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Review of groundwater chapter of SA DEM assessment of the Terramin Bird in Hand MLA

Luk JM Peeters
Sarah Marshall
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1 Introduction

The South Australian Department of Energy and Mining (DEM) engaged CSIRO to review the groundwater chapter of the government assessment of the Terramin Bird in Hand Gold Mine Lease Application (MLA). DEM provided a draft version of the groundwater chapter on 08/11/21 together with the documents the assessment is based on. On 07/12/21, an additional document, the Terramin response to DEM's letter dated 20 October 2021, was provided. On 15/12/21, an updated draft of the groundwater chapter was provided, in which the section on controlled inundation was updated. This document will be referred to as DEM groundwater advice (2021).

Dr. Luk Peeters and Dr. Sarah Marshall met with Paul Thompson (DEM), Andrew Querzoli (DEM) and Dr. Juliette Woods (Department for Environment and Water) on 05/11/21 to provide background to the MLA and discuss the scope of the review. On 7/12/21, Dr Peeters and Dr Marshall presented their preliminary findings to Paul Thomson, Andrew Querzoli, Dr. Juliette Woods and Gabor Bekesi (DEM). The final review report was approved for publication after a CSIRO internal peer review and discussed with representative of DEM, DEW and EPA on 13/1/22. The report was delivered to DEM on 28/01/22.

The groundwater outcome recommended by DEM is[1]:

The Tenement Holder must, during construction, operation and post Completion, ensure that there is no adverse impact to the quantity or quality of groundwater available to existing users, future users and groundwater dependant ecosystems as a result of mining operations.

The CSIRO review will evaluate the material provided in the context of this groundwater outcome. More specifically, CSIRO will examine if:

1. the Government assessment and recommendations are consistent with the groundwater outcome and the documentation provided,
2. the model predictions the Government assessment and recommendations rely on are conservative, i.e. that they overestimate negative impacts,
3. any issue identified during the review is material, i.e. that addressing the issue has the potential to change the predictions to the extent that a revision of the assessment or recommendation would be warranted.

To this end, CSIRO adopts the framework presented in Table 1 for evaluating the priority of any identified issue. The issues and their priority pertain to particular aspects of the reporting, modelling or analysis, not the overall risk of the project.

The next section summarizes the key Government assessments and recommendations and provides an overview of what CSIRO considers to be the key predictions that the Government assessment is based on. Note that a prediction is the quantity of interest together with its

[1] p.3 in DEM groundwater advice (2021)

likelihood, such as for instance the 95th percentile of mine water inflow. The following sections discuss the issues identified in relation to groundwater quantity and quality.

Table 1 Review framework

Priority	Description
High	demonstrates that key predictions are not conservative: potential to lead to a **substantial** change in key predictions or their range (e.g. more than 25%), such that predictions **increase**
Medium	affects the degree of conservatism: potential to lead to **minor or moderate** change in key predictions or their range (e.g. less than 25%), such that predictions **increase or decrease**
Low	does not affect the degree of conservatism: potential to lead to **minor or no** change in key predictions or their range, such that predictions are **not expected to change**

2 SA Government assessments and recommendations

The proposed mine site is situated approximately 2 km east of Woodside. The mine proposal consists of a decline to be created in the Tapley Hill formation with mine stopes in the Brighton Limestone formation which hosts the gold mineralisation, associated with the Nairne Fault. The mine design plans to mitigate groundwater inflow in the mine by grouting ahead of excavation and by avoiding known high yielding areas, such as the hanging wall fracture zone. Potential drawdown on nearby existing groundwater users and potential reduction in baseflow to the nearby Inverbrackie Creek is planned to be mitigated by aquifer reinjection of treated mine water in the Tapley Hill formation to the west of the mine and the Tarcowie Siltstone Formation to the east.

Terramin provided documentation of the hydrogeological characterisation of their site, including pumping tests and aquifer injection tests, hydrogeological conceptualisation, numerical groundwater modelling and uncertainty analysis. In addition, documentation is provided pertaining to potential impacts on groundwater quality, including the potential for acid mine drainage, salinity changes in the aquifers and changes in groundwater quality associated with reinjection of treated mine water.

The key groundwater quantity predictions SA government used in their assessments and recommendations, as identified by CSIRO are:

1. Predicted mine water inflows, and their range, for different scenarios of effectiveness of the grouting (70% reduction in inflow, 90% reduction in inflow, 90% reduction in inflow for the mine decline and 70% reduction in inflow for the mine stopes).
2. Predicted drawdown under different scenarios of grouting effectiveness and mine water reinjection
3. Predicted change in baseflow to Inverbrackie Creek under different scenarios of grouting effectiveness and mine water reinjection.

The scenario in which grouting reduces inflow in the mine declines by 90% and in the mine stopes by 70% is considered the most realistic by SA government. In assessing the adequacy of the mine reinjection scheme with 8 wells, SA government used the predicted 95th percentile of mine inflow, 28 L/s in year 5 of mining, for this scenario as a conservative estimate. The median or 50th percentile of inflow in year 5 of mining for this scenario is 18 L/s. To allow for sufficient contingency, Terramin have proposed that the MAR system will be designed to accommodate the conservative 70% grouting effectiveness scenario with higher inflow, pumping and injection rates. The 95th percentile of mine water inflow in this scenario after 5 years of mining is 39 L/s.

The combination of scenarios with formal uncertainty allows for a more comprehensive exploration of potential impacts. CSIRO does however note that mixing qualitative and quantitative assessments of likelihood does pose a challenge in communication. If the calibrated language for expressing probability of the Intergovernmental Panel of Climate Change (IPCC)[2] is adopted, where an event with probability between 1 and 10% is described as *very unlikely*, the following can be stated:

1. In the scenario considered *most realistic* by SA government (see above), it is *as likely as not* for mine inflow to exceed 18 L/s, while it is considered *very unlikely* for modelled mine inflow in year 5 of operations to exceed 28 L/s
2. In the scenario considered *conservative* by Terramin (see above), it is *very unlikely* for modelled mine inflow in year 5 of operation to exceed 39 L/s.

These groundwater quantity predictions, especially the mine water inflow, provide boundary conditions for the impact assessment of groundwater quality.

CSIRO summarised the SA government's assessments and recommendations in DEM's groundwater assessment (2021) on groundwater quantity in Table 2 and on groundwater quality in Table 3. The issues identified by CSIRO and their level of concern, as assessed by CSIRO, based on the framework in Table 1, are discussed in more detail in section 3 and 4 for groundwater quantity and quality respectively. Overall, SA government's assessment is comprehensive and CSIRO has not identified any other issues warranting further scrutiny, beyond those listed in Table 2 and Table 3.

Table 2 SA Government assessments and recommendations pertaining to groundwater quantity with indication whether issues have been identified and if so, their priority, as assessed by CSIRO. Items in square brackets in italics are added by the authors to provide context. For the assessments or recommendations for which no issue is identified, CSIRO concurs with the Government statement. For the assessments or recommendations for which an issue is identified, CSIRO does not concur with all or part of the Government statement, which is elaborated upon in section 3.

