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Kōmanawa Solutions Ltd

Report No: Z24002.m1

Groundwater Modelling Analysis for Mining Bendigo Ophir Gold Deposit

09/04/2025 version 1 Prepared by Kōmanawa Solutions Ltd. for Matakanui Gold Ltd.

Kōmanawa:

1. (verb) to spring, well up (of water)
2. (verb) to spring, well up (of thoughts, ideas)

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Version Control

Date	Version	Status	Comment
22/08/2024	1.0.0	Draft	Initial draft including first calibrated (generalized normal prior distributions for $K_{0,1,2}$, and using surface drains) pre-mining model, and predictions of mining impacts, given a final pit surface and eight years of excavation
26/08/2024	1.0.0	Draft	Internal review of Rise and Shine model
20/11/2024	**2.0.0**	Draft	Begin incorporating additional models for Come in Time and SREX deposits
02/12/2024	**2.0.0**	Draft	Draft of full hard rock mining report including analysis for Rise and Shine, Come in Time, and SREX mining areas
07/02/2025	**2.0.0**	Final	Final report generation
12/05/2025	2.0.1	Final	Minor re-wording to support a wider audience (non-modeller / non-hydrogeologists)
19/08/2025	2.0.2	Final	Disclaimer adjusted in line with Panel Convener's practice and procedure guidance, July 2025

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Key Findings - All Models

Key Findings from all models

Our key findings are:

- We conceptualise the hydrogeological environment into a thin veneer aquifer, which is poorly constrained and a more massive hard rock aquifer. By thin veneer 'aquifer' it means the soil, subsoil, regolith, and distinctly weathered rock that forms a distinct permeability zone for water movement (both unsaturated and semi-saturated). This veneer may have various characteristic thicknesses depending on the degree of weathering or even slope movement.
- In the absence of information on the veneer aquifer, we presume that there will be little draw down propagation within this aquifer due to the steep topography in relationship to the assumed minimal thickness of the veneer aquifer.
- The hard rock aquifer was explicitly modelled as a confined aquifer with three zones of hydraulic conductivity (TZ-3 (Textural Zone 3) Schist, RSSZ (Rise and Shine Shear Zone), and TZ-4 (Textural Zone 4) Schist). A Bayesian optimisation was used to estimate the hydraulic conductivity of these zones as well as the likely recharge to the hard rock aquifer from the veneer aquifer.
- All three models yielded similar poorly constrained posterior distribution for the surface drain conductance (C) parameter. This parameter is mostly compensatory with the recharge parameter (e.g., rejecting high recharge values where the recharge is too high and on steep slopes), so we are unconcerned by this insensitivity.
- All three models yielded a posterior distribution for the recharge parameter (R) between 10^{-5} m d^{-1} and the average rainfall in the area, with a most probable value of c. 10^{-4} m d^{-1} (36.5 mm yr^{-1}), which is less than 10% of the average rainfall rate in the model area 0.0013 m d^{-1} (459.5 mm yr^{-1}).
- All three models derived the most probable groundwater recharge to the hard-rock groundwater of 36.5 mm yr^{-1}, approximately 8% of annual rainfall across the area.
- There was significant disagreement between the models on the hydraulic conductivity of the TZ-3 Schist (K_0). Come in Time and SREX models showed a broad agreement on the distribution of this parameter, with a peak at 10^{-3} - 10^{-1} (0.001-0.1) m d^{-1}. Rise and Shine showed a much lower conductivity distribution (4-6 orders of magnitude lower) than the other two models for the TZ-3 Schist.
- The three models arrived at different calibration conclusions with respect to the hydraulic conductivity of TZ-3 (K0). CIT and SRX models tended to calibrate centring on the range of 1.2×10^{-8} to 1.2×10^{-10} m s-1. The RAS model calibration suggested a much lower hydraulic conductivity distribution in stochastic modelling, as low as 1×10^{-12} m s^{-1}.
- The hydraulic conductivity of the RSSZ (K_1) was well constrained by all three models, with a peak at c. $10^{-2.4}$ m d^{-1}. This consistency between the models gives confidence in the parametrisation of the RSSZ as a relatively high conductivity unit (as compared to the other schists).
- The three models arrived at similar calibration conclusions with respect to the hydraulic conductivity of the RSSZ, centring on 4.6×10^{-8} m s^{-1}. The consistency in calibration solutions provides confidence in the choice of hydraulic conductivity parameters of the RSSZ as a relatively high conductivity domain (as compared to TZ-3 and TZ-4).
- The hydraulic conductivity of the TZ-4 Schist (K_2) was less well constrained than the RSSZ but showed moderate agreement between the three models with values ranging from 10^{-7} to 10^{-3} m d^{-1}. The models suggest that the TZ-4 Schist is a relatively low conductivity unit.
- The three models arrived at different calibration conclusions with respect to the hydraulic conductivity of TZ-3 (K_2), certainly at low levels of consistently compared to RSSZ. Such agreement that was arrived at ranged between 1×10^{-8} and 1×10^{-12} m s^{-1}, suggesting TZ-4 is characterised as a low permeability schist unit.
- SREX and Come in Time parameterised the TZ-3 schist similar to the RSSZ, which we interpret as a likely mis-location of the RSSZ in the model domain for those models.
- The SREX and Come in Time models both tended to display higher hydraulic conductivities at depths that make a difference to the scenario modelling.

Key Limitations for all models

The key limitations of the modelling for all models are described in Section 6 of this report. The most important limitations are summarised below:

- The model is a steady state model and cannot provide any information on the rate of change of the water table, any non-linearity in the discharge to the pit, or the aquifer storage contributions to the pit inflow.
- The calibration and optimisation process gives us an estimate of the bulk hydraulic conductivities of these zones, however, it does not represent finer scale features (for instance local fracturing densities).
- The optimisation is limited to the available data, additional observations would likely impact the model predictions.
- The model system assumes a homogeneous and isotropic aquifer, which local fracturing that hosts groundwater would not conform with. This may change the predicted draw-down or pit fluxes derived in scenario modelling. The methodological adoption of Representative Equivalent Volume (REV) allows the results of scenario modelling to be accepted at appropriate scales of examination, i.e., not relying on fine scale results. REV is the smallest volume of rock mass where the average hydraulic properties (like permeability) are representative of the entire aquifer, allowing for a more simplified, "equivalent continuum" model.
- As the model does not include storage effects, the initial de-watering of the pit may be higher than the predicted, but should then equilibrate to the predicted values.
- Each model (Rise and Shine, Come in Time, and SREX) was conducted independently and therefore the results do not provide a holistic view of the system. This approach was undertaken to allow parameter differences between each model to be optimised independently and to reduce the computational burden and instability issues of a single large model. We believe that this approach is reasonable given the limited data available, the relatively low conductivity of the hard rock aquifer (as compared to alluvial systems), and the relative independence of the modelled impacts. All impacts should be assumed to be additive, if detailed interactions between the various model pits are needed, we would recommend a more detailed model be developed.

Key Findings - Rise and Shine

Rise and Shine: Key Findings

Our key findings are:

- Inflows to the completed pit from the veneer aquifer were estimated simply using the rainfall in the pit surface water catchment (excluding Rise and Shine Creek). These are expected to be of the order of approximately 778 m^3 d^{-1} (9 l s^{-1}). Note that this is an annual average and the actual inflow will be highly variable and "flashy".
- the optimised hydraulic conductivities of the TZ-3 Schist and TZ-4 Schist zones are less than the minimum conductivities estimated from the packer tests. This is generally considered reasonable as the packer tests are small scale measurements and these parameters represent the bulk hydraulic conductivity of the zones.
- The optimised recharge flux to the hard rock aquifer is estimated to be around 0.03 to 0.56 mm d^{-1} (11.5 - 205.3 mm yr^{-1}).
- An additional optimisation where the hydraulic conductivity parameters were constrained to the minimum and maximum values from the packer tests was also performed and yielded a recharge flux of 0.00018 to 0.001 m d^{-1} (65 to 365 mm yr^{-1}). This optimisation was not considered as reliable as the main optimisation but provides a useful sensitivity analysis. The results were not relied on in scenario modelling.
- The mining activities are unlikely to produce significant stream depletion of Shepherds Creek, with an impact on the order of 0.5 - 3 l s^{-1} of reduced discharge creek flow due to dewatering of the hard rock aquifer and no more than 9 l s^{-1} total, much of which would be related with the reduction in catchment area (e.g., capture of runoff and lateral drainage of the veneer aquifer). .
- The discharge to the pit from the hard rock aquifer is relatively small, with a maximum of approximately 5 l s^{-1}.
- Pre- and post-mining water tables are available in Section 7.4.1.
- We ran the Rise and Shine model for the Come in Time and SREX parametrisation and found that these parametrisation were incompatible with the Rise and Shine observations. For more information see Section 10.2

Rise and Shine: Key Limitations

Key limitations are described in Section 7.5 of this report. These limitations are supplemented by the limitations for all models described in Section 6 summarised in Box 0.3. The most important limitations are summarised below:

- The model does a poor job of replicating the observed heads near the Come in Time site, accordingly the model would not be suitable predicting the dewatering impacts of the Come in Time site. Instead, a separate local model was developed and a re-optimisation was undertaken to only the Come in Time observations.
- Should there be a highly fractured connection between the pit and Shepherds Creek, the model will not capture this and will significantly underestimate the impacts of the pit on the creek. We note that there is no evidence of such as connection; however should pit dewatering yield significantly higher than predicted volumes we would recommend further investigation.

Rise and Shine: Recommended Values

We recommend the following values for the key predictions of interest:

- Inflow to the pit from rainfall and the veneer aquifer is estimated to be around c. 778 m^3 d^{-1} (9 l s^{-1}). Note that this inflow will be highly temporally variable, see Section 7.1.1
- Inflow to the pit from the hard rock aquifer: c. 5 l s^{-1}, though we would suggest at least a factor of 2 safety margin, see Section 7.4.2
- Likely reduction in discharge to Shepherds Creek from the hard rock aquifer: 0.5 - 3 l s^{-1}, see Section 7.4.2
- Maximum reduction in discharge to Shepherds Creek: 12 l s^{-1}, (0.5 - 3 l s^{-1} from hard rock and up to 9 l s^{-1} from rainfall runoff and veneer aquifer). Note that this is a significant overestimate as it double counts some losses (e.g. from rainfall) and reduction in runoff associated flow will mostly occur during high flow events see Section 7.1.1 and Section 7.4.2
- The likely pre- and post-mining water table elevations are available in Section 7.4.1

Key Findings - Come in Time

Come in Time: Key Findings

Our key findings are:

- The near surface unit mapped as TZ-3 Schist shows similar hydraulic conductivity to the RSSZ in the Come in Time model. We suggest that additional fracturing in the TZ-3 in this area associated with the RSSZ could explain the similarity.
- The pit is unlikely to cause a direct reduction in Shepherds Creek with any reduction in discharge likely to occur from diverted recharge from the stream to the pit.
- Stream losses are unlikely to exceed 150 $m^3\ d^{-1}$ (1.7 $l\ s^{-1}$) and the groundwater inflow flux to the pit is unlikely to exceed 300 $m^3\ d^{-1}$ (3.5 $l\ s^{-1}$).
- pre- and post-mining water tables are available in Section 8.4.1.

Come in Time: Key Limitations

There are no further limitations to the Come in Time model beyond those described in Section 6 summarised in Box 0.3.

Come in Time: Recommended Values

We recommend the following values for the key predictions of interest:

- Inflow to the pit from the hard rock aquifer: c. 3.5 $l\ s^{-1}$, though we would suggest at least a factor of 2 safety margin, see Section 8.4.2
- Likely reduction in discharge to Shepherds Creek from the hard rock aquifer: less than 1.7 $l\ s^{-1}$, see Section 8.4.2
- The likely pre- and post-mining water table elevations are available in Section 8.4.1

Key Findings - SREX

SREX: Key Findings

Our key findings are:

- The posterior distribution of the TZ-3 Schist conductivity (K_0) and the RSSZ conductivity (K_1) are similar in the SREX model. This suggests that the near surface hard rock aquifer is relatively conductive in the SREX model domain and does not isolate the pit from the surface alluvial/veneer system. We suggest that the similarity between the TZ-3 Schist and RSSZ conductivity could be explained by additional fracturing in the TZ-3 in this area associated with the RSSZ.
- The SREX model arrived at different calibration conclusions with respect to the hydraulic conductivity of TZ-3 schist (K_0) and RSSZ hydraulic conductivity (K_1) in the RAS model. Near surface schist hydraulic conductivity calibrated to solutions relied upon in scenario modelling that included conductive (permeable) conditions promoting hydraulic connections between the surface alluvium / veneer aquifer and underlying schist lithologies.
- The posterior distribution of the TZ-3 Schist conductivity (K_0) and RSSZ conductivity (K_1) suggest that the near surface hard rock aquifer is relatively conductive in the SREX model domain and does not isolate the pit from the surface alluvial/veneer system.
- The model suggests that mining in the SREX pit is likely to have a significant impact on the adjacent wetland and alluvial systems, leading to the ground closest to the dewatered quadrant of the SREX pit becoming dewatered and depleting flowing surface water in its vicinity.

SREX: Key Limitations

The key limitations of the SREX modelling are described in Section 9.5 of this report. These limitations are supplemented by the limitations for all models described in Section 6 summarised in Box 0.3. The most important limitations are summarised below:

- The model does not include the hydrological characteristics of near surface alluvial, veneer, or wetland systems that are known to have a scattered distribution around the SREX pit. The results suggest that these systems may be significantly impacted by the mining related dewatering. However, there is limited data to support more detailed modelling of these systems at a fine resolution.
- The Rise and Shine creek is modelled as a constant head boundary, which provides an infinite water supply to the model, while the actual creek has a relatively small flow. Therefore, model scenario estimates of potential creek flow depletion should not be confused with real prospects for creek flow depletion.

SREX: Recommended Values

We recommend the following values for the key predictions of interest:

- The modelling results suggest that the hard rock system does not significantly isolate the pit from the surface alluvial/veneer system; see Section 9.4.2
- Inflow to the pit from the hard rock aquifer: Our model suggested up to 23 $l\ s^{-1}$, however the Rise and Shine Creek was implemented as an infinite source, which may positively bias this value. See Section 9.4.2
- Likely reduction in discharge to Rise and Shine Creek from the hard rock aquifer: The model predicted up to c. 17 $l\ s^{-1}$, but this was with an infinite source and is near to or greater than the total measured flow. We suggest the SREX pit in closest proximity to the northwest quadrant containing the dewatering sump of the SREX pit may fully deplete flow in the main stem of Rise and Shine Creek passing the northwest quadrant, see Section 9.4.2 Significant parts of the upgradient creek catchment flow may be diverted past the SREX pit and such mechanical approaches to reducing the impacts of the depletion effect during operational dewatering were not modelled.
- Impact to adjacent wetlands: without additional data and modelling we suggest that the alluvial system and any nearby wetlands will be significantly impacted by the mining activities – possibly leading to the drying up of the wetlands and the loss of the alluvial system, see Section 9.4.2
- The likely pre- and post-mining water table elevations are available in Section 9.4.1, but these are heavily influenced by the constant head boundary condition on the Rise and Shine Creek

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Definitions and Abbreviations

RSSZ Rise and Shine Shear Zone

TZ-3 Textural Zone 3

TZ-4 Textural Zone 4

1 Scope of Work

The purpose of the work undertaken here was to perform the following actions regarding a potential mining operation at the Rise and Shine resource in the Dunstan Mountains, Central Otago:

1. Develop a conceptual model of the hydrogeological environment in the proposed mining area.
2. Estimate the pre-mining water table.
3. Assess the likely impacts of the proposed mining activities on the groundwater system in the area including the potential downstream impacts on surface water features.
4. Predict the likely rate of de-watering required for the open cast mining activities.

2 Background

2.1 Geology

The geology of the proposed mining area has been extensively described in other reports for the project. A full description of the geological setting is beyond the scope of this report, however the area is dominated by basement rock comprised of the Rakaia Terrain schist covered in places by thin veneers of quaternary alluvium and colluvium. For the purposes of the groundwater modelling we simplified the geological environment into four distinct groups which are (in stratigraphic order):

- Surficial veneers of alluvium, colluvium, and more extensively weathered basement rock (i.e., schist).
- TZ-3 (Textural Zone 3) Schist: Rakaia Terrain Quartzofeldspathic schist and greyschist (Turnbull et al., 2001).
- RSSZ (Rise and Shine Shear Zone): The shear zone and associated fault gouges were created by both brittle and ductile deformation associated with multiple activations of the Thompson's Gorge Fault. This zone is the target of the proposed mining activities.
- TZ-4 (Textural Zone 4) Schist: Rakaia Terrain Quartzofeldspathic schist, greyschist, and gneiss (Turnbull et al., 2001).

2.2 Hydrogeology and Hydrology

2.2.1 Water Sources and Sinks

The main source of water in the catchment is rainfall runoff and rainfall recharge. Other work for this project has estimated a likely mean annual rainfall of 463 mm per year for the area (Chater, In Draft). The rainfall recharge of the area has not previously been estimated as the area does not provide a substantial groundwater resource. A key challenge in estimating groundwater recharge in the area is the unknown, and likely highly variable, hydrogeological properties of the veneer of alluvium, colluvium, and weathered basement rock. Therefore, we assess the likely inflows into the hard rock aquifer in isolation from rainfall recharge estimates (Section 2.2.2).

The dominant receiving environments immediately adjacent to the proposed mining areas are Shepherds Creek and Clearwater Creek. These creeks are perennial and fed by rainfall runoff and groundwater discharges. Sheperds creek is the primary receiving environment for the proposed mining area, with the Rise and Shine pit being located in the Shepherds Creek catchment. Measurements of flow in Shepherds Creek range from 2.2 to 113 l s^{-1}. In addition, here are several ephemeral and intermittent tributaries to Shepherds Creek in the mining area.

There are also a number of springs in the wider environment, which then runoff to the respective creeks. These springs most typically occur at the top of mass wasting features, e.g., at the steep slope transitions at the top of slumps and landslides. Despite mapped springs in the wider area of the proposed mining activities, there is no mapped spring adjacent, up or down gradient from the proposed mining area Figure 2.1.

[redacted]

2.2.2 Conceptual Hydrogeological Model of the Proposed Mining Areas

The hydrogeology of the mining area can be split into two principal components:

1. The veneer aquifer - This is conceptually a very thin surficial system that includes rainfall-runoff, short term storage or recharge, and discharge to the hard rock aquifer, springs, and/or streams.
2. The hard rock aquifer - This is the deeper, more massive, “aquifer” dominated by fracture flow.

The distinguishing characteristics between these two hydrological components is that the veneer aquifer will be an unconfined system having significantly more storage, higher hydraulic conductivity, and a more responsive flow environment as it is dominated by porous media (e.g. alluvium, colluvium, and highly weathered bedrock). The hard rock aquifer in contrast will be a confined system with less storage, lower hydraulic conductivity, and a less responsive flow environment as it is dominated by fractured rock.

We suggest that there are two principal flow paths:

1. Through the veneer aquifer, which is recharged by rainfall, and discharges to the Shepherds Creek and Clearwater Creek, with some small discharge and recharge to and from the hard rock aquifer.
2. Through the hard rock aquifer, which is recharged by the veneer aquifer, and discharges to the veneer aquifer and potentially to Shepherds Creek and Clearwater Creek (possibly via Rise and Shine Creek); either through direct connection or via the intermittent to ephemeral tributaries. Note that no direct connection to the creeks from the hard rock aquifer have been observed in or adjacent to the mining area.

2.2.3 Downstream Receivers of Water

Both Shepherds Creek and Clearwater Creek flow to alluvial aquifers. Shepherds Creek flows to the Lindis Alluvial Aquifer, and Clearwater Creek flows to the Bendigo Alluvial Aquifer. In both cases the creeks are connected to the aquifers through a drying front connection, where the creeks run dry in their lower reaches, and water is transmitted through alluvium under the creek bed.

3 Model Locations and Boundaries

Here we present the results from three discrete models that were developed to assess the hydrogeological environment of the proposed mining area. The active model domains are shown in Figure 3.1. We chose to create multiple models rather than one large model to reduce the complexity of the parameterisation (e.g., each model can be calibrated independently) and to minimise the computational burden of the models. Note that the Come in Time model is within the Rise and Shine model domain; however initial modelling was unable to replicate the observed water table in the Come in Time area, so a separate model was developed for this area. It is unlikely that the impacts of the mining activities in any given model area will impact the other model areas, so the models can be considered in isolation.

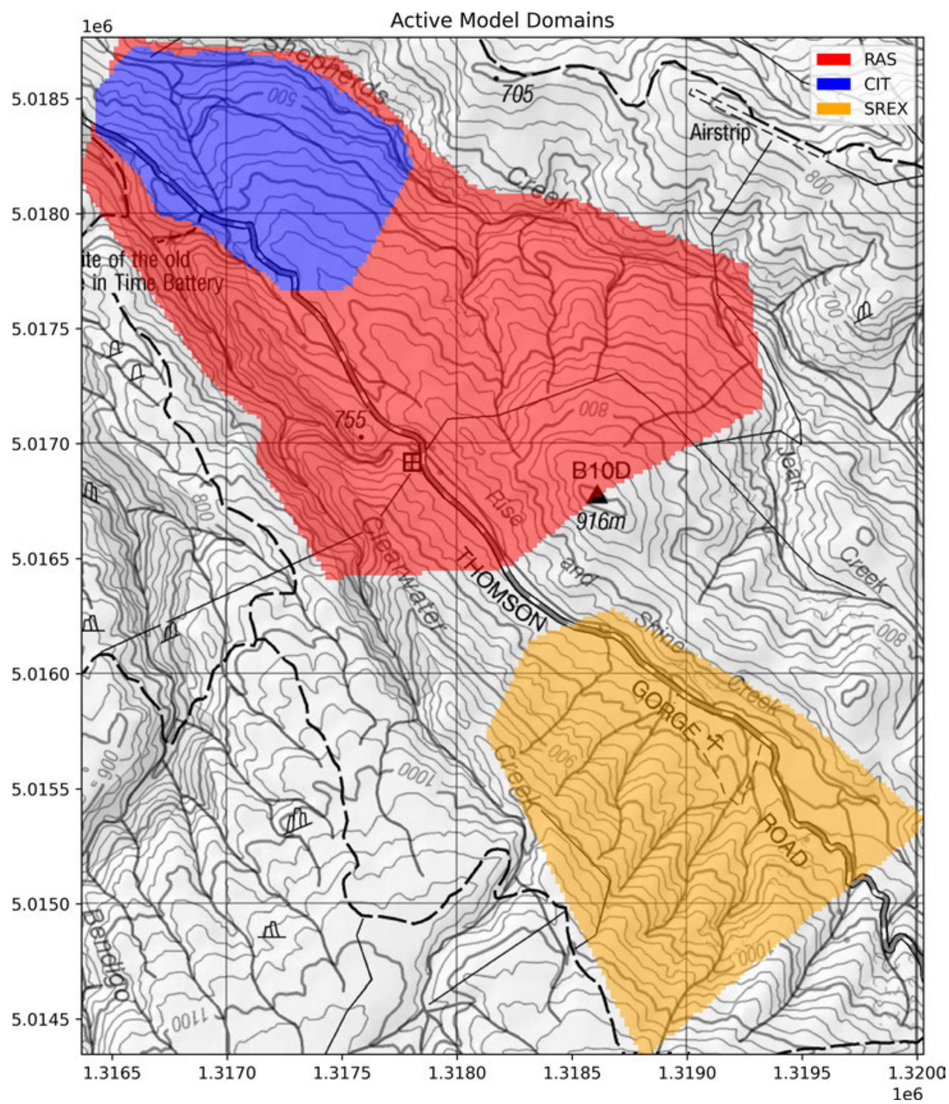

Figure 3.1: All active model domains, note RAS also includes the area for CIT.

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Date: 09/04/2025

4 Numerical Model Objectives, Conceptualisation and Approach

4.1 Numerical Model Objectives

The objectives of the modelling presented in this report are to:

1. Optimize a pre-mining groundwater model to observed water levels.
2. Estimate discharges from the hard rock aquifer to the Rise and Shine pit.
3. Estimate changes to discharges to Shepherds Creek and Clearwater Creek from the hard rock aquifer.

4.2 Numerical Model Conceptualisation

Here we have decided to only model the hard rock aquifer, and exclude the veneer aquifer from the model. We chose to exclude the veneer aquifer because:

1. Modelling unsaturated flow is highly computationally expensive and highly parameterised.
2. There is minimal to no information on the veneer aquifer, and it is likely to be very spatially variable.
3. The veneer aquifer is a thin surficial system in steep terrain. In combination, the aquifer thickness and the steep terrain significantly limits the propagation of mining impacts beyond the topographic area of the pit.
4. A more conservative approach is to simply assume that all rainfall that falls in the pit catchment (e.g. the up gradient area where water will flow into the pit) will require de-watering. Note that this approach cannot be used for the hard rock aquifer as it is much thicker and therefore drawdown could propagate much further.

Excluding the veneer aquifer from the model, we can simply conceptualise the hard rock aquifer as a simple confined system. The flow into the system from the veneer aquifer can be considered recharge, while discharges to veneer aquifer can occur through discharge to the “surface” of the model or to Shepherds Creek and Clearwater Creek.

4.3 Modelling Software

We used the industry standard MODFLOW-2005 and MODFLOW-NWT software to simulate the groundwater flow in the hard rock aquifer. MODFLOW-2005 and MODFLOW-NWT are finite difference solvers, which is well suited to simulating groundwater flow in confined aquifers. We chose MODFLOW-2005 and MODFLOW-NWT over the more recently released MODFLOW-6 because it is more computationally efficient, and we did not require the additional features of MODFLOW-6. Note that MODFLOW-2005 and MODFLOW-NWT and MODFLOW-6 will produce very similar results for the same model setup.

We undertook model construction in Python using the FloPy library and other in house Python packages. Models developed in Python are more easily reproducible than Graphical User Interface modelling programs (e.g., GW Vistas, GMS, etc.) as the code can be shared and each modelling decision is explicitly coded, rather than relying on the modeller to keep an accurate log of their actions. Additionally, Python based model implementations allows for more flexibility and automation in model construction, optimisation, and analysis.

The open source PYDREAM implementation of the MT-DREAM(ZS) algorithm is used to optimise the model parametrisation Laloy and Vrugt (2012).

For further information see Section 5.1.

4.4 Discritisation

The various model domains are discritised into a regular three-dimensional grid with layers (Z) perpendicular to the vertical datum (e.g., sea level), rows (Y) running due East-West, and columns (X) running due North-South. We chose to discretise the model as a grid rather than following the typical hydrological layering structure as this allows for higher discretisation and easier implementation of various pit shapes. Areas where the model cell elevation is greater than the ground surface are set to inactive cells. Table 4.1 shows the cells dimensions for the various models.

Table 4.1: Discretization of the models

Model	ΔX (m)	ΔY (m)	ΔZ (m)
Rise and Shine	50	50	10
Come in Time	20	20	5
SREX (580-850 m msl)	30	30	5
SREX (850-1300 m msl)	30	30	10

We temporally discretise the model as a steady state model, with the assumption that the groundwater flow is in equilibrium with the current recharge and discharge conditions. This was chosen as there is no information to support a transient optimisation of the model.

