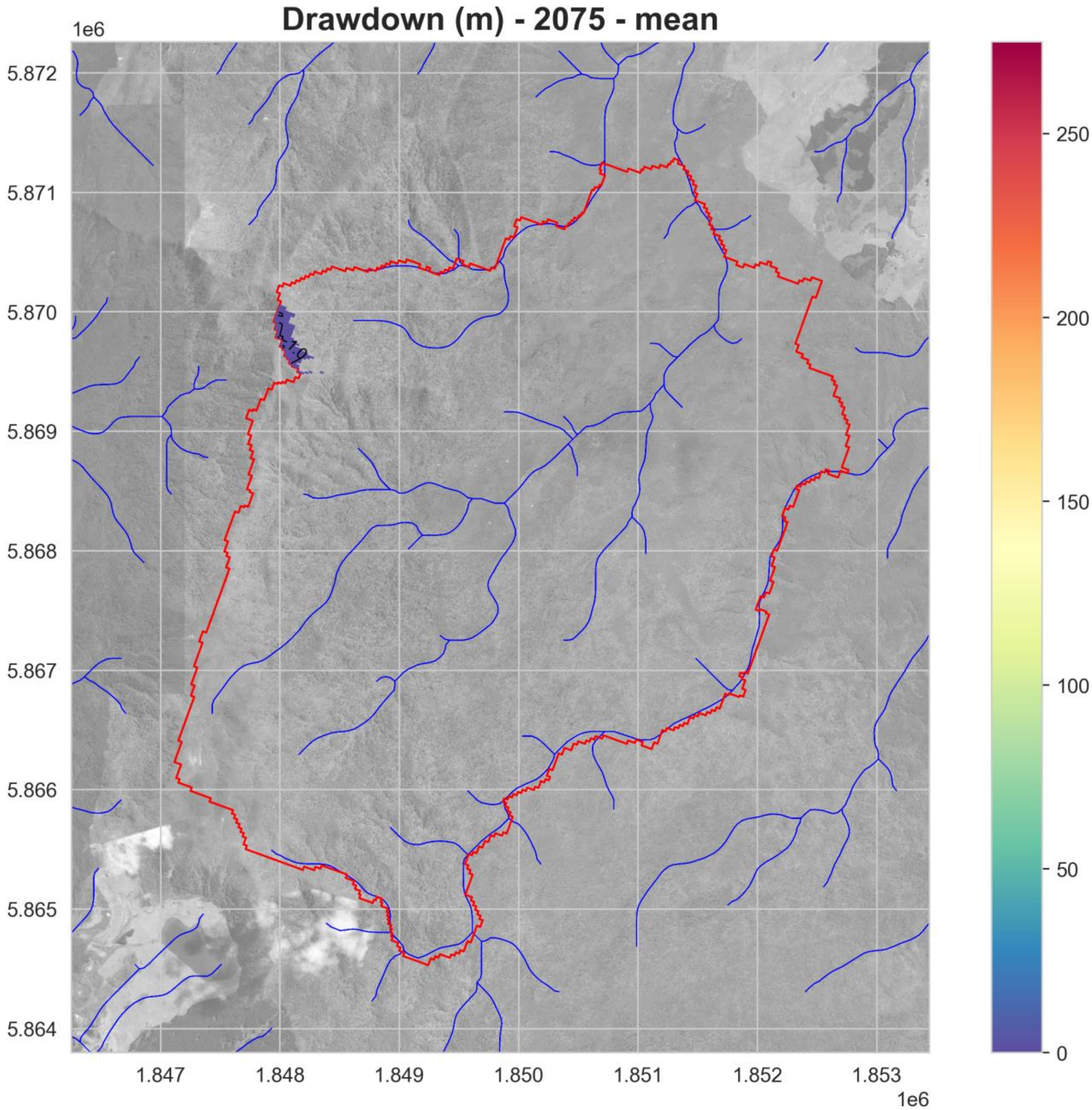

Figure 4-9 - Simulated mean 2075 (40 years post-mining) drawdown.