Nr	Government assessment or recommendation	Issue identified	CSIRO's assessment of priority
1	Terramin collected adequate field data and presented it in the MP to inform development of conceptual hydrogeology and provide a baseline to assess potential impacts on groundwater quantity receptors	no	none
2	Terramin developed an appropriate conceptual hydrogeological understanding that served as the basis for the numerical groundwater flow model to assess potential impacts of mining on receptors	yes	low
3	These numerical models have appropriate choices of model domain, spatial and temporal discretisation, aquifer parameters, boundary conditions and initial conditions. The main uncertainty identified is that the numerical model simulates fractured rock as equivalent porous media. This is a common and necessary	yes	medium

[2] Table 1 in Mastrandrea et al. 2010. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Report. Intergovernmental Panel on Climate Change (IPCC) https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

	assumption for a model domain of the required size. However, it means that model outputs are representative over medium and large scales but will be inaccurate over small scales…. This means multiple parameters sets can provide a model with a good match to observations.		
4	Government questioned the use of a single method *[chloride mass balance]* as use of additional methods would have provided a more detailed approach…. Using a potentially underestimated rainfall recharge in the model may result in uncertainty in the predicted mine inflows. This was addressed in the uncertainty analysis where recharge rates were varied.	yes	low
5	…modelling fractured groundwater flow with the equivalent porous media approach acceptable at a scale larger than REV. The consequence of a REV at several hundred meters (approximately 700 m based on hydrogeological experience) is that predictions on smaller scales may be uncertain or incorrect. If a lease is granted, it is recommended that the model would need to be reviewed to incorporate tested hydraulic properties as a requirement for the PEPR *(program for environment protection and rehabilitation)*.	yes	low
6	… while 90% may be achievable it is appropriate that allowance is made for predicted inflows associated with a 70% grouting effectiveness for at least the stoping area to allow for sufficient contingency…Based on this, DEM considers the hybrid scenario to be more likely than the 70% or 90% effectiveness scenarios which apply a broad grouting effectiveness over the whole mine which is not realistic	no	none
7	… eight wells are likely to be effective in managing the P95 *[hybrid scenario]* peak flow in year 5 of 28 L/s	no	none
8	Terramin provided a hydrogeological risk assessment for the proposed MAR system that used predictions from the modelling to demonstrate that the proposed MAR system will meet the relevant principles of the WAP	no	none
9	The conservative P95 70% grouting effectiveness *[+ MAR]* scenario shows an increase in water available at all wells.	no	none
10	If the mine was completely flooded and Terramin did not attempt to recover the mine at all, modelling results shows that under a worst case 70% grouting effectiveness scenario existing users would still be able to access groundwater, and after 80 days groundwater would	yes	low

	return to steady state levels. Under the 90% grouting effectiveness scenario, existing users would once again not be impacted, and groundwater recovery would take place within approximately 10 days.		
11	The model predicts MAR will mitigate any reduction in baseflow to the *[Inverbrackie]* creek.	no	none
12	the mitigation measures were modelled adequately to predict effectiveness in reducing impacts on receptors. Government notes that the implementation of mitigation measures in the BIH numerical groundwater flow model are based on the following: - An assumption that the grouting will represent a 'hybrid', 70% (or 90%) reduction of the unmitigated mine inflow. - An assumption that the grouting-mitigated mine inflow is reinjected to the groundwater system	no	none
13	Terramin evaluated model uncertainty adequately to present plausible ranges for predicted impacts. The ranges and distribution for each of the parameters were considered appropriate by SA Government.	yes	high
14	all potential impact events identified in the Mining Proposal where an outcome was not proposed and confirms that the source, pathway and receptor do not exist, hence, an outcome is not required for those impact events Table 10-6 of the Mining Proposal.	no	none

Table 3 SA Government assessments and recommendations pertaining to groundwater quality with indication whether issues have been identified and if so, their priority, as assessed by CSIRO. Items in square brackets in italics are added by the authors to provide context. For the assessments or recommendations for which no issue is identified, CSIRO concurs with the Government statement. For the assessments or recommendations for which an issue is identified, CSIRO does not concur with all or part of the Government statement, which is elaborated upon in section 4.

Nr	Government assessment or recommendation	Issue identified	CSIRO's assessment of priority
1	…additional baseline groundwater quality data is required to support detailed design of mitigation strategies and compliance criteria. The information provided in the MP, and the response document, demonstrates that there are likely to be a sufficient number of appropriately located wells (targeting each hydrostratigraphic unit) to enable the establishment of baseline groundwater quality.	no	none

2	Terramin have proposed that all water from underground and the IML will report to a turkey's nest dam before undergoing treatment to remove contaminants	no	none
3	… that the groundwater model used to inform the water quality impact assessment has used appropriate inputs and provides qualitative results that could be reviewed further with baseline data	yes	low
4	The risk of AMD *[acid and metalliferous drainage]* is considered low as the proposed mine design avoids the supergene zone which has been identified as highest risk of encountering PAF material.	yes	low
5	Government considers that appropriate strategies have been proposed to manage the risk of AMD and support the recommendations made by Tonkin and recommend that should a lease be granted they be a requirement of the PEPR	no	none
6	Government considers that the proposed method of water treatment is well understood and the conceptual design is appropriate to manage identified contaminants.	no	none

3 Groundwater quantity

Table 2 lists 6 issues;

- high priority: the range of predictions based on the uncertainty analysis
- medium priority: the implementation of the conceptual hydrogeological model in the numerical groundwater model
- low priority: the groundwater model conceptualisation, recharge assessment, the need to review the groundwater model in the vicinity of the mine and the controlled inundation

The following sections provide an in-depth discussion of these issues, starting with the high concern, followed by medium and low concern.

3.1 Range of predictions based on the uncertainty analysis

As indicated in section 2, the range of predicted inflows at year 5 of mining operations is a key groundwater model prediction. Particular emphasis is on the 95th percentile under various scenarios, as it represents an extreme which is used to evaluate the adequacy of the mine reinjection scheme.

CSIRO is of the opinion that the estimated 5th and 50th percentiles of predicted mine inflows across the various scenarios are adequate. The rejection sampling approach chosen to simulate the range of predictions results in a robust estimate of the 5th and 50th percentile. The 95th percentiles are however considered to be underestimated in the uncertainty analysis because:

1. The sample size after constraining the Monte Carlo ensemble is not sufficient to reliably estimate the 95th percentile and,
2. The sampled distribution of effective hydraulic parameters (i.e. those averaged across a flow path) cover a smaller range than the range of each individual zone's distribution.

In the following sections, we provide a more in-depth discussion of this finding. We start with evaluating if the rejection sampling approach is able to reduce predictive uncertainty, followed with an illustrative example of how the random sampling of hydraulic conductivity zones can lead to an underestimate of the 95th percentile.

3.1.1 Rejection sampling

In the uncertainty analysis, 10,000 random realisations are evaluated from the prior distributions for the 117 parameters. Appendix A of Appendix B7A[3] provides the prior and posterior parameter distributions. Parameters are log-normally distributed, with the exception of the recharge parameters, which are uniformly distributed. Each parameter is considered independent in the

[3] Golder (2021) Bird in Hand groundwater modelling – nonlinear uncertainty analysis

sampling, with exception of the recharge parameters (excl. recharge zone ‘rch_10’), which are tied together to maintain their relative spatial distribution.

