Jacinth Mineral Sands Mine

Groundwater Flow Modelling

Final Report | C

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Iluka Resources

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Project Manager:	Ruolin Wu
Author:	Brian Barnett, Ye Ma and Erin McIntosh
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Jacobs Australia Pty Limited

Floor 11, 452 Flinders Street
Melbourne VIC 3000
PO Box 312, Flinders Lane
Melbourne VIC 8009 Australia
T +61 3 8668 3000
F +61 3 8668 3001
www.jacobs.com

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Contents

Executive Summary

This report describes a groundwater modelling investigation aimed at updating and verifying an existing groundwater model of the palaeochannel aquifer located near Iluka's Jacinth Mine in South Australia. The aquifer hosts a wellfield that has been operated almost continuously since 2009 to provide water for operations at the Jacinth Mine. The work included a significant re-design of the existing model to include important findings from recent airborne electromagnetic surveys that have provided valuable insights into the size and thickness of the productive aquifer. It has also included migration of the model from the finite-difference MODFLOW numerical code to the finite-element Feflow code to take advantage of a number of useful simulation features available in the standard Feflow package.

The updated and modified model was calibrated and verified by splitting the observed groundwater head data and groundwater extraction records into two independent data sets that represent different time periods in the record of historic operation of the wellfield. One period was used to calibrate the model and the other for verification purposes. The calibrated model parameters were assigned to the verification model with no further adjustment and the model used to simulate the verification period. The results indicate that the model provides a reasonable representation of observed groundwater behaviour thus providing confidence that the model will provide a similar level of reliability in future predictive scenarios.

Model predictions supported by uncertainty analysis demonstrate that there is a reasonable level of confidence that the existing wellfield is capable of meeting all foreseeable mine water demand for the Jacinth, Ambrosia and Atacama mines. This has been demonstrated through model predictions that show the required water demand can be sustained for the duration of mining without widespread desaturation of the aquifer and without breaking pump suction in individual production wells.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to develop a groundwater model of the Jacinth Mineral Sands Mine in accordance with the scope of services set out in the contract between Jacobs and Iluka Resources Ltd. That scope of services was developed and agreed with Iluka.

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1. Introduction

Jacobs has been commissioned by Iluka Resources Ltd (Iluka) to upgrade and verify an existing numerical groundwater model and to undertake predictive model analysis to help determine the capacity of the resource to supply water to the Jacinth, Ambrosia and Atacama mines into the future. The wellfield targets shallow palaeochannel sediments which host a highly saline non-renewable groundwater resource that has little or no replenishment from rainfall infiltration. The groundwater flow model for the Jacinth wellfield was originally developed by SKM (now trading as Jacobs) in 2006 (SKM, 2006) and updated in 2011 (SKM, 2011). Subsequent model reviews and informal validation, combined with recent electromagnetic survey interpretations, suggest the palaeochannel aquifer has a greater width than represented in the existing model, and another palaeochannel aquifer system may be present in the region of Lake Ifould (Iluka, 2018).

The scope of the modelling project is to:

- Collate and analyse data provided by Iluka on the aquifer and wellfield, including wellfield operating records and measurements of groundwater heads in monitoring wells.
- Use existing interpretations of recently acquired airborne electromagnetic (AEM) survey data to develop an improved understanding of the extent and thickness of the palaeochannel aquifer.
- Convert the model to the finite-element Feflow Version 7.1 software package (Diersch, 2014).
- Update the model structure to align with information obtained from the AEM interpretations.
- Re-calibrate the model (if necessary) using all previously available data (up to the end of 2013).
- Verify the model by comparing model-predicted outcomes to observations obtained post-calibration (2014 to present).
- Undertake life-of-mine predictive scenarios based on current and estimated future mine water demand estimates for Iluka's Jacinth, Ambrosia and Atacama mines.
- Undertake a predictive uncertainty analysis to assesses a range of potential outcomes.

2. Synthesis of Electromagnetic Interpretations

Iluka provided Jacobs with interpreted AEM data obtained from two independent surveys that cover the region surrounding the existing wellfield. Within Iluka, these are referred to as Hoist (GPX Airborne, 2005) and Tempest (Fugro Airborne Surveys, 2007). The locations of the surveys are presented in Figure 2.3. The surveys highlight the contrast in resistivity (and electrical conductivity) of the sediments saturated with highly saline groundwater in the aquifer compared to the basement outside the aquifer that contains little or no saline groundwater.

The most important information obtained from the data are the inferred base and lateral extent of the palaeochannel aquifer. PDF files containing transects of interpreted electrical conductivity data in Map Grid Australia (MGA) Zone 53 coordinates were provided together with Iluka-interpreted base of aquifer profiles based on the Hoist data. The Iluka-interpreted aquifer base assumes the aquifer is defined by electrical conductivity that exceeds 500 mS/m, with a limited extrapolation of base elevations between neighbouring pockets of high conductivity. Refer to Figure 2.1 for an example of the data and interpretation provided. The Iluka-interpreted base of aquifer elevations from the Hoist transects was geo-registered and digitised to produce an array of points that define the base of aquifer.

The same interpretation method was applied to the Tempest data set in that base and extent of aquifer were interpreted as being defined by the 500 mS/m contour and points were digitised from the cross section images. However, the interpretation of the Tempest data was hampered by difficulties in distinguishing the 500 mS/m colour contour from the colour flood scale (refer to Figure 2.2).

The Hoist and Tempest interpretations were combined to produce an array of geo-registered data points that were then converted to MGA Zone 52 to align with the coordinate system used in the groundwater model. A geological model in the Leapfrog software package was developed from the resultant data.

A review of the interpreted base of aquifer surface highlighted a step at the edge between the two data sets suggesting a consistent shift between the Hoist- and Tempest-derived data. The shift is understood to be an artefact of the difficulties in identifying the 500 mS/m contour within the Tempest colour flood images. The effect was removed by raising the entire Tempest-derived data by a uniform amount. Finally, the combined base of aquifer surface was migrated about 5 m downward so that the interpreted surface aligned with drilling logs that confirm the base of the aquifer at the wellfield at about -30 metres Australian Height Datum (mAHD).

The resultant base and extent of the aquifer is presented in Figure 2.4. The aquifer is significantly more extensive than the relatively narrow palaeochannel previously modelled. An upgrade of the model to include the inferred aquifer extent was deemed appropriate and was implemented in the current project.

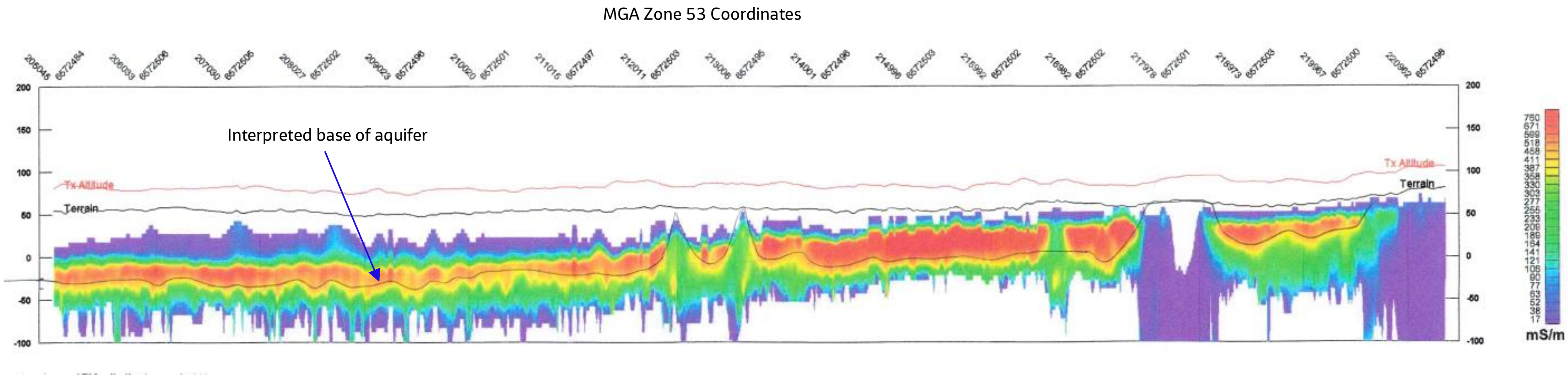

Figure 2.1: Example of a Hoist data transect (at 6572500 m North) provided by Iluka.

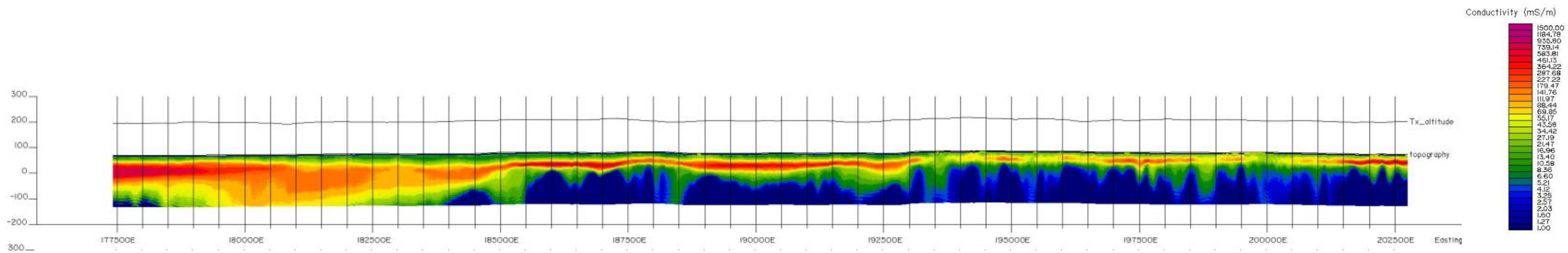

Figure 2.2: Example of a Tempest data transect (at 65900337 m North) provided by Iluka.

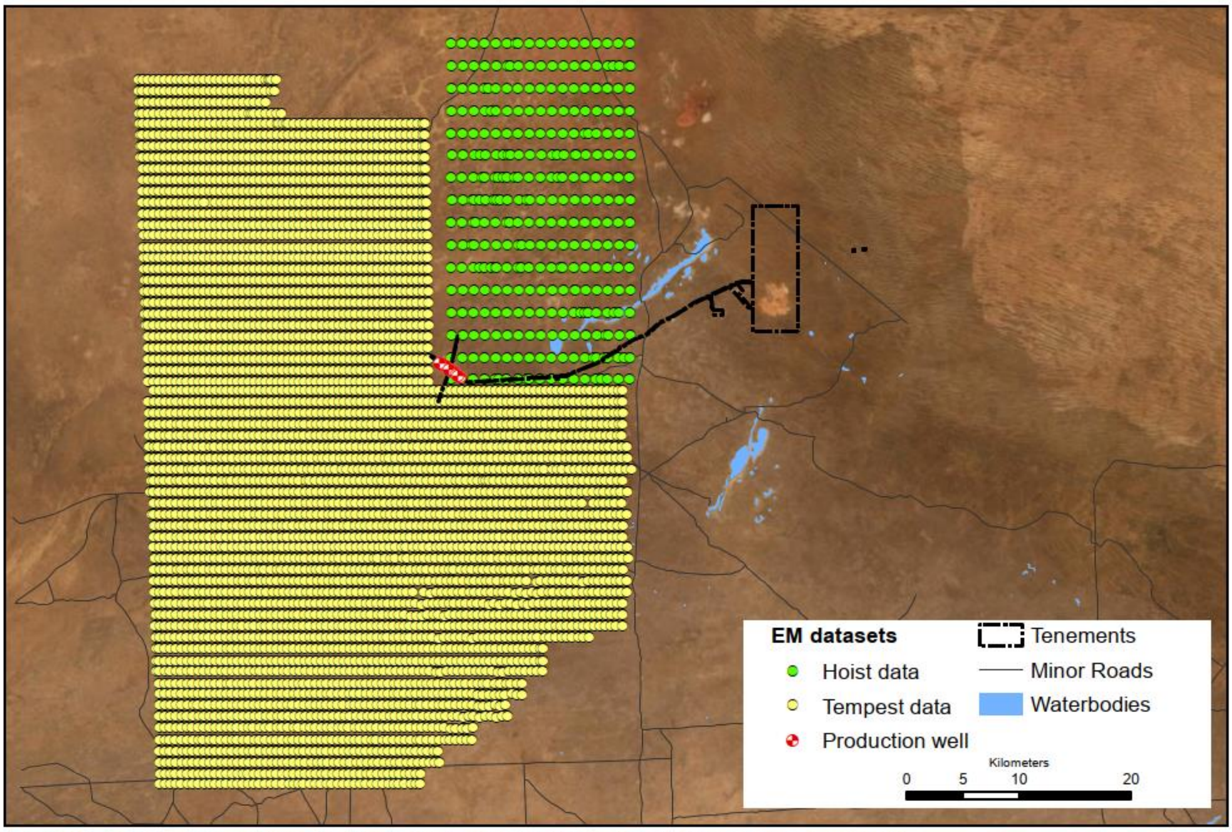

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Figure 2.3: AEM survey data used to define the aquifer base.

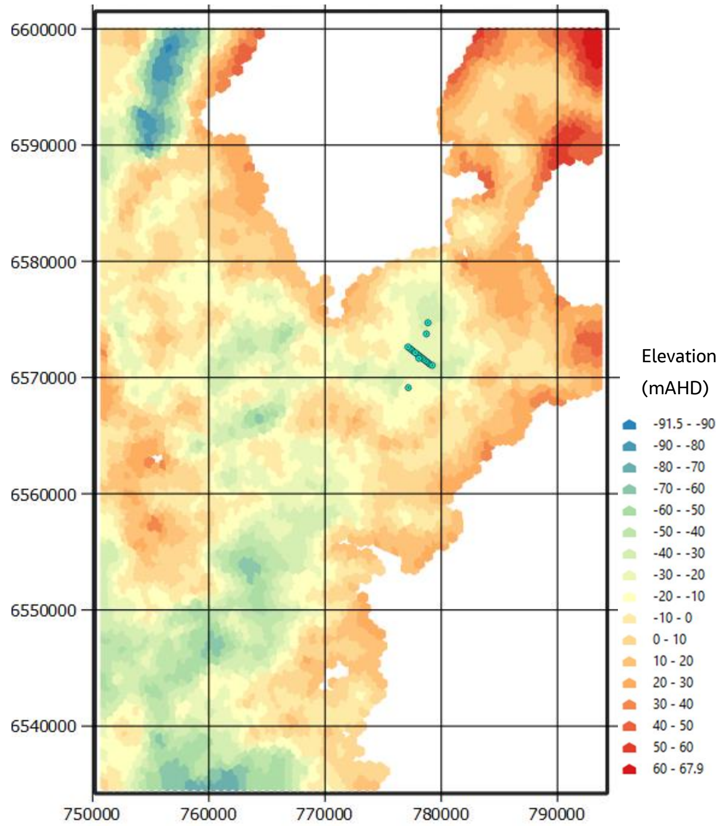

Figure 2.4: Base of aquifer elevation (mAHD) inferred from AEM surveys – aquifer is absent in the unshaded area[1].

[1] Unless otherwise stated, all maps are presented in MGA Zone 52 using elevations relative to the Australian Height Datum (mAHD)

3. Model Design

The existing groundwater model of the palaeochannel wellfield groundwater supply for the Jacinth-Ambrosia Project was developed by SKM (SKM, 2007 and 2011). The aquifer geometry in this model incorporated the likely extent of the palaeochannel as interpreted from drilling information and earlier AEM survey data from the Eucla Basin Groundwater Investigations (SKM, 2006). The model used the MODFLOW numerical simulation code (McDonald and Harbaugh, 1989) and the Visual Modflow interface (Waterloo Hydrogeologic, 2012). Subsequent model reviews and analytical modelling suggested that observed head hydrograph correlations improve with higher storage values and a more extensive aquifer. This observation was subsequently reinforced by recent AEM interpretations indicating the palaeochannel aquifer has a much greater areal extent than previously modelled (refer Figure 2.4).

3.1 Software Code

The existing model was converted from MODFLOW 2000 to the Feflow finite-element modelling code to take advantage of Feflow's flexible meshing options that allow for fine spatial resolution to be included in areas of importance (such as the central wellfield) combined with coarser resolution in areas of lesser importance. This allows for a numerically efficient mesh that concentrates numerical effort in the area of most interest.

The choice of Feflow for the current project aligns with recent Iluka groundwater model development at other sites, where Feflow is becoming the software package of choice. It also introduces a number of flexible and powerful boundary conditions, unsaturated zone modelling functionality and well pumping options that are useful for simulating the wellfield operations.

3.2 Unsaturated Zone Modelling

The Feflow unsaturated zone modelling option was adopted to provide the ability to simulate the delayed drainage of water from the unsaturated zone as the watertable declines in response to groundwater withdrawal. The model uses the van Genuchten approach (van Genuchten, 1980) to represent the changes in effective hydraulic conductivity with moisture content in the unsaturated zone.

3.3 Expansion of the Model Domain

The model domain was increased substantially to cover the extent of the palaeochannel aquifer as identified in AEM interpretations (refer to Section 2). While the expanded model domain and increased extent of aquifer represents an improvement in the hydrogeological conceptualisation, it is based on an interpretation of remotely sensed resistivity data that may include errors that may propagate or contribute to model uncertainty. The predictive uncertainty associated with the extent of aquifer is addressed in the uncertainty analysis described in Section 5. The model domain, mesh and previous model extent are presented in Figure 3.1.

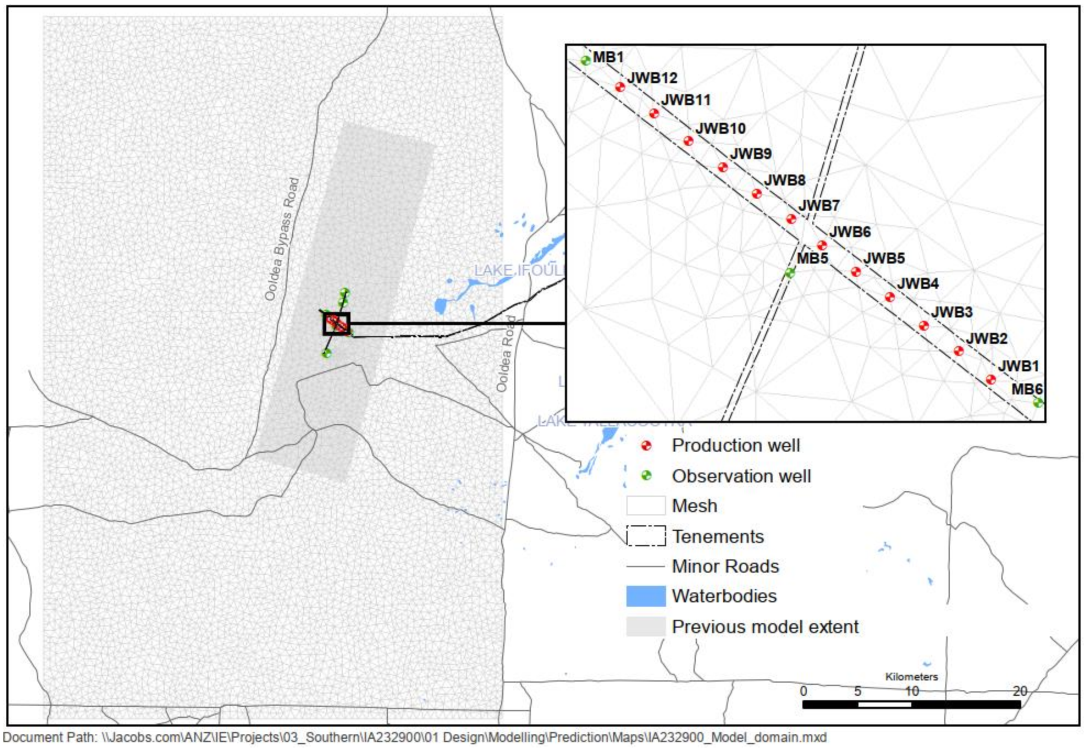

Figure 3.1: Model domain and mesh

3.4 Model Layer Structure

The revised palaeochannel aquifer extent can be seen in Figure 3.2. The geological model that defines the base elevation, thickness and extent of the aquifer was developed by merging the electromagnetic data sets with the observations obtained from the drilling of the production and monitoring wells. The bottom elevation of the aquifer is presented in Figure 2.4 with the resulting aquifer thickness shown in Figure 3.3. The palaeochannel aquifer is present over much of the extended model domain with the greatest extent over the western portion of the model.