4.5 Model Boundary Conditions

Four boundary conditions are implemented in the model:

1. Constant head cells along the creeks to simulate generalised discharge to surface water features either directly or via the veneer aquifer. The use of constant head cells also allows for scenario models to predict potential inflows from the creeks (via the veneer aquifer) to the hard rock aquifer should the pit de-watering induce drawdown. This uses the MODFLOW CHD package.
2. Distributed recharge across the land surface to simulate the generalised inflows from the veneer aquifer to the hard rock aquifer. This uses the MODFLOW RCH package.
3. Drain cells across the model to simulate the potential discharge from the hard rock aquifer to the veneer aquifer. This uses the MODFLOW DRN package. Note in places most or all of the recharge applied to a model cell may be immediately discharged to the drain package. This occurrence suggests no recharge from the veneer aquifer to the hard rock aquifer in these locations. These cells also prevent unrealistically high groundwater levels caused by refused recharge, where, numerically, the model is forced to uptake the prescribed recharge, but in reality the recharge would be refused and the water would remain in the veneer aquifer.
4. Drain cells to simulate the discharge to the pit. This uses the MODFLOW DRN package. When the pit excavation is included in the model, an additional discharge pathway is created from the hard rock aquifer to the pit. The impacts of this excavation may be: reductions in discharges to the creeks, as well as reduction in discharges to the veneer aquifer, or increases in recharge from the veneer aquifer. The de-watering of the pit is simulated by creating additional drain cells throughout the excavated area, with a very high conductance relative to the model conductivity (10^3 m^2/day).

5 Model Parameterisation and Optimisation

5.1 Model Optimisation Framework

The MT-DREAM(ZS) algorithm is used to optimise the model Laloy and Vrugt (2012).

This algorithm seeks to minimise the mismatch between the observed head data and the modelled head at the same borehole locations, by adjusting the model parameters while respecting the "likely" model parameter (i.e., prior).

This mismatch is represented by the log-likelihood function:

$$L(\bar{h}|\theta) = -\frac{n}{2}\log\sum_{i=1}(h_i - \hat{h}_i)^2 \tag{5.1}$$

Where:

- $\theta = (K_0, K_1, K_2, R, C)$, the model parameters
- $\bar{h}$ is the observed head measurements
- n is the number of boreholes with observations
- h_i is the observed head at borehole i
- $\hat{h}_i$ is the modelled head at borehole i

When L values close to zero represent a better fit to the observed water levels, while more negative values indicate a model which is less able to reproduce the observed water levels. The algorithm takes the prior parameter probability distribution $P(\theta)$, which represents the available information about the parameters before optimisation, and estimates a posterior parameter probability distribution $P(\theta|\bar{h})$, given the head observations.

The relationship between the posterior and prior distributions is given by Bayes' theorem:

$$P(\theta|\bar{h}) = \frac{P(\theta)L(\bar{h}|\theta)}{\int_\theta P(\theta)L(\bar{h}|\theta)d\theta}. \tag{5.2}$$

Conducting an optimisation of the model parameters using the MT-DREAM(ZS) algorithm has significant advantages over traditional optimisation methods. Groundwater models are typically poorly-posed numerical problems, with many parameters and few observations. In practice, this means that many different parameter sets can replicate the observed data equally well. These non-unique models can have significantly different values for the prediction of interest (e.g., the amount of de-watering required). The MT-DREAM(ZS) algorithm works to constrain the likely parameter values (i.e., the prior) to those parameters which are able to reproduce the observed data (i.e., the posterior). This means that the output is not a single, likely non-unique, model, but rather a distribution which can provide uncertainty analysis and quantify the likely range of predictions.

5.2 Parameterisation Strategy

We have chosen to use a simple parametrisation scheme for the model. A more highly parameterised model can typically better fit the observation data but may yield overfitting and less reliable predictions. Given the relatively little observation data available we have chosen to parameterise the model with five parameters. These parameters are:

1. The hydraulic conductivity of TZ-3 Schist(K_0 $[m/day]$)
2. The hydraulic conductivity of RSSZ (K_1 $[m/day]$)
3. The hydraulic conductivity of TZ-4 Schist(K_2 $[m/day]$)
4. The average distributed recharge flux (R $[m/day]$)
5. The surface drain conductance (C $[m^2/day]$)

5.2.1 Hydraulic Conductivity Zones

We divided the model into three hydraulic conductivity zones in accordance with the three geological zones represented within the model Section 2.1. We assume that the hydraulic conductivity of each zone is homogeneous (the same across the entire zone), and isotropic (the same in all directions). These assumptions are a simplification of the true geological environment as conductivity in the hard rock aquifer is driven by fracture density and connectivity; however in the absence of compelling evidence to the contrary, it is better to assume homogeneity and isotropy than to *a. priori.* assume a more complex structure. Here we define the upper zone

(TZ-3 Schist) as the area between the land surface and the Thompson's Gorge Fault surface (Figure 5.1). The middle zone (RSSZ) is defined as the area from the Thompson's Gorge Fault surface to 40 m below this surface. The lower zone (TZ-4 Schist) is defined as all the area more than 40 m below the fault surface. The distribution of each of these parameter zones for the various models are shown in the model schematics (CIT: Section 8.1.3, RAS: Section 7.1.3, SREX: Section 9.1.3).

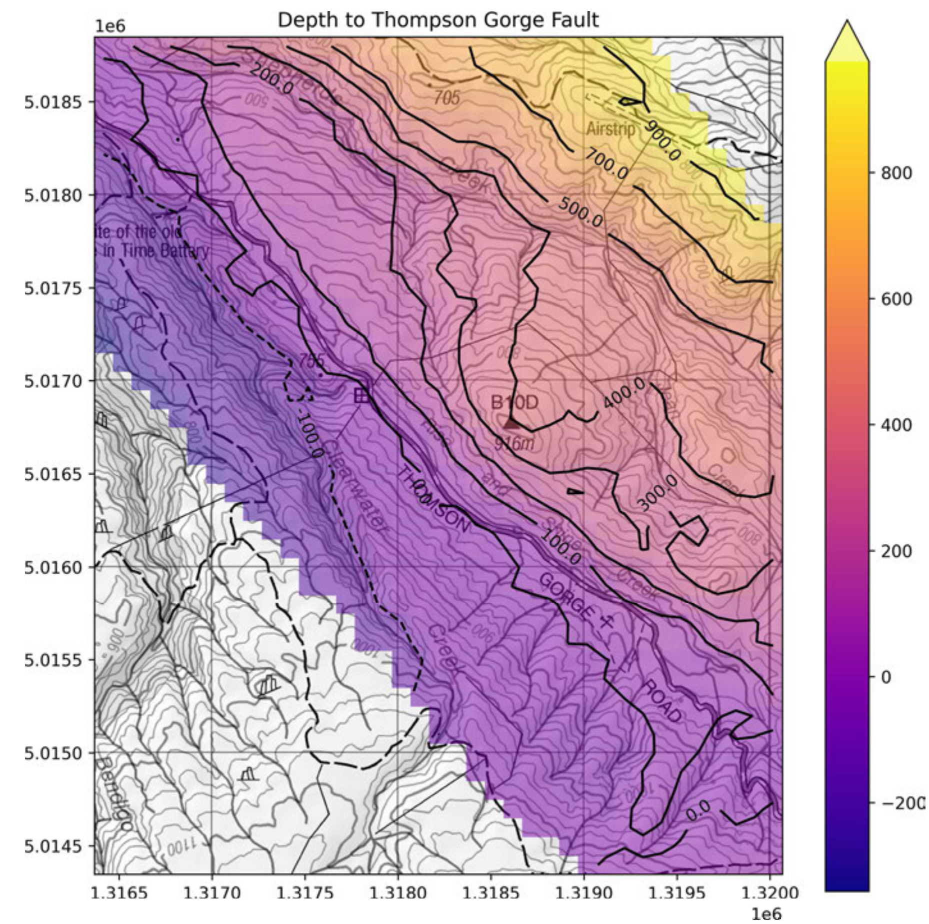

Figure 5.1: Depth to the Thompson Gorge Fault.

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5.3 Prior Parameter Distributions

The prior parameter distributions are used to define the likely range of values for each of the model parameters and constrain the model. For instance, we know that the hydraulic conductivity of the hard rock aquifer is likely to be relatively low, so it would not be defensible if the model matched the observed data with a very high hydraulic conductivity. We defined prior parameter distribution based on all available data, but often inflated the prior (e.g., a larger prior) to ensure that the "true" value is contained within the prior distribution. The prior parameter distributions are shown in Figure 5.2.

The hydraulic conductivity priors of each zones (K_0, K_1, K_2), are based on the minimum and maximum estimates of hydraulic conductivity from packer tests in the nearby Cromwell Gorge. The gorge outcrops TZ-4 Schist and may be more fractured (and thus have higher conductivity) than the hard rock aquifer in the model area as the gorge is in a mass wasting risk area. The packer tests were conducted to inform mass wasting risks.

Nevertheless, the packer tests are the best available data and are used to inform the prior distribution. Here we have chosen a generalized normal distribution, which has a relatively even probability across the range between the minimum and maximum packer test estimate and then decreases as to zero at around two degrees of magnitude above and below these estimates. The prior distribution of the recharge flux (R) is not easily constrained as it relates to the transport of water from the poorly constrained veneer aquifer and the hard rock aquifer. Due to this uncertainty we have modelled the prior distribution as a uniform distribution (no value is more likely than the others) between $10^{-7} - 10^{-2}$ m d^{-1} which encapsulates our knowledge of the possible recharge, it may be very low, but probably should not exceed the average rainfall rate in the model area. The conductivity of the surface drains (C) is not well related to an actual physical parameter given our use case. It should be relatively high, water should be able to seep out of the hard rock aquifer as there is no evidence of artesian pressures, but is otherwise unconstrained. Therefore, we have set a wide uniform distribution between $10^{0} - 10^{5}$. m^2 d^{-1}. All prior distributions are specified in the log base 10 transformed space. The parameter values range over multiple orders of magnitude and a log transformation allows for a more even distribution and sampling of the parameter.

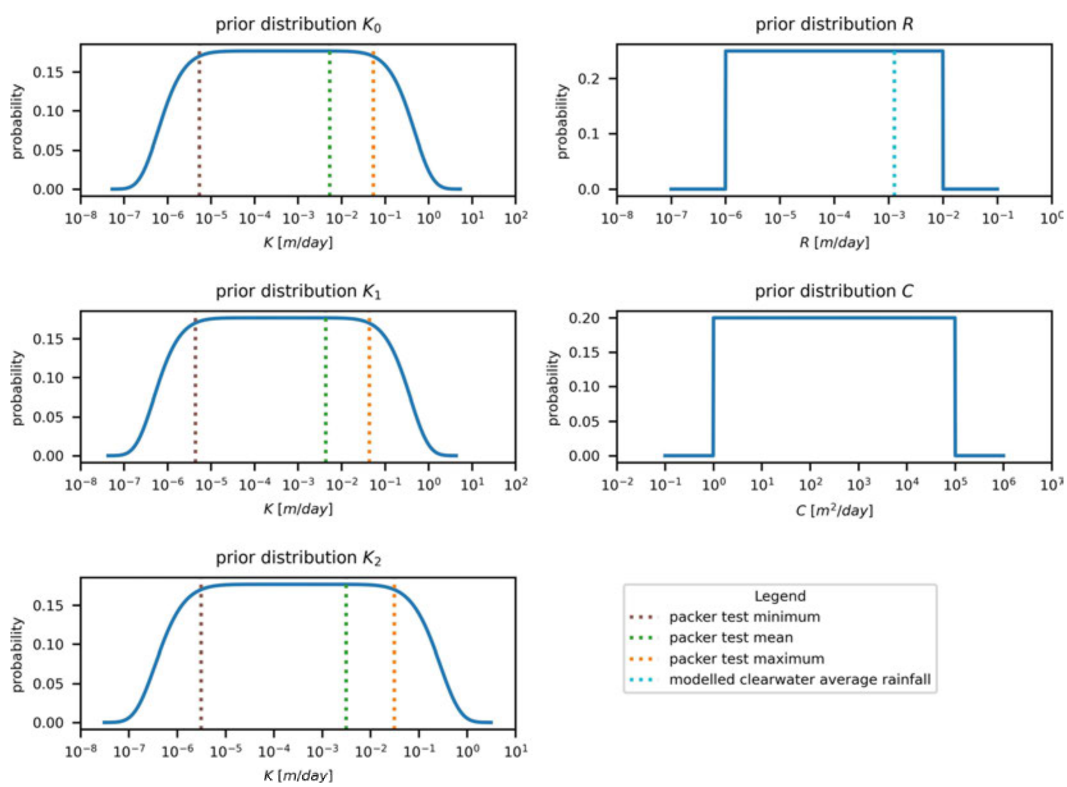

Figure 5.2: Prior parameter distributions.

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6 *A. Priori. Limitations*

Here we highlight the known limitations of this model based only on its conceptualisation, structure, build and parameterisation. These limitations are:

- The veneer aquifer is not explicitly represented in any of the models and any de-watering of this aquifer is assumed to be minimal beyond the topographic area of the pit. This assumption is reasonable due to the thin nature of the veneer aquifer and the steep terrain.

- Any calculated discharges to the creeks are likely to be conservative as they are represented as discharges to the veneer aquifer, which may store water and/or lose some additional water to evapotranspiration.
- The models are steady state models, which assumes that the groundwater flow is in equilibrium with the current recharge and discharge conditions. This may not be the case, and the models may not be able to represent transient flow processes.
- The hydraulic conductivity of the hard rock aquifer is parameterised into three zones. The optimisation process will give us an estimate of the bulk hydraulic conductivities of these zones, however, it will not be able to represent finer scale features (for instance local fracturing densities).
- The use of constant head cells along the creeks represents a potential infinite source of water into the model, and direction connection from the aquifer to the creeks. This may overestimate the impacts of de-watering the hard rock aquifer on the creeks.
- The models are optimised to a relatively small dataset of water level observations. The optimisation process is stochastic, which limits the probability that the actual effects will be beyond the range of the model effects, but additional data would further constrain the model and the posterior distribution.

7 Rise and Shine Model

7.1 Rise and Shine Numerical model structure and Conceptualization

7.1.1 Rise and Shine Rainfall Volumes in the Catchment of the Pit

To assess the maximum likely inflows from the veneer aquifer to the mining pit we have made a conservative surface water catchment for the pit excluding the catchment of Rise and Shine Creek. The catchment is c. 613,610 m^2 (0.61 km^2). Applying the annual mean rainfall (0.463 m) yields a total volume of c. 284,100 m^3 of water that could potentially flow into the pit each year, or an average rate of 778 m^3/day (9 l s^{-1}). The partitioning between runoff and recharge is poorly constrained, however the steep terrain suggests most of this volume will be rainfall runoff and therefore “flashy” with most of the inflow occurring during rainfall events. Note this estimate does not account for any impact of snowfall and/or snow transport.

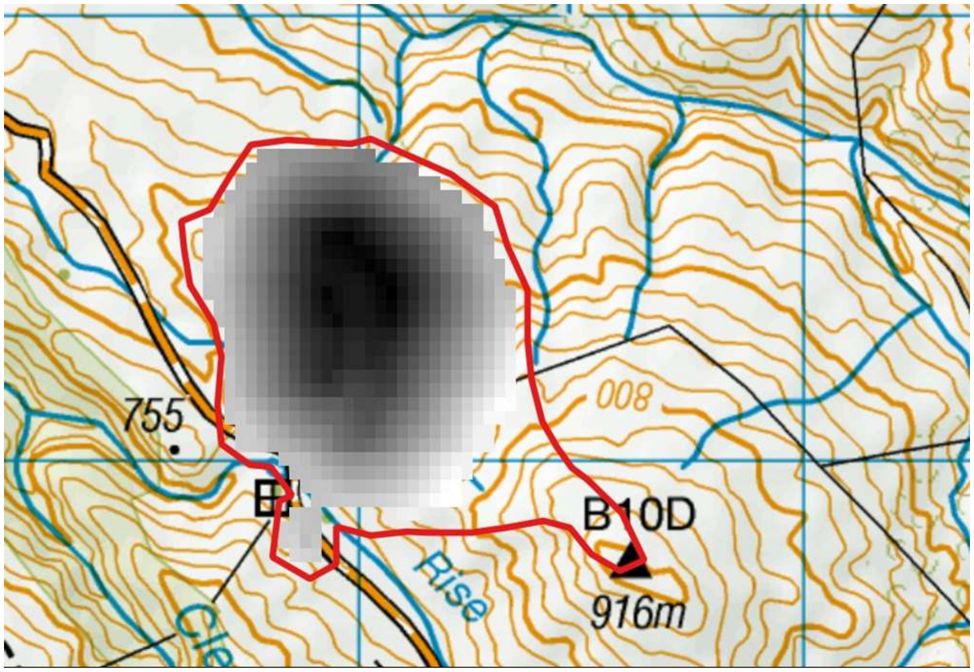

Figure 7.1: RAS: Catchment area of the Rise and Shine pit.

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7.1.2 Rise and Shine Model Domain and Discritisation

The model domain is defined as the area between Shepherds Creek and Clearwater Creek, extending form trig point B10D in the South-East to a small saddle of near point 585 in the North-West. The model area is shown in Figure 7.2. The model area comprises the ridge where the proposed Rise and Shine and Come in Time sites are located. The model boundary - where not formed by the creeks - is truncated at assumed groundwater divides. Outside of this boundary, groundwater flow is not expected to be impacted by the proposed mining activities.

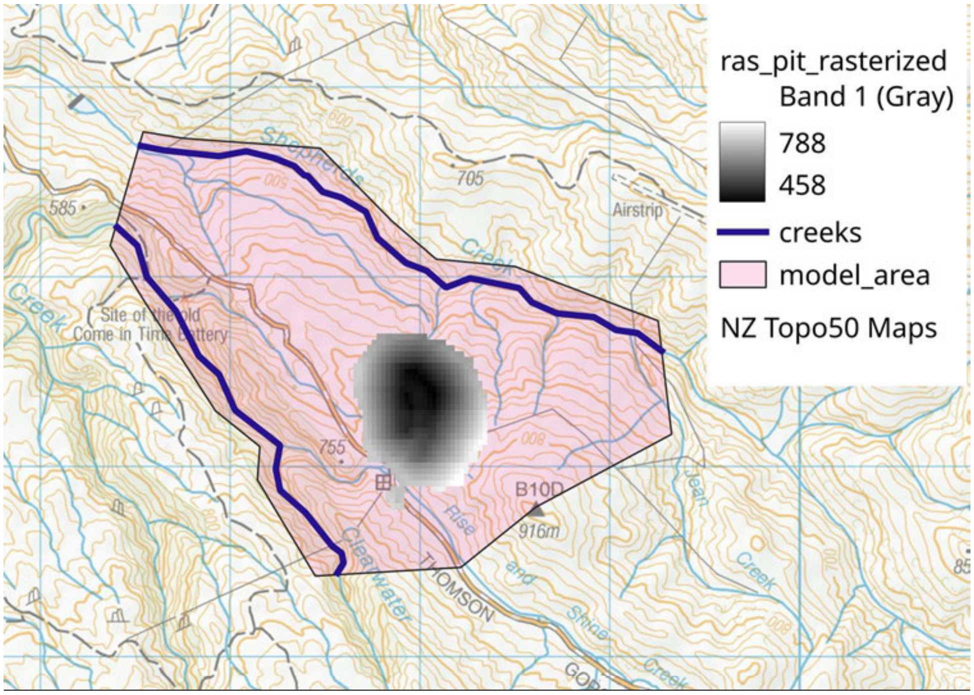

Figure 7.2: RAS: Model area, final pit surfaces and creeks.

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7.1.3 Rise and Shine Hydraulic Conductivity Zones

The rise and shine model is divided into three hydraulic conductivity zones. These zones are show in Figure 7.3.

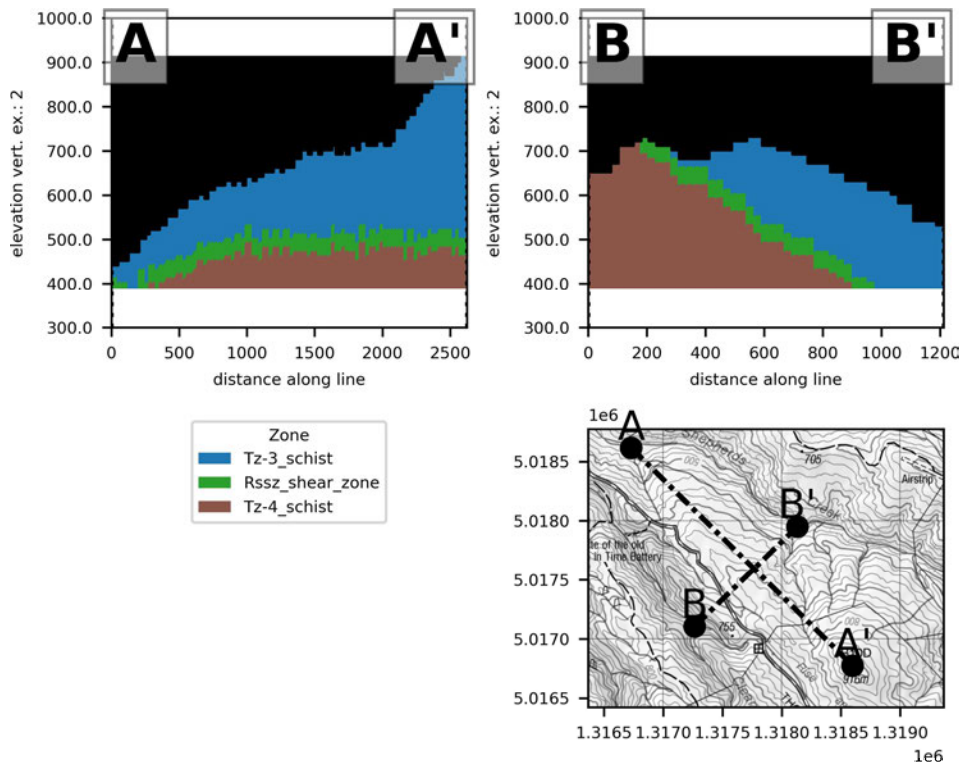

Figure 7.3: RAS: Cross-sections of the three hydraulic conductivity zones.

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7.1.4 Rise and Shine Boundary Conditions

The location of these boundary conditions are shown in Figure 7.4.

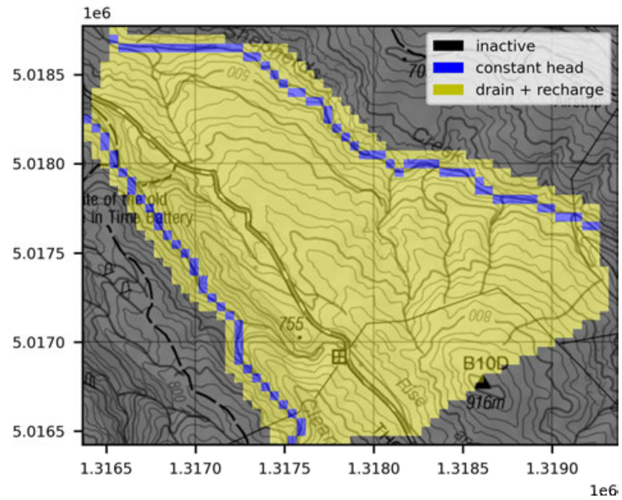

Figure 7.4: RAS: Boundary conditions applied across the surface of the model domain.

Black cells are inactive, blue cells are constant head cells, and yellow cells are surface drain and recharge cells.

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7.1.5 Rise and Shine Mining Activity Representation

The proposed mining plan for the area consists of the excavation of the Rise and Shine pit over a period of eight years. This pit will largely be removing the overburden in the TZ-3 Schist, and reach the RSSZ deposit. Excavation will require de-watering of the pit, effectively lowering the water table at the pit. Once the pit is complete, underground working will extend from the base laterally into the RSSZ, requiring additional de-watering.

Pit excavation and underground workings will both impact groundwater flow around the site. Groundwater flow direction near the pit in both the veneer and hard rock aquifers will be altered to flow towards the excavated area. This is due to de-watering decreasing the groundwater head. This will result in some amount of groundwater which would otherwise flow towards Shepherds Creek and Clearwater Creek flowing into the pit, and subsequently being de-watered.

When the pit excavation is included in the model, an additional discharge pathway is created from the hard rock aquifer to the pit. The impacts of this excavation may be reductions in discharges to the creeks, as well as reduction in discharges to the veneer aquifer, or increases in recharge from the veneer aquifer.

The development of the pit over the eight years of excavation is estimated as a linear progression from the pre-mining land surface to the final pit surface. These surfaces are shown in Figure 7.5.

Due to the relatively small scale of the model area, and the time over which the pit is excavated, it is expected that the impacts to groundwater flow will not lag significantly behind the excavation. As a result, temporal change to groundwater flow can be modelled as a series of steady states over the eight years.

The drains cells introduced in each new steady state model are shown in Figure 7.6. We chose to implement the pit in this manor as it is a pragmatic solution to simulate de-watering without altering the fundamental model structure.

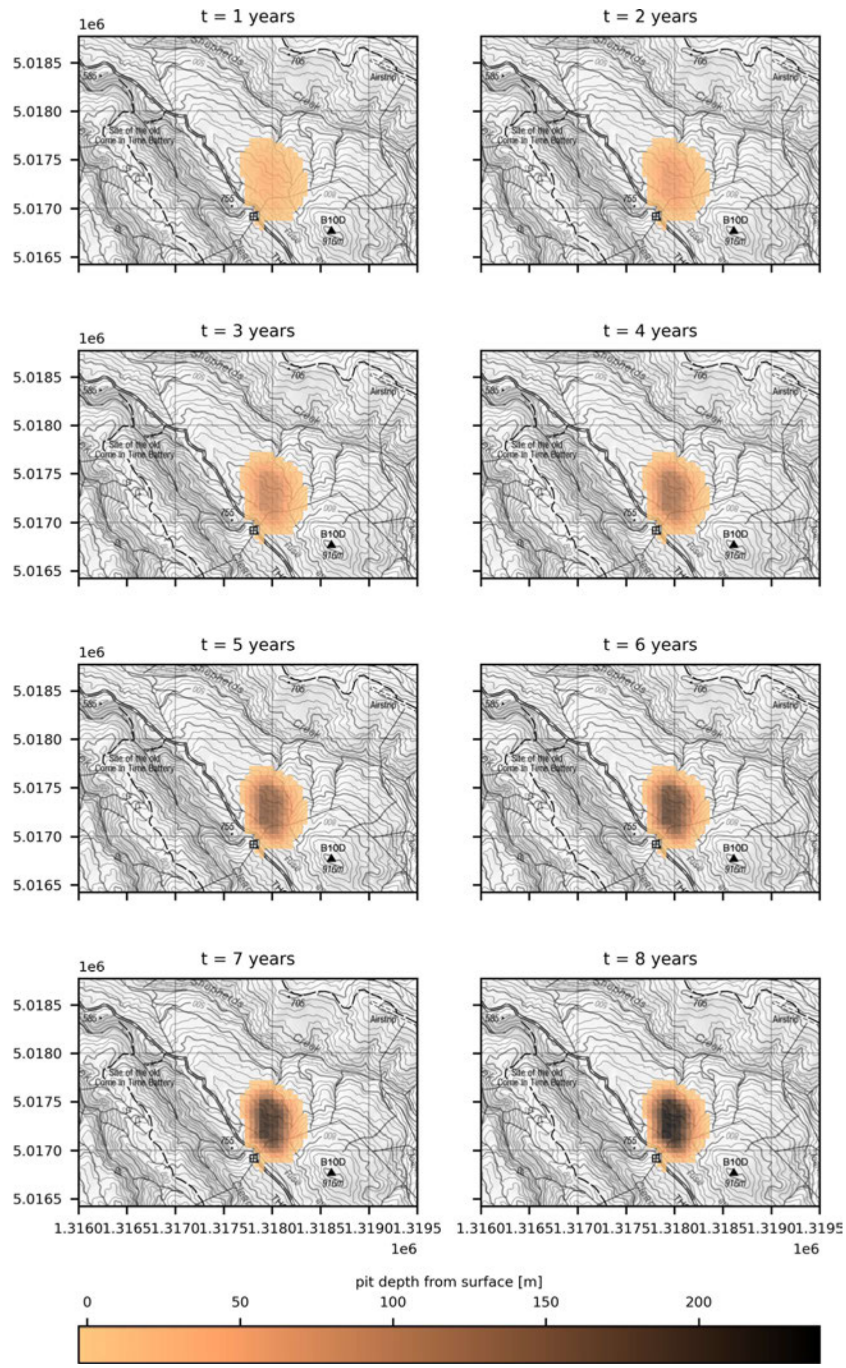

Figure 7.5: RAS: Depth from surface to pit bottom, over 8 years of excavation.