The report does not specify which sampling algorithm is used to generate the 10,000 realisations or how the covariance between recharge parameters is maintained. We note that recharge zone 11 (‘rch_11’) in the SE of the model domain (Fig. 45) appears not to be included in the uncertainty analysis. We also note that recharge zone 7 (‘rch_7’) directly to the NW of the planned mine site is assigned zero mm/yr recharge, which does not vary in the Monte Carlo sampling. We could not find what hydrogeological feature this recharge zone represents as it is not present in Appendix H1[4] or the model update in Appendix H9[5].

The model has a large number of parameter zones defined, especially for the horizontal hydraulic conductivity. While the prior distribution of each hydraulic conductivity parameter is very wide, varying over at least four orders of magnitude, the range of the equivalent hydraulic conductivity is much smaller. Equivalent hydraulic conductivity is a measure of the hydraulic conductivity averaged across a hydraulic flow path.

From the ensemble 10,000 parameter combinations, only those are retained that satisfied the following criteria:

1. Convergence in steady state simulation
2. SRMS of less than 10%
3. Simulated inflow to Inverbrackie Creek less than 1800 ML/yr
4. Less than 1 % error in the simulated water balance for steady state simulation
5. Convergence in transient simulation for the unmitigated, 70% effective, 90% effective and hybrid grouting scenario
6. Less than 5 % error in the cumulative simulated water balance for transient simulation at the end of mining (year 5.25 of simulation) with the head change criterion for convergence relaxed from 0.1 m to 0.2 m
7. Achieving target grouting effectiveness (within 2.5% of target) with PEST optimisation of drain conductance value

The large number of realisations that fail to produce a water balance with an acceptable error in the predictive transient simulations is an indication that the model is not very robust when used to simulate stress on the system (i.e. mine water extraction). In this context, a robust model is a model that is numerically stable for a wide range of parameter combinations, not only the parameter combinations during the calibration process. Middlemis and Peeters (2018) recommend to stress-test a model to ensure that the model converges for a range of realistic parameter combinations. The model might fail to produce an acceptable water balance mismatch either because the parameter combinations are unrealistic (e.g. very high K with very low S) or

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[4] AGT (2017) Bird-in-Hand Gold Project Groundwater Assessment

[5] Golder (2019) Bird-in-Hand Gold Project – Investigation into Managed Aquifer Recharge. Stage 2 Injection tests and Stage 3 Groundwater model validation

because of the numerical implementation. If the latter, this would result in incorrectly rejecting parameter combinations which in turn compromises the range of predicted impacts and the level of conservatism in the estimated inflows. This can be assessed by comparing parameter combinations that do meet the water balance criterion with parameter combinations that do not meet the criterion. Should the water balance criterion preferentially reject elevated values for the hydraulic conductivity parameters in the vicinity of the mine, it is possible that the P95 is underestimated.

Table 4 shows the evolution of the ensemble size during the various stages of the rejection sampling. This table is based on section 3.0 Results in Appendix B7A[6]. We note a discrepancy between the number of realisations in the ensemble size in section 3.2.3 and what we deduced from sections 3.2.1 and 3.2.2 for the transient 70% effective grouting (resp. 146 and 148) and the hybrid scenario (resp. 101 and 114).

The large number of realisations that fail to produce a water balance with an acceptable error in the predictive transient simulations is an indication that the model is not very robust when used to simulate stress on the system (i.e. mine water extraction). In this context, a robust model is a model that is numerically stable for a wide range of parameter combinations, not only the parameter combinations during the calibration process. Middlemis and Peeters (2018)[7] recommend to stress-test a model to ensure that the model converges for a range of realistic parameter combinations. The model might fail to produce an acceptable water balance mismatch either because the parameter combinations are unrealistic (e.g. very high K with very low S) or because of the numerical implementation. If the latter, this would result in incorrectly rejecting parameter combinations which in turn compromises the range of predicted impacts and the level of conservatism in the estimated inflows. This can be assessed by comparing parameter combinations that do meet the water balance criterion with parameter combinations that do not meet the criterion. Should the water balance criterion preferentially reject elevated values for the hydraulic conductivity parameters in the vicinity of the mine, it is possible that the P95 is underestimated.

Table 4 Ensemble sizes as result of rejection sampling (HCLOSE is the head change criterion for convergence)

Description	Realisations retained in ensemble
Initial sample size	10,000
Steady state converged (HCLOSE < 0.1m)	6,602
Steady state SRMS < 10%	624
Steady state Baseflow < 1800 ML/yr & losing/gaining ratio > 20%	301
Transient unmitigated converged (HCLOSE < 0.2 m)	220

[6] Golder (2021) Bird in Hand groundwater modelling – nonlinear uncertainty analysis

[7] Middlemis H, Peeters L J M (2018) Uncertainty analysis—Guidance for groundwater modelling within a risk management framework. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy Commonwealth of Australia

Transient 90% effective grouting converged (HCLOSE < 0.2 m)	220
Transient 70% effective grouting converged (HCLOSE < 0.2 m)	219
Transient hybrid grouting converged (HCLOSE < 0.2 m)	219
Transient unmitigated water balance error < 5%	218
Transient 90% effective grouting water balance error < 5 %	135
Transient 70% effective grouting water balance error < 5 %	165
Transient hybrid grouting water balance error < 5 %	112
Transient 90% effective grouting, target effectiveness achieved	125
Transient 70% effective grouting, target effectiveness achieved	148
Transient hybrid grouting, target effectiveness achieved	114
Transient unmitigated, final ensemble size	218
Transient 90% effective grouting, final ensemble size	125
Transient 70% effective grouting, final ensemble size	146
Transient hybrid grouting, final ensemble size	101

The goal of the rejection sampling process is to generate an ensemble of simulated predictions that is consistent with the observations and knowledge of the system that is sufficiently large to allow to reliably estimate the range of relevant predictions. In this case, the 95th percentile (P95) is used to represent the upper range of a prediction. However, uncertainty in predictions is only reduced through rejection sampling if the criteria constrain the parameters to which the predictions are sensitive. A formal sensitivity analysis can help identifying to which parameters the predictions are most sensitive.

The numerical modelling reports do not provide a formal sensitivity analysis in which it is identified which parameters can be constrained by the observations (historical groundwater levels, Inverbrackie baseflow) and which parameters are most influential to the mine inflow and drawdown predictions. The modelling report[8] does not provide the post-calibration values, but the differences between prior and posterior parameter ranges[9] is provided in Appendix A of Appendix B7A[10]. Table 5 summarizes the 15 parameters that changed the most between prior and posterior. A change between prior and posterior indicates that a parameter can be constrained by the observations. Cross-reference with maps with the spatial distribution of the parameters (Fig. 23 to 47 in Appendix A of Appendix B7A), indicates that the parameters that can be constrained are recharge and hydraulic properties in the shallow parts of the model, generally in the west and in the vicinity of Inverbrackie Creek. The changes are towards an increase in hydraulic conductivity and a decrease in recharge. This indicates prior parameter distributions are overestimating groundwater levels, which is corrected in the posterior.