To allow for vertical movement of groundwater within the aquifer, the model includes three layers representing the unconfined aquifer setting within the palaeochannel (Layers 1, 2 and 3). A fourth model layer represents bedrock beneath and surrounding the palaeochannel aquifer. Layer 1 extends across the full model domain and represents a partially-saturated layer of regolith above the aquifer. In the absence of further evidence on the permeability of the shallow sediments, it has been assigned aquifer parameters within the area of the palaeochannel and basement properties elsewhere.

The AEM interpretations described above provide a clear definition of an electrical conductivity gradient at the top of the aquifer. This feature is likely to represent the pre-development watertable rather than a geological surface given that the AEM maps the contrast in electrical conductivity (anomaly) associated with the saline groundwater present within the palaeochannel aquifer. The data sets also provide estimates of ground surface elevation at each survey point. Both the ground surface and the upper limit of the conductivity anomaly were used to construct model layers as follows:

- Base of the aquifer (base of Layer 3) is taken directly from the interpreted AEM data as described above.
- Layer 1 is partially-saturated and extends from ground surface which has been obtained directly from the terrain data collected during the AEM surveys. The upper limit of the AEM conductivity anomaly has been used to define the base of Layer 1 (regolith) which is close to watertable elevation.

- The thickness of aquifer between the base of Layer 1 (close to watertable elevation) and the base of the aquifer is divided into two equally thick layers that represent the saturated part of the palaeochannel aquifer.
- The basement is represented in Layer 4 which extends from the interpreted base of aquifer to an elevation of -150 mAHD.

The available data provides no indication of hydrogeological parameter variability in the lateral or vertical dimension. Accordingly, parsimony assumptions have been adopted through uniform aquifer parameters assigned to the aquifer volume (including Layer 1). The layer structure provides for an appropriate representation of vertical hydraulic gradients that may develop as the aquifer is stressed by groundwater withdrawal and provides a framework for implementing increased complexity in terms of parameter variability with depth should this be required in future. The model layer structure is shown in Figure 3.2.

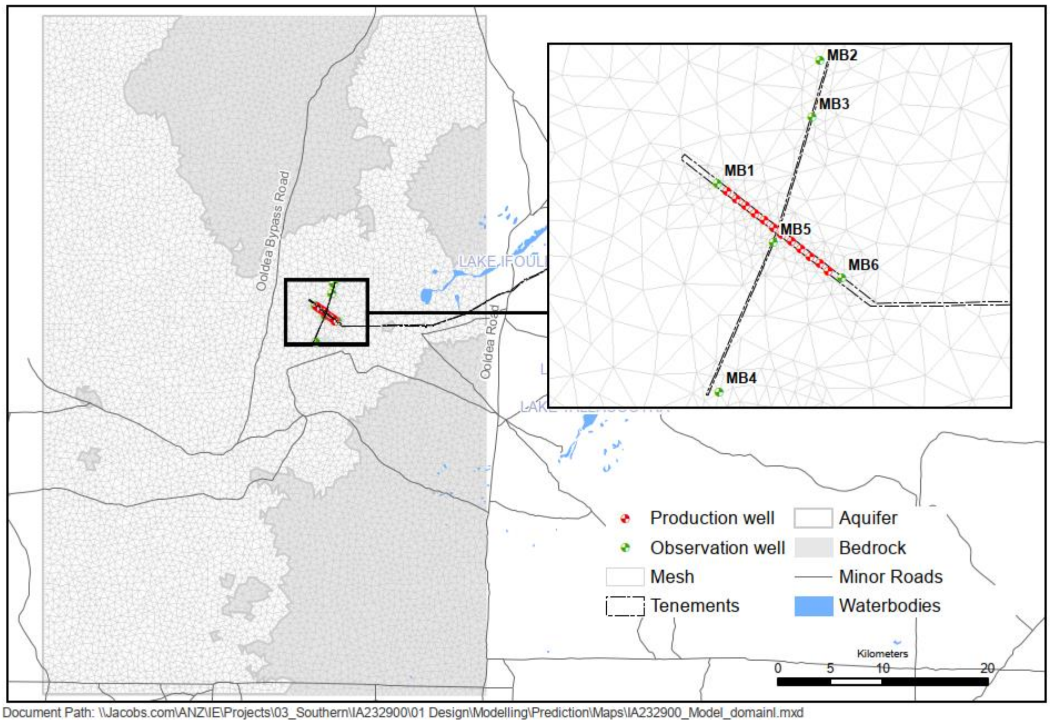

Figure 3.2: Aquifer extent and monitoring network

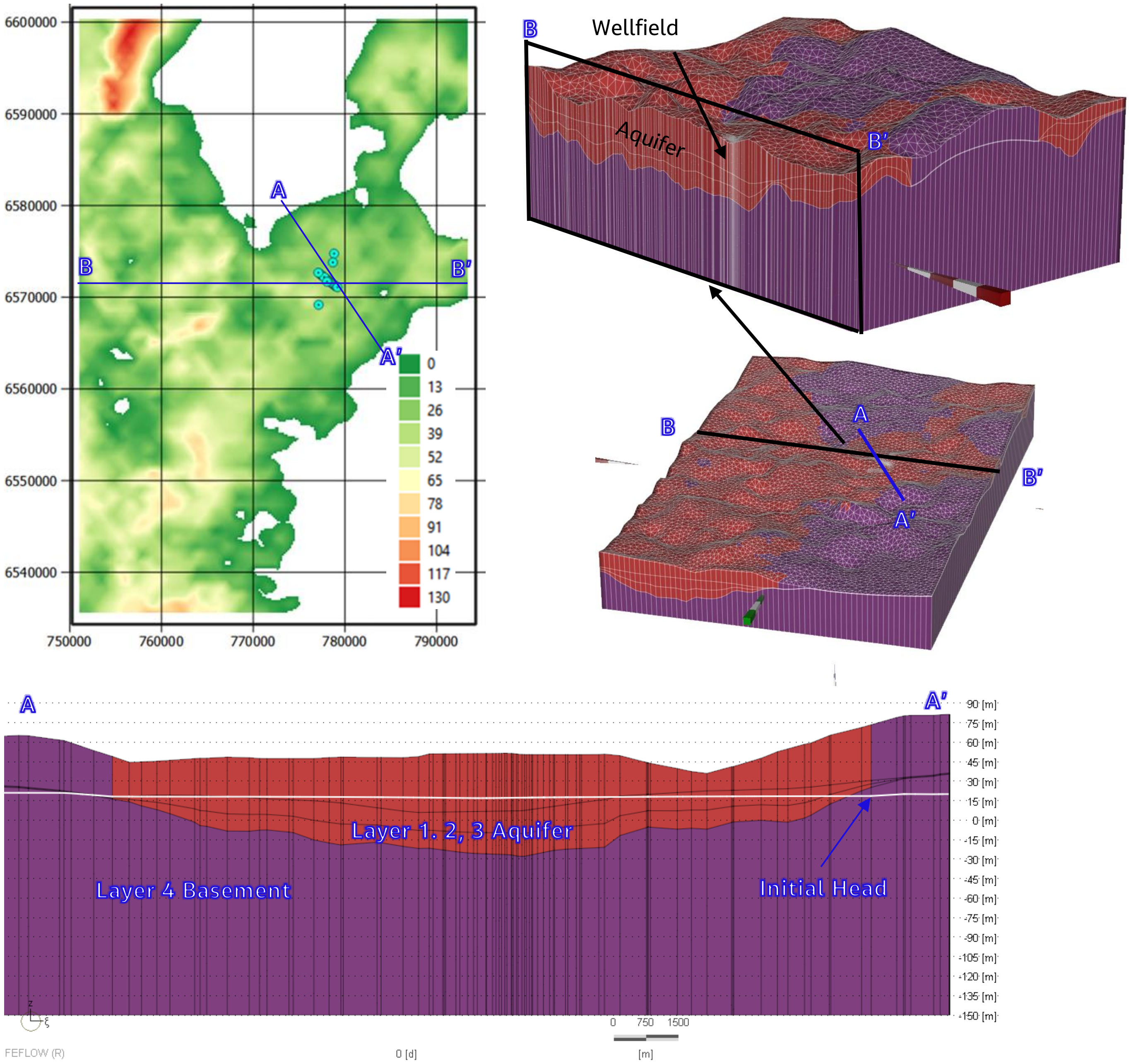

Figure 3.3: Aquifer thickness (m) and model layers

3.5 Boundary Conditions and Stresses

No-flow boundary conditions have been assigned to all of the external model boundaries and no recharge is applied to the model. The model can be described as a bathtub with no natural (pre-development) losses nor replenishment. These assumed conditions are consistent with the available data including:

- there were no measurable hydraulic gradients in the pre-development wellfield,
- average annual rainfall is less than 200 mm (BOM Station 016098 at Tarcoola),
- the unsaturated zone is relatively thick, and
- the absence of recharge-related responses in watertable elevation measured in monitoring wells.

When the aquifer is stressed by groundwater extraction, the basement will yield some groundwater from storage and this may slowly seep into the aquifer with time. Otherwise, all groundwater extraction will be sourced from changes in aquifer storage.

The production wells are modelled using the Well Boundary Conditions. The extraction rates for each of the wells in the model replicate the recorded pumping history for the individual wells. The locations of the production wells are included in Figure 3.1.

3.6 Approach to Calibration and Verification

As noted above, the aquifer is conceptualised as having no present-day recharge or discharge of groundwater and is characterised as a bathtub with no hydraulic head gradients and with no temporal trends or fluctuations in head. To simulate this conceptualisation, the model is constructed with a uniform initial head condition, no-flow boundaries assumed on all external edges of the model domain and with no natural recharge or discharge mechanisms. Any pre-wellfield groundwater model will maintain a constant head equal to the defined initial condition. Accordingly, a pre-wellfield calibration, either in steady-state or transient mode, is not warranted and was not attempted. Calibration and verification are necessarily limited to matching the modelled groundwater behaviour to observations of groundwater response arising from historic wellfield operations.

In order to provide greater confidence in the calibration of the model, it was agreed that a verification exercise should be included in the modelling procedure. The verification method was based on splitting the available groundwater observation data into two distinct data sets, one used for transient calibration and the other for verification. The historic model and associated data were split into two time periods; from the start of wellfield operations in 2009 until the end 2013 being used for the transient calibration, followed by a verification period from 2014 to 2019. The intention was to calibrate the model using the calibration data set alone. The verification procedure allowed model-predicted behaviour to be compared to measured groundwater behaviour as the aquifer is stressed by continuing groundwater withdrawal from the wellfield.

4. Calibration and Verification

4.1 Procedure

Calibration was initially undertaken using the available groundwater extraction and observed groundwater head responses for the period 2009 to the end of 2013, as shown in Figure 4.1. The automated parameter estimation software PEST (Doherty and Hunt, 2010) was initially used to assist with optimisation of the aquifer parameters to achieve the best match between measured and modelled groundwater head responses in the monitoring wells. The best calibration obtained by PEST was subsequently modified to align with more realistic judgement-based estimates of specific yield and vertical hydraulic conductivity (Kv). In this sense, there are two versions of the calibration, the original PEST version and the modified calibration that aligns with the conceptualisation; the latter being carried forward for predictive analysis. The PEST calibration parameters were subsequently assessed as part of the uncertainty analysis described in Section 6.

Following calibration, the model was run for the verification period (2014 to 2019) and the results reported without further adjustment of model parameters (Figure 4.1). The verification procedure is aimed at testing or demonstrating the previously attained calibration against an independent data set.

Figure 4.1 shows that most of the monitoring wells recorded a recovery in heads measured during a period of wellfield shutdown in 2016 and 2017. This response reflects a flattening of the cone of depression accompanying the cessation of groundwater withdrawal and does not represent groundwater recharge from external sources.

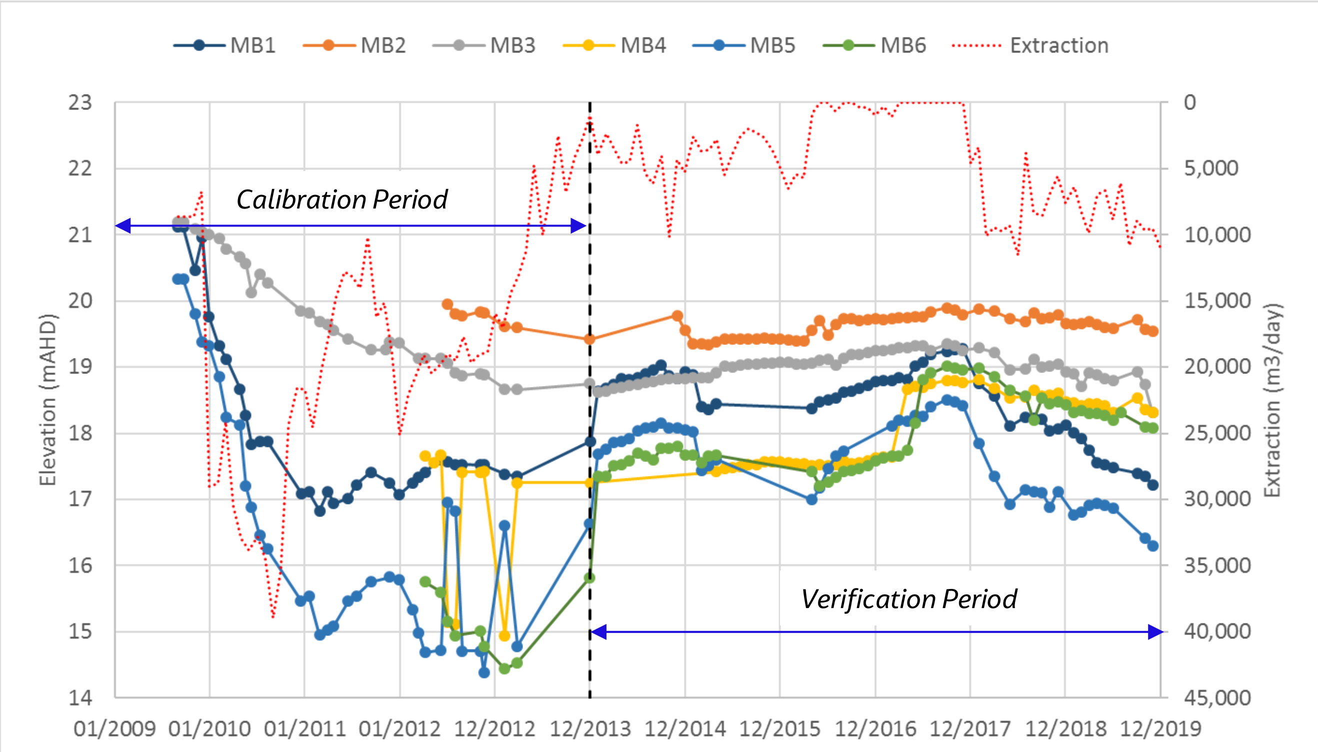

Figure 4.1: Observed groundwater extraction and heads for the total wellfield

4.2 Calibration Results

The PEST optimised and adjusted best calibration results were obtained with the hydrogeological parameters presented in Table 4.1.

Table 4.1: Summary of aquifer parameters obtained from calibration

Parameters		Aquifer parameters				Van Genuchten*	
		K_h (m/day)	K_v (m/day)	Specific storage	Porosity	Alpha (1/m)	n
PEST optimised parameters	Aquifer (Layers 1, 2, 3)	64.2	0.12	5.8E-06	0.37	0.4	1.04
	Basement (Layer 4)	0.001	0.001	1.0E-07	5E-04	0.4	1.04
With manually adjusted parameters	Aquifer (Layers 1, 2, 3)	64.2	6.4	5.8E-06	0.20	0.4	1.04
	Basement (Layer 4)	0.001	0.001	1.0E-07	5E-04	0.4	1.04

* *Curve defining parameters*

The comparison between model-predicted heads and the observed heads is shown in Figure 4.2 (the PEST optimised calibration results are presented in Appendix A). Calibration statistics for the preferred calibration (manually adjusted PEST parameters) indicate a Scaled RMS Error (SRMS) of 25%, which would usually suggest that the calibration is of questionable quality. However, the SRMS value is inversely proportional to the total range of groundwater heads in the calibration data set (maximum measured head minus minimum head) which, in this instance, is extremely small. Under these circumstances, achieving lower values for the SRMS may not be possible. Models that are able to obtain SRMS values of less than 10% are often of regional systems that include significant topographic relief and substantial ranges of head elevations within the calibration data set. For the current model and available calibration data, a 25% SRMS error is considered perfectly adequate.

Calibration hydrographs of the monitoring wells at the wellfield are presented in Figure 4.3. The results suggest a reasonable level of calibration has been attained with predicted hydrographs comparable to the measured drawdown. The timing of the initial drawdown response in the model is more rapid than observed and may reflect heterogeneous aquifer properties near the watertable elevation that lead to a delayed release of water on initial groundwater extraction. After the initial drawdown response, the model-predicted head responses follow closely the measured hydrographs.