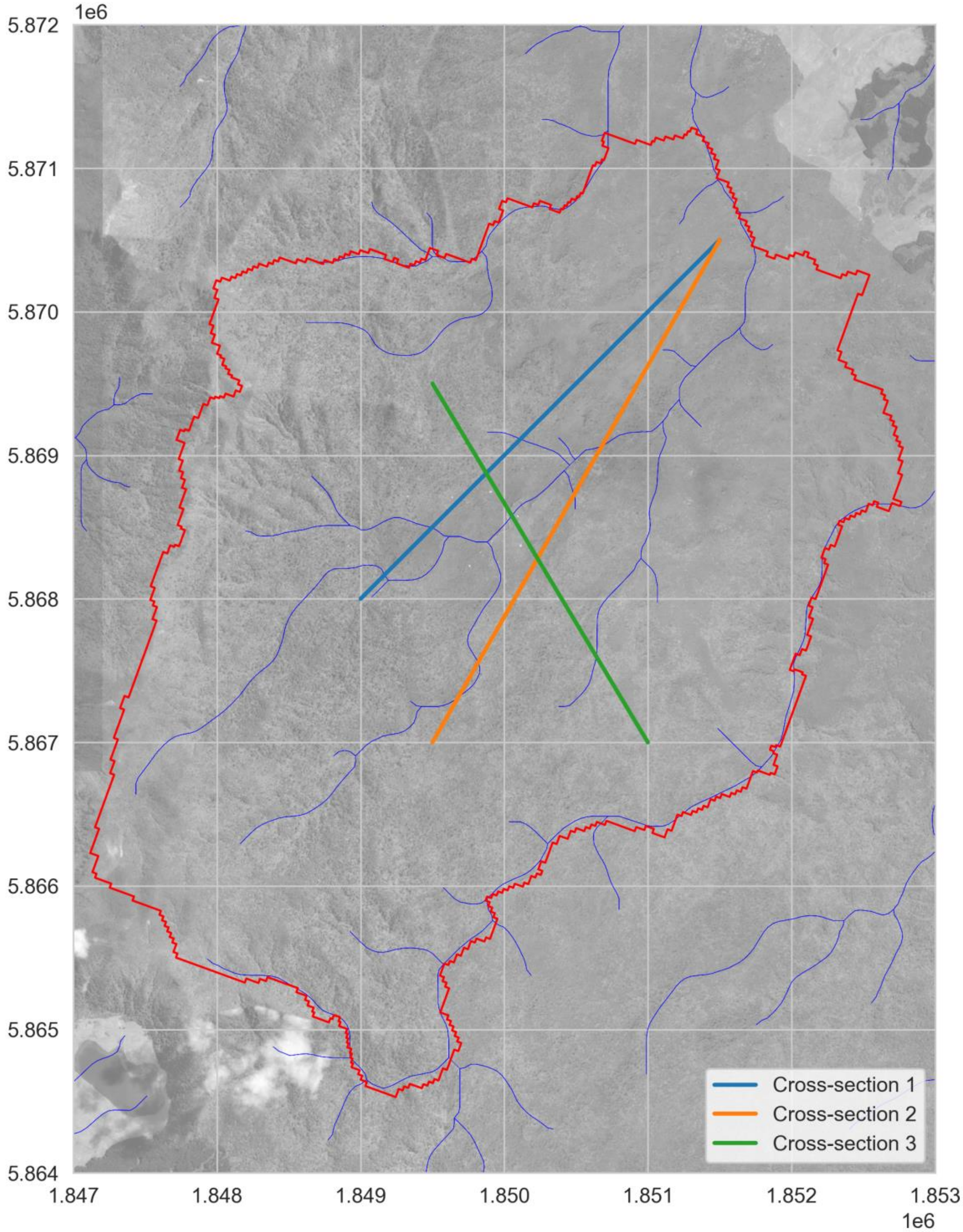

Figure 4-10 - Location of cross-sections.