[8] AGT (2017) Bird-in-Hand Gold Project Groundwater Assessment

[9] Prior parameter ranges are the initial parameter ranges at the start of the uncertainty analysis. Posterior parameter ranges are the parameter ranges at the end of the uncertainty analysis, where parameter values and combinations that lead to model predictions that are not consistent with the observations are removed

[10] Golder (2021) Bird in Hand groundwater modelling – nonlinear uncertainty analysis

It is noteworthy that none of the parameter fields of hydraulic conductivity or storativity in the vicinity of the mine change between prior and posterior. On theoretical grounds, the mine inflow predictions will be most influenced by hydraulic conductivity and storativity in the vicinity of the location of water extraction. While not conclusive, similar prior and posterior parameter distributions for the parameters to which the prediction is most sensitive, is an indication that the calibration process, or in this case the rejection sampling, has not reduced predictive uncertainty. In other words, the calibration process has not increased confidence in some of the parameters and the model predictions therefore rely partly on initial, uncalibrated values. A formal sensitivity analysis can help identifying which parameters the mine inflow is most sensitive to and help guide data collection (both in constraining the initial parameter estimates or including different calibration targets).

Table 5 The 15 parameters with the largest difference between prior and posterior mean

Parameter name	Geological unit (model layer)	Prior mean (m/d)	Posterior mean (m/d)	mean % change
Kh_44	Kanmantoo Fm. (Layer 1)	0.0051	0.01	96
Kh_48	Tapley Hill Fm. (Layer 7)	0.16	0.28	75
Kv_6	Tapley Hill Fm. (Layer 6)	4.90E-04	8.40E-04	71
Kh_3	Tapley Hill Fm. (Layer 6)	0.2	0.34	70
rch_8	Tapley Hill Fm. (Layer 6)	24	13	-46
rch_9	Tarcowie Siltstone (Layer 1)	40	22	-45
rch_6	Tapley Hill Fm. (Layer 6)	29	16	-45
rch_2	Tapley Hill Fm. (Layer 6)	15	8.3	-45
rch_3	Tapley Hill Fm. (Layer 6)	18	10	-44
rch_5	Tapley Hill Fm. (Layer 6)	69	39	-43
rch_4	Tapley Hill Fm. (Layer 6)	170	97	-43
Kh_40	Kanmantoo Fm. (Layer 2)	0.049	0.07	43
rch_1	Tapley Hill Fm. (Layer 6)	110	63	-43
Kh_8	Tapley Hill Fm. (Layer 6)	0.1	0.14	40
Kh_53	Tapley Hill Fm. (Layer 7)	0.01	0.014	40

3.1.2 Equivalent hydraulic conductivity distribution

The predicted mine inflow is a function of the equivalent horizontal hydraulic conductivity assigned to the model grid cells in the vicinity of the proposed mine site, which, for the flow equivalent for hydraulic conductivity zoned along the main direction of flow, is the harmonic mean of horizontal hydraulic conductivity values:

$$K_{eq} = \frac{\sum_{i=1}^{n} l}{\sum_{i=1}^{n} \frac{l_i}{K_i}} \qquad \text{Eq. 1}$$

where l_i $[L]$ is the length of a parameter zone i and K_i $[L/T]$ the horizontal hydraulic conductivity of zone i.

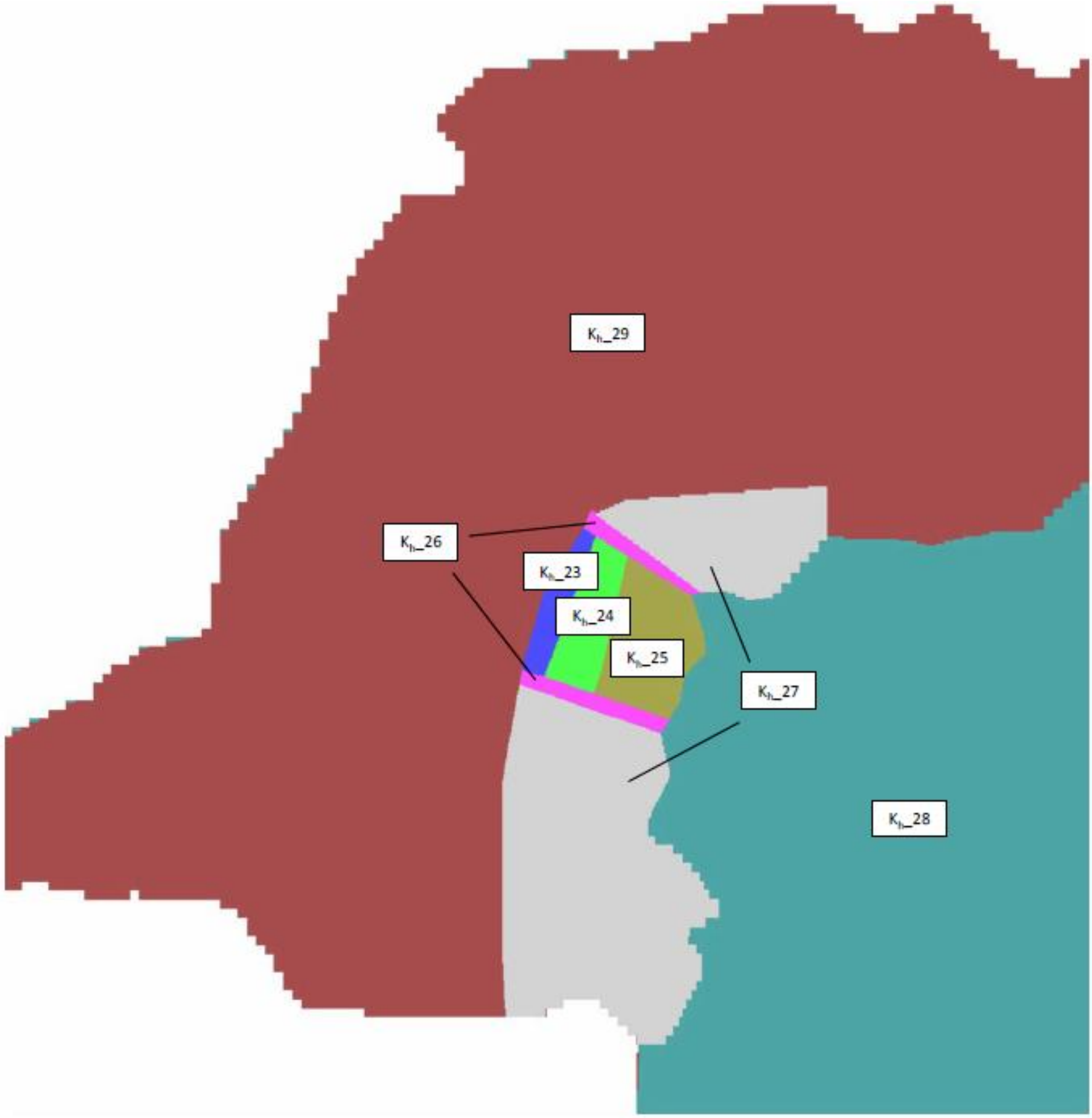

Figure 1 Parameter zonation in Layer 5 (Fig. 25 in Appendix B7A)

Consider the area in which the mine stopes will be developed in layer 5, which comprises parameter zones Kh_23 and Kh_24 (Figure 1). The equivalent K for this area (assuming zones have similar length and flow is perpendicular to the longest side of each K-zone) is:

$$K_{eq} = \frac{2}{\frac{1}{K_{h\_}23} + \frac{1}{K_{h\_}24}} \quad \text{Eq. 2}$$

The posterior distribution after rejection sampling is very similar to the prior distribution for both parameter zones, with a standard deviation that is designed to cover 2 orders of magnitude (0.67 of log10 K). Figure 2 shows the equivalent log10 hydraulic conductivity distribution calculated using Eq. 2 for 10,000 random samples drawn from the normal distribution with mean and standard deviation for Kh_23 and Kh_24 taken from the prior values in table 7 in Appendix B7A.