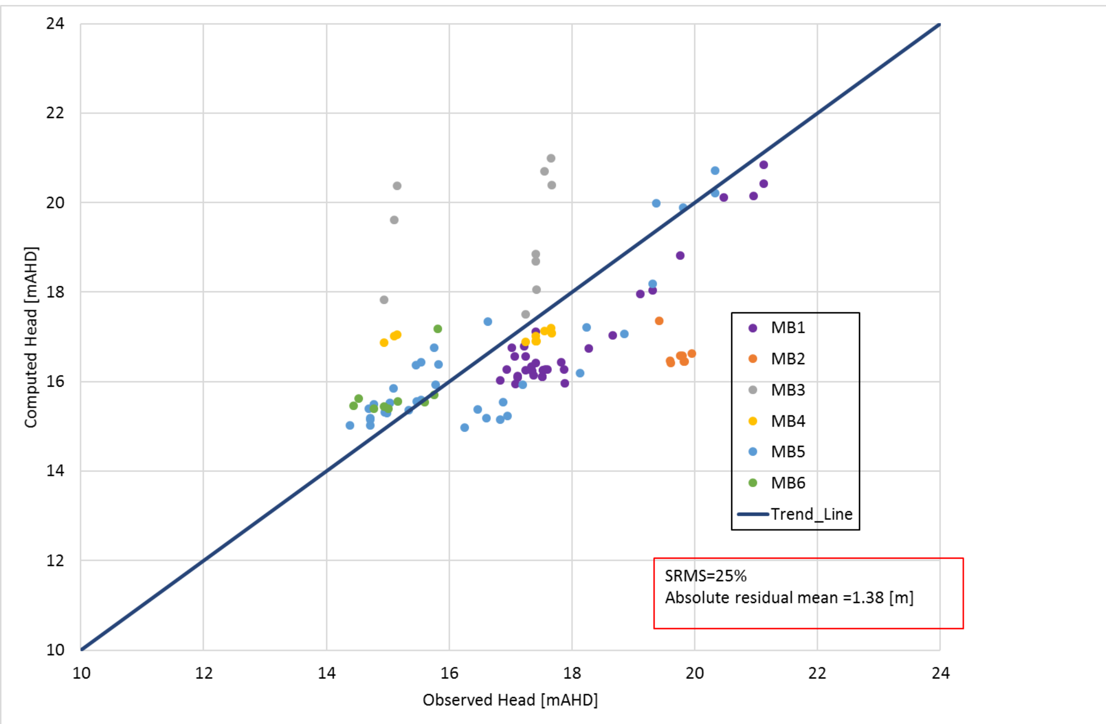

Figure 4.2: Calibration scatter plot

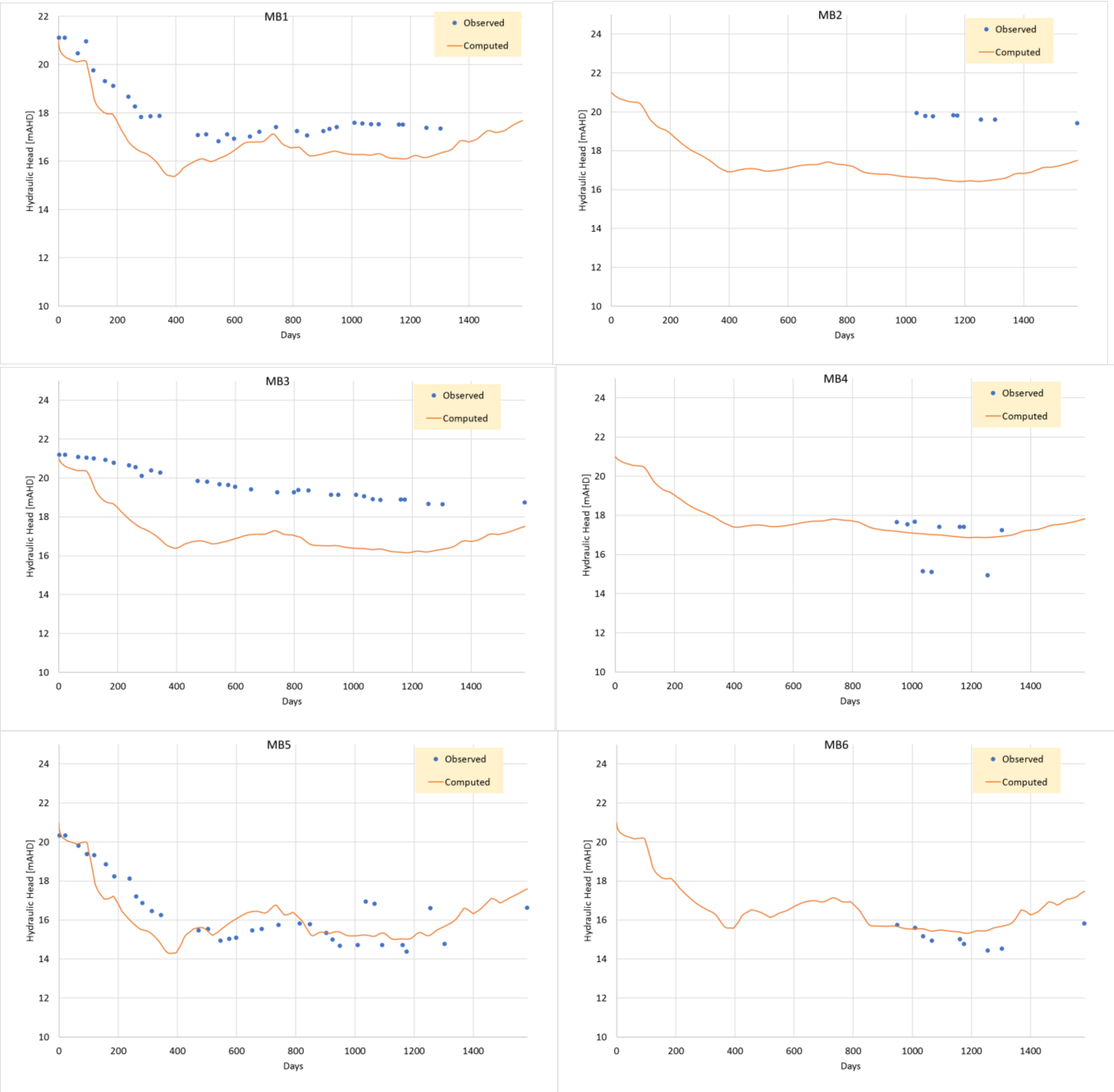

Figure 4.3: Calibration hydrographs (manually adjusted PEST parameters). Day 0 is 1 September 2009 and Day 1582 is 31 December 2013.

4.3 Verification Results

Results for the verification model are presented in Figure 4.4 and Figure 4.5. The fit between model-predicted and observed head data is much improved with the SRMS value of 12% obtained on the verification data set. The model verification result provides additional confidence in the adopted hydraulic parameters for the aquifer and basement with the conclusion that the model is well suited for use in predictive analysis.

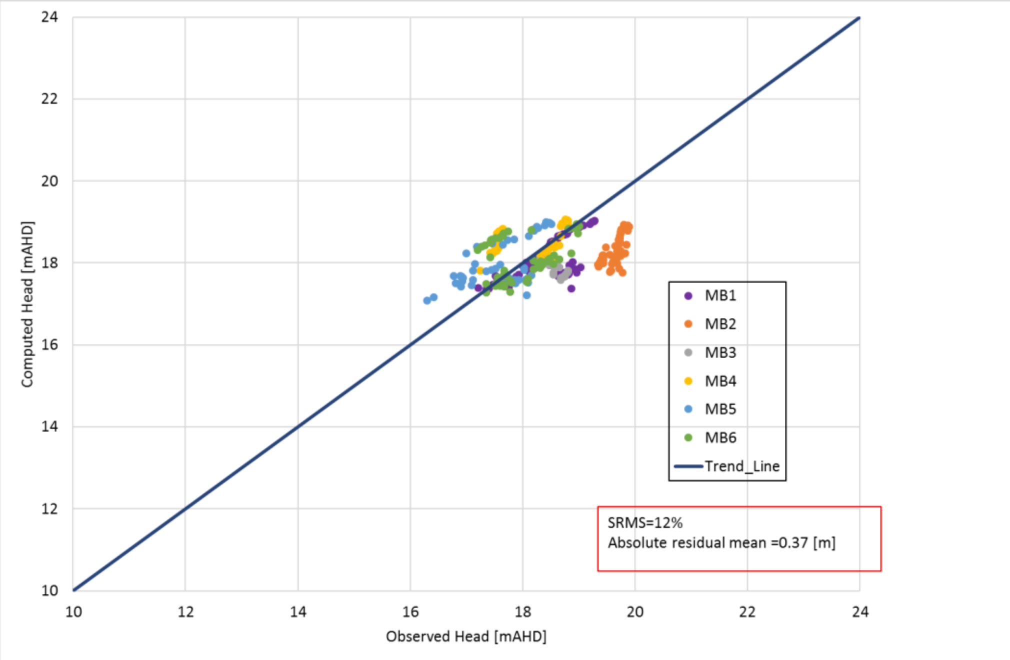

Figure 4.4: Verification scatter plot

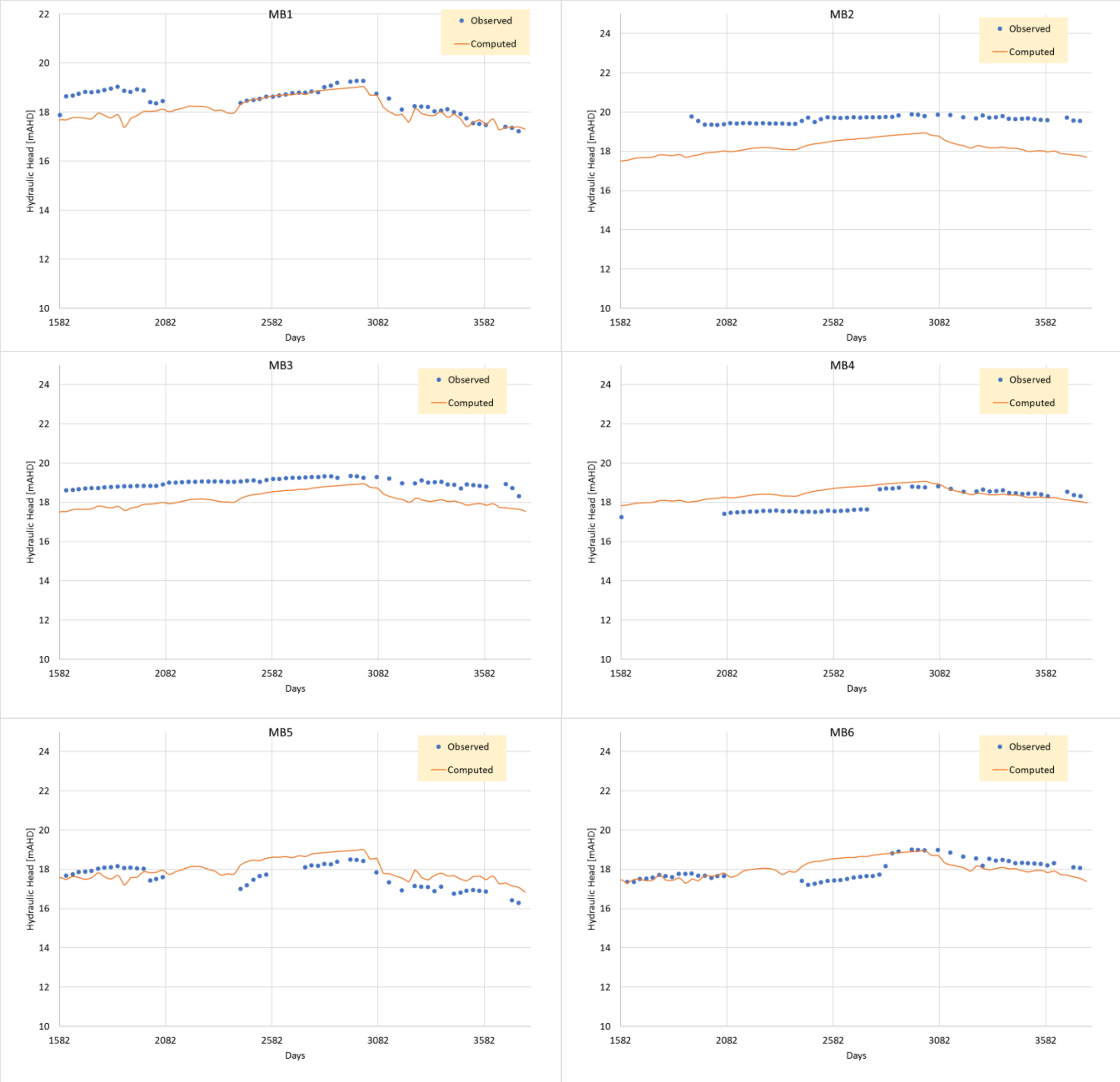

Figure 4.5: Verification hydrographs. Day 1582 is 31 December 2013 and Day 3773 is 31 December 2019.

5. Predictive Scenarios

5.1 Procedure

The preferred calibrated and verified hydraulic parameters were used to develop predictive models aimed at simulating the use of the existing wellfield to meet future mine water demands for the Jacinth, Ambrosia and Atacama mines. The predicted groundwater elevations at the end of the verification period (December 2019) were adopted as the initial conditions for the predictive scenarios. To simulate groundwater extraction from the production wellfield, time-varying Well Boundary Conditions were assigned to existing production well locations (Figure 5.1). Extraction rates were varied to meet the estimated mine water demand until December 2035 (i.e. the remaining life of the mines). To allow for well and pump maintenance, only 10 of the existing 12 wells were operated at any one time; for the purpose of the predictive scenarios JWB11 and JWB12 were inactive. The model was run for an additional 30 years post-mining to assess the rate and extent of recovery after the wellfield is shut in.

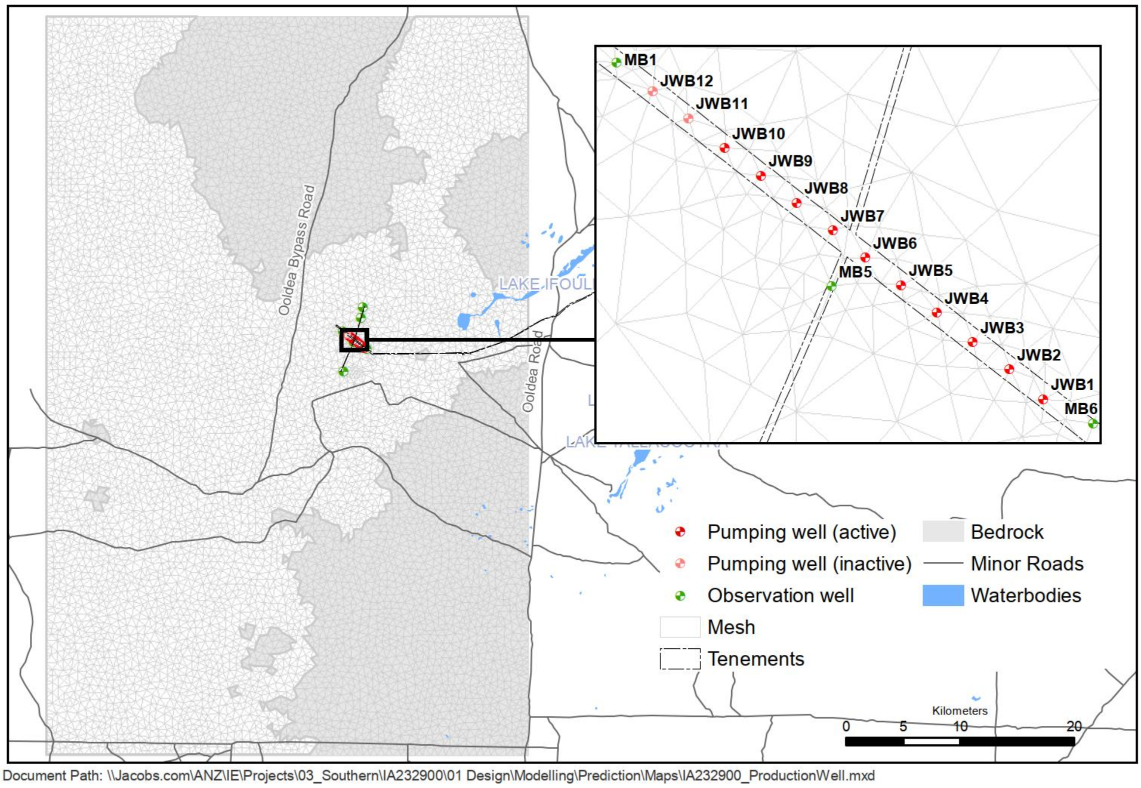

Figure 5.1: Location of production wells

The following water demand periods were included in the predictive scenarios:

- 31 December 2019 to 31 December 2024: mining at Ambrosia
- 1 January 2024 to 31 December 2029: mining at Ambrosia and Atacama, or Atacama and Jacinth
- 1 January 2030 to 31 December 2035: mining at Atacama
- 1 January 2036 to 31 December 2039: rehabilitation

Table 5.1 and Figure 5.2 present a summary of the water demand scenarios considered in this assessment. Low, medium and high demand assumptions were adopted for Scenarios 1, 2 and 3 respectively. The scenarios were developed according to various assumptions on future water demand from the Jacinth, Ambrosia and Atacama mines according to alternative tailings management options. Scenario 1 assumes that tailings storage facility

(TSF) embankments will comprise stacked sand tailings, these retaining modified co-disposal (ModCoD) tailings. Currently, this tailings disposal approach is being practiced at the Jacinth Mine and produces an average water demand of about 300 m^3/h.

At the Jacinth Mine, tailings were previously disposed by the ModCoD method into facilities that had engineered embankments. Water demand at this time was significantly higher, resulting in palaeochannel aquifer extraction rates of approximately 900 m^3/h. Scenario 3 assumes tailings disposal in this manner and hence represents a substantially higher demand on the water supply wellfield.

Scenario 2 represents the mid-point between Scenario 1 and Scenario 3 demands.

Table 5.1: Water demand for each scenario (Iluka, 2020)

Start date	End date	Pumping (m^3/d)		
		Scenario 1	Scenario 2	Scenario 3
1/01/2020	1/01/2024	7248	14496	21720
2/01/2024	31/12/2029	10872	21744	31200
1/01/2030	31/12/2035	3624	7272	10872
1/01/2036	31/12/2039	130	130	130
1/01/2040	1/01/2070	0	0	0

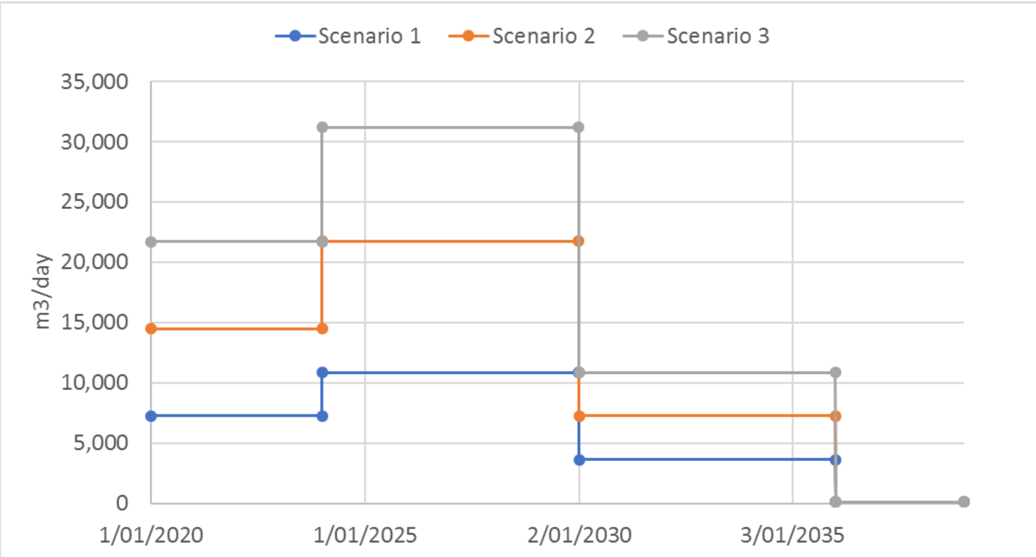

Figure 5.2: Water demand for predictive scenarios.

Model results were used to assess the ability of the existing wellfield to meet a given water demand by confirming supply requirements can be achieved without completely dewatering the aquifer at the wellfield, nor breaking well pump suction.

Production well construction data are presented in Table 5.2. Assuming that ten wells are operating at any one time, the maximum extraction rate per well for the high demand scenario (Scenario 3) is around 36 L/s between 2024 to 2039.

Table 5.2: Production well construction details (SKM, 2011)

Well	Surveyed Elevation (mAHD)	SWL (mAHD)	Well Diameter (mm)	Depth (mAHD)	Top pf Screen (mAHD)	Pump Elevation (mAHD)
JBW01	69.6	21.5	381	-32.6	-20.0	-19.0
JBW02	69.7	21.8	381	-27.1	-13.0	-12.3
JBW03	68.6	21.4	406	-27.0	-13.0	-12.4
JBW04	66.0	18.7	406	-33.0	-24.0	-23.0
JBW05	67.6	21.5	381	-30.3	-14.0	-13.1
JBW06	66.7	26.0	381	-26.0	-13.0	-12.3
JBW07	66.0	20.6	381	-31.1	-16.0	-15.1
JBW08	65.7	21.0	381	-30.0	-15.0	-13.9
JBW09	65.1	19.7	406	-32.0	-21.0	-20.2
JBW10	64.9	20.8	406	-31.0	-19.0	-17.8
JBW11	63.9	20.3	406	-18.0	-6.0	-5.0
JBW12	63.8	21.3	406	-30.5	-15.0	-13.6

5.2 Results

5.2.1 Scenario 1 – Low Demand

Figure 5.3 and Figure 5.4 show the predicted heads at the active production wells (wells 1 to 5 and 6 to 10 respectively) and the associated pump elevations. The predicted heads at the wellfield remain above the shallowest pump elevation of -5 mAHD (SKM, 2011) and the base of the aquifer (-26 mAHD) suggesting that the current configuration of extraction wells is able of meet the Scenario 1 demand for future mining at the Jacinth, Ambrosia and Atacama mines. Indeed, predicted drawdown at each production well is small compared to the maximum available drawdown.