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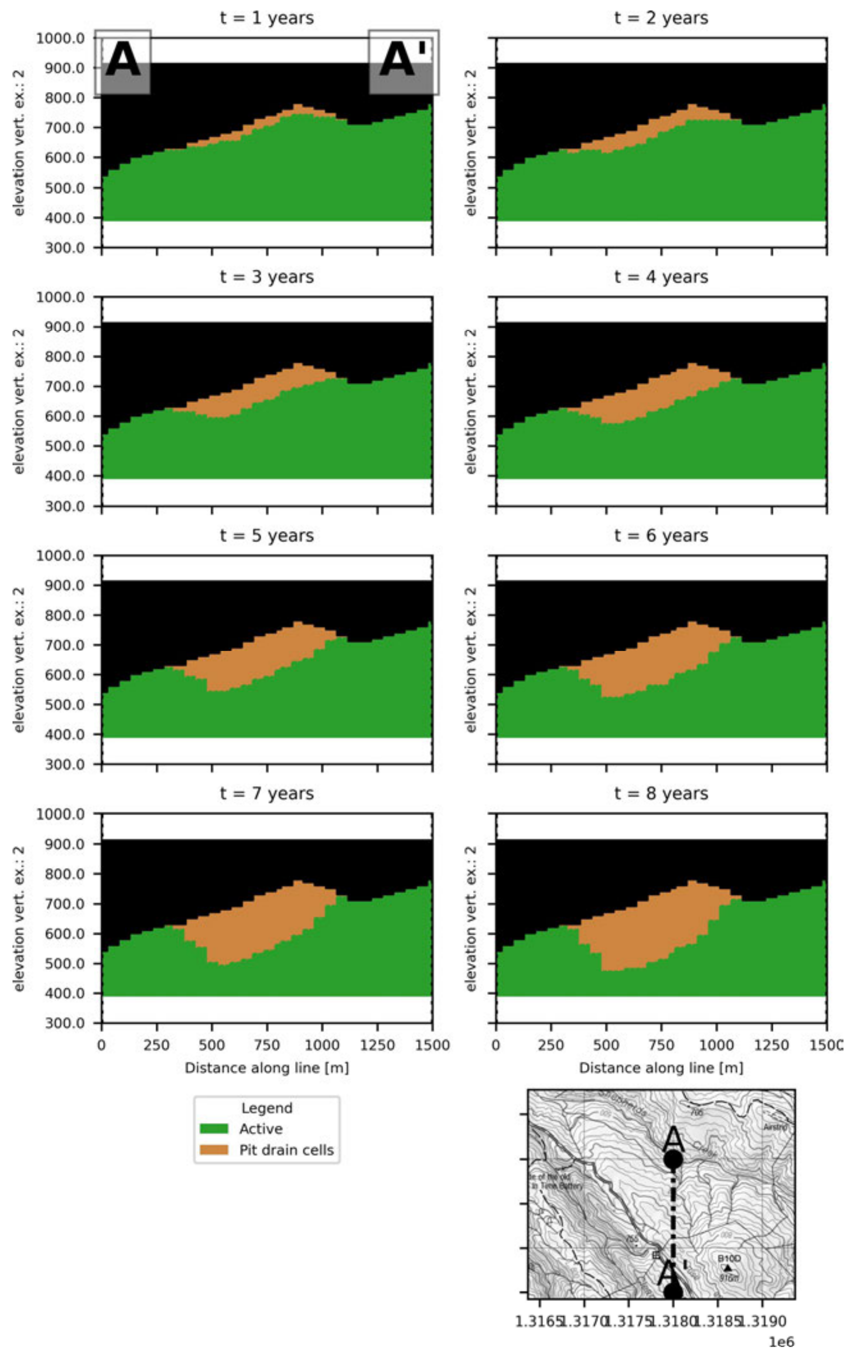

Figure 7.6: RAS: Drain cells introduced in each new steady state model.

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7.2 Rise and Shine Water level Observations for Model Optimisation

Water table surveys were carried out in August 2023 and January 2024. The observed heads are shown in Figure 7.7. These observations are used to optimise the model. The average of these measured values at each site are taken as the optimisation targets. Within the model domain there are head observations for 64 boreholes. 14 of these boreholes are located near the Come in Time site, with the remaining 50 boreholes located around the Rise and Shine site.

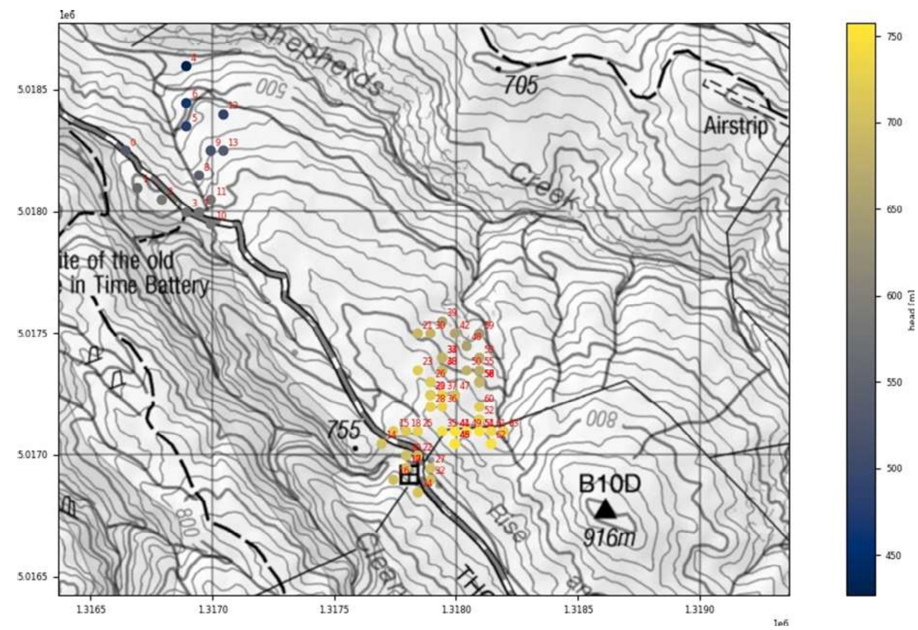

Figure 7.7: RAS: Observed head at exploration wells across the model domain.

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7.3 Rise and Shine Optimisation results

7.3.1 Rise and Shine Fit to Observed Heads

The fit between the optimised model and the observed heads is shown in Figure 7.8. The residuals are the difference between the observed and modelled head at each borehole. In addition, the modelled and measured heads are shown in Figure 7.9.

The model generally over predicts the head at the boreholes near the Come in Time site, and over and under predicts the head at the boreholes near the Rise and Shine site. The relatively poor fit to the observed heads near the Come in Time site is not significantly problematic for the prediction of impacts from the Rise and Shine site as it is significantly distant from the Rise and Shine site. However, this does mean that this model should not be used to predict the impacts of the Come in Time site. A separate model was developed for this site, see Section 8. The model over and under predicting the observed heads at the Rise and Shine site means there is some process that the model cannot replicate with the current parameterisation and/or structure. The most likely tension is the global recharge rate. This rate drives the fit of the heads on the relatively flatter ridge line, while forcing higher than observed levels in the steeper terrain. A spatially distributed recharge layer would likely improve the fit of the model to the observed heads, but also significantly increases the risk of overfitting. At the hydraulic conductivities observed and modelled, a small change to recharge can yield large changes in modelled head, therefore we believe that these misfits do not represent a significant source of error in the model for the predictions of interest.

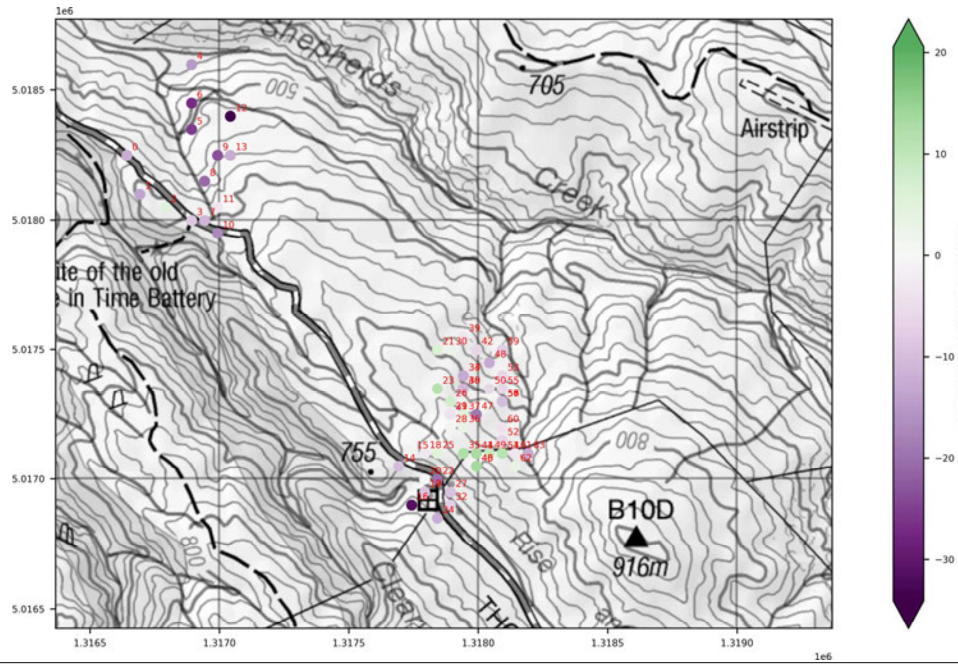

Figure 7.8: RAS: Water level residuals.

Average difference between the observed and modelled head at each of the boreholes. Purple points show where the model is overestimating the head. Green points show where the model is underestimating the head.

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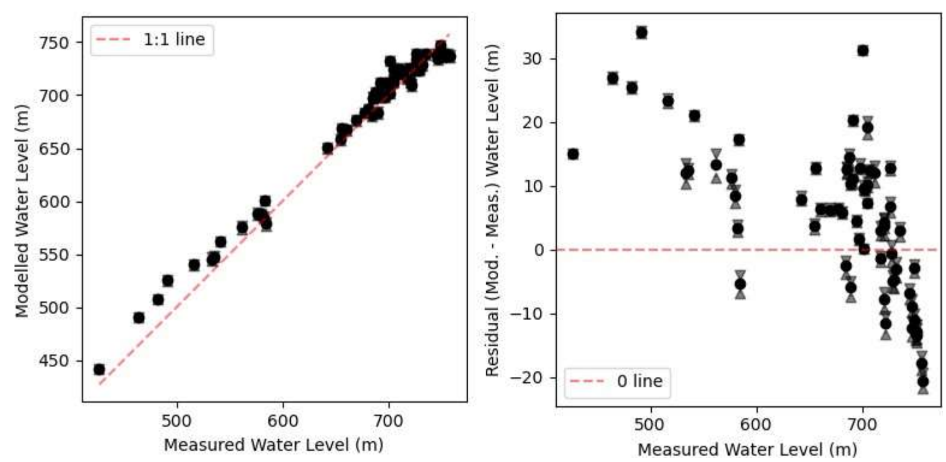

Figure 7.9: RAS: Measured vs modelled heads.

Measured vs modelled heads at each of the boreholes. The dashed line represents a 1:1 relationship. The triangles represent the simulation min/max values and the circle represents the mean value.

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7.3.2 Rise and Shine Posterior Parameter Distributions and Predictions of Interest

The estimated posterior parameter distributions are shown in Figure 7.10. The hydraulic conductivities of the TZ-3 Schist and TZ-4 Schist zones are estimated to range from $10^{-7.5}$ - $10^{-5.5}$ m/day. This is less that estimated from the packer tests, however this is not unexpected as the packer tests are small scale measurements and located in a mass wasting zone. The parameters of the TZ-3 Schist and TZ-4 Schist zones are consistent with literature values for un-fractured metamorphic rock (10^{-5} - 10^{-8} (Freeze and Cherry, 1979)). It is worth noting that the prior parameterisation of the hydraulic conductivity of the TZ-3 Schist and TZ-4 Schist zones suggested that hydraulic conductivity of this level was significantly unlikely. This means that the model was forced into this lower hydraulic conductivity range by the observed water levels otherwise it would have "preferred" a more, *a. priori.*, likely parameterisation. This provides strong evidence that the observed water levels require the posterior lower hydraulic conductivity values.

than

The hydraulic conductivity of the RSSZ is estimated to be around 10^{-1} - 10^{-3} m/day. This is within the range of the packer test estimate. It is much higher than the other zones, which is not unexpected given that this zone features a different fracture environment. The conductance of the surface drains is estimated to be around 10^{4} m^2/day. The raw recharge flux is estimated to be around c. $10^{-4.5}$ - $10^{-3.25}$ m/day, which is less than 10% of the average rainfall rate in the model area $10^{-2.90}$ m/day.

Figure 7.12 shows the modelled average flux in or out of the hard rock aquifer. The optimised model predicts that the hard rock aquifer is being recharged at the areas with higher elevation and relatively flat topography, and is discharging to the veneer aquifer at the ephemeral and intermittent streams, and areas with lower elevations.

By summing up the fluxes across the areas of the model domain, associated with each of the creeks catchments, the discharge to Shepherds Creek and Clearwater Creek can be estimated. The predicted distribution of discharges to each of the catchments from the optimised model is shown in Figure 7.13.

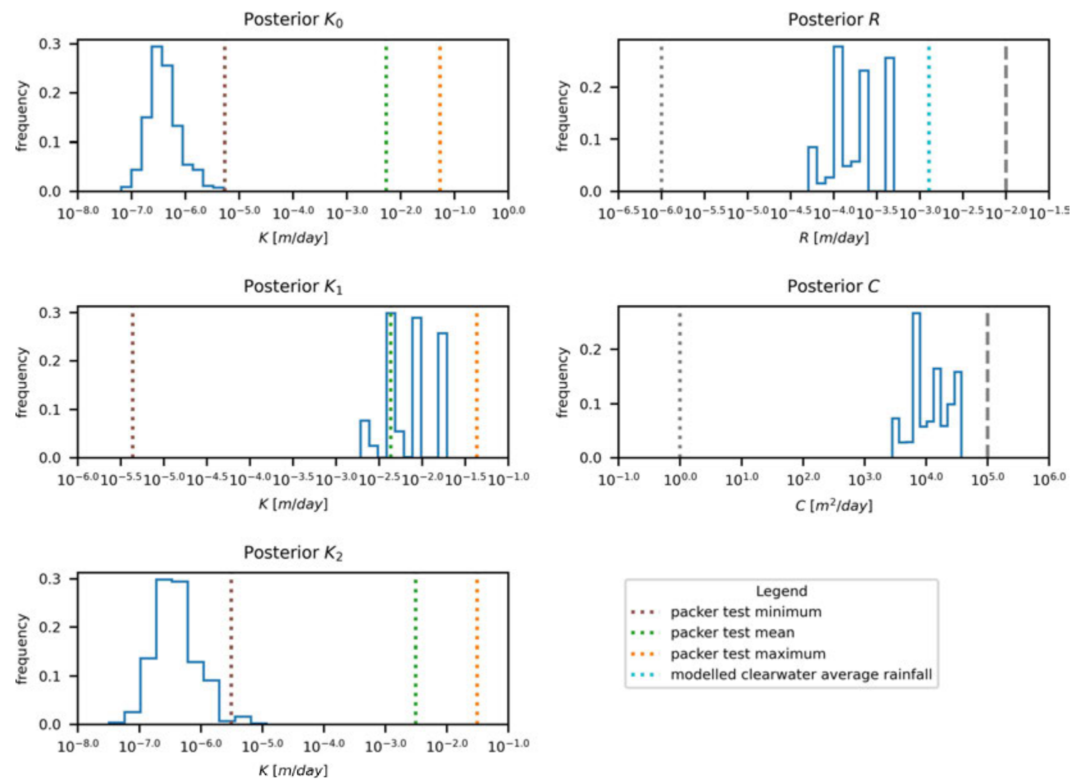

Figure 7.10: RAS: Estimated posterior parameter distributions.

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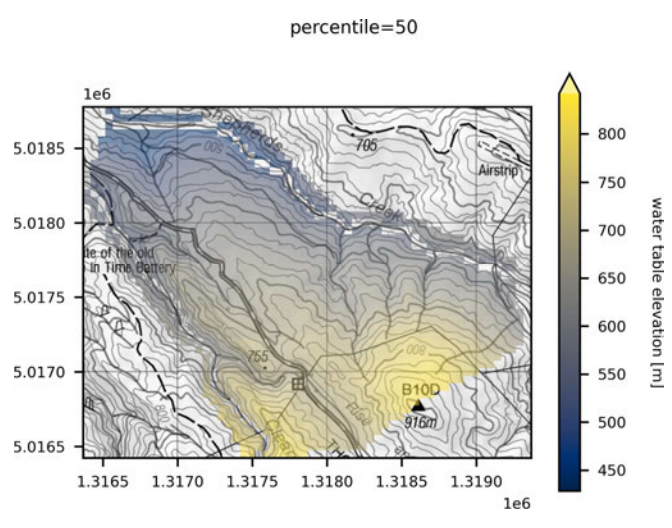

Figure 7.11: RAS: Average modelled water table elevation.

Yellow shading shows areas of high water table elevation. Blue shading show areas of low water table elevation.

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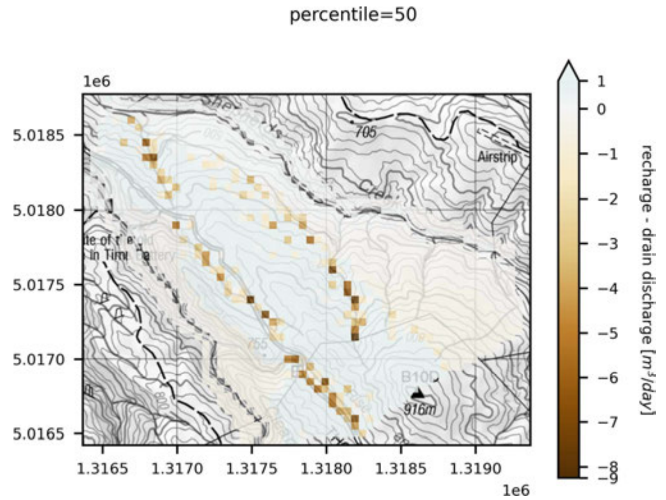

Figure 7.12: RAS: Average flux in and out of the hard rock aquifer.

Green cells represent aquifer recharge, and brown cells represent aquifer discharge.

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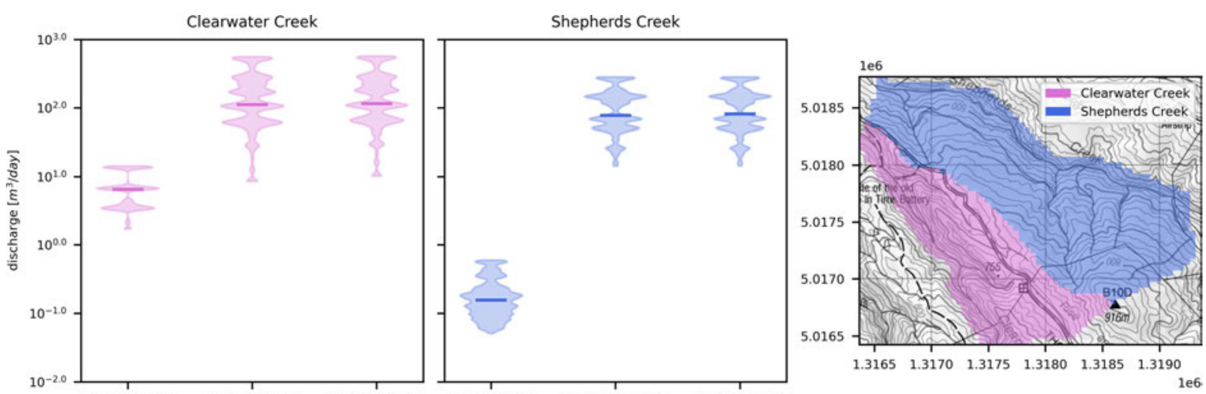

Figure 7.13: RAS: Distribution of discharges to each of the catchments.

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7.3.3 Rise and Shine Constrained Optimisation Results

The main optimisation produced best estimate of the hydraulic conductivity of the TZ-3 Schist and TZ-4 Schist zones that falls below the observed packer test estimates. Packer tests are not measurements of bulk hydraulic conductivity and were conducted in a potentially more fractured area (the Cromwell Gorge) therefore the below observed values are not unexpected. However, we have also run an optimisation where the hydraulic conductivity of the TZ-3 Schist and TZ-4 Schist zones are constrained to the observed range of the packer tests to assess the scale of impact that this constraint would have on the modelled predictions. The results of this constrained optimisation are shown in Figure 7.14. Note that here the posterior distribution of the hydraulic conductivity of the TZ-3 Schist and TZ-4 Schist zones is highly constrained to the lower end of the packer test range, further suggesting that the observed water levels require the lower hydraulic conductivity values.

The key parameter of interest here is the global recharge value. The constrained model suite increases the recharge from c. $10^{-4.5}$ - $10^{-3.25}$ m/day, (main suite) to c. $10^{-3.75}$ - $10^{-3.0}$ m/day (constrained suite). The constrained optimisation suite has a similar fit to the observed heads as the best suite. These results are available in Appendix A.1

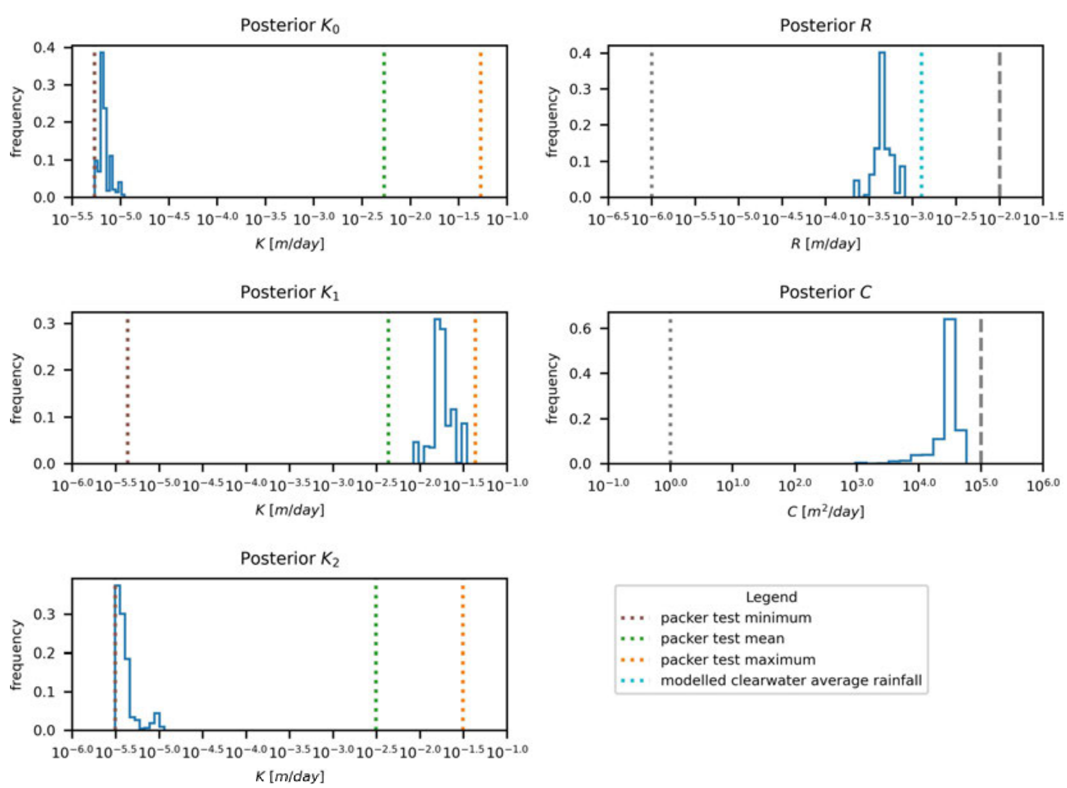

Figure 7.14: RAS: Estimated posterior parameter distributions with hydraulic conductivity constrained to packer test range.

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7.4 Rise and Shine Mining Impact Predictions

7.4.1 Rise and Shine Mining Impacts to Groundwater Levels

Water table elevations were predicted for the hard rock aquifer, pre and post mining, for each year of the 8 year mining period. The water table contours are shown in Figure 7.15 to Figure 7.22. These water levels and their contours have also been made available as GIS rasters and line shapefiles. As expected, the water table in the pit declines significantly; however the impacts do not extend far from the pit. Even after 8 years of mining (the final pit depth) there is a distinct flow divide between the pit and the Shepherds Creek. This suggests that the impacts on Shepherds Creek will be a reduction in groundwater discharge to the creek, rather than inducing flow from the creek to groundwater.