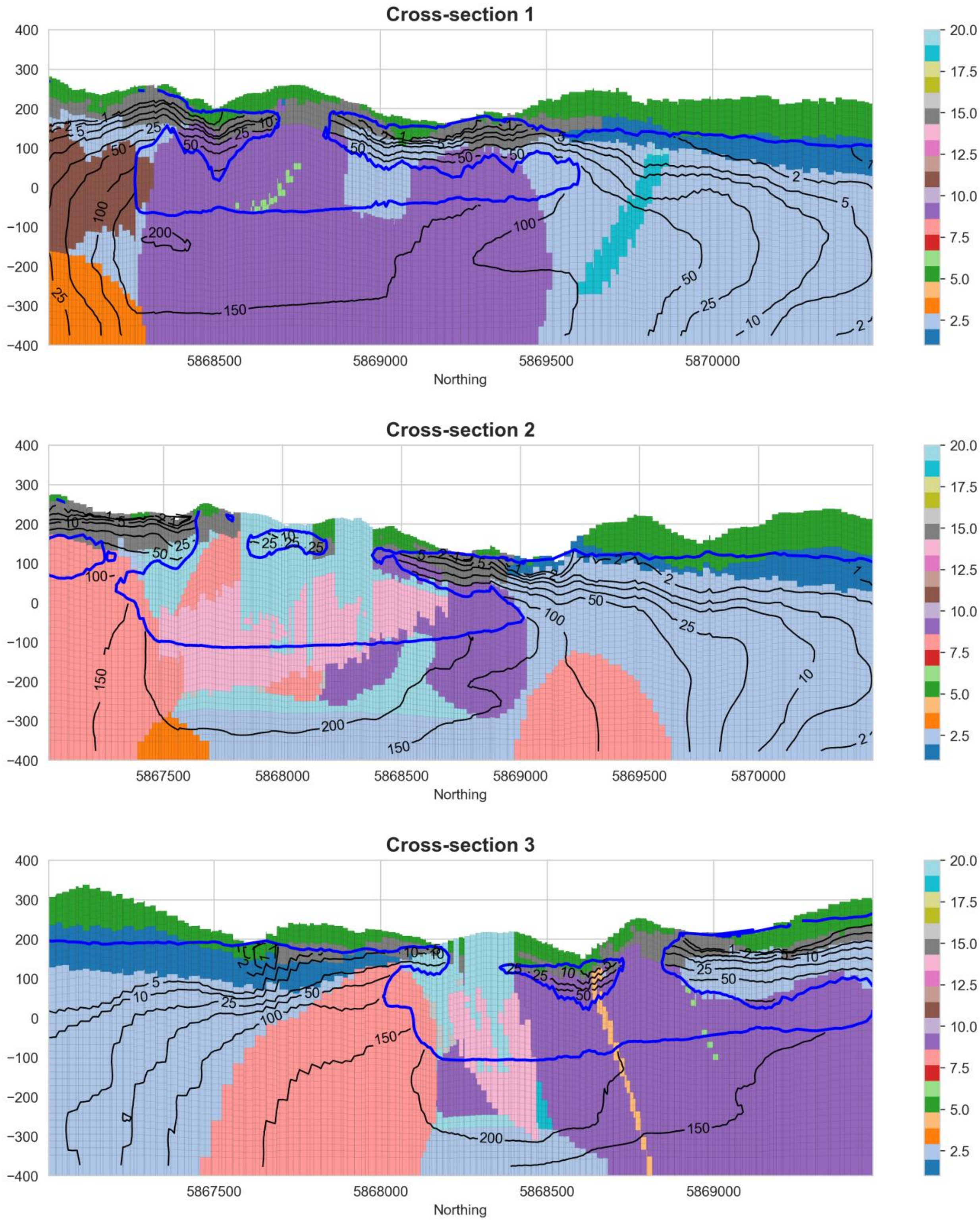

Figure 4-11 - Simulated mean 2035 (end of mine) drawdown contours (black) and zero-pressure isoline (blue), shaded by HSU code.