This figure shows that the standard deviation of the distribution of the equivalent hydraulic conductivity values is 0.61, which is smaller than that of the individual parameter zones.

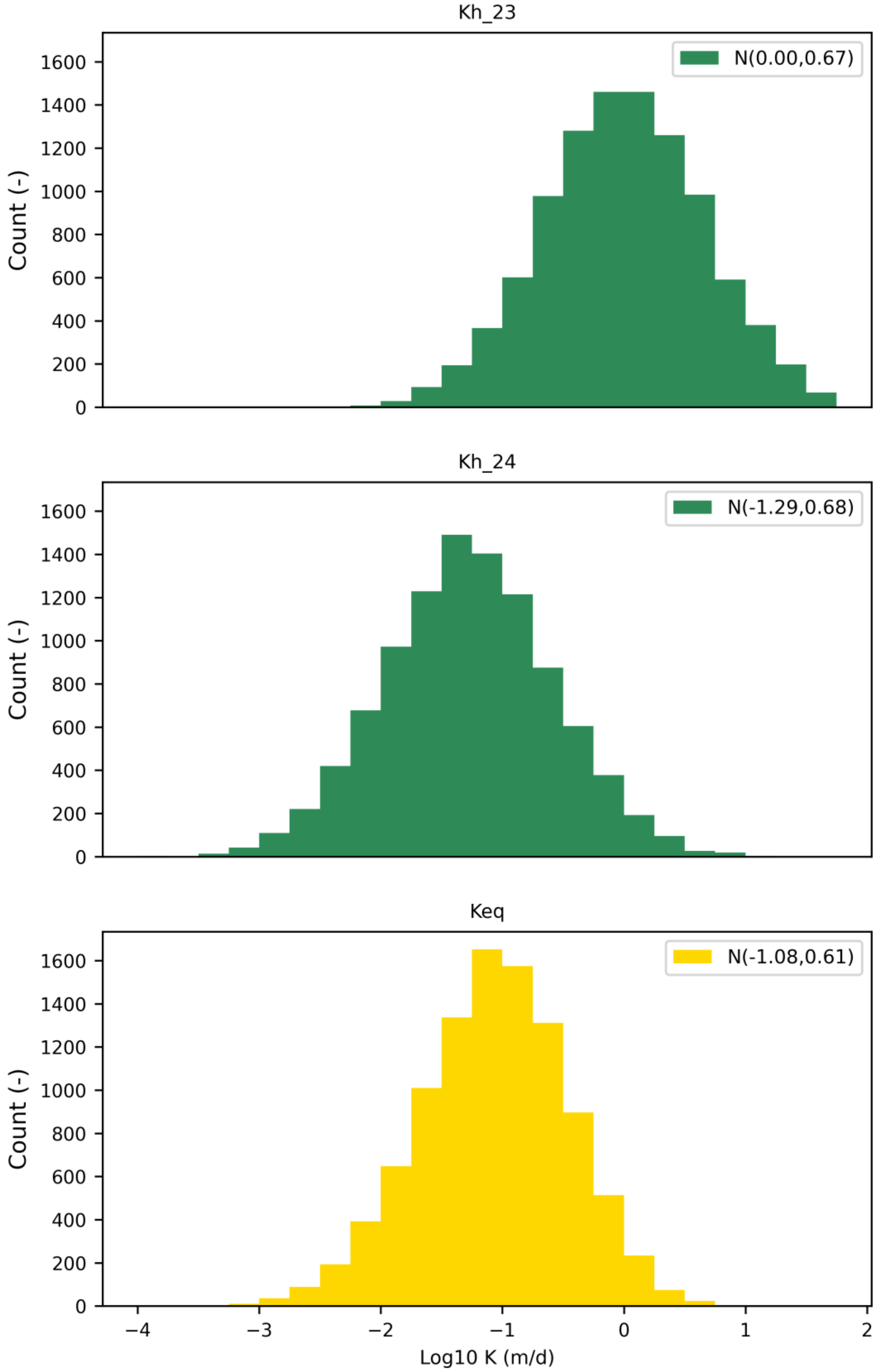

Figure 2 Histograms of equivalent hydraulic conductivity of zones Kh_23 and Kh_24 (Layer 5, proposed mine area), based on 10.000 random samples. The numbers in brackets are respectively the mean and standard deviation.

Without rerunning the groundwater model and uncertainty analysis again, it is difficult to quantify the effect of sampling a narrower range of K values on the 95th percentile estimate of mine water inflow. We can however illustrate what the effect would be using a much simpler model. We chose the analytic solution to estimate inflow to a tunnel by Perrochet (2005)[11]:

$$Q \cong \frac{2\pi T s_0}{\ln\left(1 + \sqrt{\frac{\pi T t}{S r_0^2}}\right)} \qquad \text{Eq. 3}$$

where $Q\ [L^3/T]$ is the inflow, $T\ [L^2/T]$ is the aquifer transmissivity, $s_0\ [L]$ is the drainage or drawdown level, t $[T]$ is time, $S\ [-]$ is storativity and $r\ [L]$ is the diameter of the tunnel. This equation cannot represent the complexity of the numerical groundwater, but it does capture the essence of unmitigated mine dewatering. Evaluating this equation is very rapid, so it is possible to evaluate a large number of parameter combinations. The equation is developed for confined aquifer conditions. At the depth of mining, the aquifer can be considered confined.

Figure 3 shows the result of evaluating 10,000 parameter combinations randomly selected from the equivalent hydraulic conductivity distribution estimated in Figure 2 (Keq_1) and the same distribution with standard deviation equal to 0.67 (Keq_2). Storativity is based on posterior parameter distribution for specific storage of layer 5 (Table 7 in Appendix B7A). The following parameters are chosen to be of a similar order of magnitude as the condition represented in the groundwater model. The saturated thickness is chosen to be 50m. Time period is set to 5 years, drawdown to 100 m and diameter of tunnel to 1 m.

The predicted inflow distributions shown in Figure 3 are very skewed, with a long tail. This means the prediction interval is not symmetric; the 5th percentile will be close to the 50th percentile, but the higher percentiles (70th, 80th, 95th percentile) will be much larger than the 50th percentile.

The distributions of predicted inflow are very similar, but because the distributions are very skewed (i.e. have a long tail), the 95th percentile estimated from the equivalent K distribution with standard deviation of 0.67 is about 40% greater than the 95th percentile estimated from the equivalent K distribution with standard deviation of 0.61. We note that this potential underestimate is of a similar order of magnitude as the difference in inflow between the grouting scenarios (P95 70% effective grouting is 39 L/s, P95 hybrid grouting is 28 L/s).