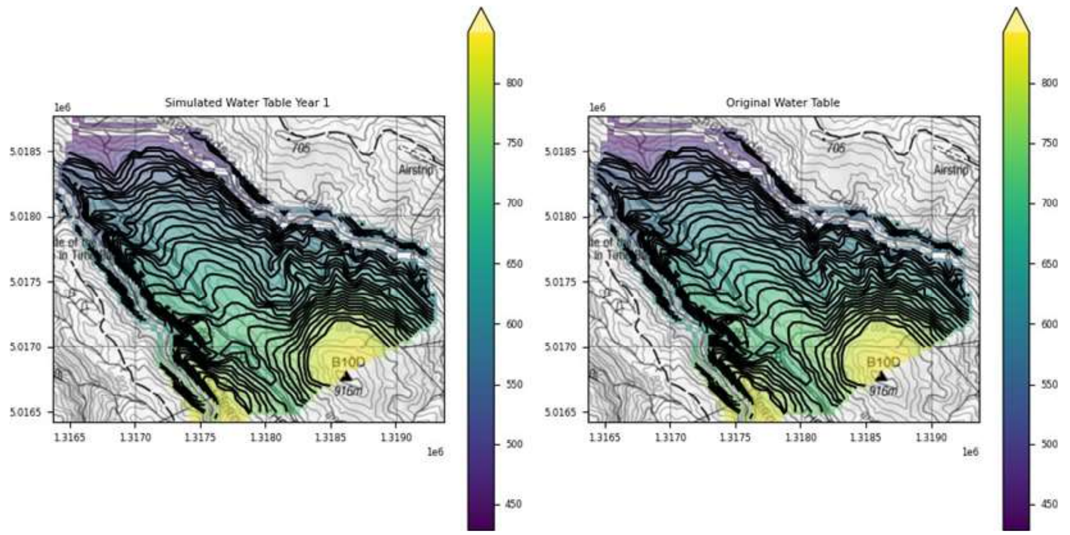

Figure 7.15: RAS: Predicted water table elevation for the hard rock aquifer year 1.

Water table contours are show every 10 m from 500 - 800 m.

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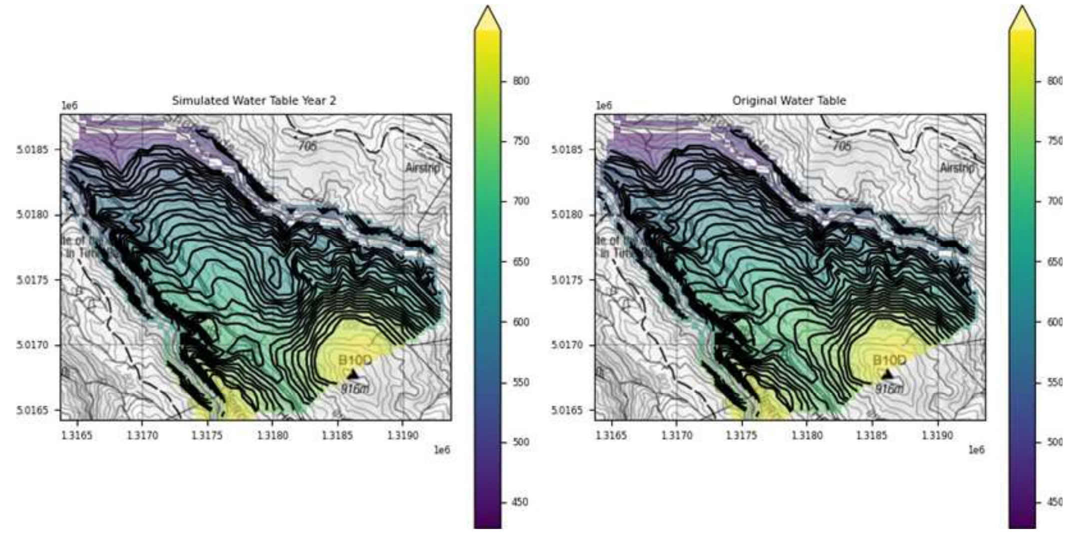

Figure 7.16: RAS: Predicted water table elevation for the hard rock aquifer year 2.

Water table contours are show every 10 m from 500 - 800 m.

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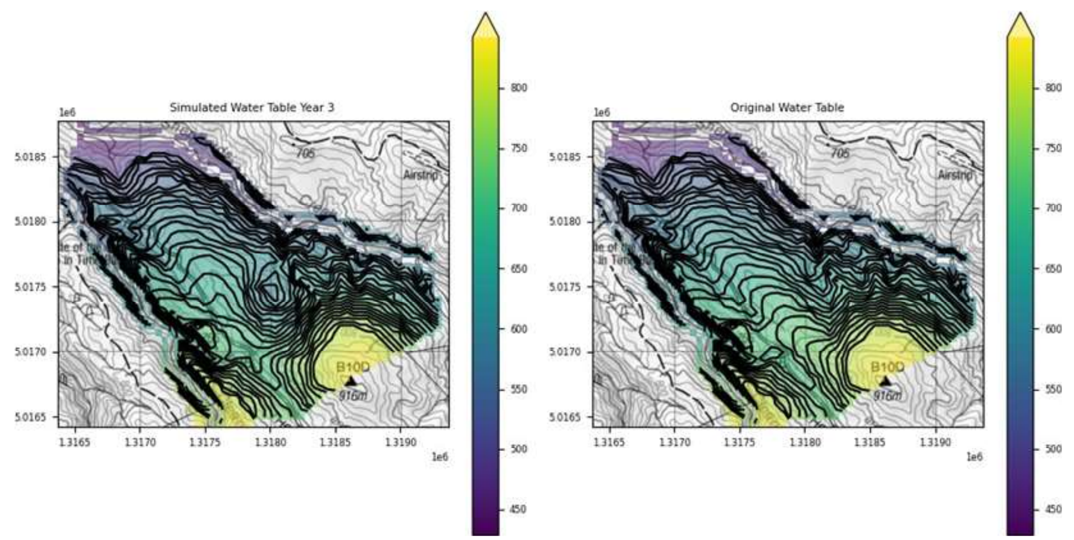

Figure 7.17: RAS: Predicted water table elevation for the hard rock aquifer year 3.

Water table contours are show every 10 m from 500 - 800 m.

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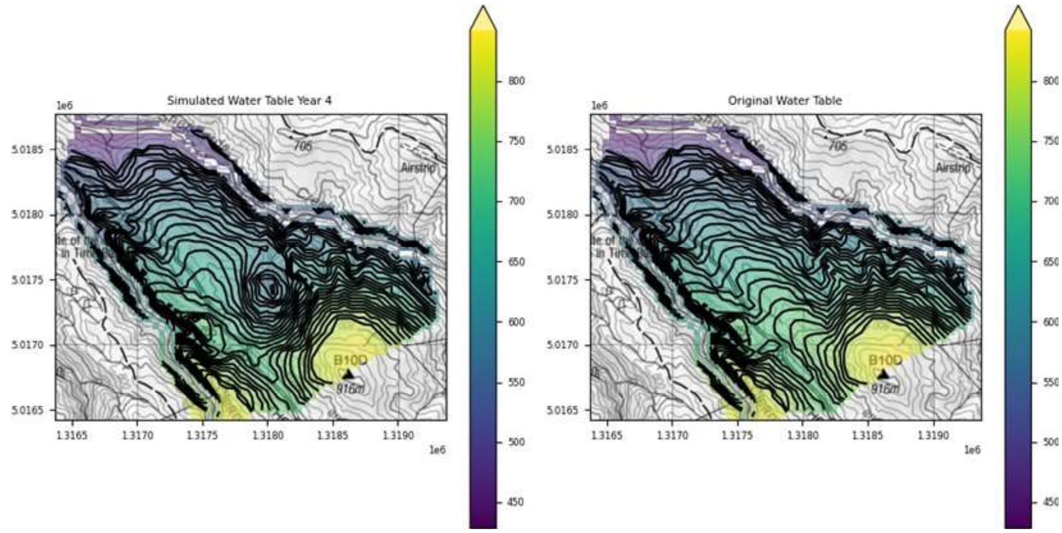

Figure 7.18: RAS: Predicted water table elevation for the hard rock aquifer year 4.

Water table contours are show every 10 m from 500 - 800 m.

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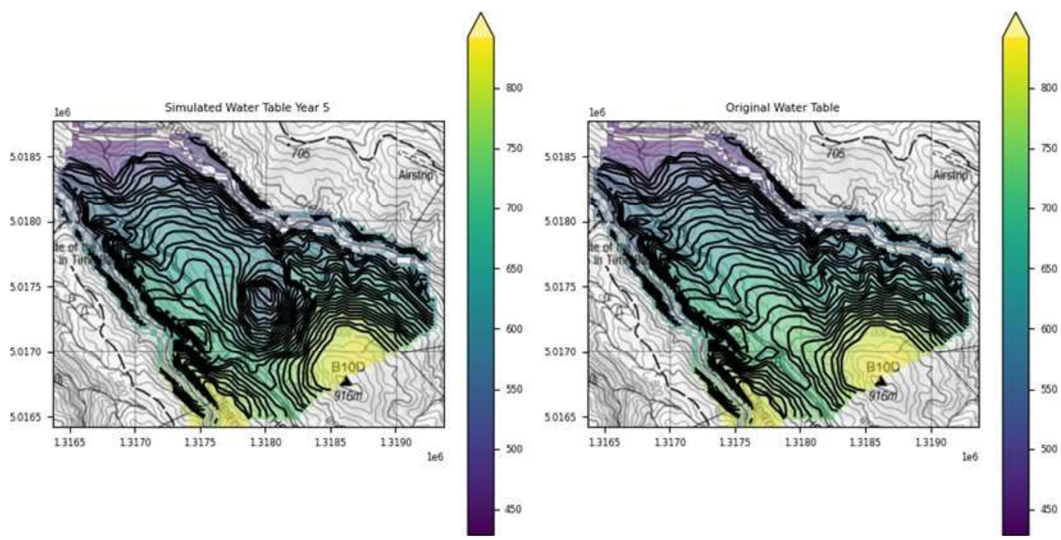

Figure 7.19: RAS: Predicted water table elevation for the hard rock aquifer year 5.

Water table contours are show every 10 m from 500 - 800 m.

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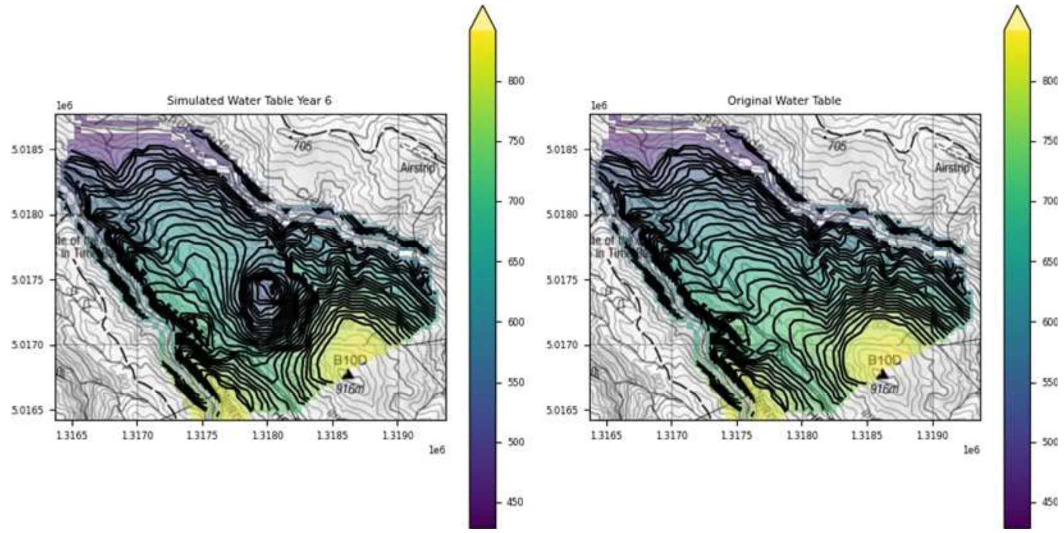

Figure 7.20: RAS: Predicted water table elevation for the hard rock aquifer year 6.

Water table contours are show every 10 m from 500 - 800 m.

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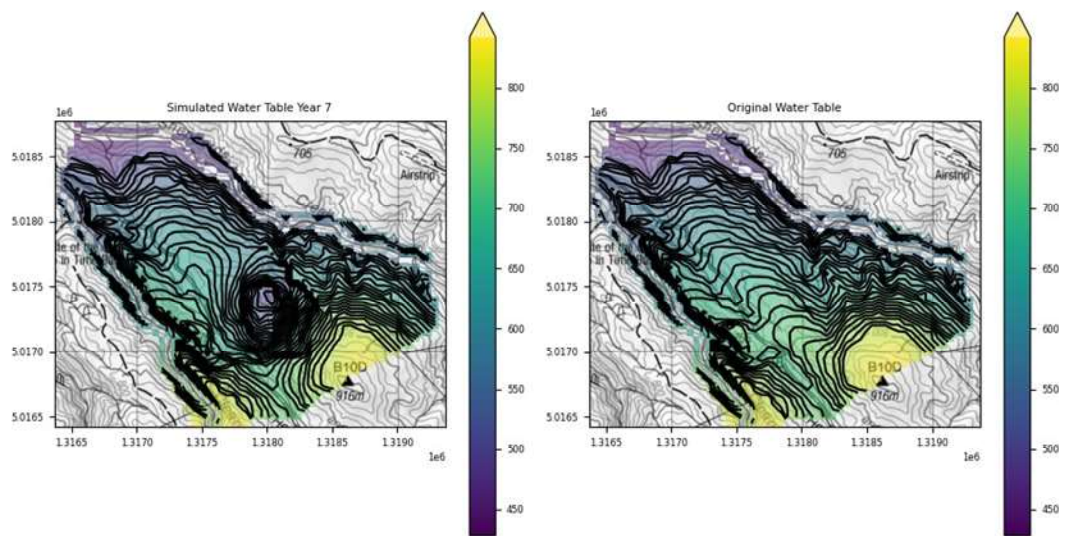

Figure 7.21: RAS: Predicted water table elevation for the hard rock aquifer year 7.

Water table contours are show every 10 m from 500 - 800 m.

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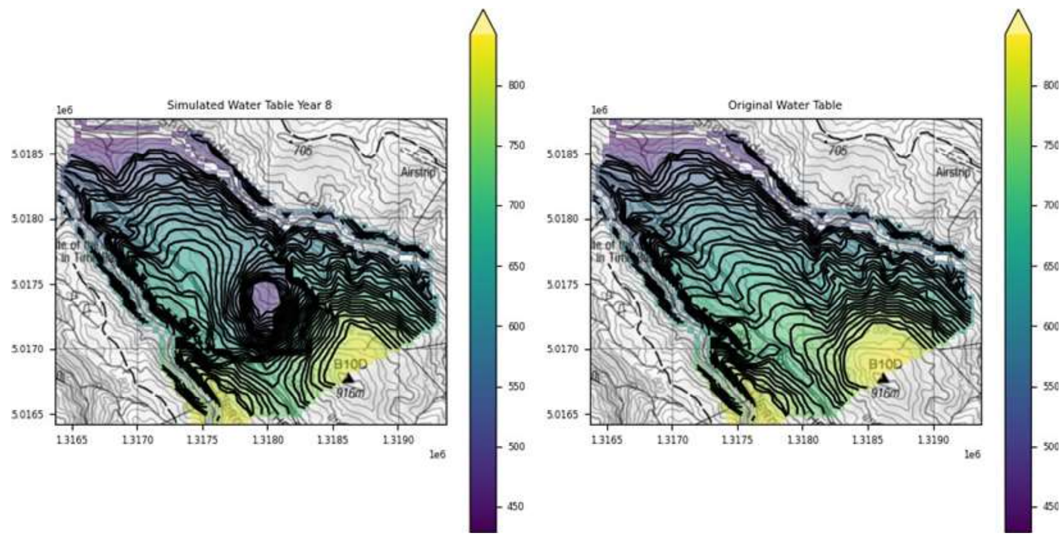

Figure 7.22: RAS: Predicted water table elevation for the hard rock aquifer year 8.

Water table contours are show every 10 m from 500 - 800 m.

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7.4.2 Rise and Shine Predicted Changes to Discharges

Figure 7.23 shows the predicted changes to the discharges to Shepherds Creek, Clearwater Creek and the discharges to the mine pit over the 8 years of excavation from the hard rock aquifer. The impact of the mining operation on the hard rock discharges to Shepherds and Clearwater Creeks are relatively minimal with 0.5 - 3 l/s and 0.1 - 2 l/s, respectively. Similarly, the discharge to the pit is relatively small, with a maximum of c. 5 l/s. For context the estimated rainfall, runoff, and discharge from the veneer aquifer to the pit was estimated to be 778 m^3/day (9 l/s) Section 7.1.1. This suggests that the most of the impact of the pit on the surface water features will be associated with the reduction in catchment area rather than stream depletion. We note that the model predicts almost no impacts to the constant head boundary representing the creek within the model domain.

The total discharge to the mining pit is low with a maximum modelled rate of 14 l/s (5 l/s from the hard rock aquifer and 9 l/s from rainfall and the veneer aquifer). The most significant component of the discharge is the surface water inflow from runoff and the veneer aquifer. This will likely be a relatively "flashy" source of water, with significant variability in the discharge rate across the year. We would also suggest that the de-watering be built with a significant buffer (at least a factor of 2) to the hard rock aquifer discharge to account for the uncertainty in the modelled discharge rates and the potential higher inflows associated with storage and local fracturing.

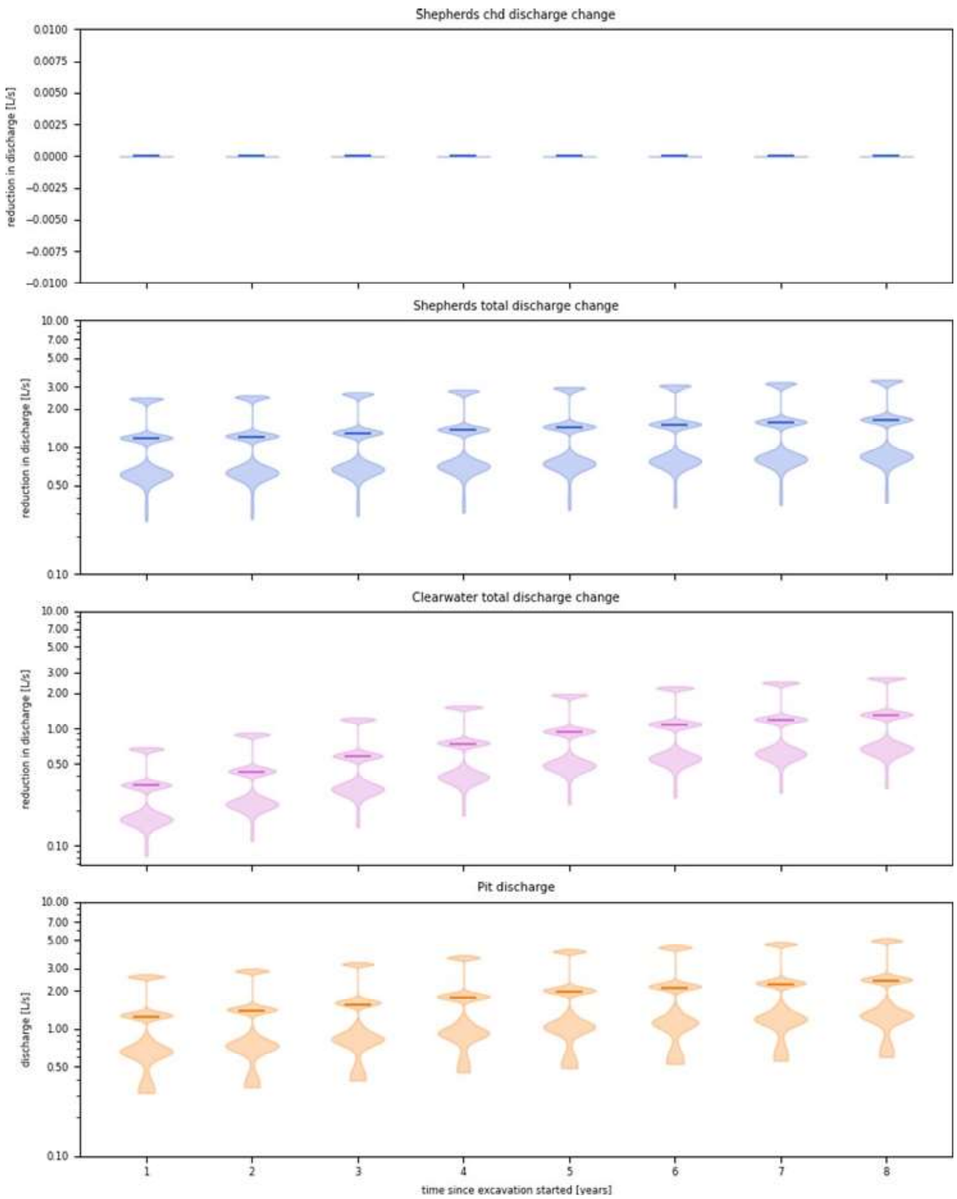

Figure 7.23: RAS: Predicted changes to discharges, over 8 years of excavation.

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7.4.3 Rise and Shine Changes to Discharges Under the Constrained Model

Here we present the changes to the discharges under the constrained model. Please note that this model is considered to be less reliable than the main optimisation results presented in Section 7.4.2 and is only presented here as a sensitivity analysis to the optimisation results. The results of the constrained model are shown in Figure 7.24. This model predicts a higher rate of discharge to the pit with a maximum of 10 l/s. This increased discharge is likely predominantly based on the higher recharge rate in the constrained model. Nevertheless, the discharge to the pit is still relatively low, not exceeding the estimated inflow from the veneer aquifer and runoff.

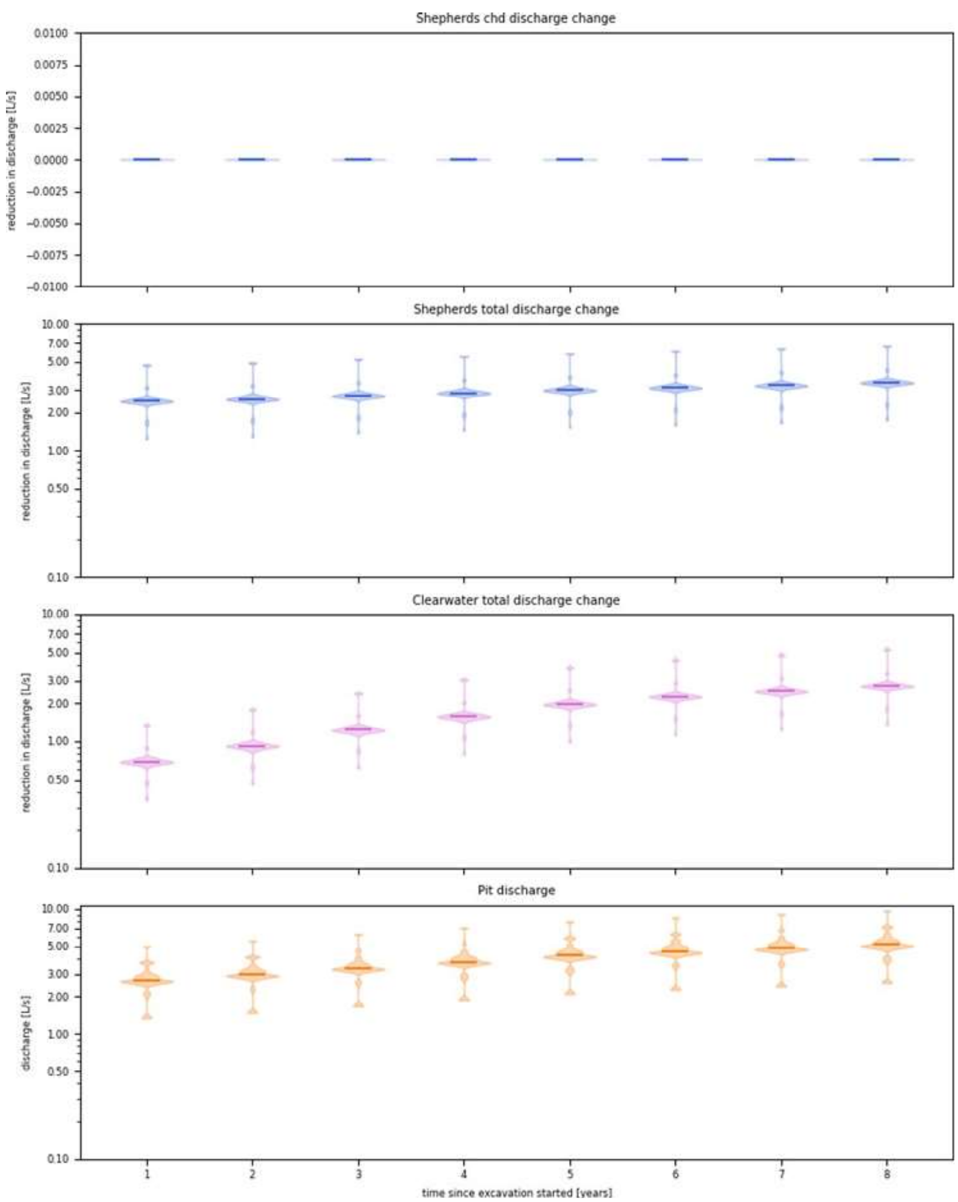

Figure 7.24: RAS: Predicted changes to discharges, over 8 years of excavation.

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7.5 Rise and Shine Limitations Arising from the Optimisation and Scenarios

The optimisation provides a best fit to the observed heads, but also introduces some limitations to the model; these are:

- The poor fit of the model to the observed heads near the Come in Time site means that the model should not be used to predict the impacts of the Come in Time site. Instead, a separate model was developed Section 8.
- The conflict between the observed and modelled heads at the Rise and Shine site suggests that the model is not capturing some process that is important to the groundwater flow in the area. The most likely tension is the global recharge rate.
- The model is not transient, and therefore cannot provide any information on the rate of change of the water table or any non-linearity in the discharge to the pit. Therefore the storage component of the pit inflow is not captured.
- The model results assume a homogeneous and isotropic aquifer. Should there be a highly fractured connection between the pit and Shepherds Creek, the model will not capture this and will significantly under- estimate the impacts of the pit on the creek. We note that there is no evidence of such as connection; however should pit dewatering yield significantly higher than predicted volumes we would recommend further investigation.

8 Come in Time Model

8.1 Come in Time Numerical model structure and conceptualization

8.1.1 Come in Time Model Domain and Discritisation

The Come in Time model domain is a subset of the original Rise and Shine model domain (see Figure 8.1). We focused on this smaller area as the original model could not fit the observed heads in the Come in Time area (see Section 7.5). The model was discretized into 20 m × 20 m × 5 m cells (X,Y,Z, respectively). As per the Rise and Shine models the X, Y and Z dimensions are aligned with East-West, North-South and vertical directions, respectively. The higher resolution (relative to Rise and Shine) was chosen as the model area is smaller and so the computational cost is lower. The model elevation ranges from 400 - 700 m msl, which fully encompasses the top of the land surface, the pit, and the valley floor with at least 50 m of sub-surface rock.

8.1.2 Come in Time Boundary Conditions

The boundary conditions for the Come in Time model are shown in Figure 8.1. The boundary condition strategy is the same as the Rise and Shine model and the SREX model (see Section 4.5). Briefly, the model is a steady state, confined system with no-flow boundaries on the sides, bottom, and above the surface layer. Shepherds Creek is represented as a constant head boundary with a head of the surface elevation of the cell. Finally the ground surface has a series of surface drains 1 m above the top of the model to represent refused recharge and flow into the vainer aquifer.

The mining pit is represented as a series of high conductance drains in the affected model cells. The pit is implemented as a single excavation event with the pit surface as the final pit surface. Plan and cross-section views of the pit are shown in Figure 8.1, Figure 8.4 and Figure 8.3.