5. Conclusions

The groundwater model developed by FloSolutions (2023a) was updated to include a highly parameterised approach to model calibration and uncertainty analysis. Calibration to steady state observations of estimated static hydraulic head, head differences and watershed baseflow improved the fit to data relative to the results reported in FloSolutions (2023a). However, despite the use of a highly parameterization scheme, the remaining residuals suggests the influence of observation and/or model defects (i.e., inability of the model to fully represent the true groundwater system).

Transient observations of changes in hydraulic head values were compared against simulated values using the parameter ensemble informed by steady state calibration and, the fit with observation data is similar to the results reported in FloSolutions 2023a at the selected locations presented in that document. It is important to emphasize that calibration was undertaken assuming average rainfall conditions and that no transient calibration to seasonal/varying rainfall has been conducted given the limitations on the current model recharge setup. Nevertheless, given that head oscillations due to transient rainfall are relatively small (a few meters), it is unlikely that they will have a significant impact on the predictions of interest.

A combined predictive simulation of mine development was constructed based on model files provided by FloSolutions (2023a) and designed to simulate steady state background groundwater system, historical transient changes due to time varying recharge, planned mine development and 40 years of post-mining recovery. Predictions of drawdown at observation locations, changes in groundwater flux to surface watersheds and mine inflow were produced using the parameter ensemble informed by steady state calibration.

The simulation of the life-of-mine and recovery periods provided estimates for the various predictions of interest and their associated uncertainty. Simulated drawdown results for 2035 (end-of-mine) show that while drawdowns are significant in the deep portions of the model (near the underground workings), drawdown at water table elevations are relatively small (less than 20 m) for the vast majority of the model domain. Recovery results obtained for 2045 (10 years after end-of-mine) suggest that groundwater levels will recover to near pre-mine levels, with residual drawdowns of up to 2 m at water table depths. Simulated groundwater flows show maximum inflow rates of 38l/s for peak flows at upper 95th percentile, stabilizing to values under 28 l/s from 2029 until end-of-mining. Relative to the maximum drawdown predictions produced by FloSolutions (Figure 4.13 of FloSolutions 2023a), this analysis produced greater predicted maximum drawdowns at almost every observation location. The correlation between observation location depth and predicted drawdown, discussed in FloSolutions (2023a) was also observed in this analysis.

Predictions of mine inflow rate produced by this analysis are slightly lower than the results of the initial FloSolutions (2023a) modelling. This difference may be partially due to the postprocessing of simulated inflow rates into more representative time weighted averages across the predictive stress periods. Raw simulated flow rates can often produce very high flux values for short time steps at the start of stress periods after changes in boundary condition values. These high flux rates are not necessarily representative of likely inflow, as the mining boundaries were introduced in the model in a stepwise manner with monthly stress periods (as opposed to continuous excavation).

Model predictions of flux changes to watersheds, which represent baseflow impact produced by this analysis are higher than predictions of the initial FloSolutions (2023a) modelling, particularly in the model zones 7, 8 and 9 closest to the proposed mine. Given that the original parameter values from FloSolutions (2023a) were used to determine the prior parameter ranges, reasons for changes are likely associated to new and updated data utilised in the calibration process.

6. Recommendations

During the review, update and predictive uncertainty analysis applied to the modelling produced by FloSolutions (2023a), several limitations were identified that could only be partially addressed with the scope, timeframes and data available. Based on these observations the following recommendations are made for future modelling of the WUG.

- Convert the model to an unstructured grid: Currently, the model discretization is defined as a regular rectangular grid, and discretisation is unnecessarily carried out to the margins of the domain, increasing computational burden. It is recommended to redefine the grid using quadtree or Voronoi meshing so that the areas of interest are refined and there are not excessive numbers of inactive cells in the model. This will be likely to improve simulation run-time and numerical stability.
- The ongoing monitoring of existing and future boreholes are likely to provide valuable information about seasonal cycles over time, which can augment the existing data sets and elucidate relationships between net groundwater recharge and specific yield. Once this dataset is in place, it is recommended that the model be recalibrated in transient mode so that relationships between rainfall, evapotranspiration and specific yield expressed in the transient data sets can inform and reduce the uncertainty of the model parameters.
- Improvement of net recharge setup with a more detailed representation of infiltration and evaporation boundaries (as opposed to rainfall based net recharge). The current model recharge setup uses a single net recharge value for each model cell and evapotranspiration is not implemented, which is a significant simplification and reason why seasonal/rainfall related groundwater level changes were not accounted into calibration process. Application of these recommendations are the recommended minimum model upgrade necessary once the model is recalibrated with groundwater level transient responses to varying rainfall.
- Development of a consolidated database with all observation data, including borehole construction details, locations, historical observations (raw and derived), in order to streamline model calibration review and continual improvement efforts and provide a consistent data source for future modelling exercises.