This is an indication that sampling a narrower equivalent K range can lead to an underestimate of the 95th percentile of inflow. It is not possible to unequivocally assess the magnitude of this underestimate without rerunning the model, but this analysis indicates that the value of mine inflow after 5 years that is considered to be very unlikely to be exceeded in the most realistic scenario may be closer to the value considered very unlikely in the conservative scenario.

We also note that the histograms for SRMS (Fig 1 in Appendix B7A) and calculated baseflow (Fig 2 in Appendix B7A) also show skewed distributions, but the distribution of predicted inflow (Tables 1

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[11] Perrochet P (2005) A simple solution to tunnel or well discharge under constant drawdown. Hydrogeology Journal 13:886–888. https://doi.org/10.1007/s10040-004-0355-z

to 3) are symmetric (i.e. the difference between P50 and P95 and between P50 and P5 is similar). This is not consistent with the expected skewed distribution on theoretical grounds. Without a comparison of parameter values retained in the ensembles against the prior or posterior, it is not possible to conclusively evaluate whether this an artefact of the modelling or an adequate representation of reality. We speculate that higher values of transmissivity or storativity cause numerical issues, leading to large water balance errors. If these values are rejected because they cause numerical instability rather than because they are physically not realistic, it will also lead to an underestimate of the P95 of inflows.

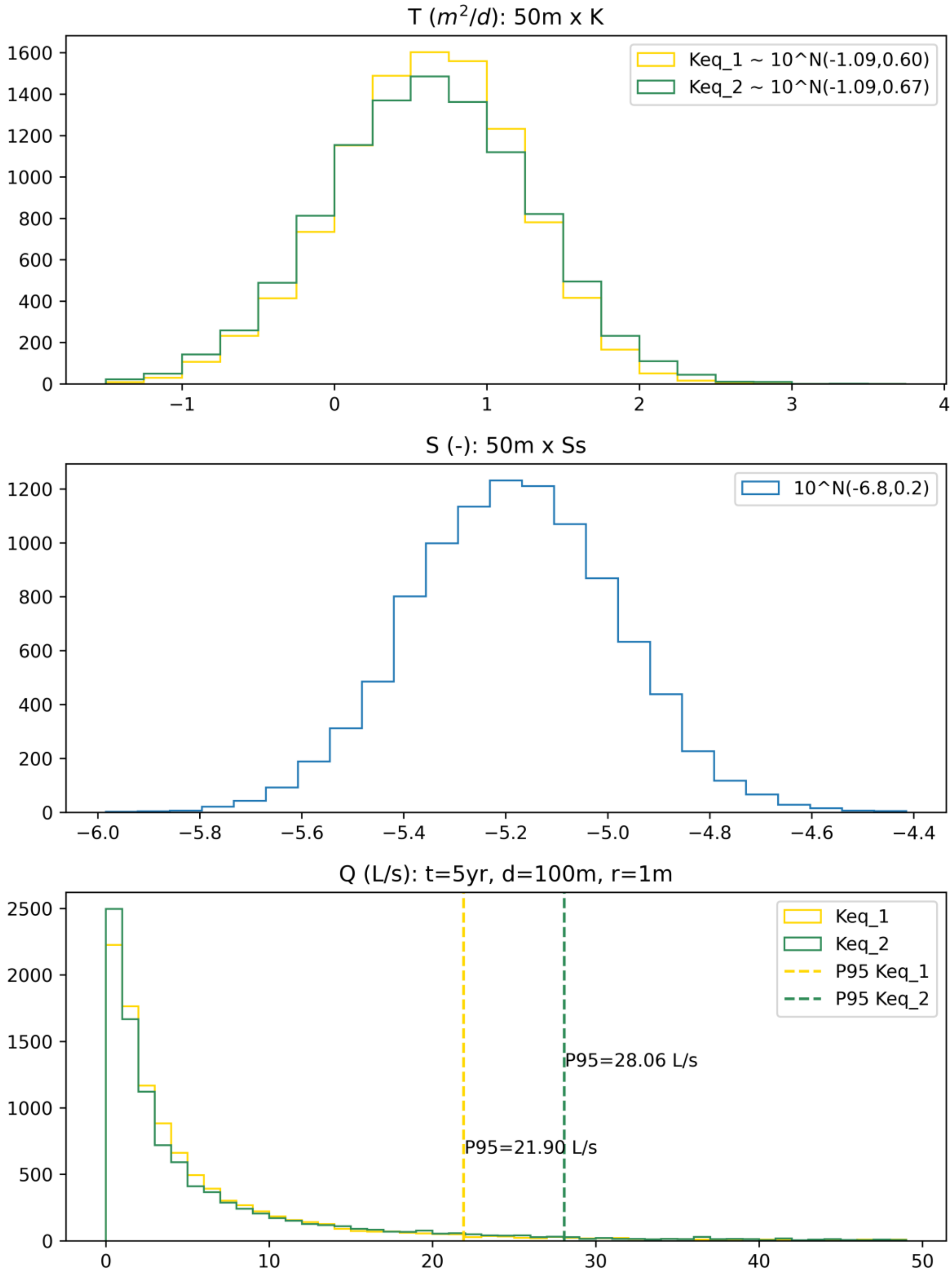

Figure 3 Mine inflow calculated using Eq. 3 (Perrochet, 2005) for 10,000 parameter combinations randomly selected from the equivalent hydraulic conductivity distribution estimated in Fig. 2 (Keq_1) and the same distribution with standard deviation equal to 0.67 (Keq_2). Storativity is based on posterior parameter distribution for specific storage of layer 5 (Table 7 in Appendix B7A). Saturated thickness is chosen to be 50m. Time period is set to 5 years, drawdown to 100m and diameter of tunnel to 1m.

3.1.3 Convergence

The results in Figure 3 also allow to test for convergence of the percentiles (Figure 4). Convergence means that the predicted values stabilise with increasing number of realisations. The top plot shows the convergence for 5th, 50th and 95th percentile for inflows calculated with Keq_1 and Keq_2 for the entire ensemble of 10,000 samples. It shows that the 5th and 50th percentiles converge rapidly, but that the 95th percentile only starts to converge after 2000 realisations.