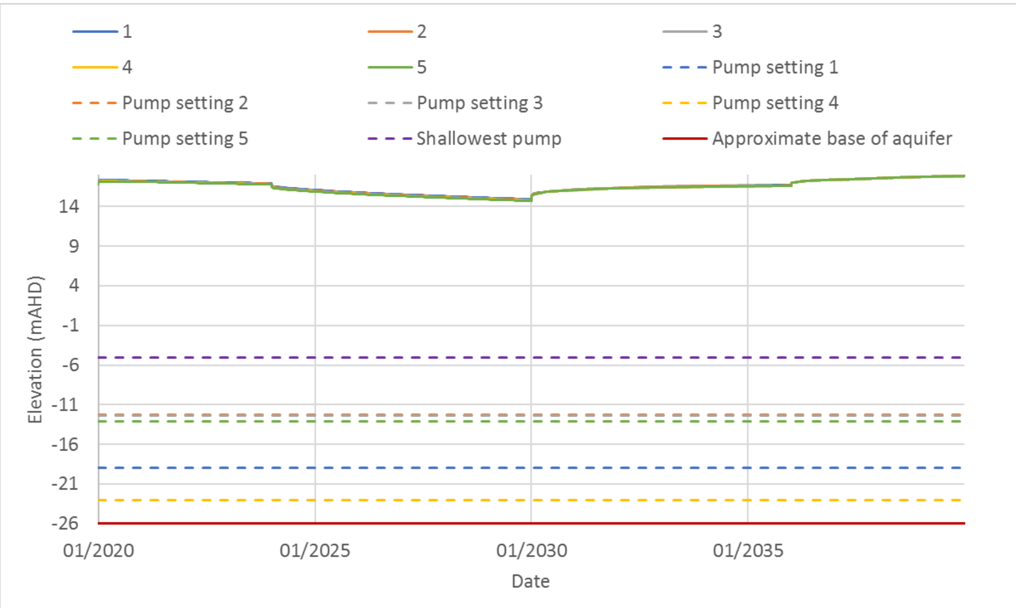

Figure 5.3: Scenario 1 - Predicted heads in production wells and pump elevations (Wells 1-5)

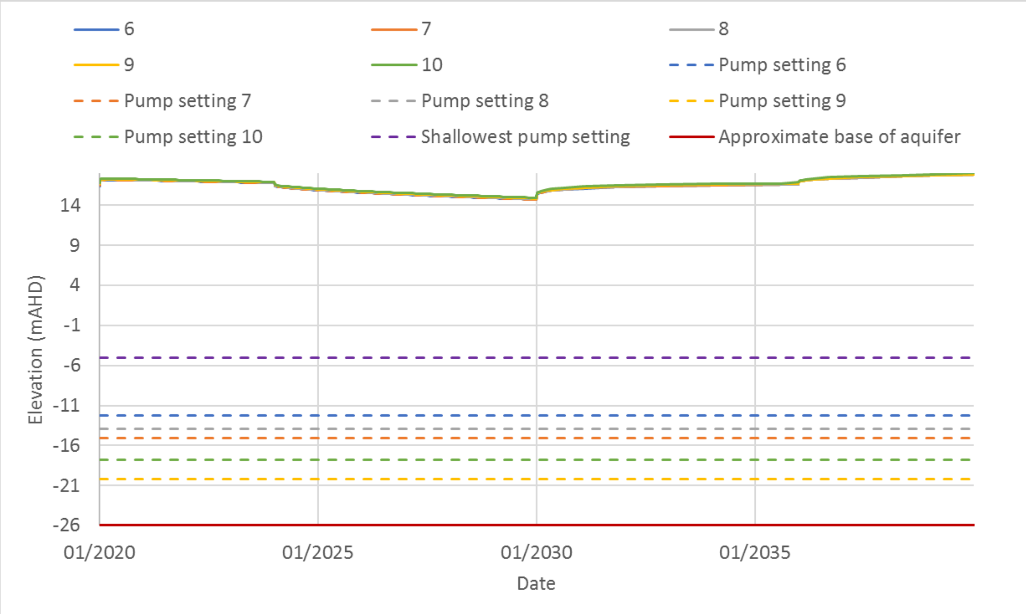

Figure 5.4: Scenario 1 - Predicted heads in production wells and pump elevations (Wells 6-10)

The predicted groundwater elevation at each monitoring well is presented in Figure 5.5 and the combined calibration, verification and predictive scenario hydrographs are included in Appendix B. Groundwater levels are predicted to stabilise after about 25 years post-mining with the heads approximately 2.5 m lower than pre-mining levels. As negligible recharge to the groundwater system is assumed, groundwater extraction is not replenished, and groundwater levels are not expected to recover fully.

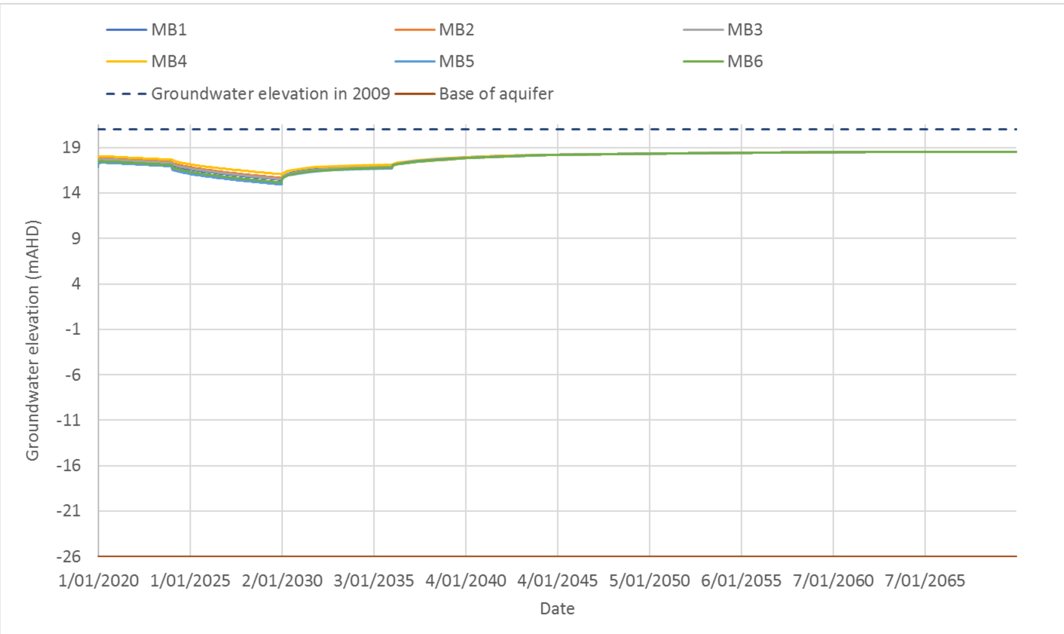

Figure 5.5: Scenario 1 - Predicted groundwater elevation in monitoring wells.

The predicted drawdowns in December 2019 and December 2029 are presented in Figure 5.6 and Figure 5.7 representing the current and maximum predicted drawdown respectively. Drawdown was calculated by comparing the predicted heads to the groundwater heads prior to abstraction (21 mAHD). The effects of groundwater extraction are evident near the wellfield, with around 4 m of drawdown predicted in 2019 increasing to 6 m in 2029. At the end of mining at Ambrosia/Atacama or Atacama/Jacinth in December 2029, 2 m of drawdown is predicted 22 km west of the wellfield where the aquifer is present. The result presented in

Figure 5.6 confirms the importance of understanding palaeochannel aquifer extent and geometry, and points to the potential sensitivity of drawdown predictions to these dimensions and to the storativity of the system in total.

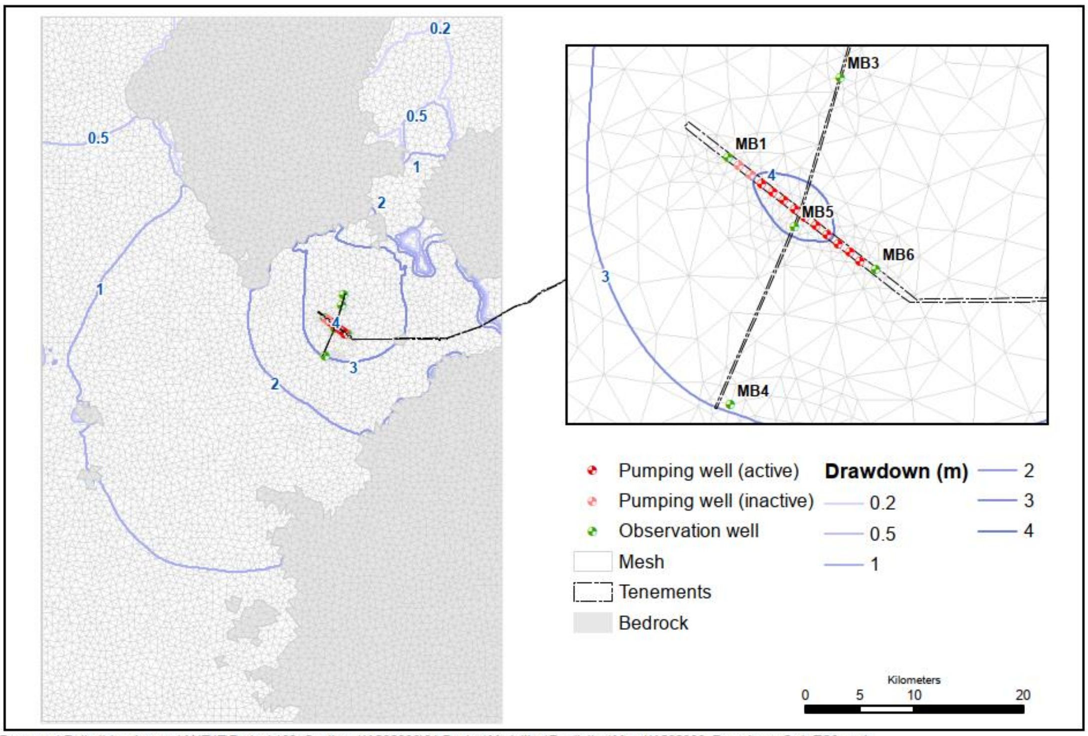

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Figure 5.6: Scenario 1 - Drawdown at December 2019 (initial conditions)

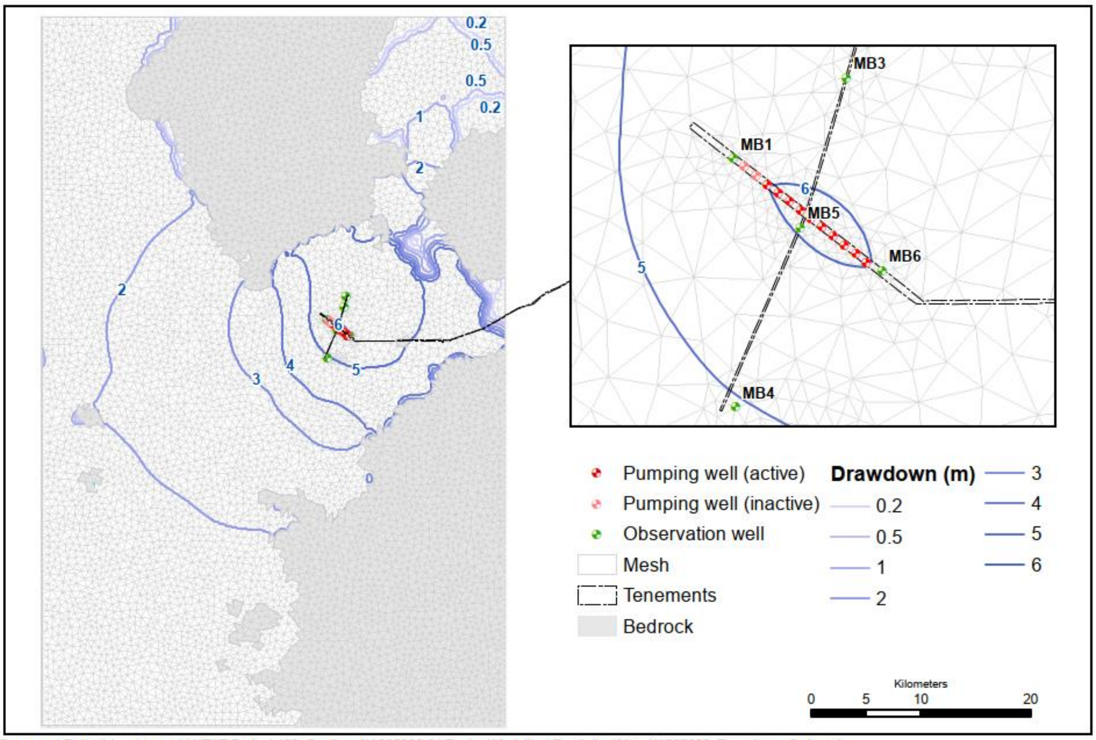

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Figure 5.7: Scenario 1 – Predicted drawdown in December 2029 - End of mining at Ambrosia/Atacama or Atacama/Jacinth.

The predicted saturated thickness of the aquifer in December 2019 and December 2029 are presented in Figure 5.8 and Figure 5.9 respectively. The saturated thickness at the wellfield is predicted to reduce by 2 m over 10 years, being from 40 to 45 m at the wellfield in 2019 and reducing to 38 to 43 m by 2029. The desaturated (fully dewatered) area is predicted to increase slightly around the edges of the aquifer.

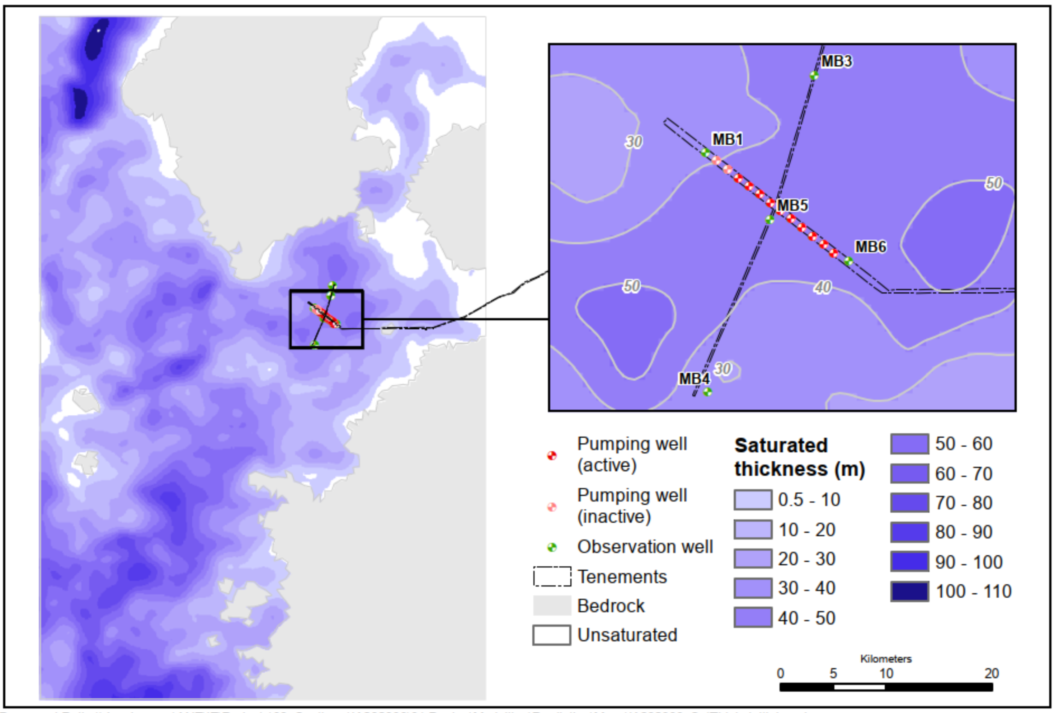

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Figure 5.8: Scenario 1 - Predicted saturated thickness in December 2019 (initial conditions).

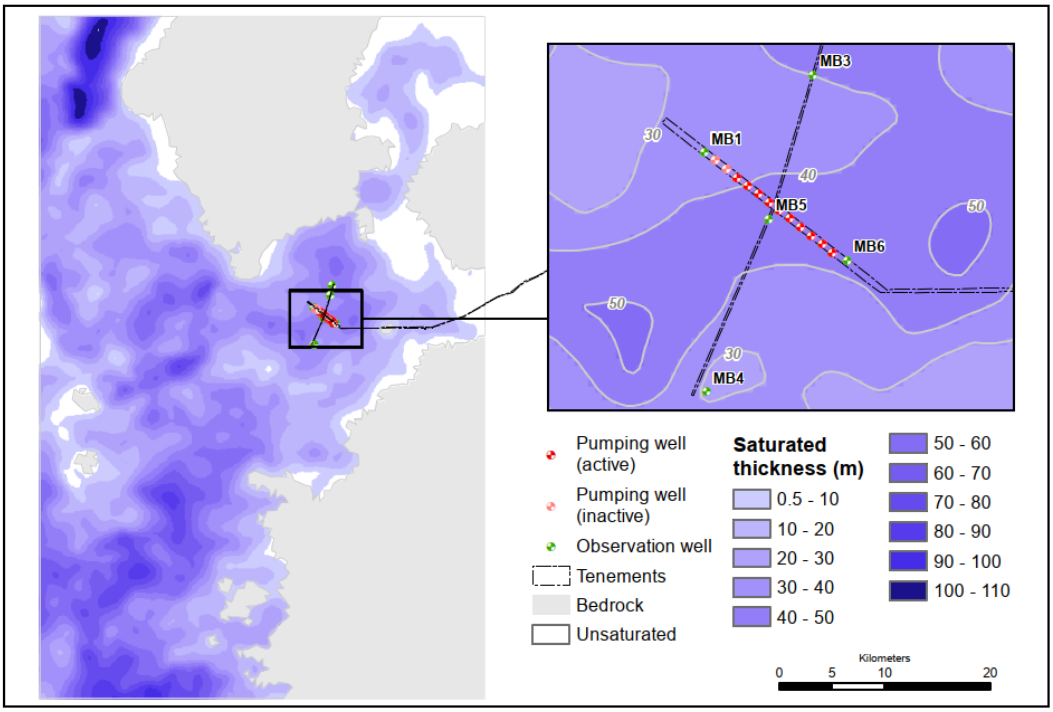

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Figure 5.9: Scenario 1 - Predicted saturated thickness in December 2029 - end of mining at Ambrosia/Atacama or Atacama/Jacinth.

5.2.2 Scenario 2 – Medium Demand

The pump elevations and the predicted groundwater elevation at the production wells for Scenario 2 are presented in Figure 5.10 and Figure 5.11 for pumping wells 1 to 5 and 6 to 10 respectively. Estimates suggest that the groundwater heads will remain above pump intake levels over the duration of mining. The drawdown is predicted to be about 5.5 m greater at the wellfield than in Scenario 1 which reflects the increased groundwater extraction rates included in this scenario. The results indicate that the existing wellfield is able to meet the future water demand for Scenario 2.