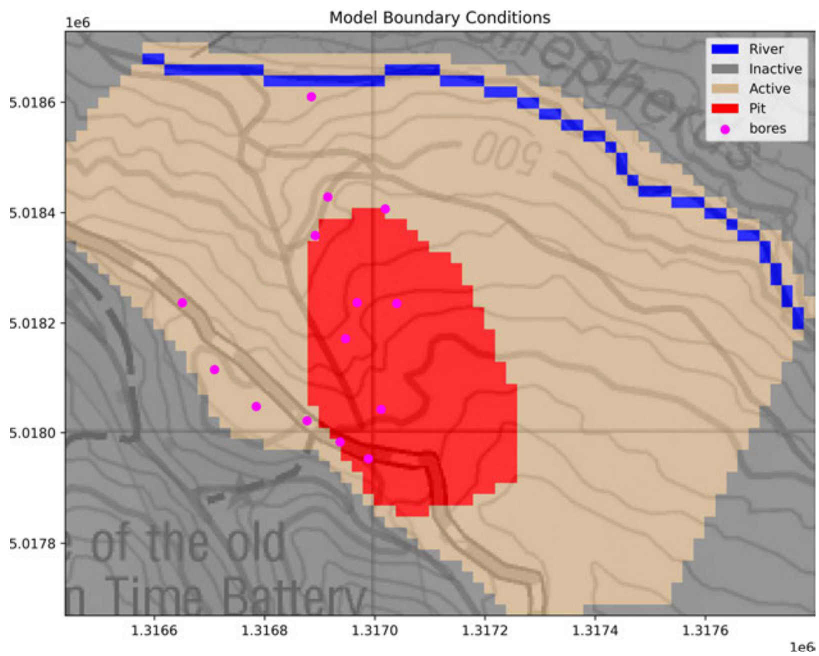

Figure 8.1: CIT: Boundary conditions.

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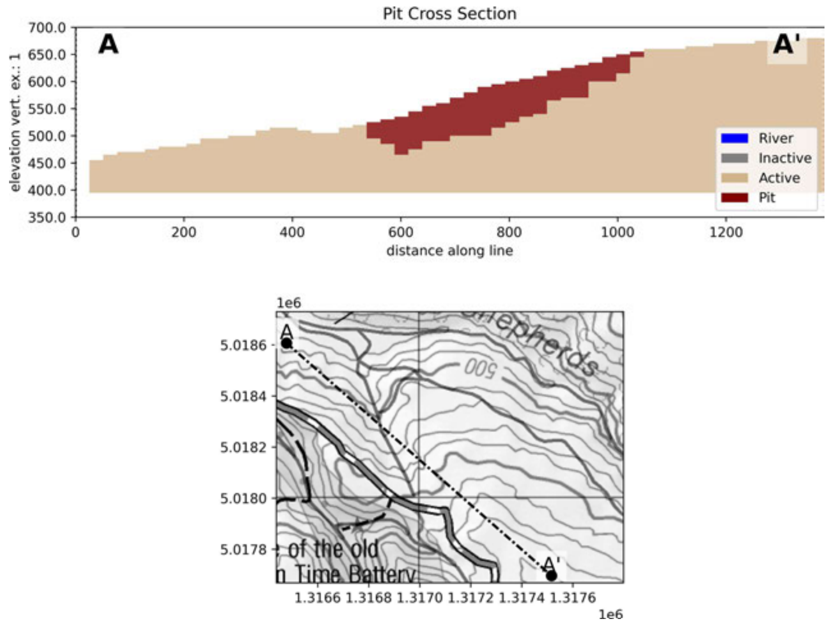

Figure 8.2: CIT: East-West cross-sections of the pit shell.

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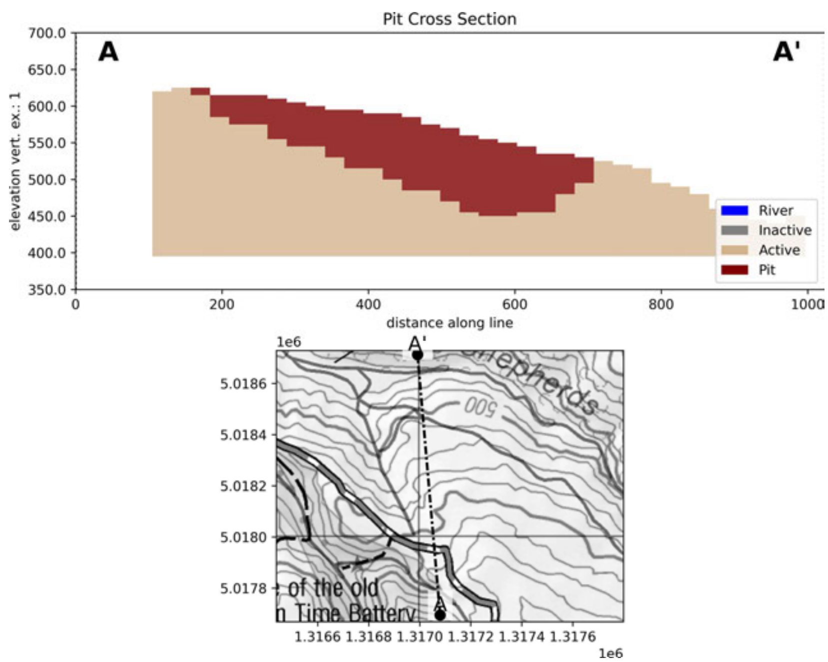

Figure 8.3: CIT: North-South cross-sections of the pit shell.

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8.1.3 Come in Time Hydraulic Conductivity Zones

We implemented identical hydraulic conductivity zones to the Rise and Shine and SREX models Section 5.2.1. Figure 8.5 and Figure 8.4 show cross-sections of the hydraulic conductivity zones in the Come in Time model.

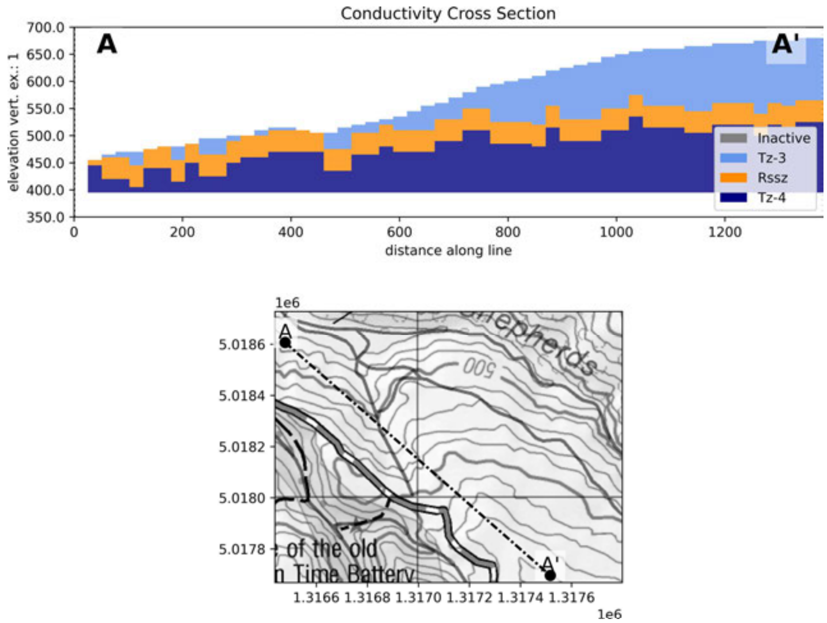

Figure 8.4: CIT: East-West cross-sections of the three hydraulic conductivity zones.

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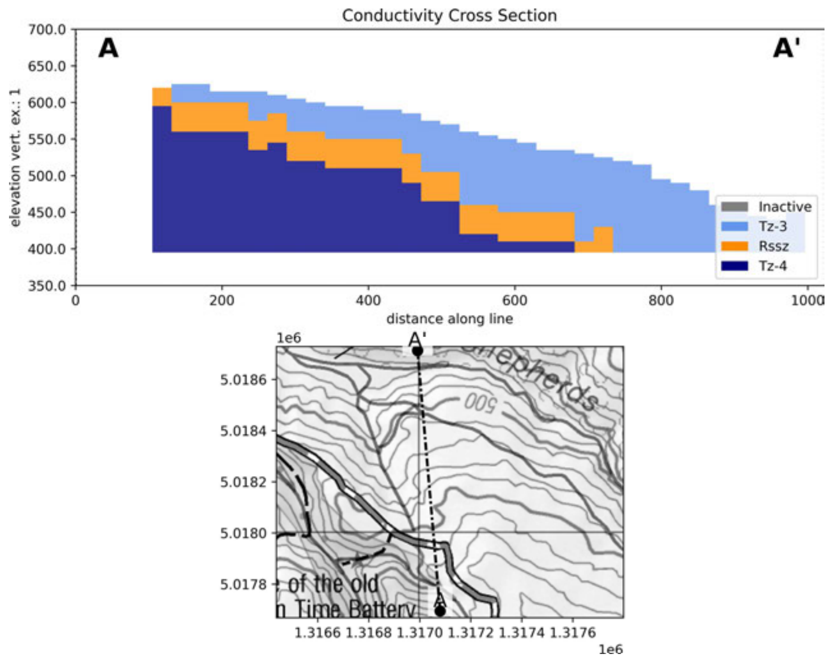

Figure 8.5: CIT: North-South cross-sections of the three hydraulic conductivity zones.

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8.2 Come in Time Water level Observations for Model Optimisation

There are 14 water level observations in the active Come in Time model domain, which are a subset of the Rise and Shine observations. The observed heads are shown in Figure 8.1. For more information on the observations see Section 7.2.

8.3 Come in Time Optimisation Results

Figure 8.6 shows the log likelihood evolution of the Come in Time model during the optimisation process. The model shows a rapid increase in the log likelihood in the first 300 iterations, and then converges to a stable values within -1125 to -1080. We have chosen to keep all realisations with a log likelihood greater than -1120 as the posterior distribution. Note the log likelihood calculation is provided in Equation 5.1 with more positive values indicating a better fit to the observed heads. The plateau in the log likelihood suggests that the model has reached a maximum stable representation of the observed heads within the structural and parameter constraints of the model.

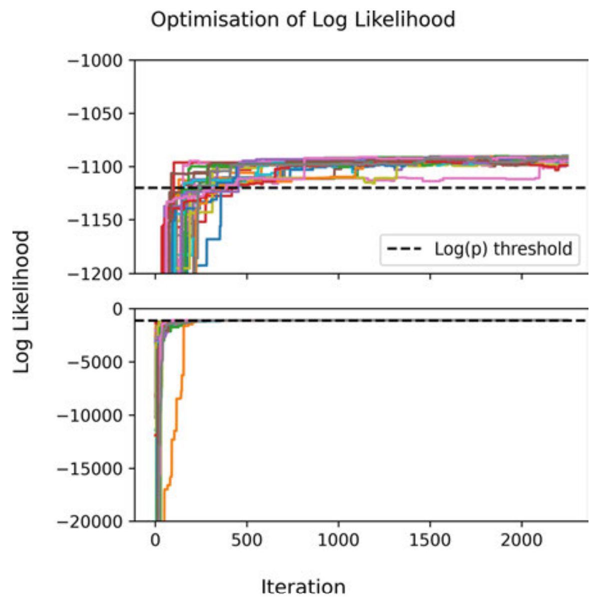

Figure 8.6: CIT: Log likelihood evolution.

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8.3.1 Come in Time Fit to Observed Heads

The modelled heads are compared to the observed heads in Figure 8.7 and are shown spatially in Figure 8.8. The model adequately fits the observed heads considering the rather simple model structure, the limited number of observations, and the uncertainty in the open hole observations. We consider the model to be a suitable representation of the physical system given the constraints of the data available.

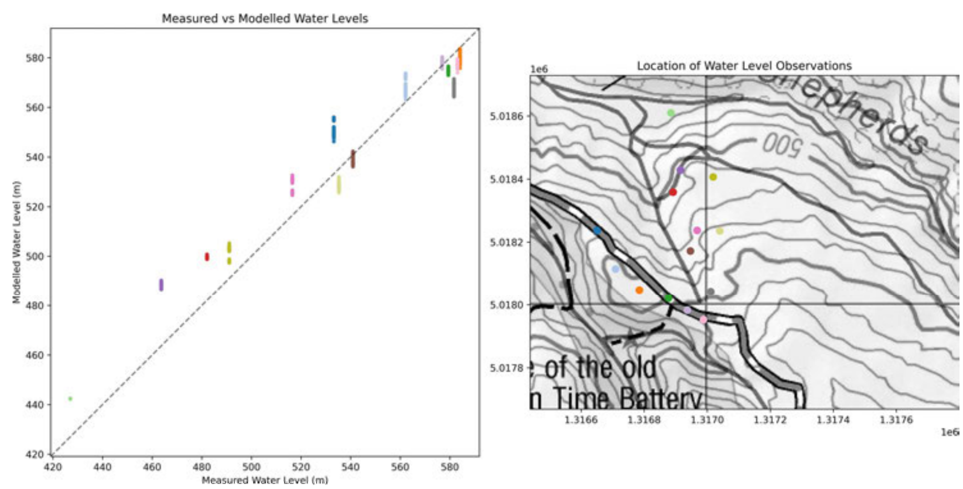

Figure 8.7: CIT: A comparison of measured and modelled heads.

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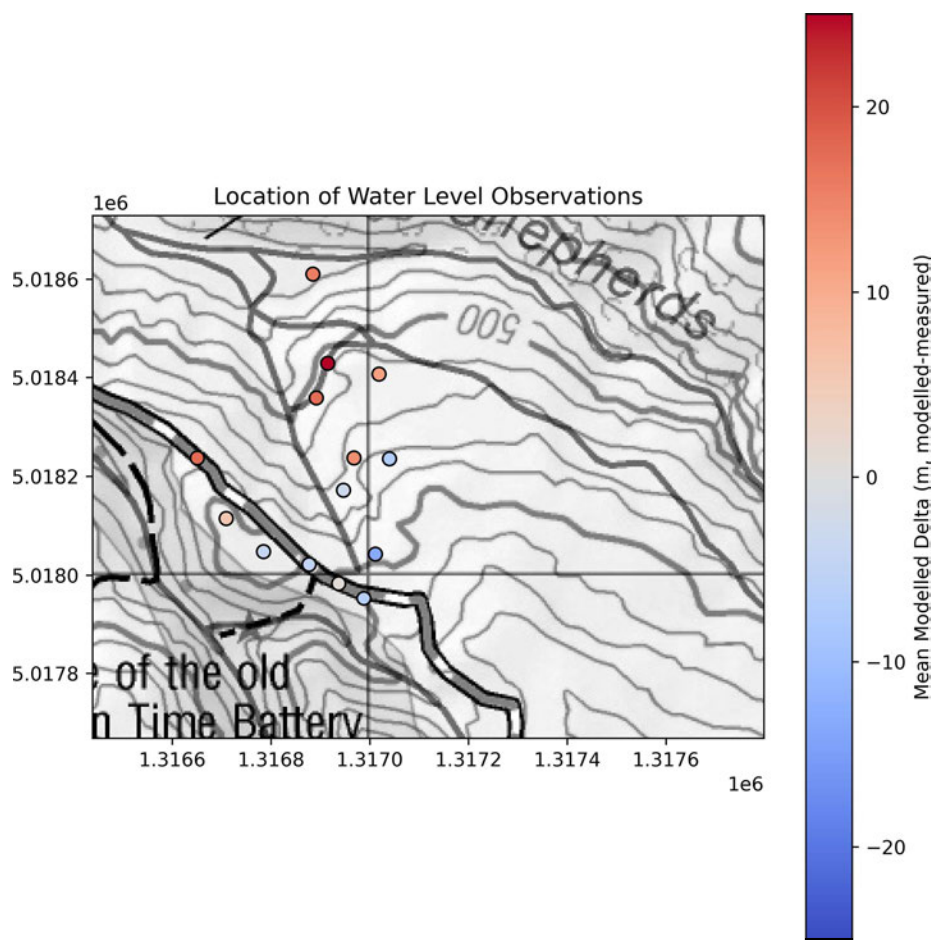

Figure 8.8: CIT: Spatial distribution of measured-modelled misfit.

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8.3.2 Come in Time Posterior Parameter Distributions

The posterior parameter distributions are shown in Figure 8.9. The initial results included higher recharge rates that the average rainfall in the area, which is not physically plausible – therefore we have truncated the posterior to all recharge rates less than the average rainfall. The model optimisation was initiated with 28 chains with each chain evenly spaced across the prior distribution of the parameters (see black points in Figure 8.9) except surface drain conductance (C). The optimisation serves to constrain the prior distribution (see blue probability density function in Figure 8.9) to the posterior distribution (see red histogram Figure 8.9). Here the optimisation caused the following changes to the prior distribution:

- **Recharge (R):** There was minimal constraint of the prior to the range of $10^{-5.5}$ m d^{-1} to the truncation to the average rainfall.
- **Drain Conductance (C):** The posterior is effectively identical to the prior suggesting the parameter had minimal affect on the water level observations. We are not concerned by this insensitivity as the surface drains are a compensatory structure in the model.
- **TZ-3 Conductivity (K_0):** The prior was highly constrained to the range of $10^{-4.5}$ to $10^{-2.5}$ m d^{-1}. This is very similar to the posterior distribution of RSSZ conductivity (K_1).
- **RSSZ Conductivity (K_1):** The prior was highly constrained to the range of $10^{-4.5}$ to $10^{-2.5}$ m d^{-1}, with some small portion of the posterior distribution occurring between 10^{-7} to 10^{-5} m d^{-1},. We suggest the small number of very low conductivity values are incidental and suggest that the RSSZ is likely to be a relatively high conductivity unit.
- **TZ-4 Conductivity (K_2):** The prior was somewhat constrained to the range of 10^{-7} to 10^{-3} m d^{-1}. In general the posterior distribution suggests that the TZ-4 is a relatively low conductivity unit.

The difference in parameterisation between the Rise and Shine, Come in Time, and SREX models is discussed in Section 10.1. There we also discuss the general interpretation of the parameter distributions and the implications for the hydrogeological environment of the area.

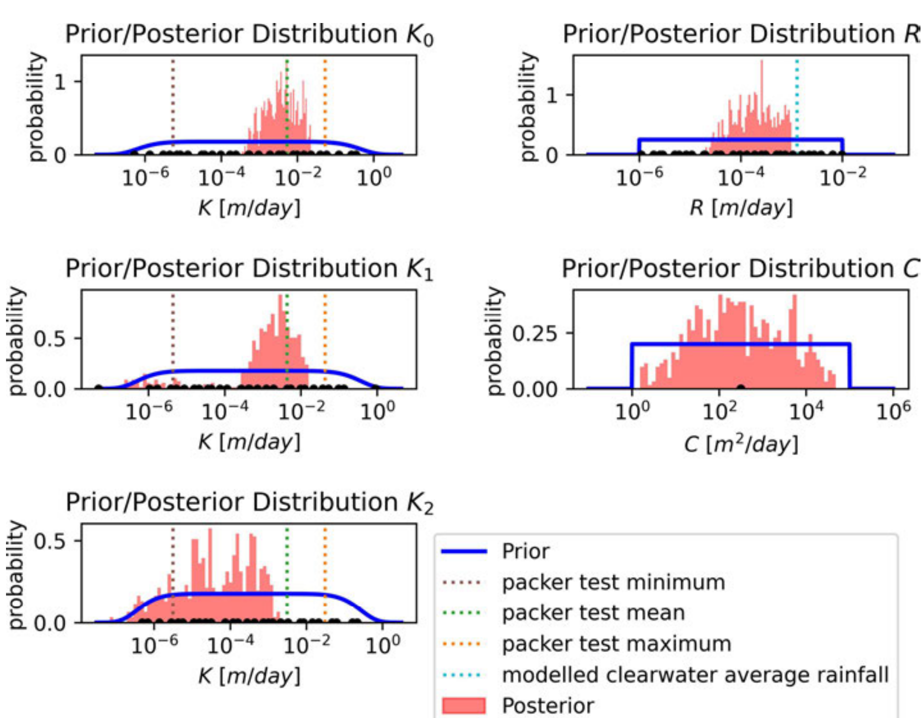

Figure 8.9: CIT: Posterior parameter distribution.

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8.3.3 Come in Time Fit Modelled Unaffected Water Table

The modelled unaffected water table is shown in Figure 8.10.

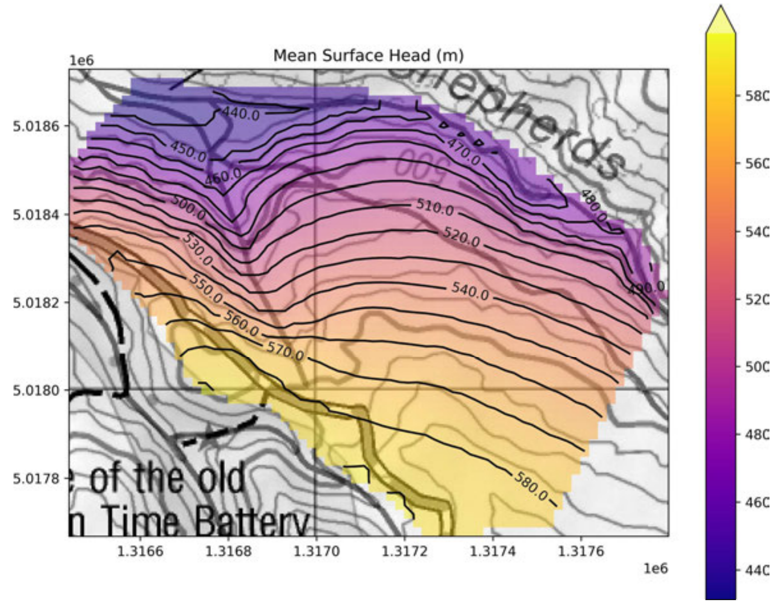

Figure 8.10: CIT: Mean modelled heads.

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8.4 Come In Time Mining Impact Predictions

8.4.1 Come In Time Mining Impacts to Groundwater Levels

A comparison of the predicted heads with and without mining is shown in Figure 8.11. The minimum, median, and maximum predicted draw-down of the posterior distribution are shown in Figure 8.12, Figure 8.13, and Figure 8.14, respectively.

The water table impacts are relatively constrained to the pit area, with the maximum draw-down of 50 m in the pit area. An area of draw-down extends South East towards the Rise and Shine pit, with a maximum draw-down of 25 m at the edge of the active model domain. This area of draw-down is likely exacerbated by the no flow boundary condition on the South East side of the model domain. In addition, the Rise and Shine model predicts much lower hydraulic conductivity in the TZ-3 than the Come in Time model, which will limit the extent of the South-East draw-down of the Come in Time model. If the potential interaction between the Rise and Shine and Come in Time pit induced draw-down is a concern. We suggest that a more highly parameterised version of the Rise and Shine model be developed to investigate the potential interaction between the two pits.

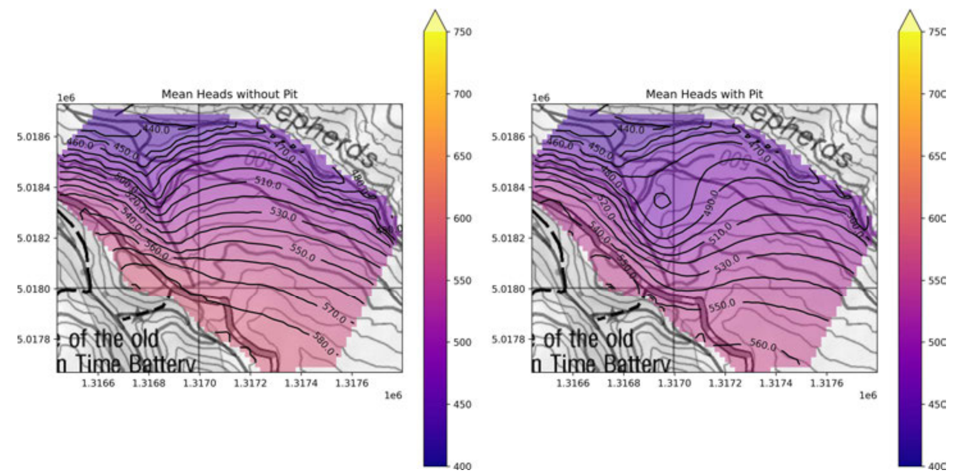

Figure 8.11: CIT: Predicted heads with and without mining.

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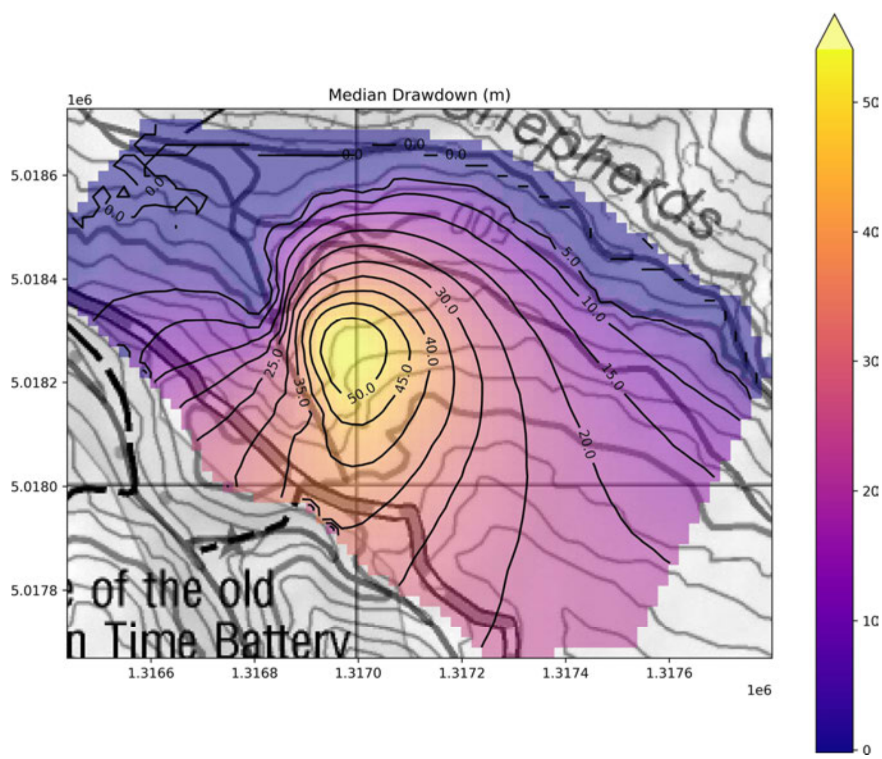

Figure 8.12: CIT: Median predicted mining induced draw-down.