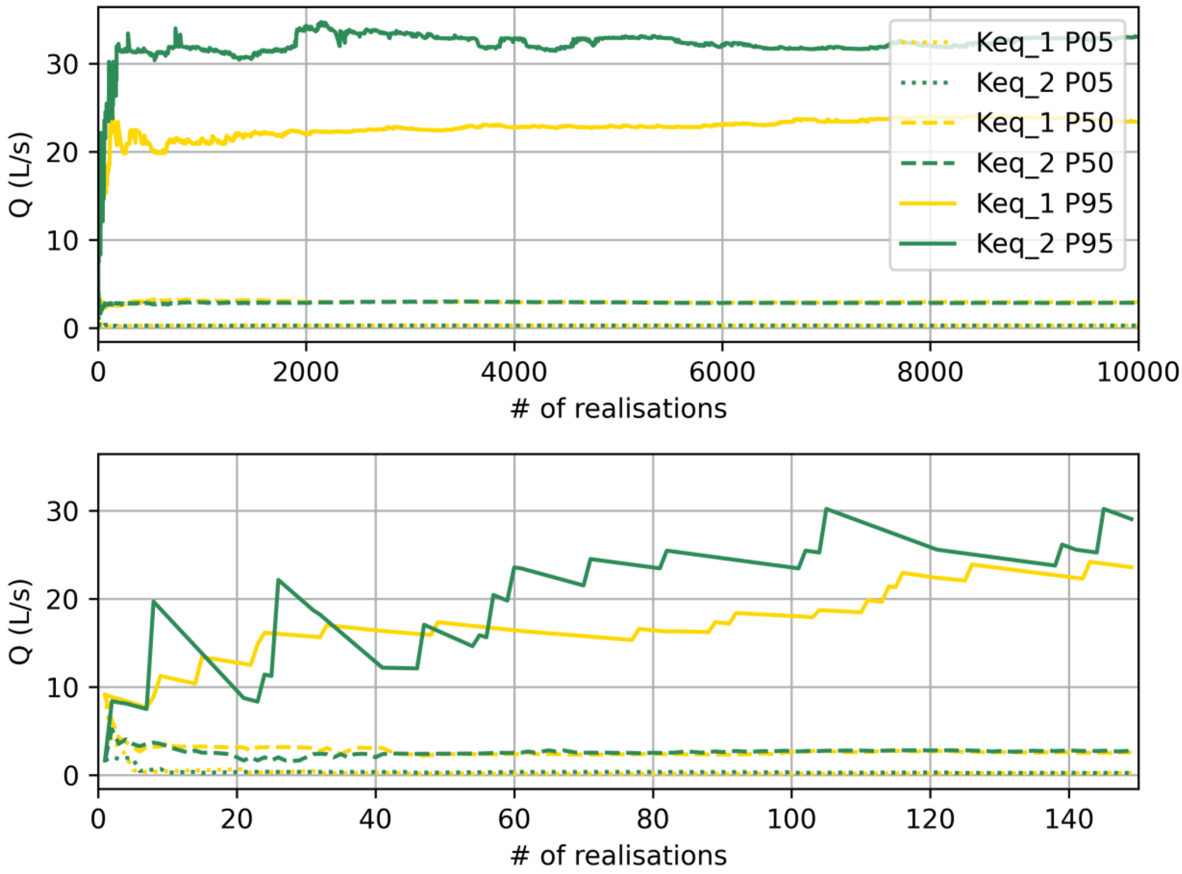

Figure 4 Convergence of 5th, 50th and 95th percentile for inflows calculated with Keq_1 and Keq_2. The bottom plot shows the first 150 realisations only.

The bottom plot of Figure 4 shows only the first 150 realisations. This plot is similar to those presented in Appendix B7A (Figure 46 to Figure 52). Considering the bottom plot in isolation may lead to a conclusion that the results have converged, but comparison with the top plot illustrates that this conclusion is not justified. In this specific case, the P95 for inflows calculated with Keq_2 is underestimated. It has to be noted that insufficient sampling can lead to either an underestimate or an overestimate.

Figure 4 also shows that the 5th and 50th percentile for the inflows calculated with Keq_1 and Keq_2 are almost identical. This provides confidence in the median mine inflow rates calculated with the numerical groundwater model.

3.2 Implementation of conceptual model in numerical model

The MLA is in a fractured rock aquifer, where hydraulic parameters are dominated by the secondary permeability (faults and fractures) with less influence of lithology. The hydrostratigraphic units in the hydrogeological conceptualisation do largely follow stratigraphy (Figure 5). This is consistent with the information presented in the groundwater assessment reports.

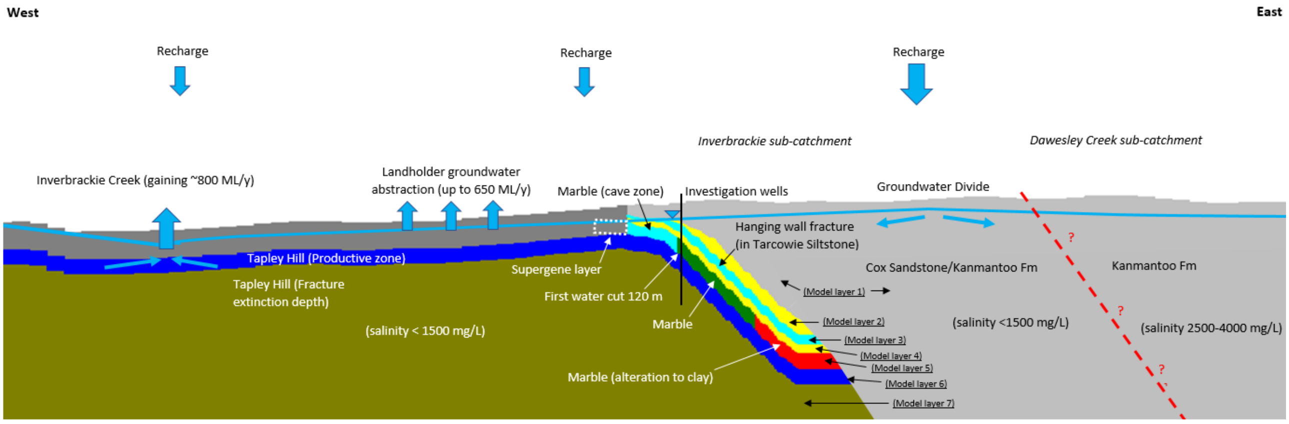

Figure 5 Conceptual hydrogeological cross section (Fig F3 in Appendix H1)

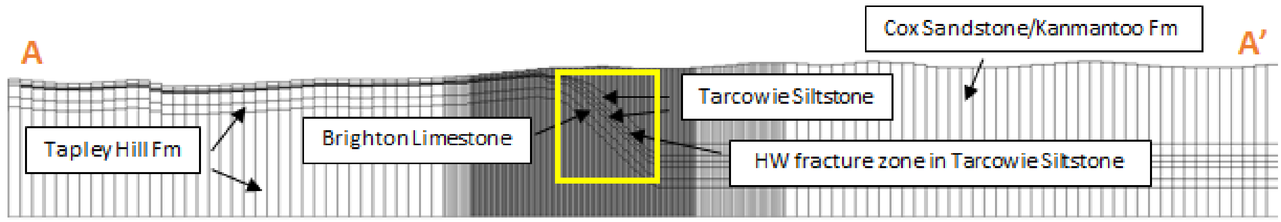

Figure 6 Model discretisation and layering (Fig. F4 in Appendix H1)

Figure 6 shows how this conceptualisation of hydrostratigraphic units is translated in the discretisation and layering of the numerical model. Hydrostratigraphic units are largely represented as individual layers. The layers in the vicinity of the fault zone and the mineralisation are steeply dipping. This creates following issues:

1. Horizontal and vertical conductivity in the model represent flow along and perpendicular to the dip of the model layer. Lateral flow is a combination horizontal and vertical conductivity. This makes it almost intractable to infer from the model report which parameters are controlling mine water inflow and whether this represents an adequate representation of the conceptualisation.
2. Layers 1-5 are very thin and unsaturated in the west of the model. This makes that:
    a. Hydraulic parameters assigned to zones in the west of the model are irrelevant (they are excluded from the calculations)
    b. Lateral drawdown in layer 5, which hosts the drainage features for mine stopes, cannot directly propagate to the west. The drawdown can only propagate westwards by propagating downward into layer 6.

c. The watertable is hosted in layer 6 in the west and layer 1 in the east. The report[12] does not show which layers are simulated as confined or unconfined where in the model. This can have a large impact on simulated results as the storativity in unconfined layers is up to four orders of magnitude larger than storativity in confined layers.