This report's descriptions of the theory, data, approaches, and results are intended for a reader with expertise and experience in predictive uncertainty analysis and decision support modelling. The technical vocabulary and details may be challenging and/or misleading for other readers, who may wish to first familiarize themselves with the technical background. Such readers may find value in the tutorials, webinars, and papers available at the Groundwater Modelling Decision Support Initiative's website, www.gmdsi.org.

7. References

Bakker, M., Post, V., Langevin, C.D., Hughes, J.D., White, J.T., Starn, J.J. and Fienen, M.N. (2016), Scripting MODFLOW Model Development Using Python and FloPy. Groundwater, 54: 733-739. https://doi.org/10.1111/gwat.12413

Barnett et al, 2012, Australian groundwater modelling guidelines, Waterlines report, National Water Commission, Canberra.

Commonwealth of Australia. (2023). Information Guidelines Explanatory Note Uncertainty analysis for groundwater modelling. CANBERRA, ACT, Australia: Department of Climate Change, Energy, the Environment and Water. Retrieved from http://www.iesc.environment.gov.au/.

Doherty, J. (2015a). Calibration and uncertainty analysis for complex environmental models. Brisbane, Australia.: Watermark Numerical Computing. Retrieved from www.pesthomepage.org.

Doherty, J. (2015b). Groundwater Data Utilities Part B: Program Descriptions. Watermark Numerical Computing. Retrieved from http://www.pesthomepage.org/Downloads.php.

Doherty, J. (2021, March). LUMPREM - A Simple Lumped Parameter Model for Unsaturated Zone Processes (Version 1). Retrieved from https://pesthomepage.org/programs.

FloSolutions 2023a, FY2023 Hydrogeology Support for WUG: Hydrogeologic Conceptual Site Model, September 13, 2023, prepared for Oceana Gold NZ Limited

FloSolutions 2023b, FY2023 Hydrogeology Support for WUG: Numerical Groundwater Model, September 18, 2023, prepared for Oceana Gold NZ Limited.

Panday, S. L., C.D., Niswonger, R.G., Ibaraki, Motomu, and Hughes, J.D., 2013, MODFLOW–USG version 1: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation, in: U.S. Geological Survey Techniques and Methods, Book 6, chap. A45, 66 p., https://pubs.usgs.gov/tm/06/a45.

Peeters L.J.M., Middlemis H., 2023. Information Guidelines Explanatory Note: Uncertainty analysis for groundwater modelling, A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of Climate Change, Energy, the Environment and Water, Commonwealth of Australia, 2023.

Tonkin, M., and Doherty, J., 2009, Calibration-constrained Monte Carlo analysis of highly-parameterized models using subspace methods: Water Resources Research, v. 45, W00B10, doi:10.1029/2007WR006678.

White J.T. 2018, A model-independent iterative ensemble smoother for efficient history-matching and uncertainty quantification in very high dimensions, Environ. Model. Softw., 109 (2018), pp. 191-201

White, J.T., Hunt, R.J., Fienen, M.N., and Doherty, J.E., 2020, Approaches to Highly Parameterized Inversion: PEST++ Version 5, a Software Suite for Parameter Estimation, Uncertainty Analysis, Management Optimization and Sensitivity Analysis: U.S. Geological Survey Techniques and Methods 7C26, 52 p., https://doi.org/10.3133/tm7C26.