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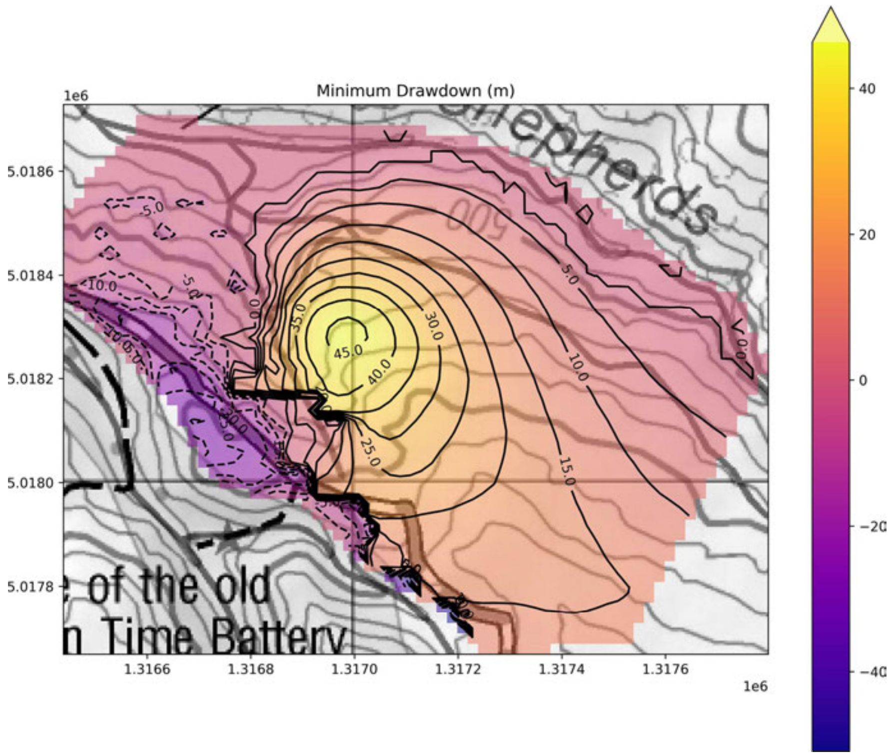

Figure 8.13: CIT: Minimum predicted mining induced draw-down.

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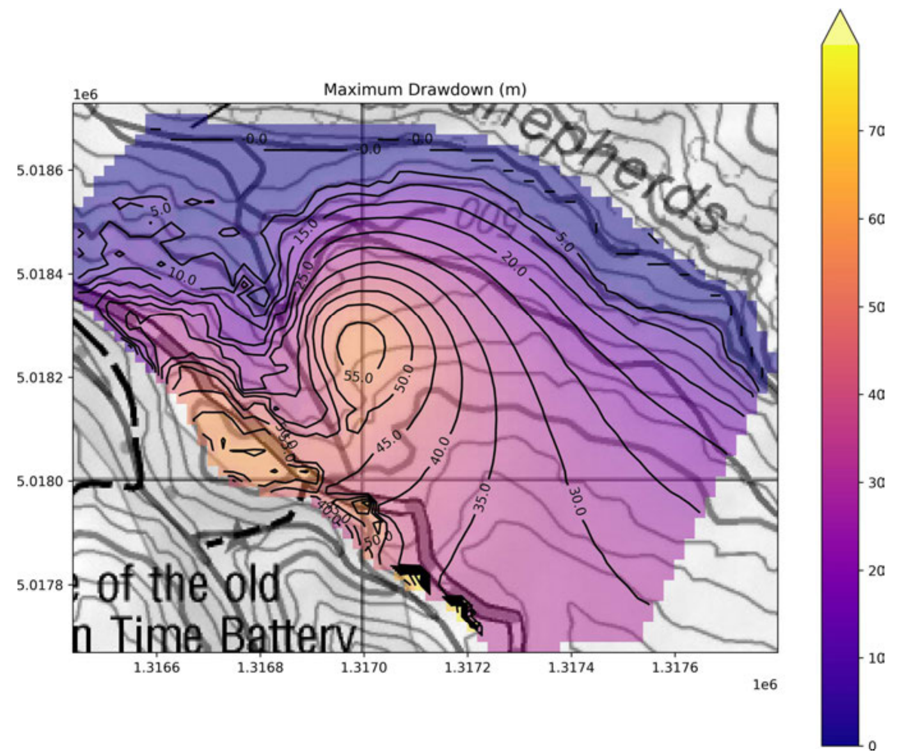

Figure 8.14: CIT: Maximum predicted mining draw-down.

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8.4.2 Come In Time Predicted Changes to Discharges

The probability and cumulative density functions of the predicted changes to the discharges, and the relationship between pit flux and stream losses are shown in Figure 8.15. Stream losses are unlikely to exceed 150 m^3day^{-1} (1.7 $l\ s^{-1}$) and the pit flux is unlikely to exceed 300 m^3day^{-1} (3.5 $l\ s^{-1}$). The induced draw-down of the pit (see Figure 8.10) is not sufficient to induce flow from the stream to the pit. As such, the changes in stream flow are associated with diverted recharge from the stream to the pit.

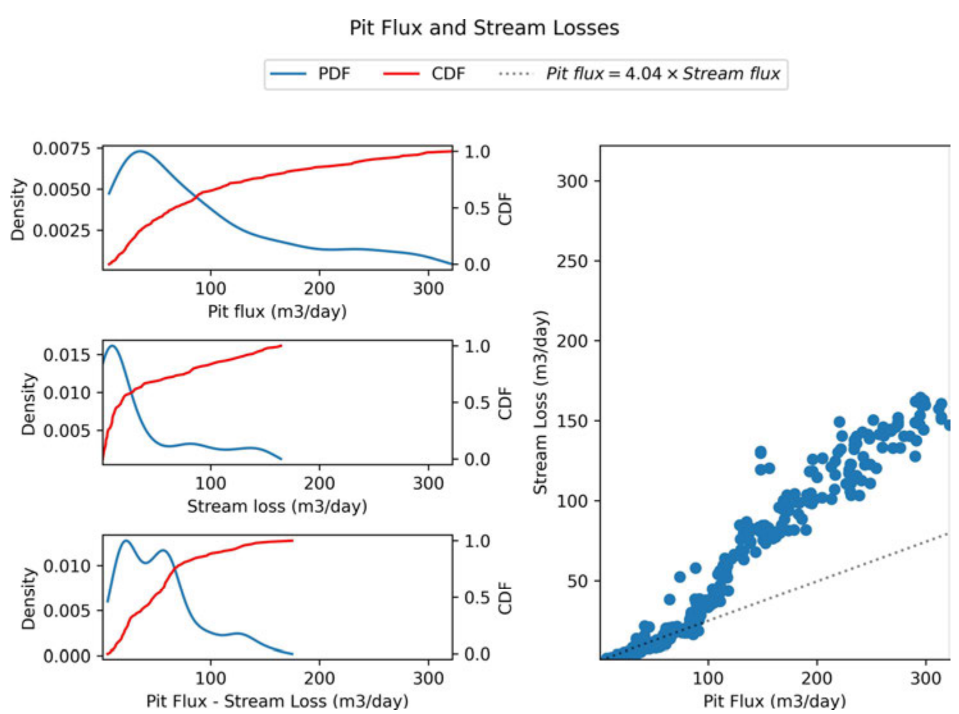

Figure 8.15: CIT: Stream and pit flux.

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8.5 Come In Time Limitations Arising from the Optimisation and Scenarios

The optimisation has several limitations including:

- The model structure is simple and there are only a few observations in the active model domain, so the model may not capture all the processes in the area.
- The model is not transient, and therefore cannot provide any information on the rate of change of the water table or any non-linearity in the discharge to the pit. Therefore, the storage component of the pit inflow is not captured.
- The model results assume a homogeneous and isotropic aquifer, any local fracturing may change the predicted draw-down or pit fluxes. We note that unlike the Rise and Shine model, there is no risk of a direct connection between the pit and the surface water features as the bottom of the pit is above the valley floor.

9 SREX Model

9.1 SREX Numerical Model Structure and Conceptualization

9.1.1 SREX Model Domain and Discritisation

The SREX model domain is outside the original Rise and Shine model domain (see Figure 9.1). The model was discretized into 30 m × 30 m spatial cells (X,Y, respectively). For the Z dimension the model was discretized into 5 m cells from 580-850 m msl and 10 m cells from 860-1300 m msl. As per the Rise and Shine models the X, Y and Z dimensions are aligned with East-West, North-South and vertical directions, respectively. The higher resolution (relative to Rise and Shine) was chosen as the model area is smaller and so the computational cost is lower. The model elevation ranges from 580 - 1300 m msl, which fully encompasses the top of the land surface, the pit, and the valley floor.

9.1.2 SREX Boundary Conditions

The boundary conditions for the SREX model are shown in Figure 9.1. The boundary condition strategy is the same as the Rise and Shine model and the Come in Time model (see Section 4.5). Briefly, the model is a steady state, confined system with no-flow boundaries on the sides, bottom, and above the surface layer. Rise and Shine Creek is represented as a constant head boundary with a head of the surface elevation of the cell. A key difference in the SREX model is that an area of Rise and Shine Creek was removed from the model (see the gap in the blue cells close to the "R" in Gorge Road, Figure 9.1). Rise and Shine Creek is directly adjacent to the SREX pit, so there would likely be significant interaction between the creek and the pit. Instead, we have assumed that the mining process will ensure that this portion of the creek does not interact with the pit (e.g., via lining/diversion). Finally, the ground surface has a series of surface drains 1 m above the top of the model to represent refused recharge and flow into the vainer aquifer.

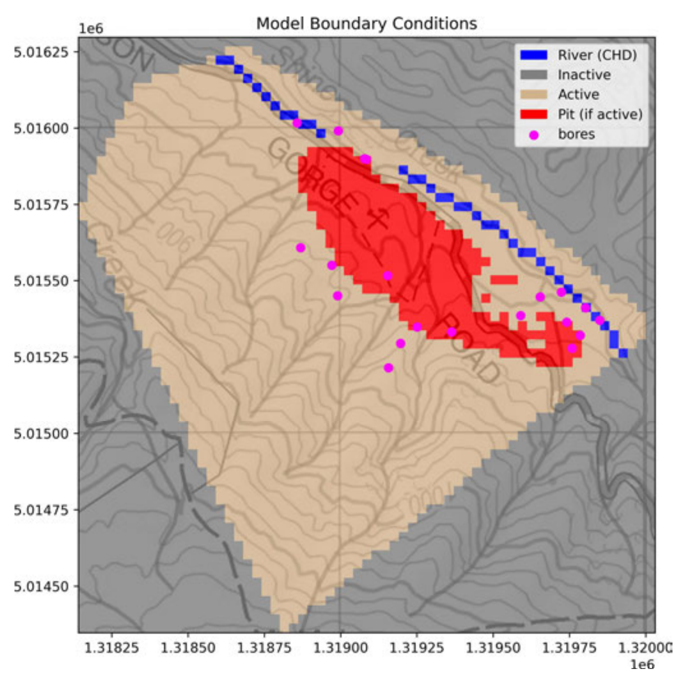

Figure 9.1: SREX: Boundary conditions.

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The mining pit is represented as a series of high conductance drains in the affected model cells. The pit is implemented as a single excavation event with the pit surface as the final pit surface. Plan and cross-section views of the pit are shown in Figure 9.1, Figure 9.4 and Figure 9.5.

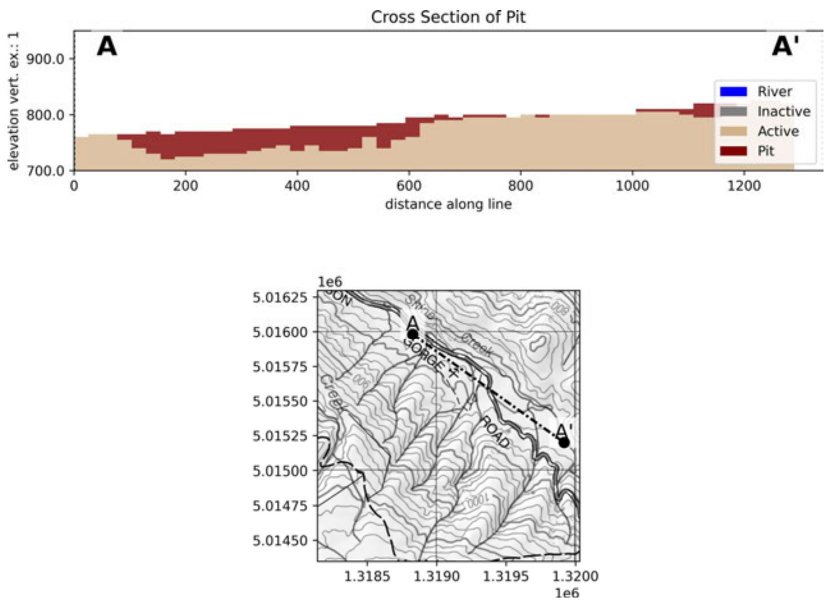

Figure 9.2: SREX: East-West cross-sections of the pit.

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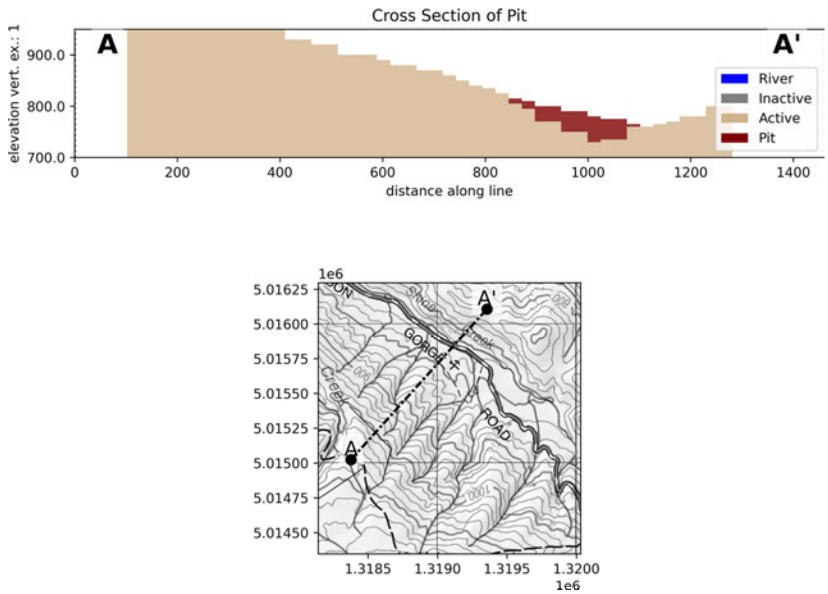

Figure 9.3: SREX: North-South cross-sections of the pit.

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9.1.3 SREX Hydraulic Conductivity Zones

We implemented identical hydraulic conductivity zones to the Rise and Shine and Come in Time models Section 5.2.1. Figure 9.5 and Figure 9.4 show cross-sections of the hydraulic conductivity zones in the SREX model.

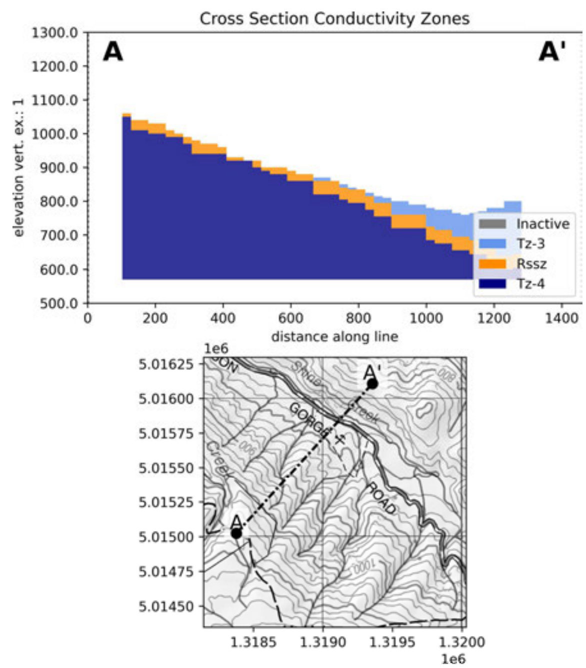

Figure 9.4: SREX: East-West cross-sections of the three hydraulic conductivity zones.

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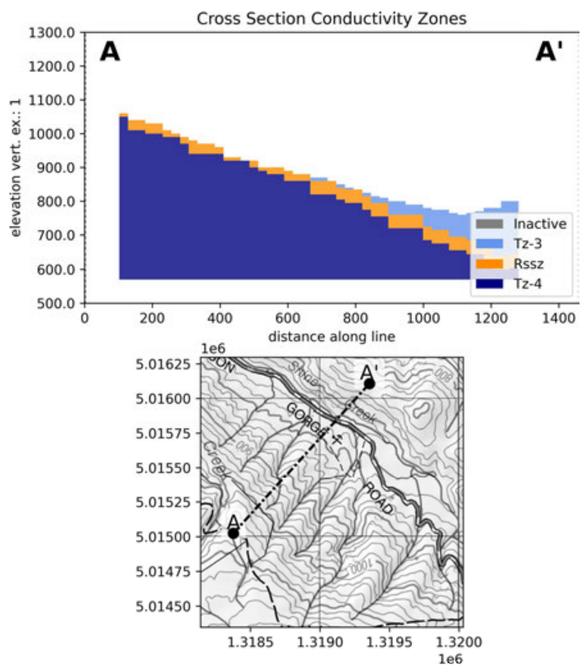

Figure 9.5: SREX: North-South cross-sections of the three hydraulic conductivity zones.

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9.2 SREX Water level Observations for Model Optimisation

There are 19 water level observations in the active SREX model domain, which were surveyed on 2023-01-01. The observed heads are shown in Figure 8.1.

9.3 SREX Optimisation results

Figure 9.6 shows the log likelihood evolution of the SREX model during the optimisation process. The model shows a rapid increase in the log likelihood in the first 200 iterations, and then converges to a stable values within -730 to -710. We have chosen to keep all realisations with a log likelihood greater than -725 as the posterior distribution. Note the log likelihood calculation is provided in Equation 5.1 with more positive values indicating a better fit to the observed heads. The plateau in the log likelihood suggests that the model has reached a maximum stable representation of the observed heads within the structural and parameter constraints of the model.

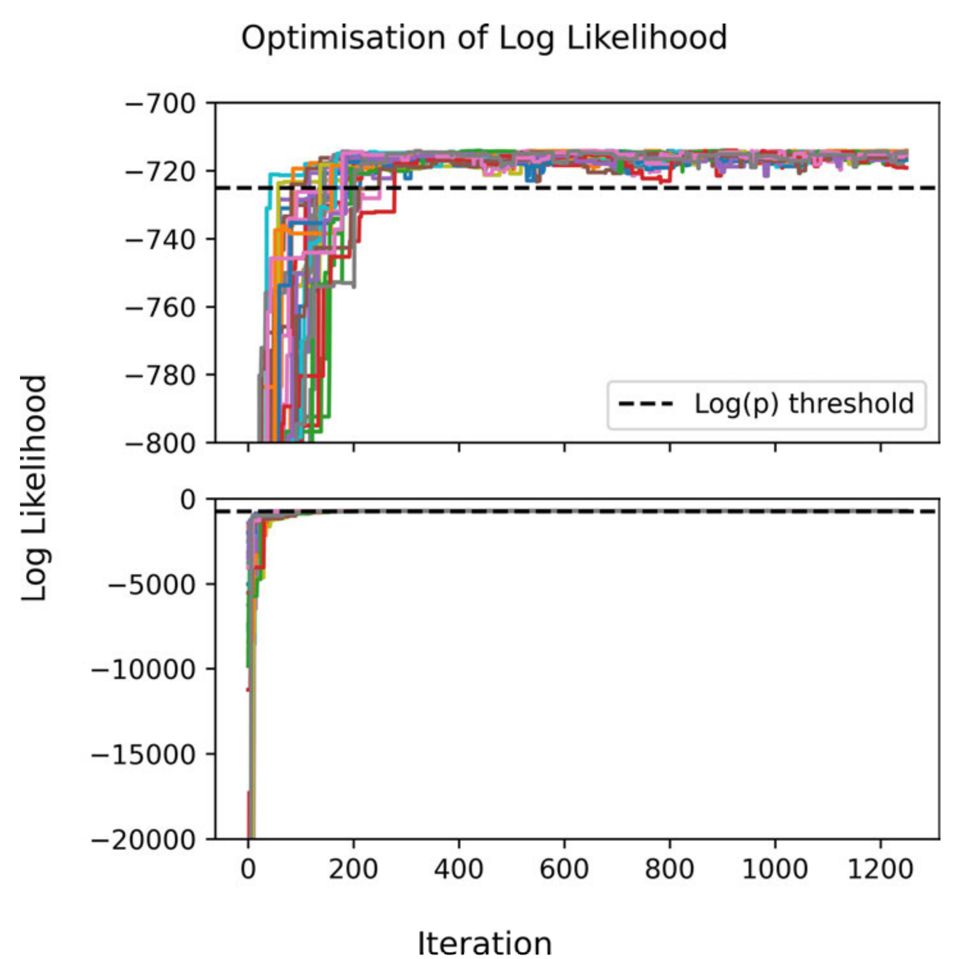

Figure 9.6: SREX: Log likelihood evolution.

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9.3.1 SREX Fit to Observed Heads

The modelled heads are compared to the observed heads in Figure 9.7 and are shown spatially in Figure 9.8. The model adequately fits the observed heads considering the rather simple model structure, the limited number of observations, and the uncertainty in the open hole observations. Importantly the spatial results show that the model both over and under-predicts the observed heads in close spatial proximity. The only exception to this is in the observations in the lower Rise and Shine Creek where the model routinely over-predicts the observed heads. Three of these observations are in the area of the removed portion of Rise and Shine Creek, which may be a contributing factor to the model misfit. In reality, the veneer aquifer is likely to be thicker in this area and would address the misfit. We consider the model to be a suitable representation of the physical system given the constraints of the data available.

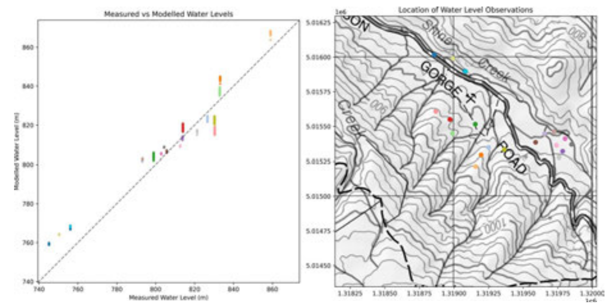

Figure 9.7: SREX: A Comparison of measured and modelled heads.

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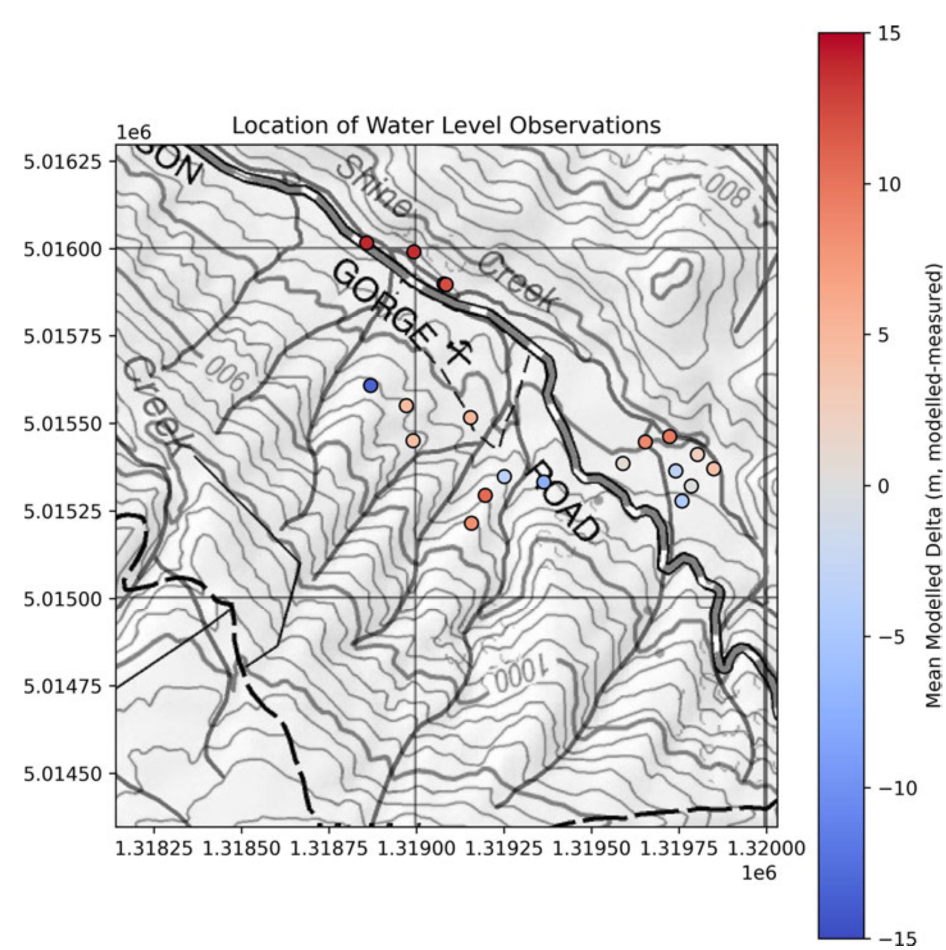

Figure 9.8: SREX: Spatial distribution of measured-modelled misfit.

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9.3.2 SREX Posterior Parameter Distributions

The posterior parameter distributions are shown in Figure 9.9. The initial results included higher recharge rates than the average rainfall in the area, which is not physically plausible – therefore we have truncated the posterior to all recharge rates less than the average rainfall. The model optimisation was initiated with 28 chains with each chain evenly spaced across the prior distribution of the parameters (see black points in Figure 9.9) except surface drain conductance (C). The optimisation serves to constrain the prior distribution (see blue probability density function in Figure 9.9) to the posterior distribution (see red histogram Figure 9.9). Here the optimisation caused the following changes to the prior distribution:

- **Recharge (R):** There was minimal constraint of the prior to the range of $10^{-5.5}$ m d^{-1} to the truncation to the average rainfall.
-
- **Drain Conductance (C):** The posterior is nearly identical to the prior suggesting the parameter had minimal affect on the water level observations. We are not concerned by this insensitivity as the surface drains are a compensatory structure in the model.
- **TZ-3 Conductivity (K_0):** The prior was highly constrained to the range of $10^{-4.5}$ to $10^{-1.5}$ m d^{-1}. This is very similar to the posterior distribution of RSSZ conductivity (K_1).
- **RSSZ Conductivity (K_1):** The prior was highly constrained to the range of $10^{-5.5}$ to $10^{-2.5}$ m d^{-1}.

- **TZ-4 Conductivity (K_2):** The prior was somewhat constrained to the range of 10^{-7} to $10^{-3.5}$ m d^{-1}. In general the posterior distribution suggests that the TZ-4 is a relatively low conductivity unit.

The difference in parameterisation between the Rise and Shine, Come in Time, and SREX models is discussed in Section 10.1. There we also discuss the general interpretation of the parameter distributions and the implications for the hydrogeological environment of the area.