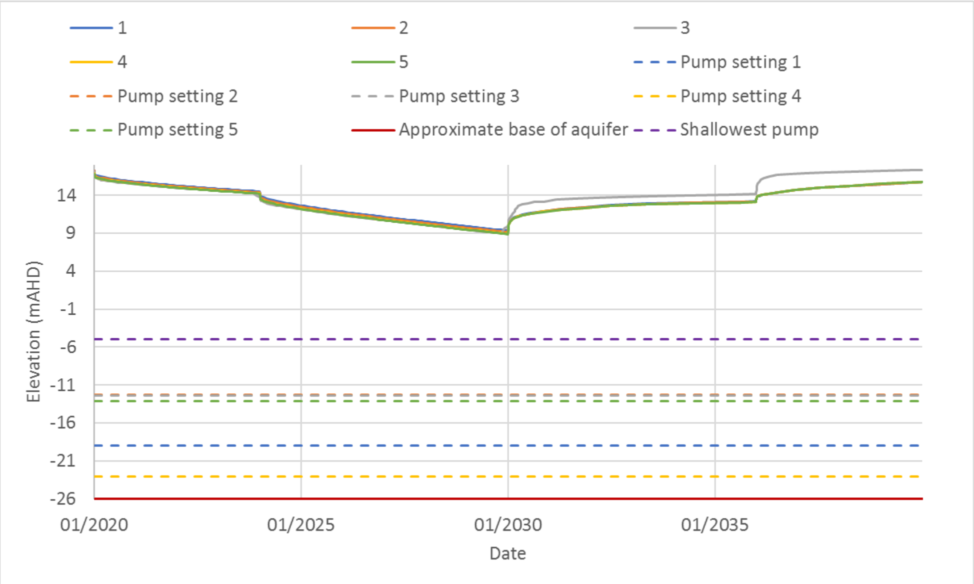

Figure 5.10: Scenario 2 - Predicted heads in production wells and pump elevations (Wells 1-5)

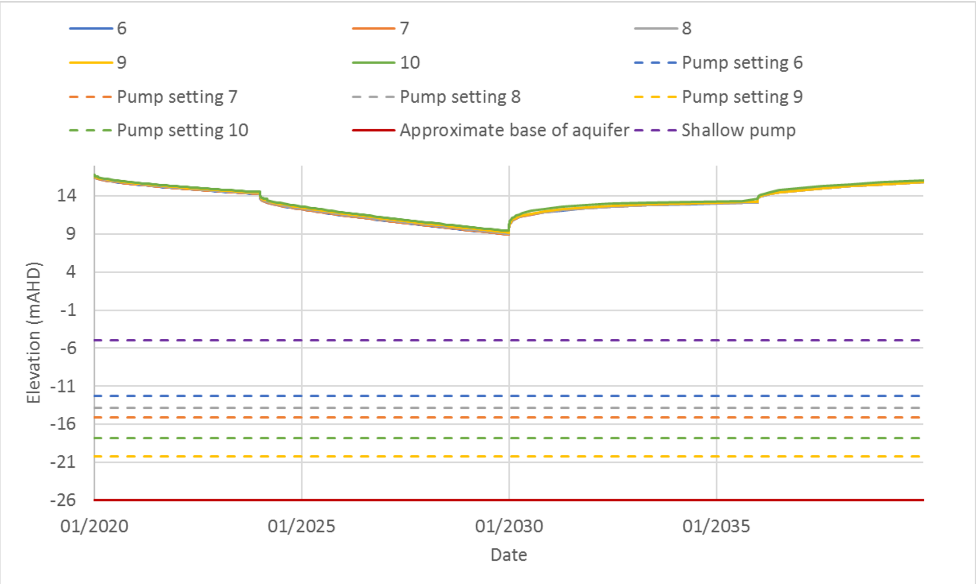

Figure 5.11: Scenario 2 - Predicted heads in production wells and pump elevations (Wells 6-10)

The predicted heads at the monitoring wells for Scenario 2 are presented in Figure 5.12. After maximum predicted drawdown of between 9 and 12 m at the end of 2029, groundwater levels are predicted to progressively recover as pumping reduces. Pumping ceases completely at the end 2039 with predicted heads eventually stabilising around 3.8 m below pre-mining levels.

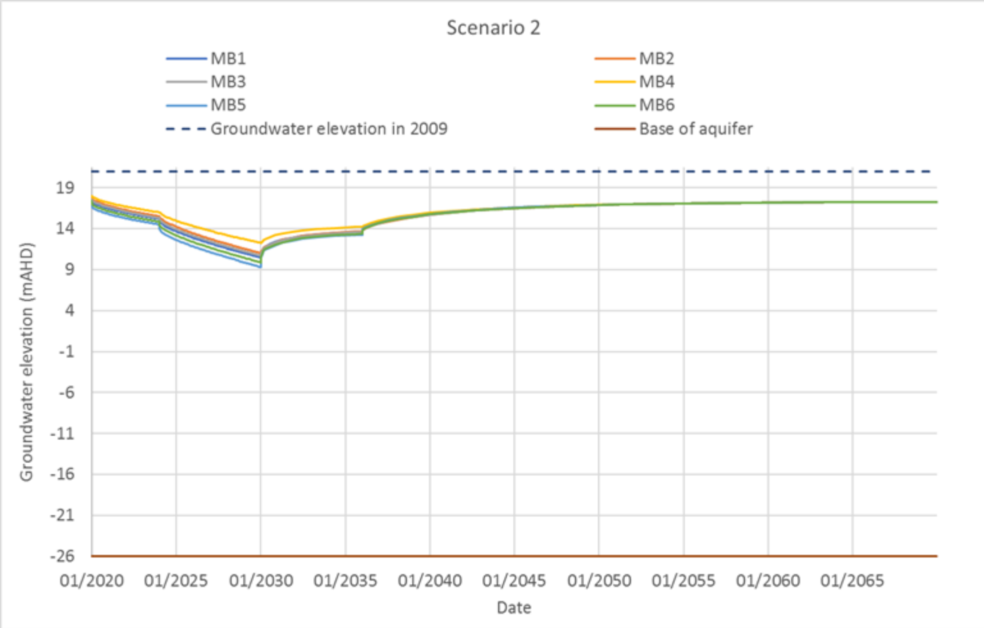

Figure 5.12: Scenario 2 - Predicted groundwater elevation in Iluka monitoring wells.

The drawdown predicted in December 2029 is presented in Figure 5.13 indicating the maximum predicted drawdown at the wellfield is 11 m, with about 2 m of drawdown predicted at the western model boundary and up to 0.5 m at the northern boundary. The predicted saturated thickness in December 2029 is presented in Figure 5.14 and illustrates a saturated thickness at the wellfield of between 33 and 37 m which is a reduction of about 5.5 m from that predicted in Scenario 1.

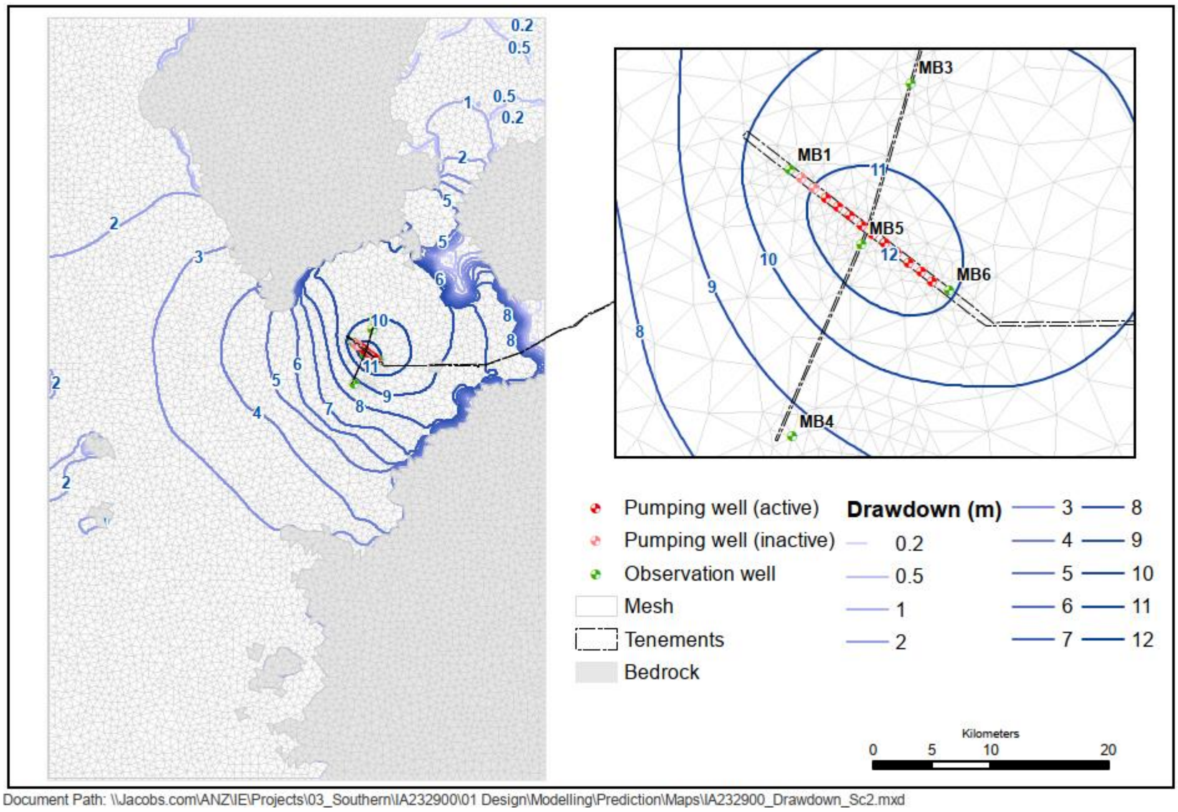

Figure 5.13: Scenario 2 – Predicted drawdown in December 2029 - end of mining at Ambrosia/Atacama or Atacama/Jacinth.

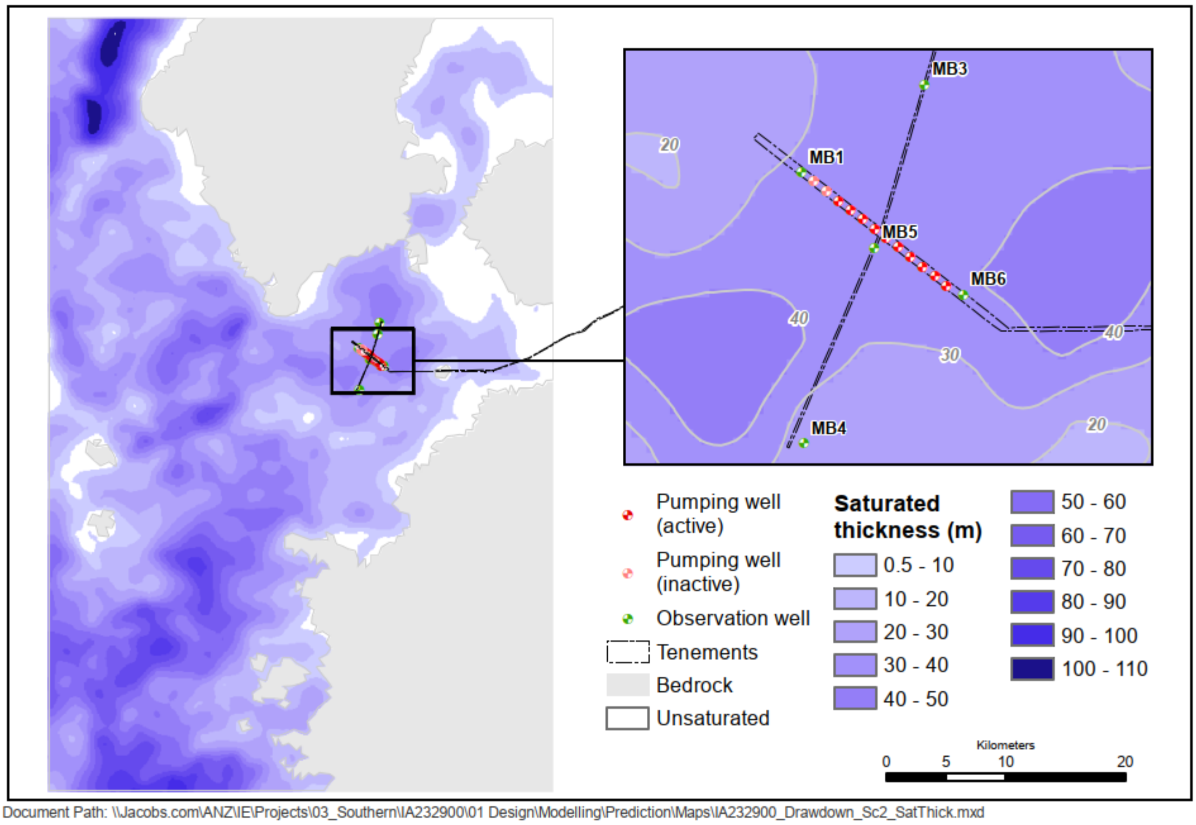

Figure 5.14: Scenario 2 - Predicted saturated thickness in December 2029 - End of mining at Ambrosia/Atacama or Atacama/Jacinth.

5.2.3 Scenario 3 – High Demand

The pump elevations and the predicted groundwater elevations at the production wells for the highest water demand scenario are presented in Figure 5.15 and Figure 5.16 for pumping wells 1 to 5 and 6 to 10 respectively. The groundwater levels in the extraction wells are predicted to remain around 6.5 m above the shallowest pump (JBW11) throughout mining. Results suggest that the future high water demand scenario can be met by operation of the current wellfield without the need for expansion.

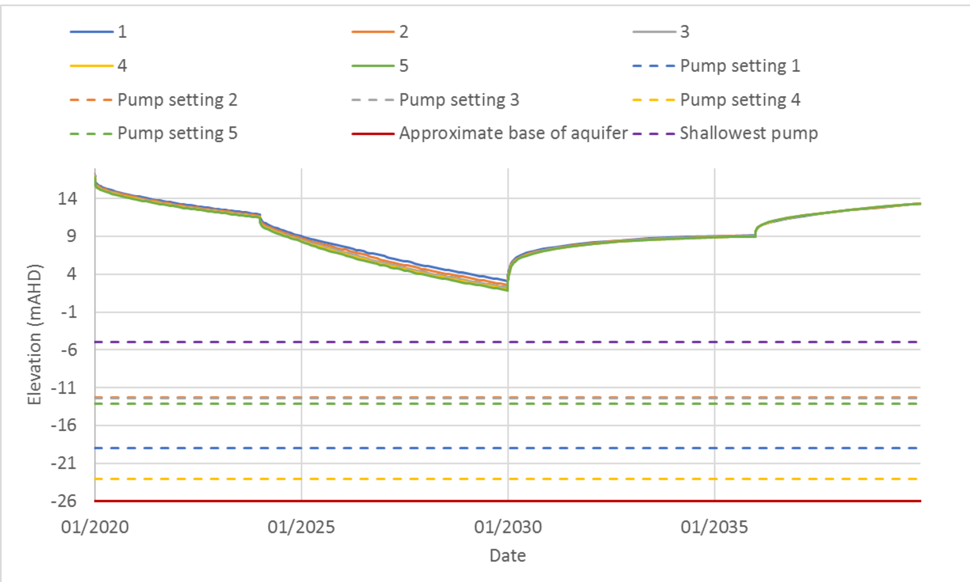

Figure 5.15: Scenario 3 - Predicted heads in production wells and pump elevations (Wells 1-5).

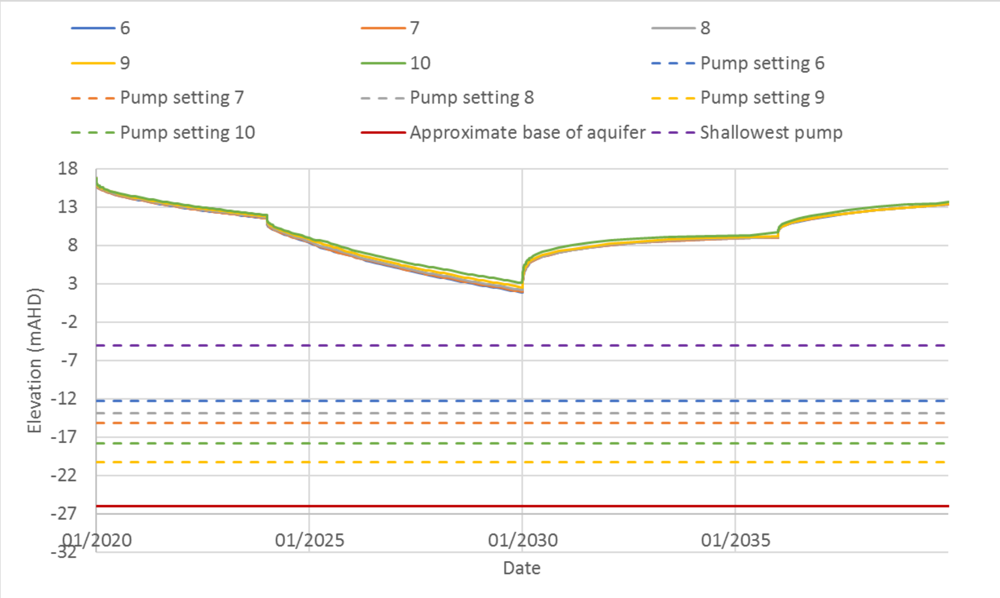

Figure 5.16: Scenario 3 - Predicted heads in production wells and pump elevations (Wells 6-10).

The predicted groundwater elevation at the monitoring wells is presented in Figure 5.17. Maximum drawdown in the monitoring well network is predicted to range from about 12 m to19 m at the end of 2029. Long term post-mining heads are predicted to remain about 5 m lower than the pre-mining levels suggesting a permanent decrease in groundwater head and unrecovered loss of storage.

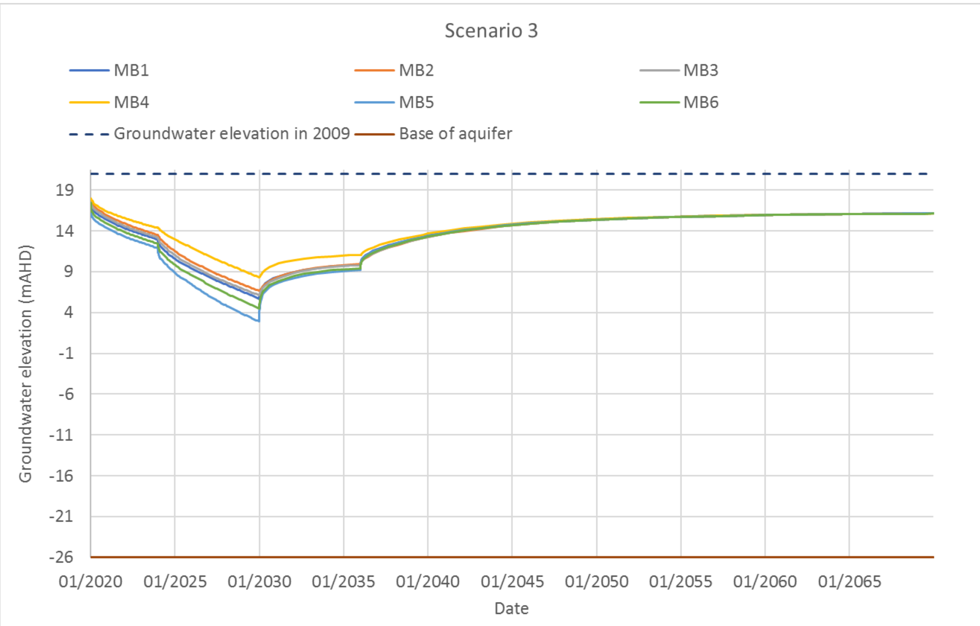

Figure 5.17: Predicted groundwater elevation in monitoring wells for scenario 3.