We note the response to similar comments raised by DEM, justifying the steeply dipping layers to represent along strike hydraulic conductivity as horizontal hydraulic conductivity and across strike hydraulic conductivity as vertical hydraulic conductivity[13].

Rapid changes in geometry and thin, unsaturated layers are known to deteriorate the numerical stability of a numerical model. While this does not seem to affect the calibrated model, the rejection sampling illustrates that especially the transient model is not very robust, with a large number of model runs failing to meet the water balance error target. As discussed earlier, this can affect the estimation of the 95th percentile of mine inflows.

It is not possible to conclusively make a statement whether the issues mentioned above will lead to an over- or underestimate of the entire range of mine inflows:

1. Potential overestimate of mine inflow in the mine decline from the west as drawdown propagates into layer 6, the productive part of the Tapley Hill formation, instead of the less productive part of the Tapley Hill formation
2. Potential underestimate of mine inflow in the mine stopes from the west as drawdown cannot propagate to the west in layer 5 but has to propagate vertically into layer 6.
3. Potential underestimate of mine inflow from the east as drawdown propagates in the Tapley Hill and Tarcowie siltstones instead of the Cox Sandstone / Kanmantoo layer.

The complexity of the layer structure makes the model less transparent and tractable. An alternative layer structure would be to use horizontal layers with uniform thickness and represent the hydrostratigraphic units through different parameter zones.

Other issues identified with the implementation of the conceptual model are:

1. The layer 3 (Tarcowie siltstone) vertical hydraulic conductivity (2.5 m/d) and specific storage (2.2 x 10^{-4}) are high. This is appropriate to represent the hanging wall fracture zone, but it is unlikely that these values should be applied across the entire model domain in layer 3. Potential impact on predictions is considered medium:
    a. May lead to an overestimate of the potential for re-injection
    b. May lead to an underestimate of drawdown in the Tarcowie siltstone towards the south east
    c. Likely to have limited impact on predicted mine inflow as mine drainage is applied in layers 5 and 6

[12] AGT (2017) Bird-in-Hand Gold Project Groundwater Assessment

[13] Comment 30 in Table 4 in Terramin (2021) Bird in Hand Gold Project Response Document

2. Layers 6 and 7 (Tapley Hill formation) have a very large number of parameter zones. There is limited discussion in the reports what this zonation is based on. Impact on predictions is considered medium:
    a. Large number of zones allow to compensate for structural issues during calibration
    b. Increases the number of parameters for the uncertainty analysis and may lead to insufficient sampling of parameter space (see section 3.1)
3. The increase in horizontal conductivity of the Kanmantoo formation with depth in the south east of the model is not explained. Horizontal conductivity often decreases with depth, especially in fractured and weathered aquifers as intensity of weathering and aperture of fractures generally decreases with depth. Impact on predictions is likely to be low as it is at a relatively large distance from the proposed mine site.
4. Recharge zone 11 is not included in the table 9 of Appendix B7A (prior and posterior distributions for uncertainty analysis). Recharge zone 7 has zero recharge assigned to it, but explanation is not provided in the model reports.

3.3 Need to review the groundwater model in the vicinity of the mine

We concur with the SA government finding the groundwater model needs refinement within the vicinity of the mine development. While the groundwater model is suited to simulate median predictions of mine water inflow, drawdown and potential for reinjection at the regional scale, it is less suited to predict local impacts. Should local impact estimation be necessary, such as in the development of a groundwater management plan, it is recommended to revise the model, with particular attention to the model structure and numerical stability of the model.

3.4 Hydrogeological conceptualisation

The hydrogeological conceptualisation is generally well supported by the results of the field investigations. The only aspect that is less supported is the position of the groundwater divide. This is mentioned in the review by IGS[14] . The position of the groundwater divide is based on a single measurement location and alternative interpretations of the potentiometric surface are possible. The impact on predictions on the position of this groundwater divide is minimal. The mine water inflow or drawdown predictions are not a function of the potentiometric surface. The parameters that are relevant for inflow and drawdown predictions are not likely to be constrained by potentiometric observations.

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[14] Innovative Groundwater Solutions (2017) Peer Review of Bird in Hand Gold Project Groundwater Assessment Report

3.5 Recharge assessment

We concur with SA government that recharge assessment can be made more robust by using multiple recharge estimation techniques. While this will improve overall confidence in the groundwater model, it is unlikely that improved recharge estimates will greatly reduce uncertainty in mine water inflow or drawdown estimates.

3.6 Controlled inundation

The simulation of controlled inundation is based on the base case parameter combinations for two scenarios (hybrid and 70% effective). The analysis would be more comprehensive if more parameter combinations were evaluated to quantify the predictive uncertainty in drawdown and recovery.

However, extrapolating from the range of drawdown predictions presented in the uncertainty analysis, it is expected that predicted range of drawdown and recovery under controlled inundation is relatively symmetric around the median. It is not expected that the range of simulated drawdown and recovery would include simulations that would indicate groundwater users would not have access to water from their bores. CSIRO therefore concurs with the government assessment that groundwater users would still be able to access groundwater under controlled inundation, for both scenarios.

4 Groundwater quality

Table 3 identifies 2 issues of low concern:

- appropriate inputs to solute transport model
- avoidance of supergene zone to mitigate risk of AMD

4.1 Inputs for solute transport model

The solute transport model to simulate the migration of saline water to the east of the mine site is based on the groundwater flow model. The issues identified in section 3.2 may affect the predicted fluxes which in turn may affect the simulation of solute transport. It is however unlikely that these changes in simulated flux will substantially alter the simulated salinity distribution.

4.2 Avoidance of supergene zone to mitigate risk of AMD

The mitigation strategy for acid and metalliferous drainage is to avoid the supergene zone, which has the highest likelihood of containing potential acid forming rocks. The mine design is based on the current mapped extent of the supergene zone and probe drilling during mining, in combination with testing for potential acid forming rocks, will be used to update the mapping of the supergene zone. It is however not clear how flexible the mine design is, should potential acid forming rock be encountered where it is currently not mapped.

5 Conclusion

The review of the groundwater chapter of the government advice on the Terramin Bird in Hand Gold Mine Lease Application established that the Government assessment and recommendations are consistent with the groundwater outcome and the documentation provided.

The review identified that while the median predictions of outflow are conservative, the parameterisation and sampling of parameters in the uncertainty analysis are likely not to result in a conservative estimate of the 95th percentile of mine water inflows.

For the other issues identified in the review, mainly pertaining to the implementation of the conceptual hydrogeological model in the numerical groundwater model, it cannot be unequivocally established whether they would lead to an over or underestimate of predicted impacts or whether they would lead to a material change in outcome.

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Contact us

1300 363 400
+61 3 9545 2176
csiro.au/contact
csiro.au

For further information

CSIRO Land and Water
Dr Luk Peeters
+61 8 8303 8405
luk.peeters@csiro.au