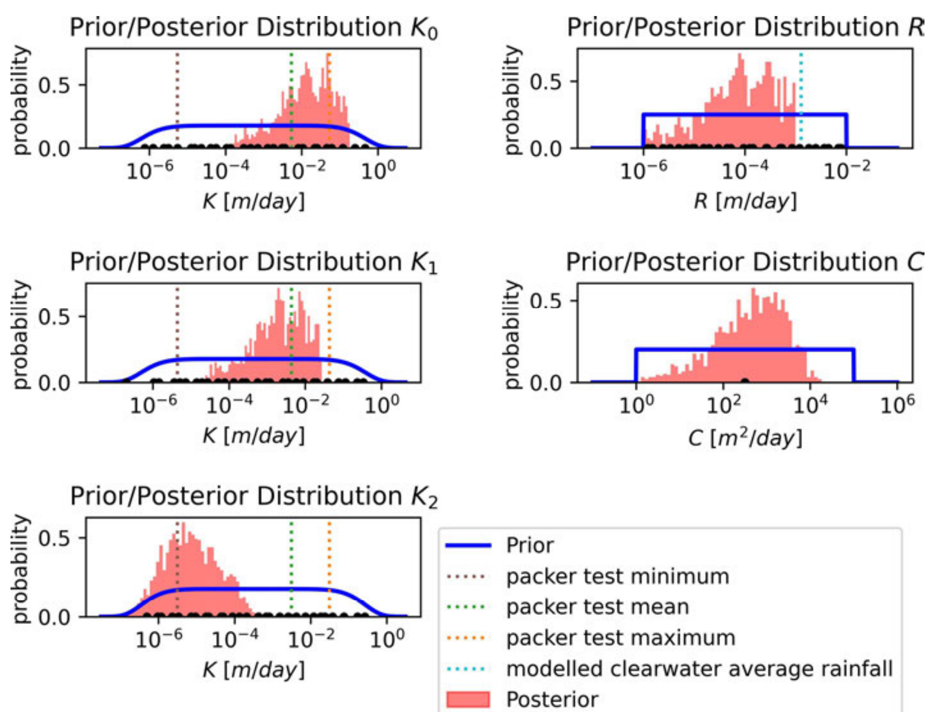

Figure 9.9: SREX: Posterior parameter distribution.

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9.3.3 SREX Fit Modelled Unaffected Water Table

The modelled unaffected water table is shown in Figure 9.10.

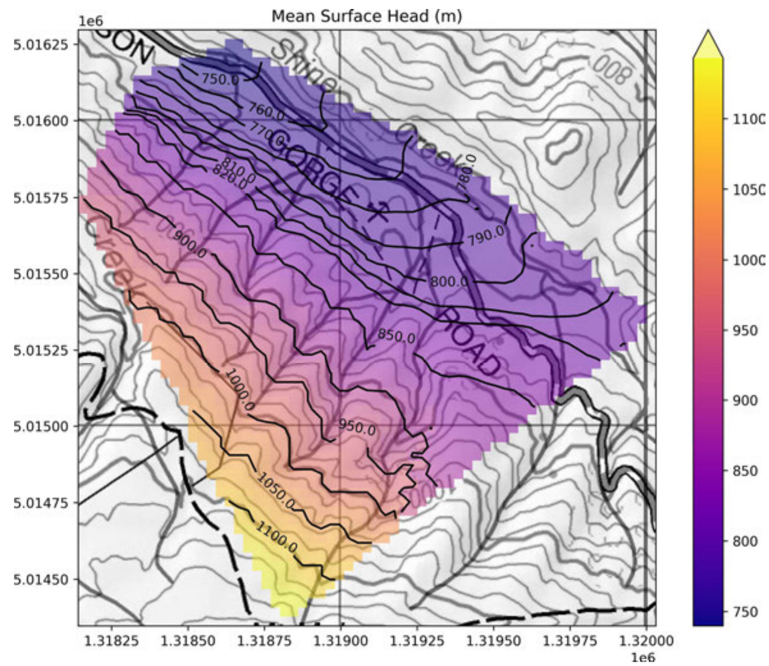

Figure 9.10: SREX: Mean modelled heads.

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9.4 SREX Mining Impact Predictions

9.4.1 SREX Mining Impacts to Groundwater Levels

A comparison of the predicted heads with and without mining is shown in Figure 9.11. The minimum, median, and maximum predicted draw-down of the posterior distribution are shown in Figure 9.12, Figure 9.13, and Figure 9.14, respectively.

The water table impacts are relatively constrained to the pit area, with the maximum draw-down of 40 m in the pit area. However, there is an extension of draw-down to the South East with a maximum draw-down of 10 m at the edge of the active model domain. The draw-down here is only occurring in the hard rock system, however there is likely a more extensive alluvial/veneer system in the valley bottom, which could propagate the draw-down further. In addition, the constant head cells representing the Rise and Shine Creek are significantly limiting the draw-down impacts. In the area where the Rise and Shine Creek was removed the draw-down is up to 25 m "under" the creek bed.

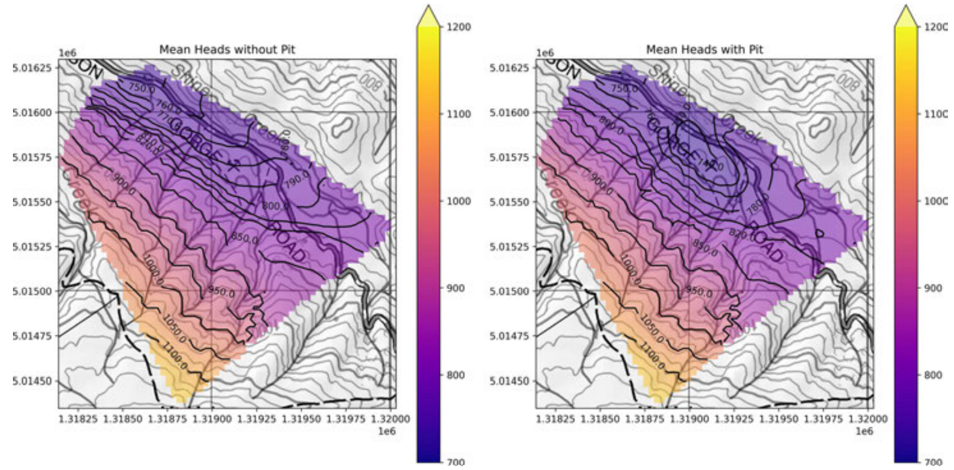

Figure 9.11: SREX: Predicted heads with and without mining.

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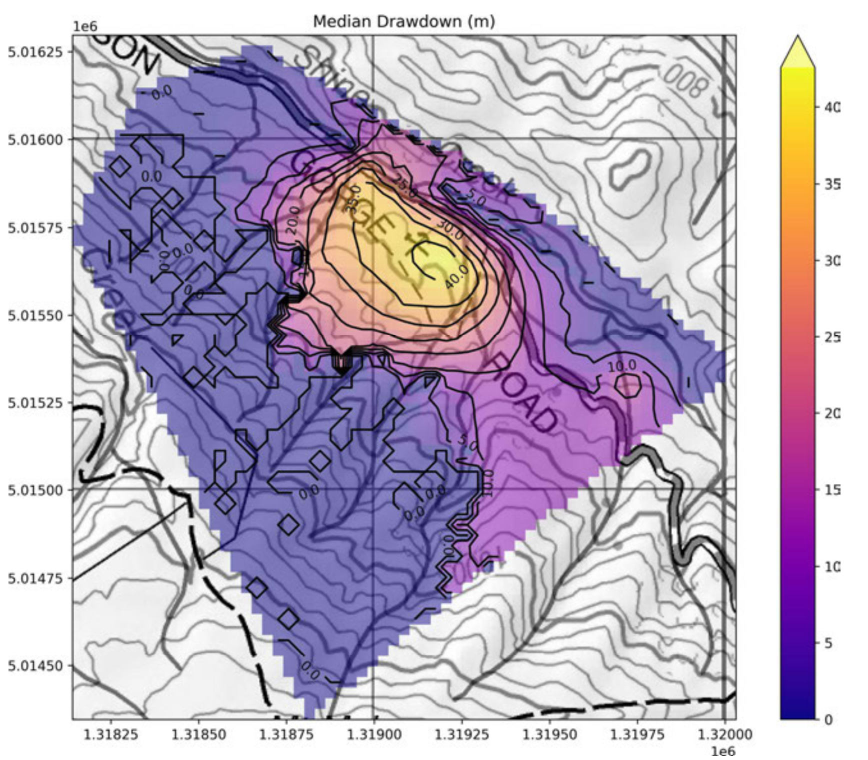

Figure 9.12: SREX: Predicted median draw-down.

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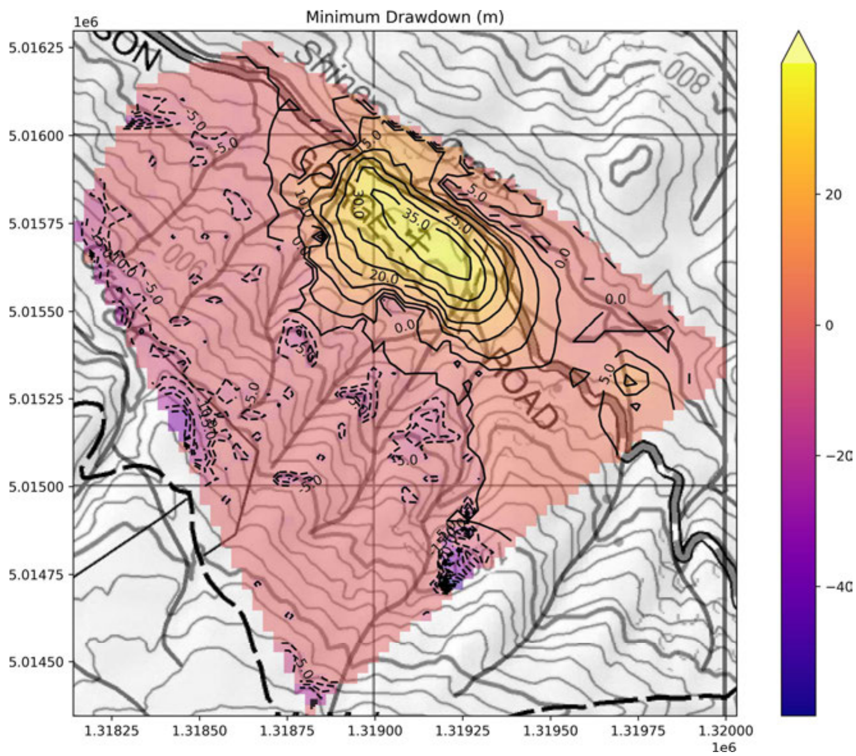

Figure 9.13: SREX: Predicted minimum draw-down.

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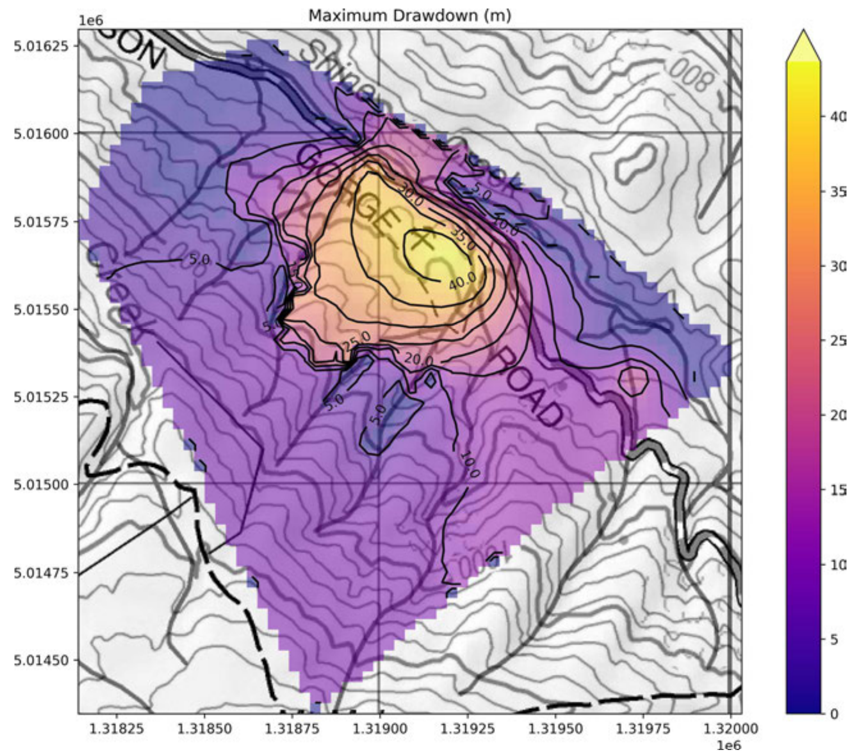

Figure 9.14: SREX: Predicted maximum draw-down.

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9.4.2 SREX Predicted Changes to Discharges

The probability and cumulative density functions of the predicted changes to the discharges, and the relationship between pit flux and stream losses are shown in Figure 9.15. There is a strong relationship between the pit flux and stream losses with pit flux being 1.57 × the stream losses. Our modelling suggest up to 2000 m^3 day^{-1} (23 l s^{-1}) of water could be removed from the pit. However, our modelling implements the Rise and Shine Creek as a constant head boundary, which has no flux limits (infinite water supply). In reality the Rise and Shine Creek has relatively small flows of c. 5-30 l s^{-1}. In lieu of more detailed modelling and additional data constraining both the hard rock and alluvial/veneer systems, we suggest that the pit is likely to significantly impact the Rise and Shine Creek and that the pit flux is likely to be on the order of 1.5 × the stream fluxes. Note that this assessment does not include any potential mitigations associated with engineered solutions (e.g., stream diversion) to reduce the dewatering effects of the pit.

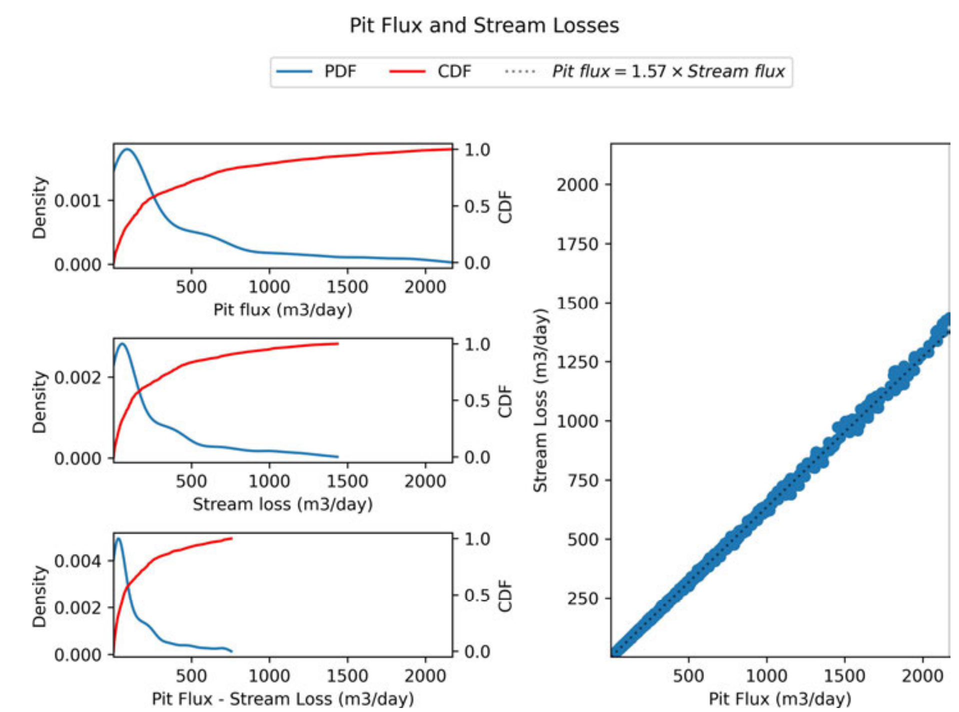

Figure 9.15: SREX: Stream and pit flux.

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There are a number of mapped wetlands and alluvial zones near to the SREX pit (Figure 9.16). In addition, Rise and Shine Creek supplies water to a number of other wetlands downstream of the mining area. Our modeling suggests that the hard rock aquifer is unlikely to prevent draw-down in the adjacent alluvial system and wetlands. In the absence of more detailed modelling we suggest that the most likely outcome is that the alluvial system and any nearby wetlands will be significantly impacted by the mining activities – possibly leading to the drying up of the wetlands and the loss of the alluvial system. There is not currently sufficient data to support more detailed modelling of the alluvial / SREX system and a data campaign would be required before any further modelling could be undertaken.

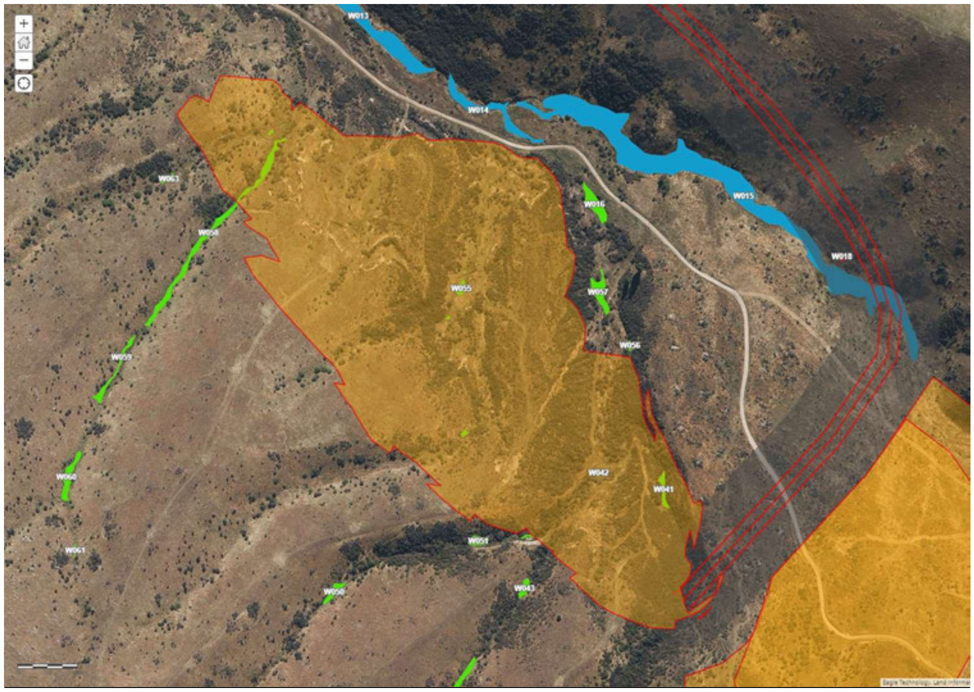

Figure 9.16: SREX: Alluvial zone and mapped wetlands.

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9.5 SREX Limitations Arising from the Optimisation and Scenarios

The optimisation has several limitations including:

- The model structure is simple and there are only a few observations in the active model domain, so the model may not capture all the processes in the area.
- The model is not transient, and therefore cannot provide any information on the rate of change of the water table or any non-linearity in the discharge to the pit. Therefore, the storage component of the pit inflow is not captured.
- The model results assume a homogeneous and isotropic aquifer, any local fracturing may change the predicted draw-down or pit fluxes.
- The model does not include the near surface alluvial, veneer, or wetland systems. The results suggest that these systems may be significantly impacted by the mining activities, however, there is not currently sufficient data to support more detailed modelling of these systems.
- The Rise and Shine Creek is modelled as a constant head boundary, which provides an infinite water supply to the model, while the actual creek has a relatively small flow.

10 Discussion of all Model Results

10.1 Posterior Distributions of all Models

The use of unique models for each of the three mining scenarios has allowed us to investigate the effect of different model assumptions on the parameterisation of the model.

The posterior parameter distribution is different for each of the models:

- **Recharge (R)**: The posterior distribution is most constrained for the Rise and Shine model and least con-

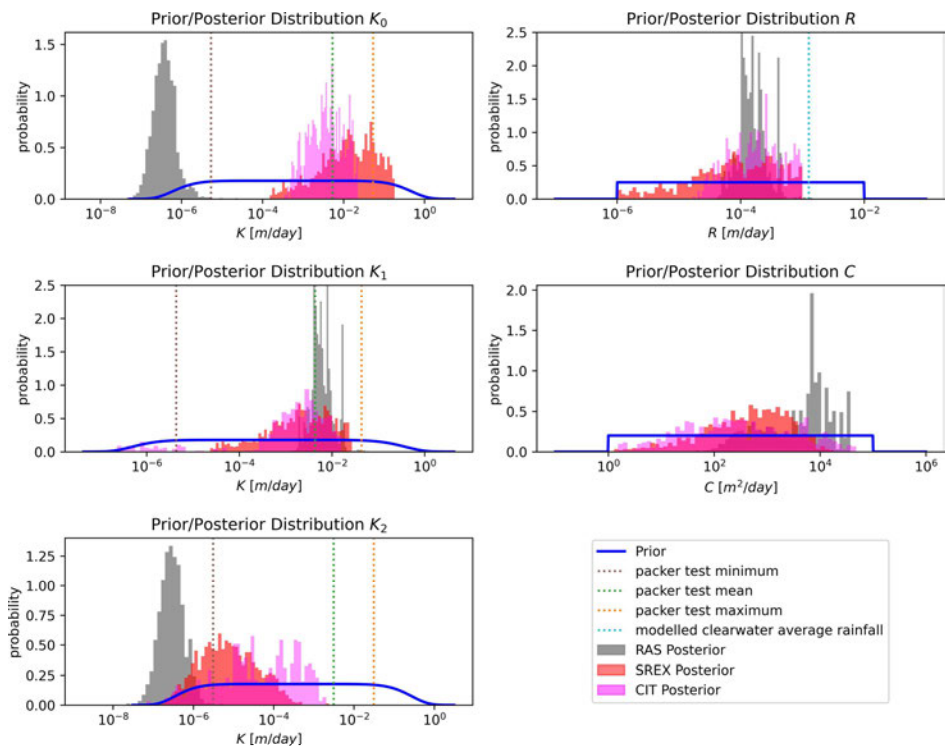

Figure 10.1: A comparison of all posterior distributions.

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strained for the SREX model. The peak of all three model distributions occurs c. 10^{-4} m d^{-1} showing general agreement between the models on this parameter.

- **Drain conductance (C)**: This parameter is very poorly constrained in all models, particularly for the SREX and Come in Time models. The parameter is mostly compensatory with the recharge parameter (e.g., rejecting high recharge values where the recharge is too high and on steep slopes).
- **TZ-3 conductivity (K_0)**: This parameter shows significant difference between the Rise and Shine model and the other two models. SREX and Come in Time show a broad agreement other the distribution thought the SREX model also includes higher conductivity values. Rise and Shine shows a much lower conductivity distribution (4-6 orders of magnitude lower) than the other two models.
- **RSSZ conductivity (K_1)**: This parameter shows good agreement between the 3 models and all three are significantly constrained relative to the prior. The model agreement gives confidence in the parameterisation of the RSSZ.
- **TZ-4 conductivity (K_2)**: This parameter shows greater agreement between the three models than the TZ-3 conductivity. Both SREX (peak at 10^{-6} - 10^{-3} m d^{-1}) and Come in Time (peak at $10^{-5.5}$ m d^{-1}) are less constrained than the Rise and Shine model (peak at $10^{-6.5}$m d^{-1}). Nevertheless, the models are suggesting conductivity values far lower than the RSSZ.

The general agreement of all three models on recharge and the RSSZ conductivity is encouraging. The moderate agreement on the TZ-4 conductivity is also encouraging as this unit is deep and even though a number of boreholes are located in this unit, the TZ-4 will also be influenced by the above units (TZ-3 and RSSZ). The poor agreement on the TZ-3 conductivity is initially more concerning as this is the unit is relatively well constrained by the borehole data and one would expect the models to agree more closely. Both the SREX and Come in Time models show a much broader distribution of TZ-3 conductivity with peaks at 10^{-3} - 10^{-1} m/day. This is in contrast to the Rise and Shine model which shows a peak at $10^{-6.5}$ m/day – up to 6 orders of magnitude lower than the

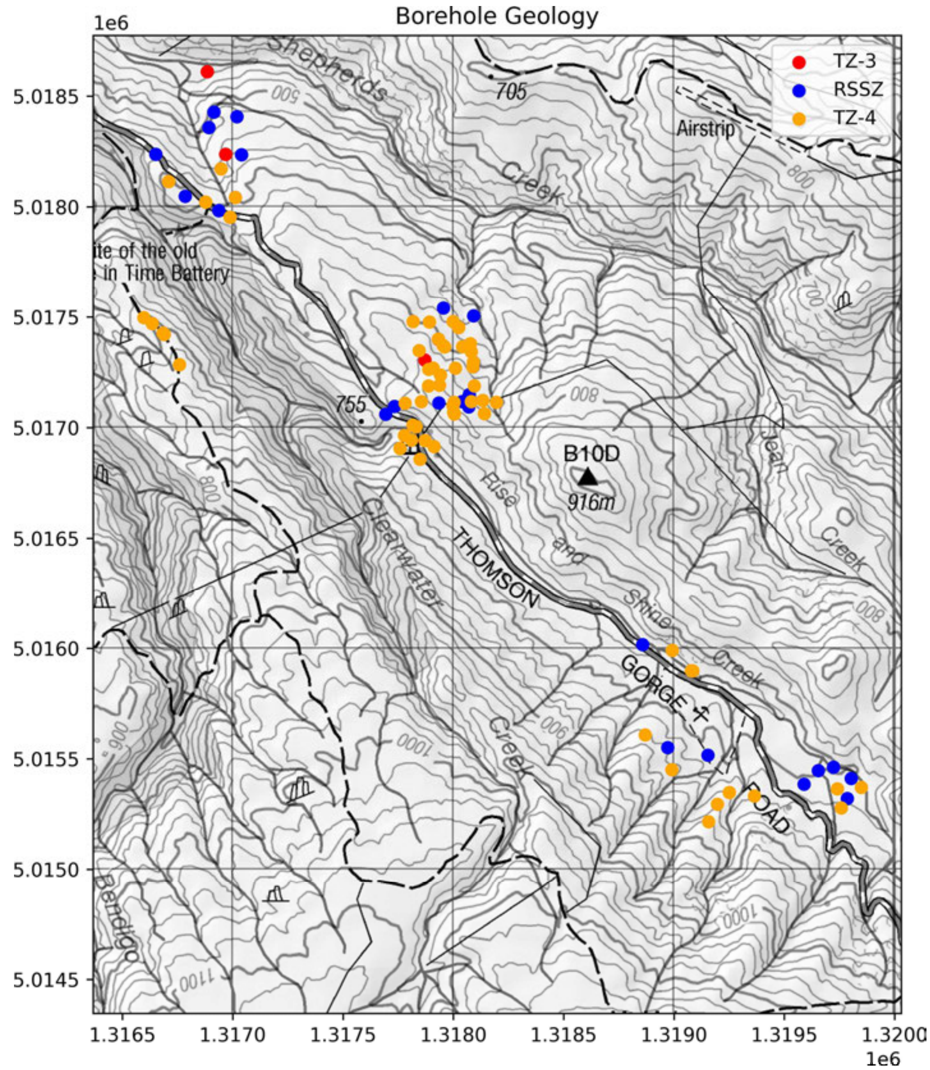

Figure 10.2: The Hk zone of the observations.