For Scenario 3, 18 m of drawdown is predicted at the wellfield in December 2029 suggesting that the drawdown is directly proportional to the assumed rate at which water is extracted from the wellfield. Predicted drawdown elsewhere in the model, and associated reduction in the saturated thickness of the aquifer, are similarly elevated compared to Scenarios 1 and 2. Most importantly, the results suggest that the existing wellfield is able to sustain the required high level demand without widespread desaturation of the aquifer and without breaking pump suction.

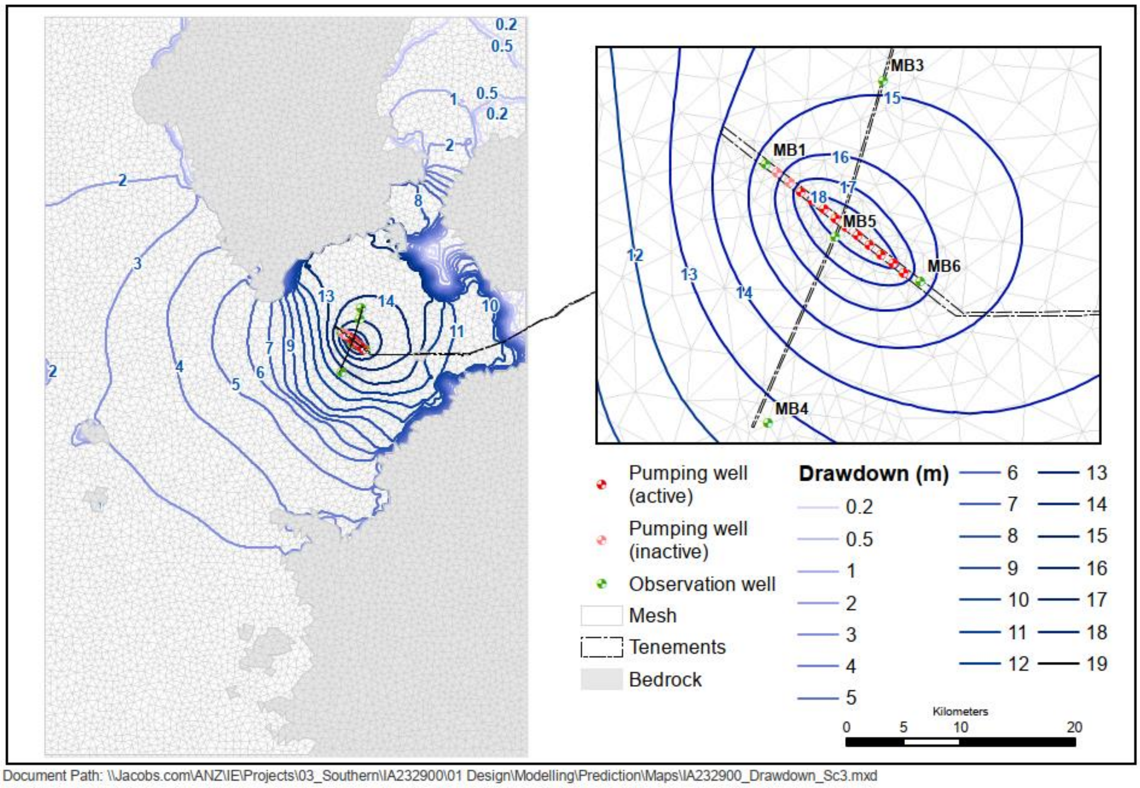

Figure 5.18: Scenario 3 drawdown at December 2029 - end of mining at Ambrosia/Atacama or Atacama/Jacinth.

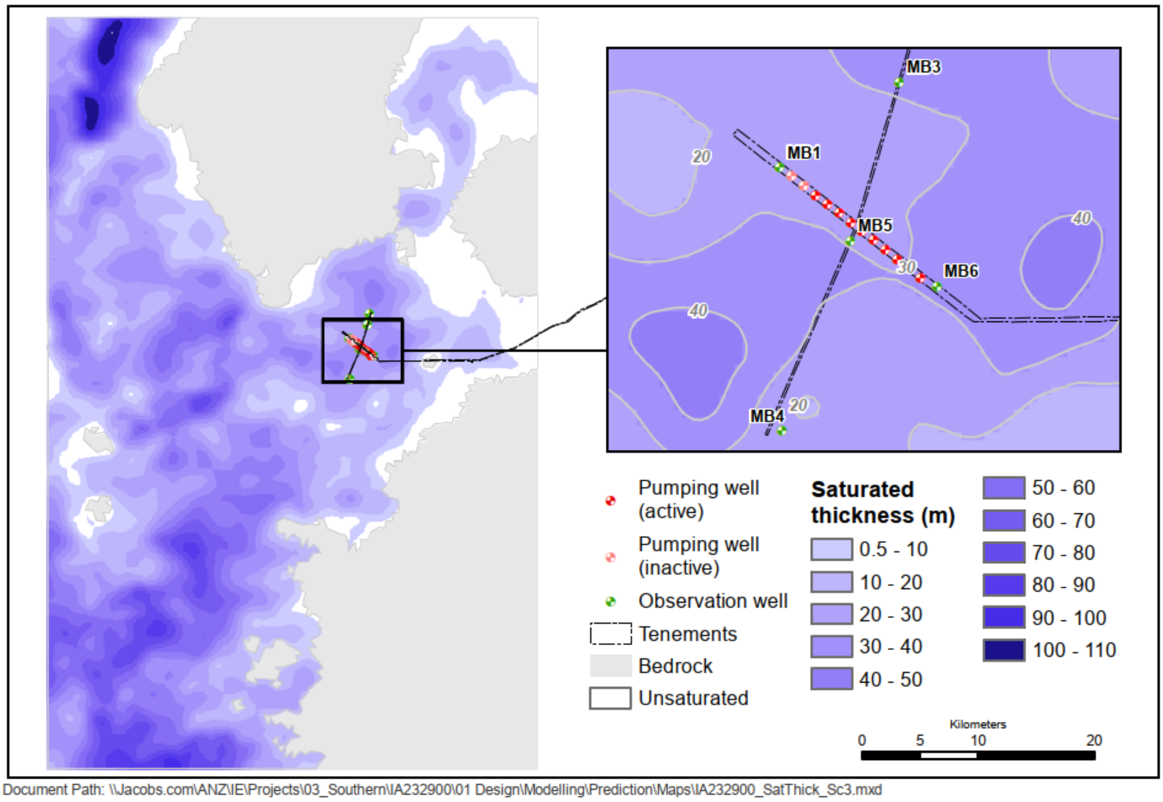

Figure 5.19: Predicted saturated thickness at December 2029 - end of mining at Ambrosia/Atacama or Atacama/Jacinth.

6. Uncertainty Analysis

An uncertainty analysis was carried out to assess the potential variability in predicted groundwater drawdown at the wellfield under the high water demand of Scenario 3. The analysis acknowledges uncertainty in the assumptions that are included in the predictive model, and that such uncertainties will influence the groundwater response to pumping and hence the conclusions as to whether the existing wellfield will be able to meet the future water demand.

6.1 Procedure

The approach adopted for the uncertainty analysis involved the selection of aquifer parameters that would lead to upper and lower limits of wellfield yield. Two different factors were considered as representing the most uncertainty in predictive models given the constraints included in calibration and verification. These are the effective porosity and the total palaeochannel aquifer volume.

The effective porosity was considered in this assessment because PEST optimisation suggested that the best match to calibration and verification data was obtained with a porosity of 37%. This level of porosity, while generally considered to be higher than expected in this type of deposit, is consistent with specific yield parameter values used in groundwater models of the nearby Jacinth Mine. Accordingly, an upper limit estimate for aquifer yield was assessed through the use of the PEST-optimised porosity and vertical hydraulic conductivity parameters.

The impact of a reduced aquifer extent on the potential of the wellfield to meet the water demand was also assessed. This approach explores uncertainty in the geophysical surveys and interpretations that have been used to define the aquifer volume. For the purposes of the uncertainty analysis, the modelled aquifer area was reduced by 30% and 50% respectively. In each case, the target reduction in aquifer area was achieved by converting aquifer properties to basement properties on the edges of the model domain (i.e., some distance from the existing wellfield). The base case and assumed reduced aquifer areas are shown in Figure 6.1.

In summary, the following uncertainty analysis scenarios were assessed:

- Uncertainty Scenario 1: High water demand,100% aquifer extent and PEST-optimised parameters.
- Uncertainty Scenario 2: High water demand, 70% aquifer extent with calibrated model parameters.
- Uncertainty Scenario 3: High water demand, 50% aquifer extent with calibrated model parameters.

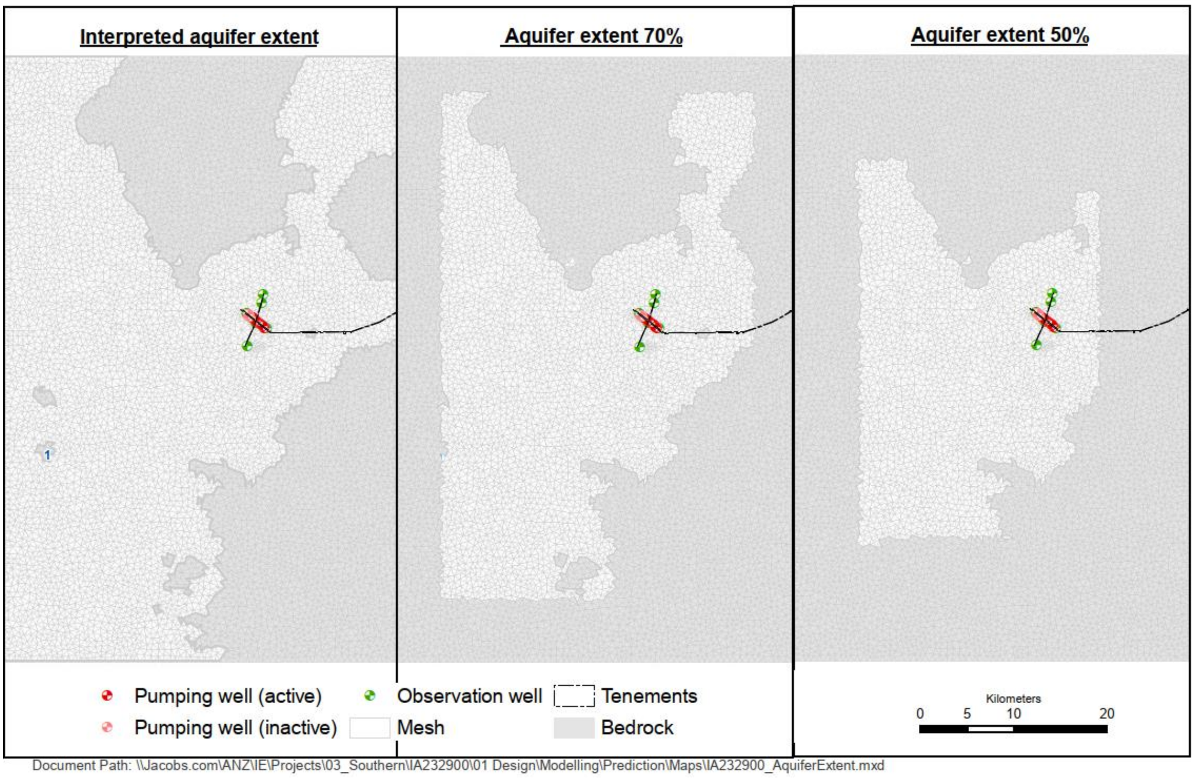

Figure 6.1: Aquifer extents adopted in the uncertainty analysis

6.2 Results

6.2.1 Uncertainty Scenario 1

The combined calibration, verification and predictive uncertainty scenario hydrographs are included in Appendix C. The predicted heads in the production wells remain above the shallowest pump elevation for the duration of mining (Figure 6.2 and Figure 6.3). The maximum drawdown at the wellfield is presented in Figure 6.4. Reduced levels of drawdown are predicted across the model domain. Likewise, the uncertainty scenario predicts an increase in the saturated thickness at the wellfield (Figure 6.5) when the higher porosity is adopted.

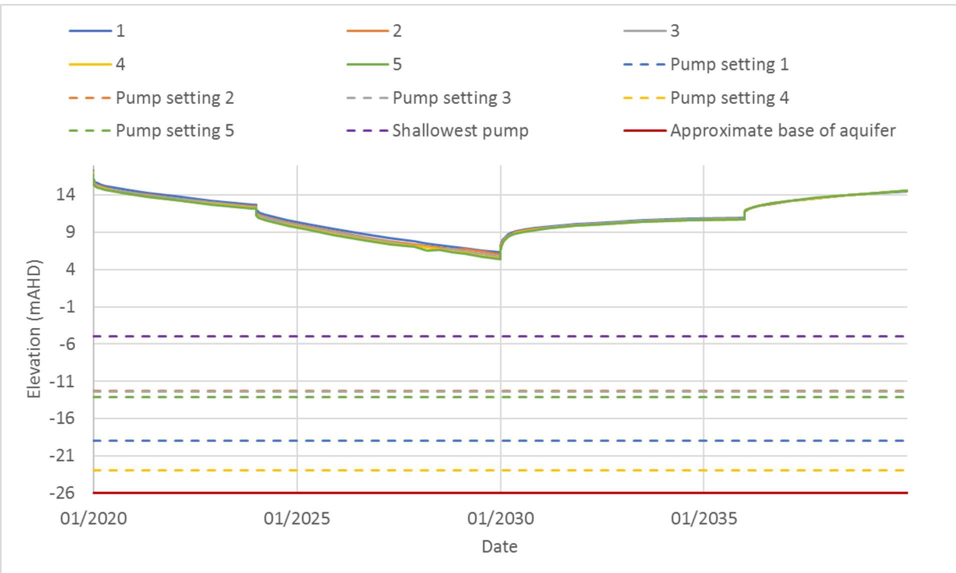

Figure 6.2: Uncertainty Scenario 1 - Predicted heads in production wells and pump elevations (Wells 1-5).

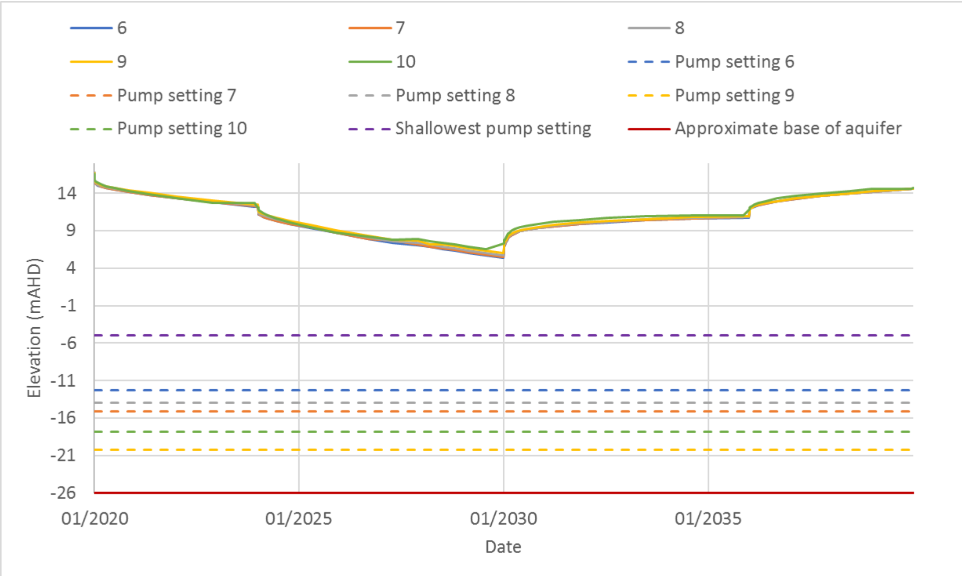

Figure 6.3: Uncertainty Scenario 1 - Predicted heads in production wells and pump elevations (Wells 6-10).

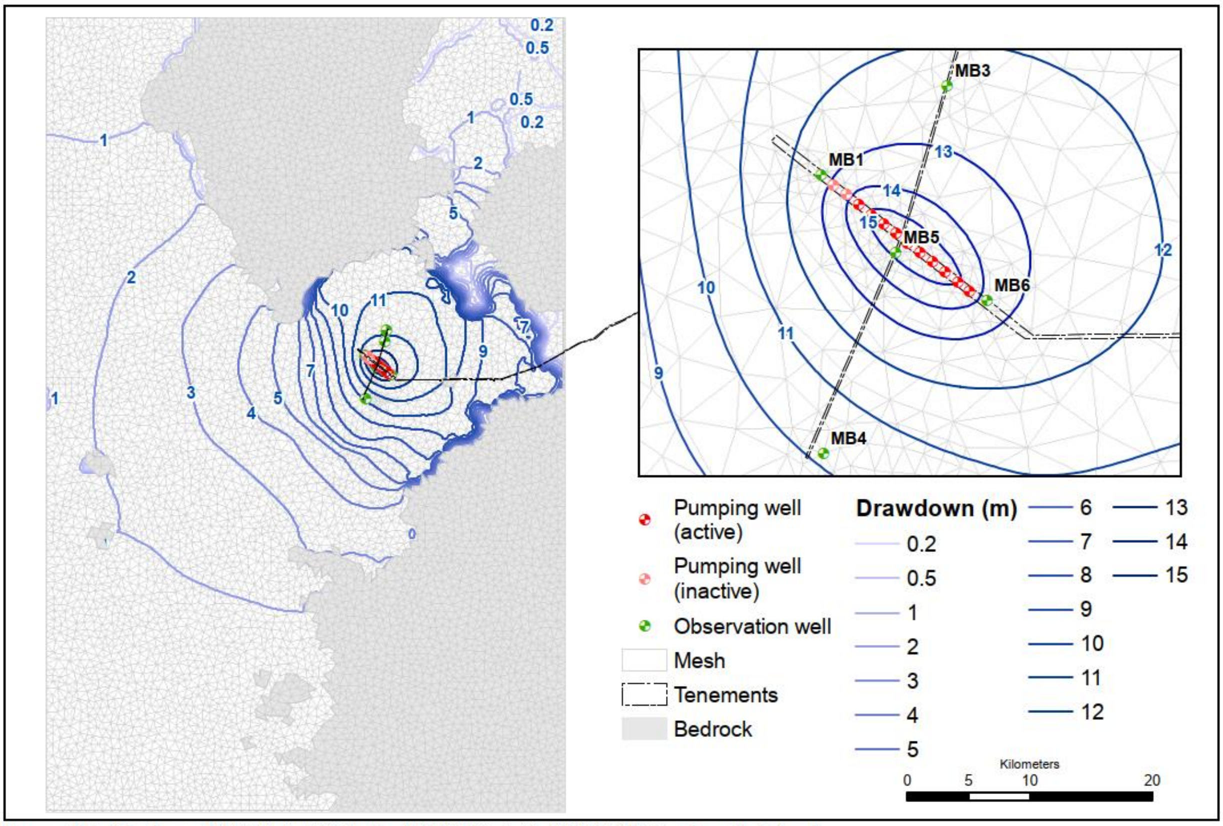

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Figure 6.4: Uncertainty Scenario 1 – Predicted drawdown in December 2029

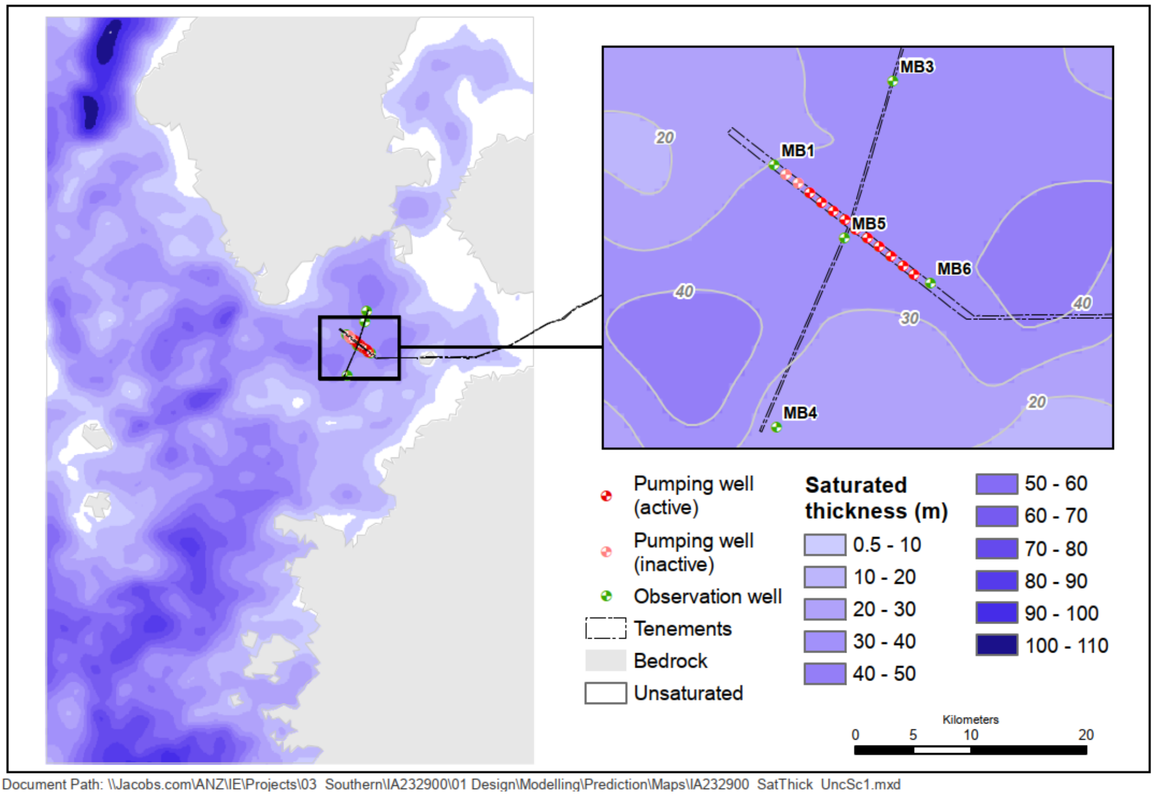

Figure 6.5: Uncertainty Scenario 1 - Predicted saturated thickness in December 2029

6.2.2 Uncertainty Scenario 2

Figure 6.6 and Figure 6.7 show the predicted groundwater levels in the production wells 1 to 5 and 6 to 10 respectively when the aquifer extent is reduced to 70% of the best estimate. The groundwater elevations in the production wells are predicted to remain around 6 m higher than the shallowest pump elevations. The drawdown has increased by around 1 m at the wellfield compared to the best estimate model with the wellfield still predicted to meet the target water demand for the remaining life of mining. Groundwater levels are predicted to stabilise around 15 mAHD or 6 m lower than the pre-mining levels. The maximum drawdown in the palaeochannel aquifer near the wellfield is predicted to be about 19 m (Figure 6.8 and Figure 6.9).

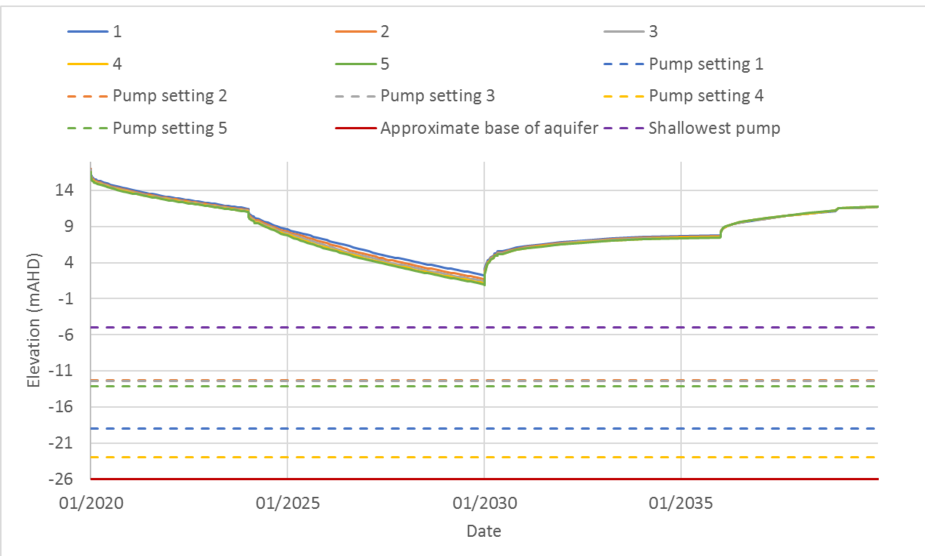

Figure 6.6: Uncertainty Scenario 2 - Predicted heads in production wells and pump elevations (Wells 1-5).

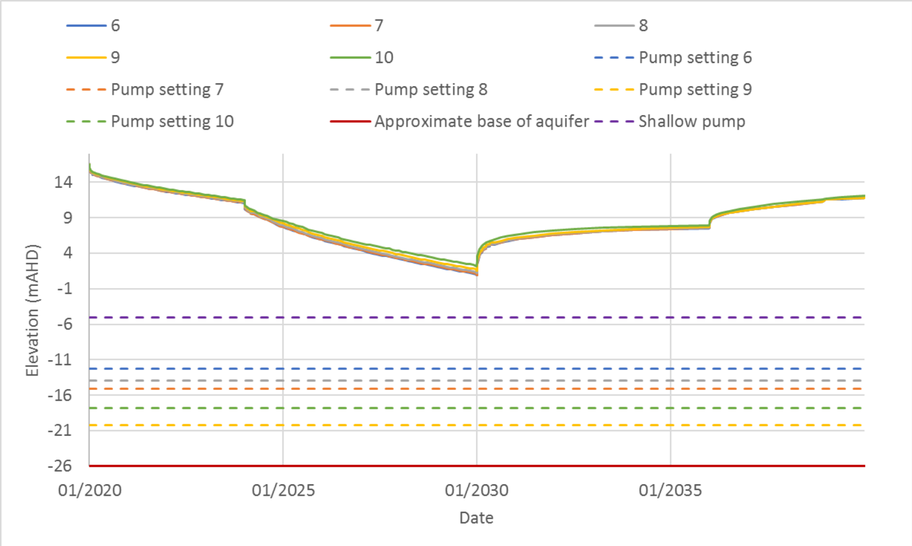

Figure 6.7: Uncertainty Scenario 2 - Predicted heads in production wells and pump elevations (Wells 6-10).

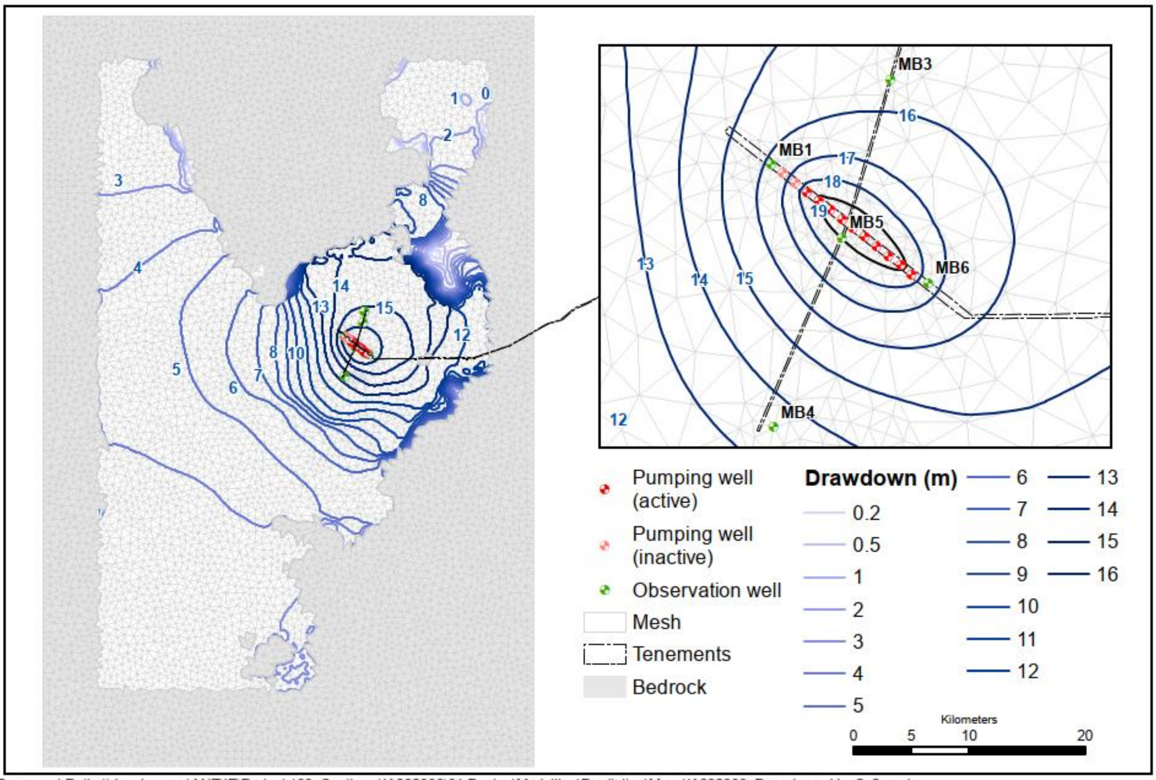

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Figure 6.8: Uncertainty Scenario 2 – Predicted drawdown in December 2029.

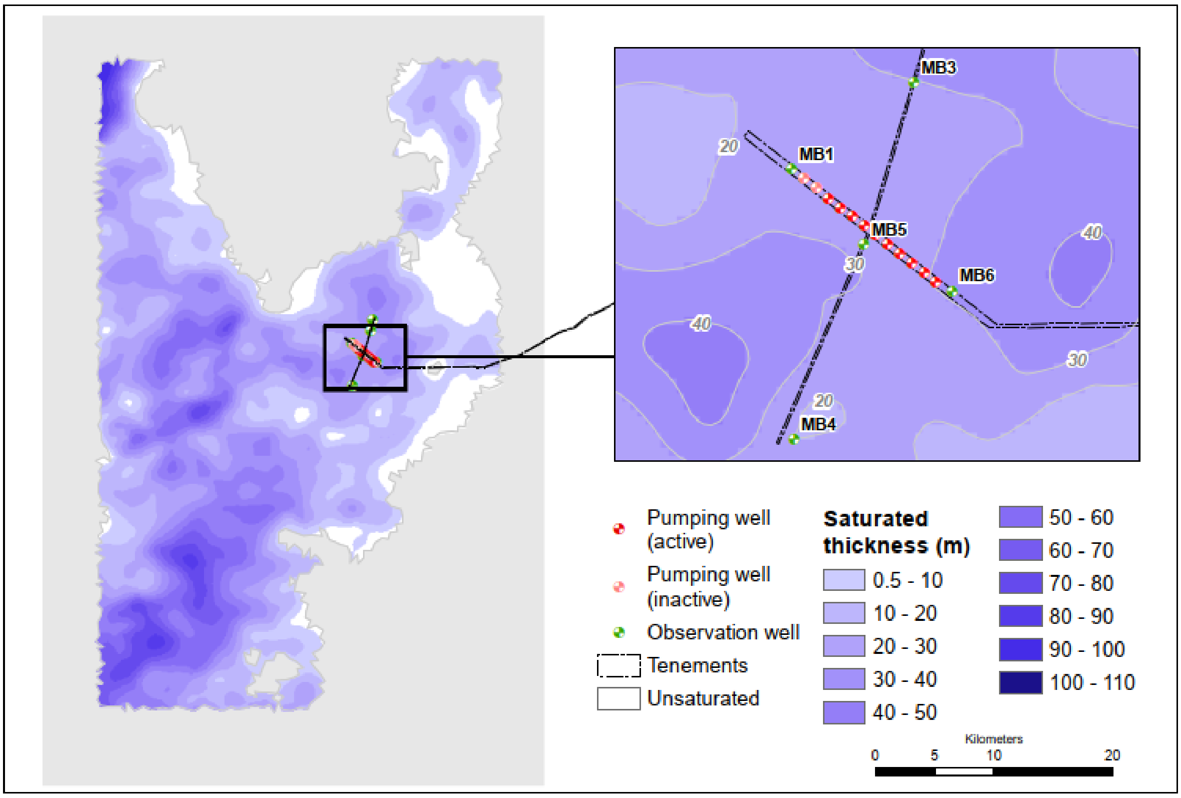

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Figure 6.9: Uncertainty analysis scenario 2 predicted saturated thickness at December 2029

6.2.3 Uncertainty Scenario 3

Figure 6.10 and Figure 6.11 show the predicted groundwater levels in production wells 1 to 5 and 6 to 10 respectively when the aquifer extent is reduced to 50% of the best estimate area. The groundwater elevations in the production wells are predicted to fall to within 3 m of the shallowest pump elevation in well JBW11 (which is assumed inactive) and to remain around 10 to 20 m above the pump elevations in the remaining production wells. It follows that pumping yields at JBW11 would likely be reduced if it were being operated. It may be concluded that the aquifer is approaching its yield limit under the assumed conditions.

The maximum drawdown in the palaeochannel aquifer is predicted to occur at the end of 2029 and is shown in Figure 6.12 and the predicted saturated thickness at the same time in Figure 6.13. The saturated thickness in the wellfield at the end of 2029 ranges from 23 to 27 m.

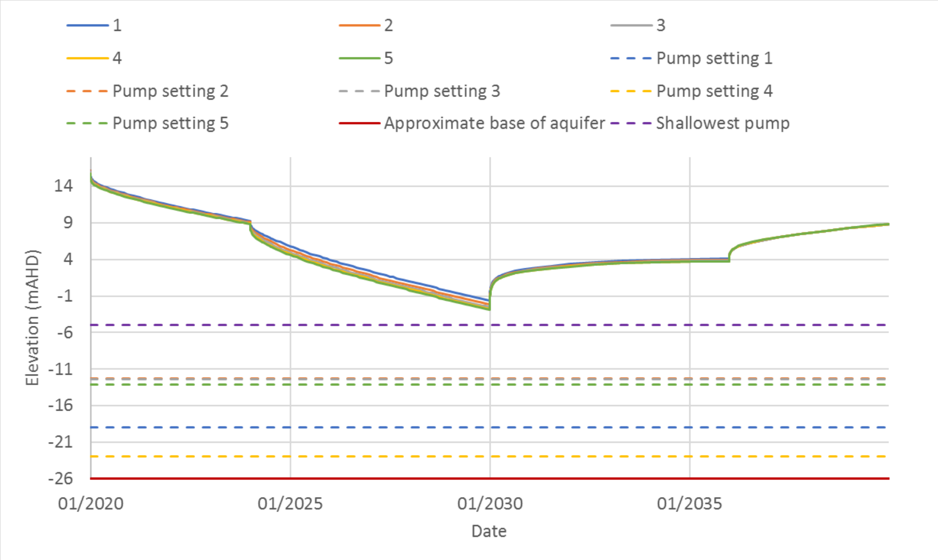

Figure 6.10: Uncertainty Scenario 3 - Predicted heads in production wells and pump elevations (Wells 1-5).

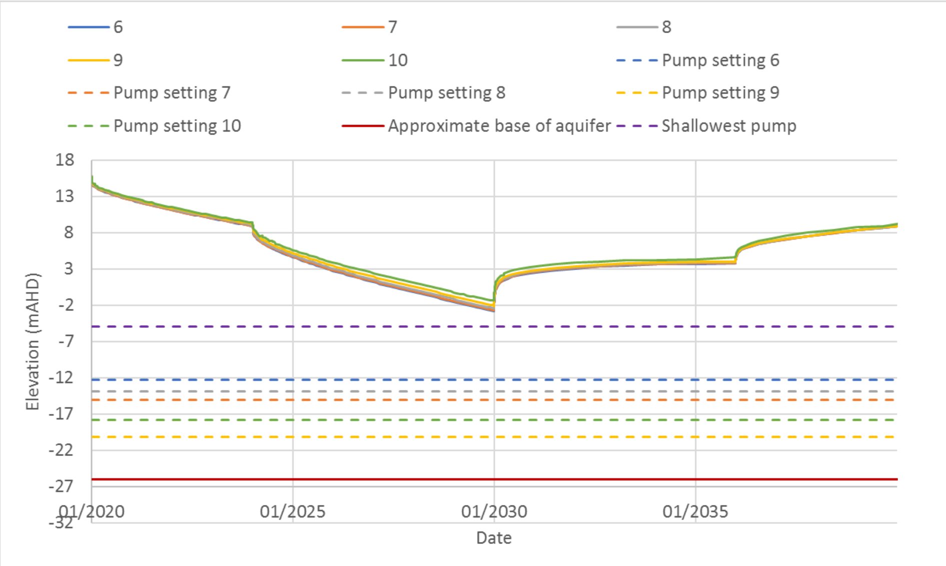

Figure 6.11: Uncertainty Scenario 3 - Predicted heads in production wells and pump elevations (Wells 6-10).