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other models. However, the conductivity of the TZ-3 in SREX and Come in Time is very similar to the RSSZ conductivity, which shows broad agreement between the models. The RSSZ is modeled to be near the surface for both SREX and Come in Time and the spatial location of the RSSZ was not well constrained in the model build. Therefore, we suggest that this discrepancy is most likely due to additional fracturing associated with the RSSZ in these areas. The water level observations in the Come in Time model are primarily located in a valley where the RSSZ is likely to be much closer to the surface than in the Rise and Shine model domain. In addition, the majority of the TZ-3 in the SREX domain is located in the toe and valley of the Rise and Shine Creek. This area may have allowed more weathered and fractured rock to persist as compared to the steep slopes of the Rise and Shine model domain. Given these mitigating factors we suggest that the apparent discrepancy in the TZ-3 conductivity is not a significant issue for the models and most probably is compensating for the imperfect location of the RSSZ in the model domain.

10.2 Rise and Shine Model Parameterised with SREX and Come in Time Parameters

Despite the explanation of the parameter disagreement in Section 10.1, we still wanted to investigate the effect of using the SREX and Come in Time parameters in the Rise and Shine model. The results of these model runs are shown in Figure 10.3 and Figure 10.4. Note that only the observations above 620 m are associated with the Rise and Shine pit, the others are the Come in Time observations. The SREX parametrisation is incompatible with the Rise and Shine observations with the model under-predicting the heads by up to 200 m. The Come in Time parametrisation is better than the SREX parametrisation, but still under-predicts the heads by up to 80 m. These results further suggest that the difference in parametrisation between the models is more likely reflective of the mis-location of the RSSZ in the SREX and Come in Time models than a fundamental difference in the hydrological environment. Therefore, using the three models independently is the most appropriate approach for the prediction of the impacts of the mining operations.

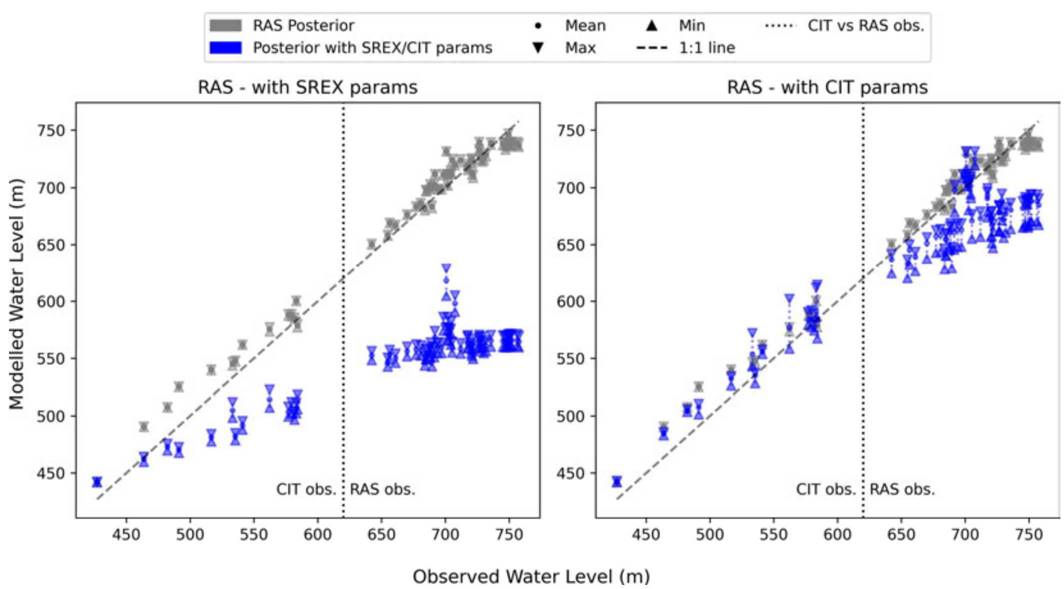

Figure 10.3: RAS: Modelled vs measured heads under alternate parameterisation.

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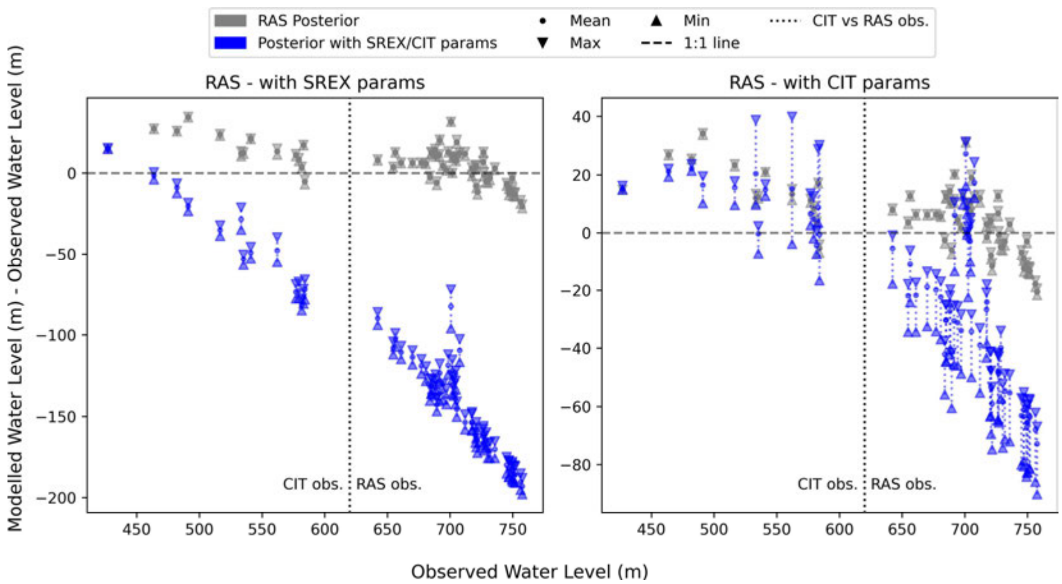

Figure 10.4: RAS: Modelled vs misfit heads under alternate parameterisation.

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Laloy, E. and Vrugt, J. A. (2012). High-dimensional posterior exploration of hydrologic models using multiple-try DREAM $_{(zs)}$ and high-performance computing: EFFICIENT MCMC FOR HIGH-DIMENSIONAL PROBLEMS. *Water Resources Research*, 48(1). 4.3, 5.1

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A Rise and Shine Appendix

A.1 Rise and Shine Constrained Optimisation Results

Here we present the results of the constrained optimisation. The prior and posterior parameter distributions are shown in Figure A.1 and Figure 7.14, respectively. The fit to the model targets are shown in Figure A.2 and Figure A.3.

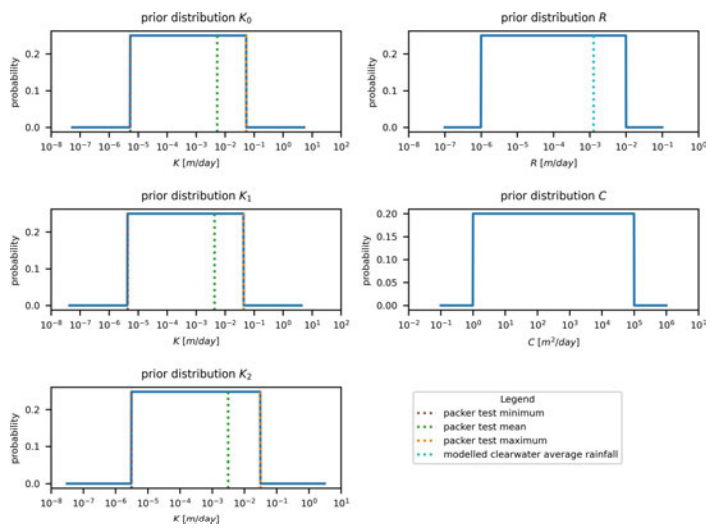

Figure A.1: RAS: Prior Values for the constrained optimisation.

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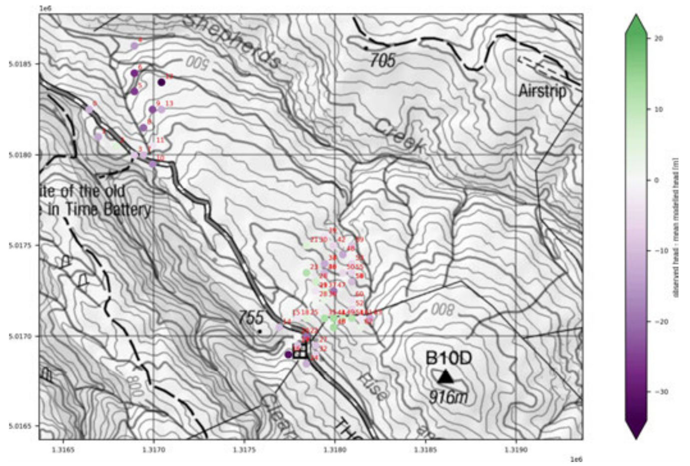

Figure A.2: RAS: Constrained optimisation residuals.

Average difference between the observed and modelled head at each of the boreholes. Purple points show where the model is overestimating the head. Green points show where the model is underestimating the head.

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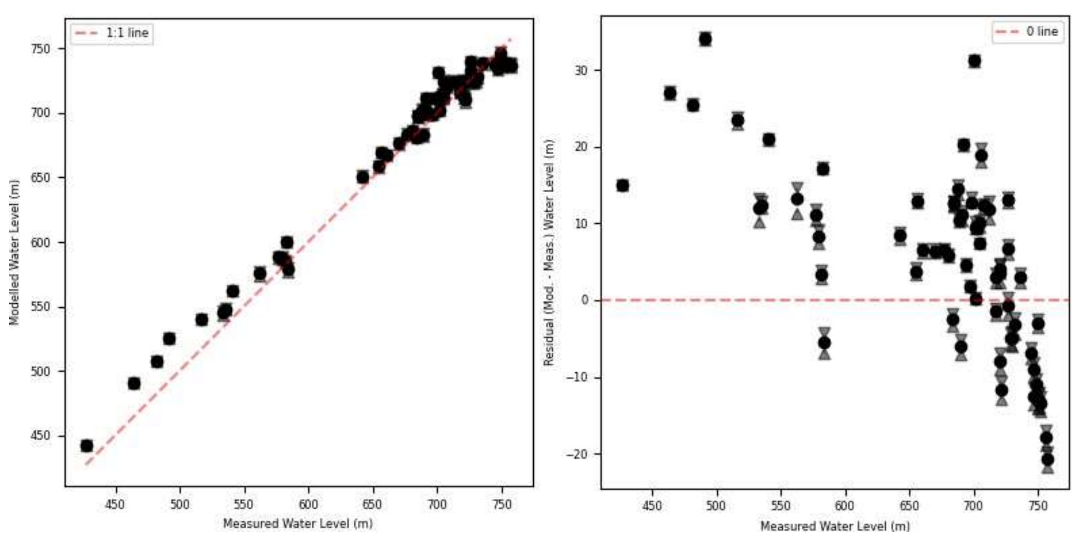

Figure A.3: RAS: Constrained optimisation modelled vs measured heads.

Measured vs modelled heads at each of the boreholes. The dashed line represents a 1:1 relationship. The triangles represent the simulation min/max values and the circle represents the mean value.

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A.1.1 RAS: Constrained Head Contours

The head contours for the constrained optimisation are shown in Figure A.4 to Figure A.4. Please note that the constrained optimisation is considered to be less reliable than the optimisation results presented in Section 7.3. We have presented these results as a sensitivity analysis to the optimisation results.

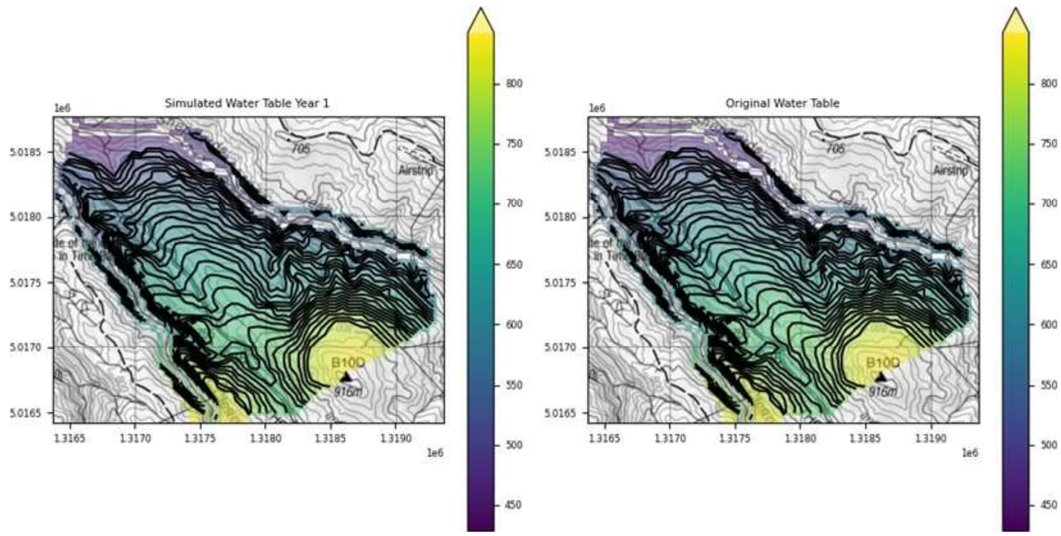

Figure A.4: RAS: Constrained optimisation predicted water table year 1.

Water table contours are show every 10 m from 500 - 800 m.

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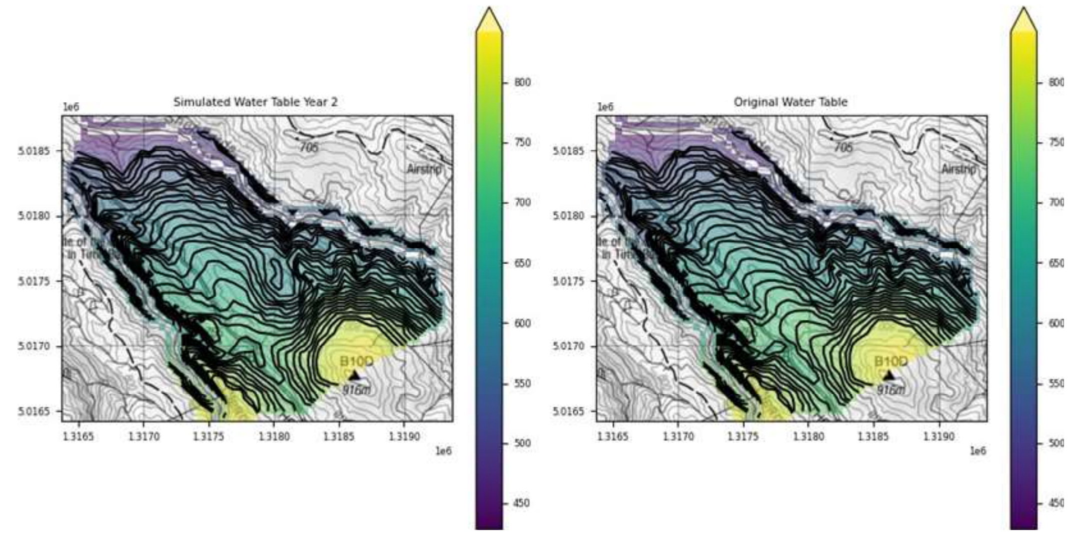

Figure A.5: RAS: Constrained optimisation predicted water table year 2.

Water table contours are show every 10 m from 500 - 800 m.

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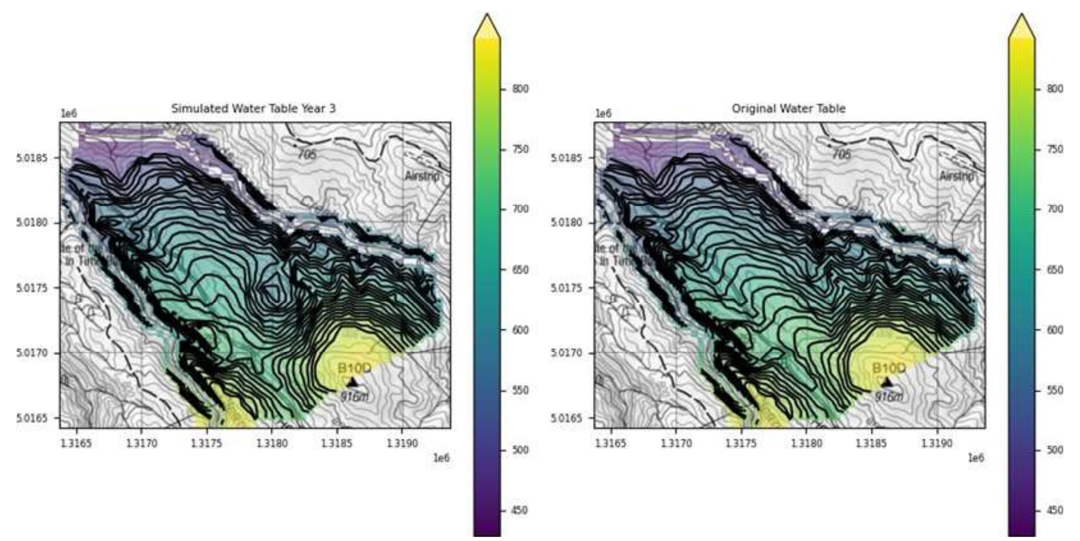

Figure A.6: RAS: Constrained optimisation predicted water table year 3.

Water table contours are show every 10 m from 500 - 800 m.

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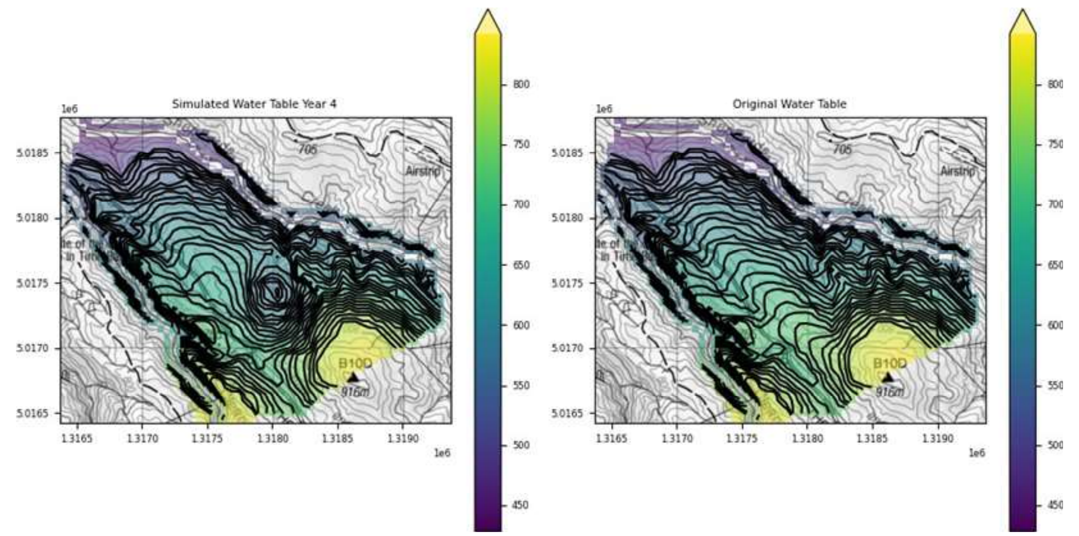

Figure A.7: RAS: Constrained optimisation predicted water table year 4.

Water table contours are show every 10 m from 500 - 800 m.

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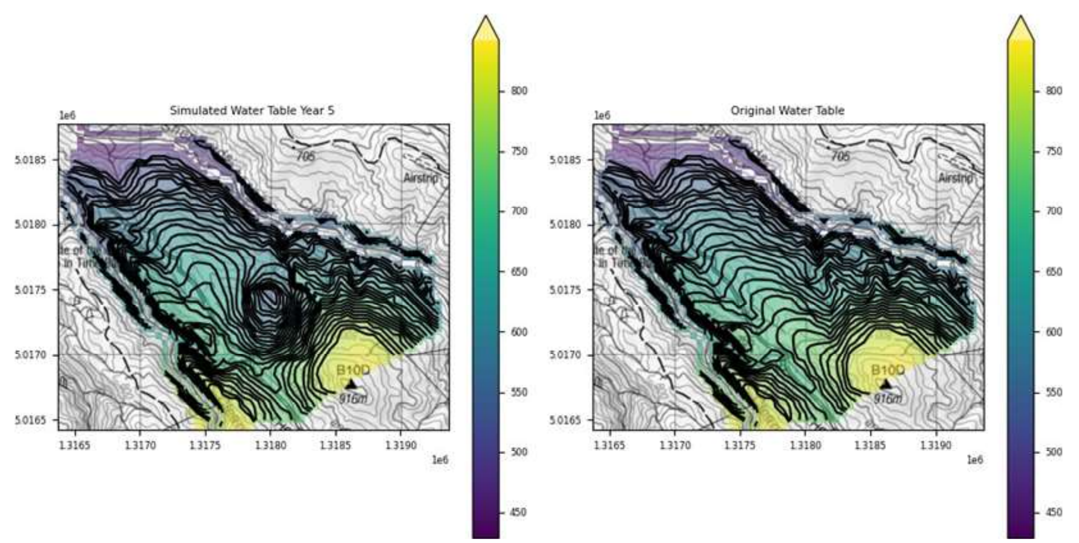

Figure A.8: RAS: Constrained optimisation predicted water table year 5.

Water table contours are show every 10 m from 500 - 800 m.

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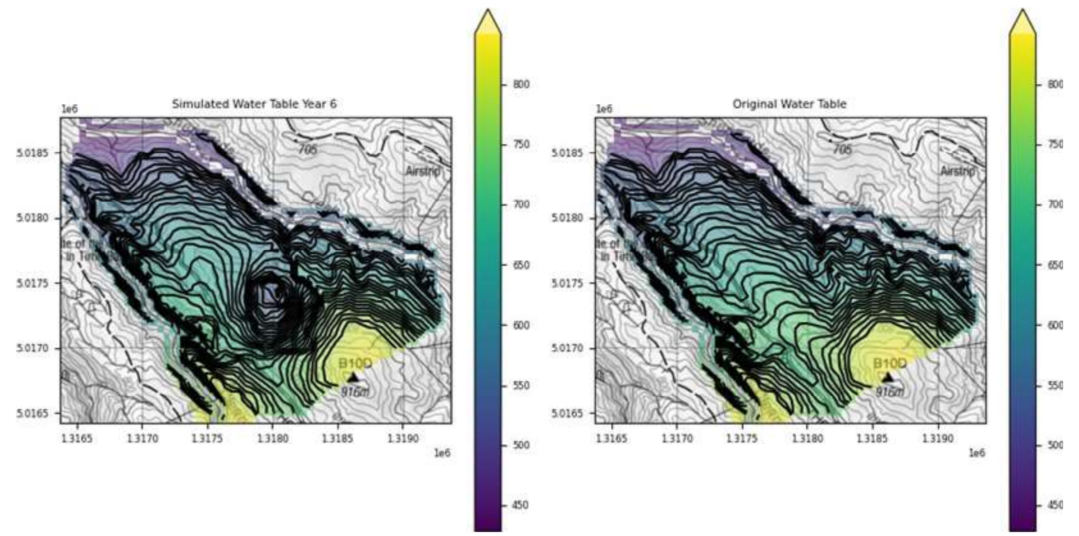

Figure A.9: RAS: Constrained optimisation predicted water table year 6.

Water table contours are show every 10 m from 500 - 800 m.

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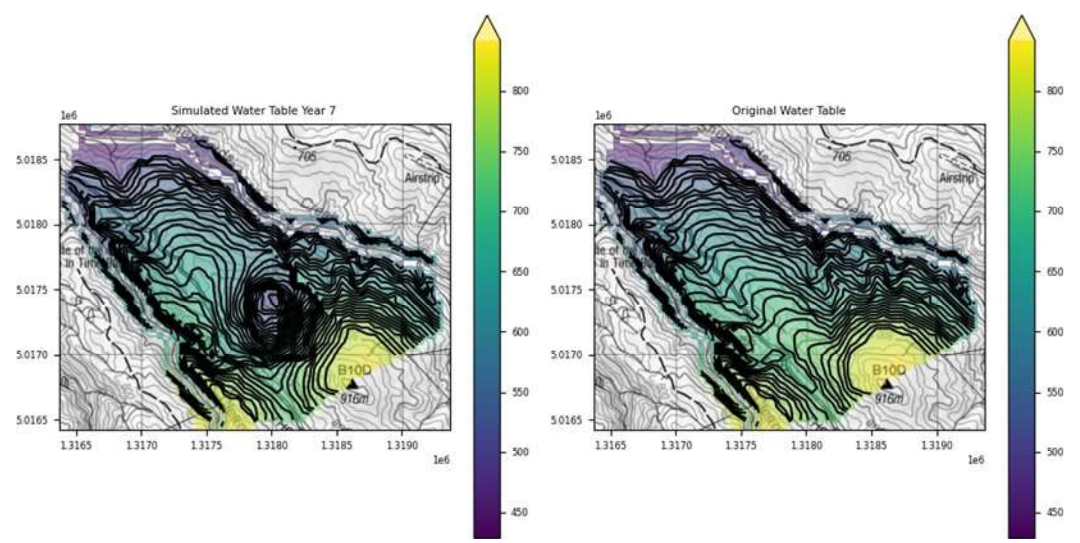

Figure A.10: RAS: Constrained optimisation predicted water table year 7.

Water table contours are show every 10 m from 500 - 800 m.

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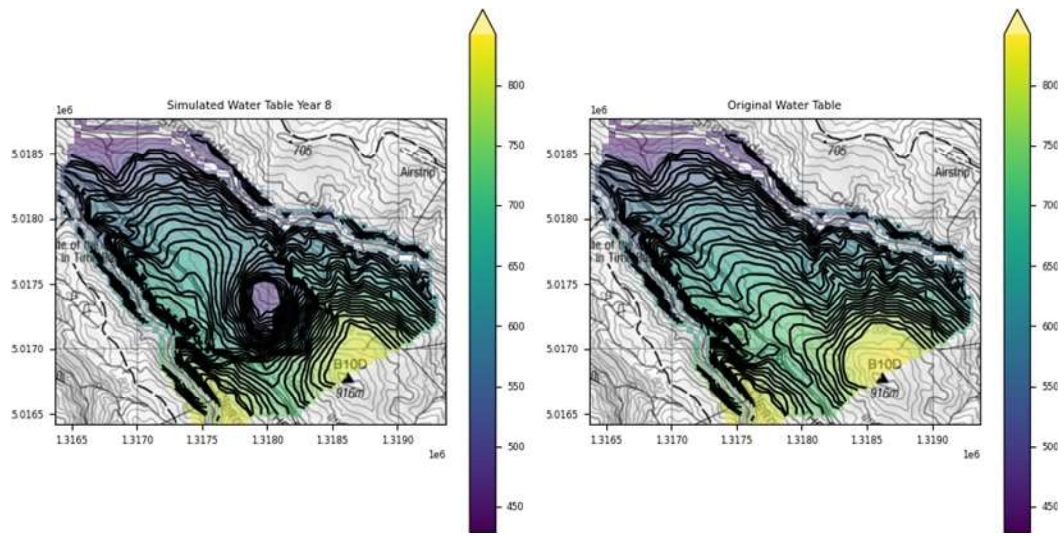

Figure A.11: RAS: Constrained optimisation predicted water table year 8.

Water table contours are show every 10 m from 500 - 800 m.

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