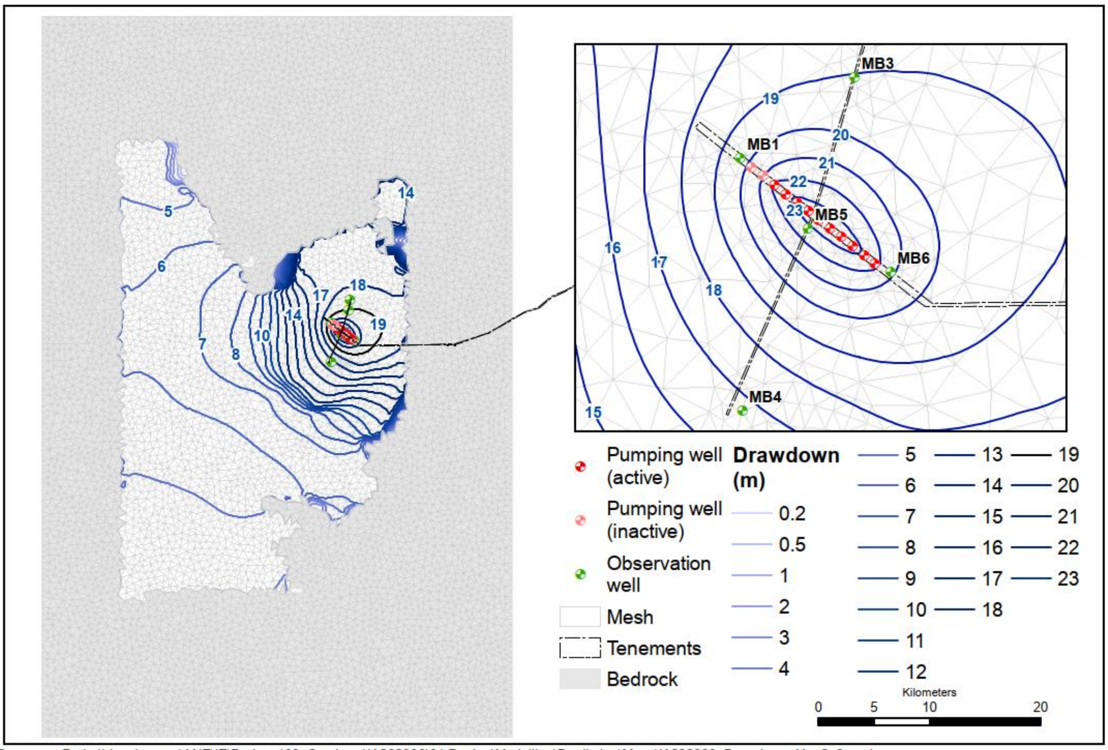

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Figure 6.12: Uncertainty Scenario 3 – Predicted drawdown in December 2029

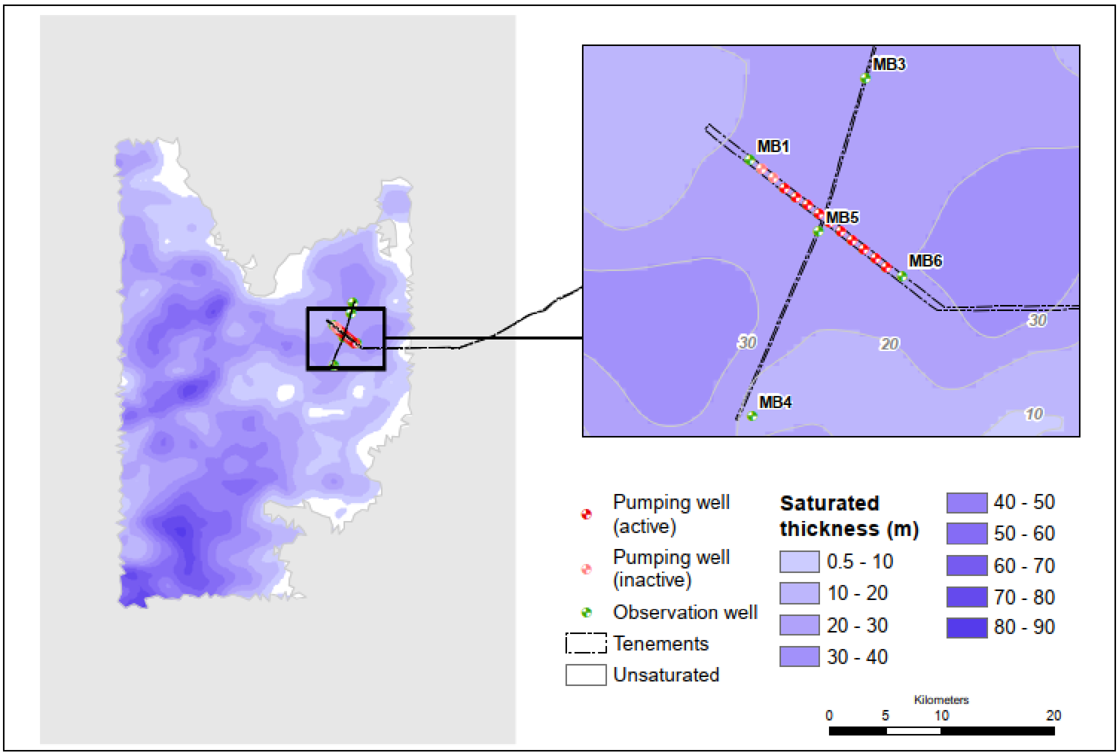

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Figure 6.13: Uncertainty Scenario 3 - Predicted saturated thickness in December 2029

7. Conclusion

The investigation has involved updating and verifying an existing MODFLOW groundwater model (SKM, 2006 and 2011) of a non-renewable palaeochannel groundwater resource currently being used for the supply of water to Iluka's Jacinth Mine. The existing model was successfully migrated to the finite-element Feflow numerical modelling code, and a number of modifications were made to better represent the current conceptualisation of the aquifer system being tapped by the wellfield. The most significant change in the model design being a substantial increase in areal extent and thickness of the aquifer. The increase in aquifer area and thickness, and revised model layer structure, resulted from interpretation of recently acquired AEM data covering a broad area surrounding the wellfield.

The wellfield has been supplying water to the Jacinth Mine, more or less continuously, since mid-2009. For the purposes of model calibration and verification, the groundwater extraction records and the available observations of associated groundwater level responses were split into two independent data sets for the periods 2009 to the end of 2013 and from 2014 to 2019. The earlier data sets were used to calibrate the model and the later data used for independent verification purposes. While the model was able to better represent groundwater behaviour in the verification period than in the calibration period, there was a reasonable match between model-estimated and observed groundwater hydrographs across the full period of historic groundwater monitoring data. This outcome suggests that Iluka can have reasonable confidence in predictive estimates, with the model exhibiting most of the characteristics of a Class 3 Confidence Level Classification after objective and relevant criteria are adopted (Barnett *et al.*, 2012).

Predictive models considered high, medium, and low wellfield water demand options based on alternative mine tailings disposal approaches at Jacinth, Ambrosia and Atacama mines. The predictive scenarios demonstrated that the existing wellfield is likely able to meet all foreseeable water demand options without completely desaturating the aquifer at the wellfield, nor breaking existing well pump suctions.

An uncertainty analysis was undertaken to assess alternative aquifer parameters and to explore the sensitivity of model results to variation porosity and to the area of the aquifer, effectively assessing potential uncertainty in AEM results and interpretations. It was found that the modelled wellfield was able to meet the high water demand scenario in all uncertainty cases, thus providing further confidence in the ability of the wellfield to meet foreseeable future water demand for Iluka's mining operations at Jacinth, Ambrosia and Atacama. That said, groundwater level and extraction monitoring within the wellfield should continue to be undertaken on at least a monthly basis, with the model itself verified annually. Any significant departure from model-estimated and observed heads should result in the re-calibration of the model, re-interpretation of the basement topography, or some combination thereof.

8. References

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Appendix A. Calibration and verification PEST results

A.1 Optimised PEST Calibration

The comparison between the calibrated model-predicted heads and the observed heads is shown in Figure A.1. If the predicted heads perfectly matched the observed heads in every well, all the points would fall on the perfect match line shown on the chart. Calibration hydrographs of the monitoring wells at the wellfield are presented in Figure A.2.

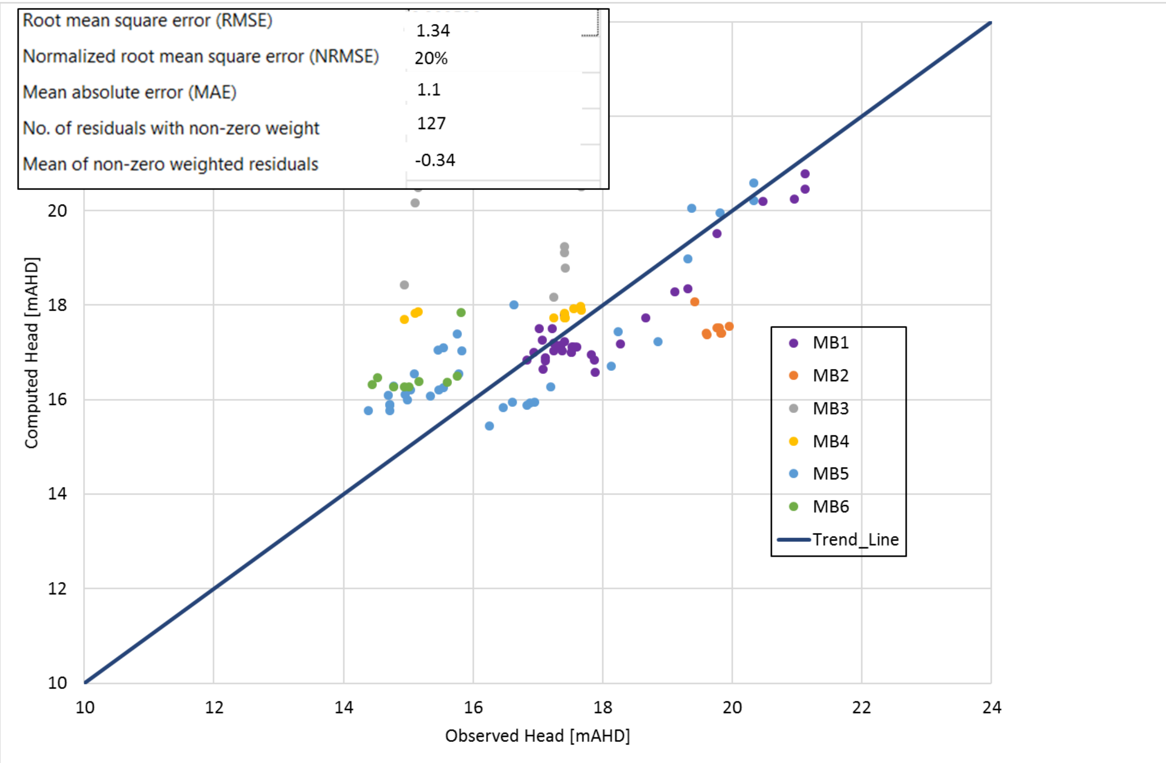


Figure A.1: Calibration scatter plot (optimised PEST parameters)

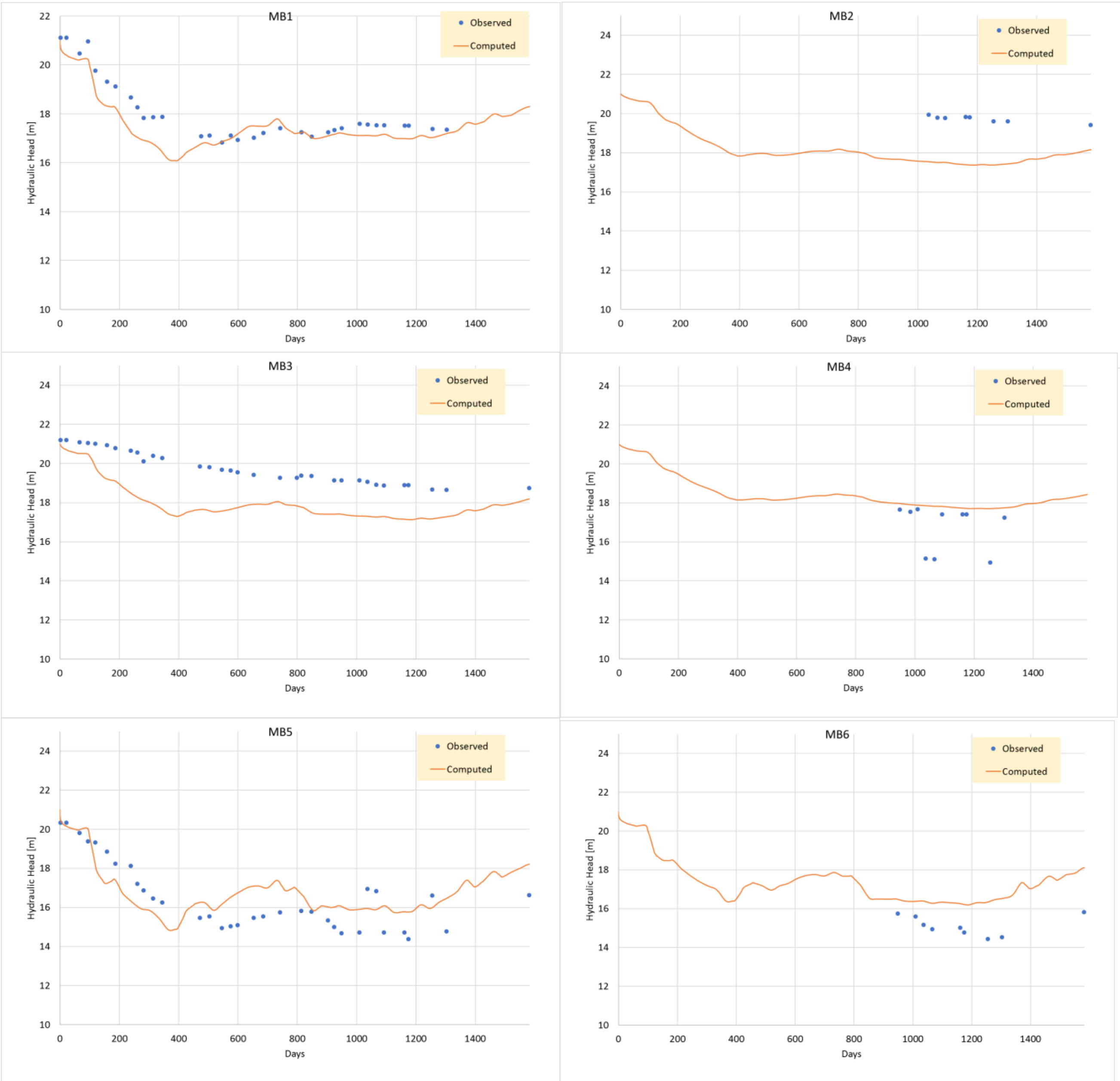


Figure A.2: Calibration hydrographs (PEST optimised parameters)

A.2 Verification of the PEST optimised model

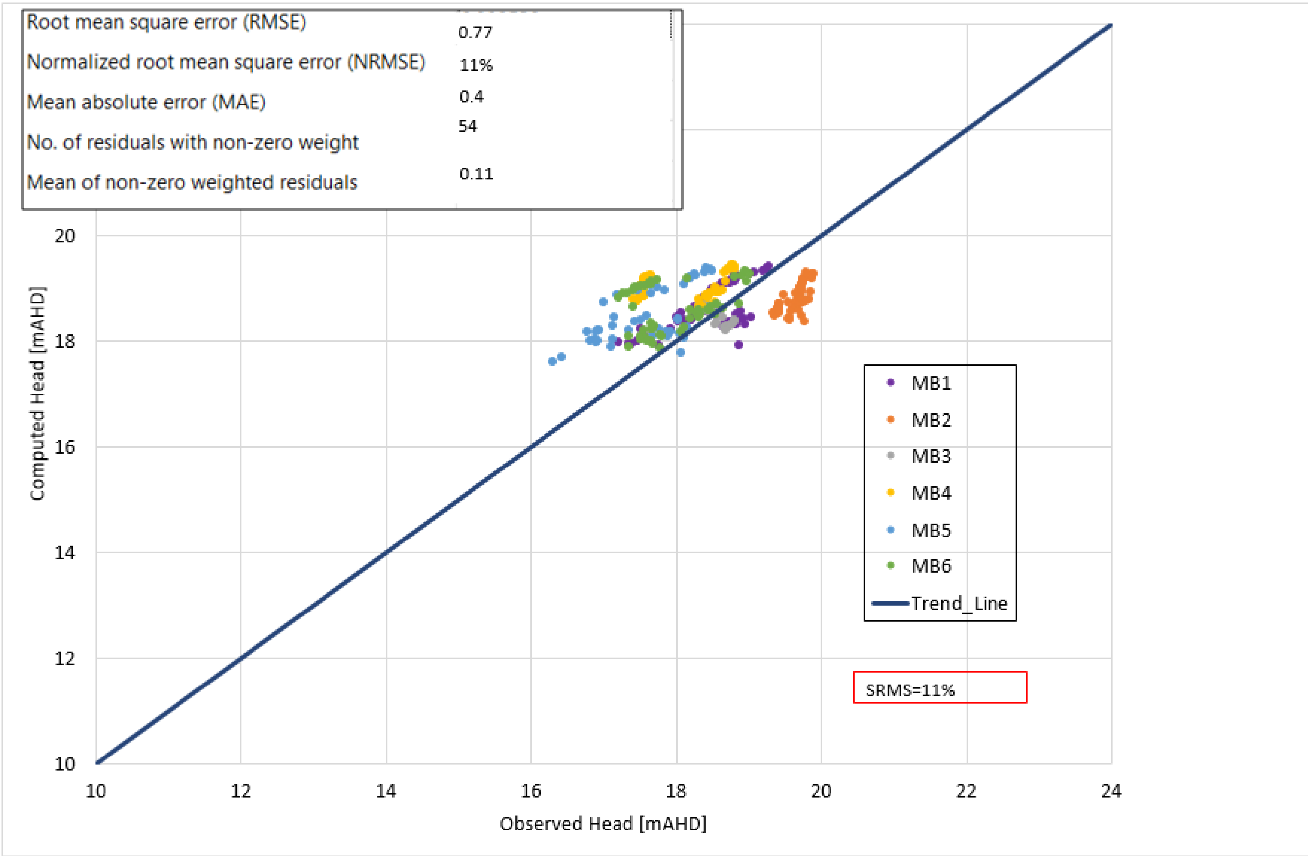


Figure A.3: Validation scatter plot (PEST parameters)

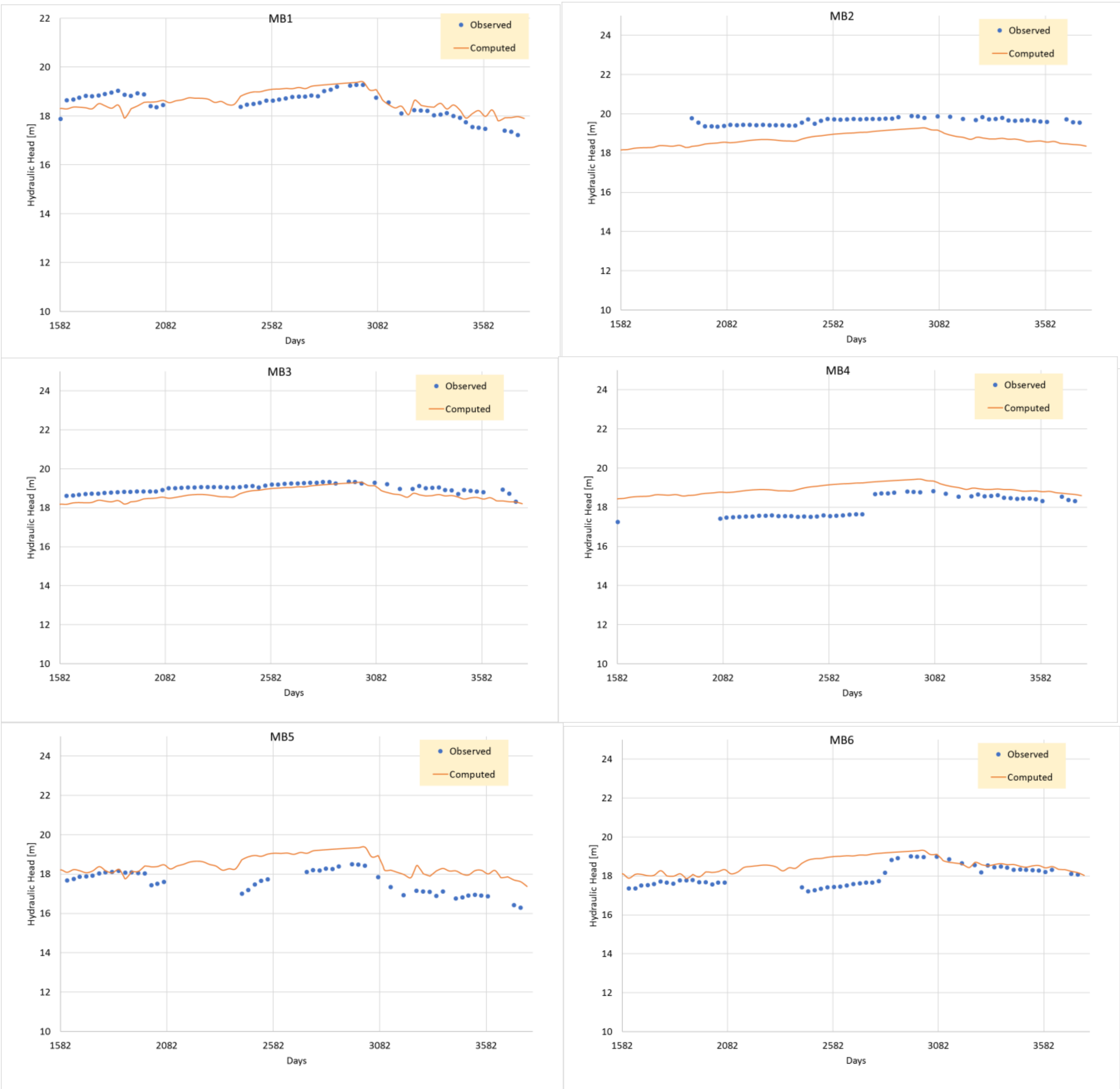
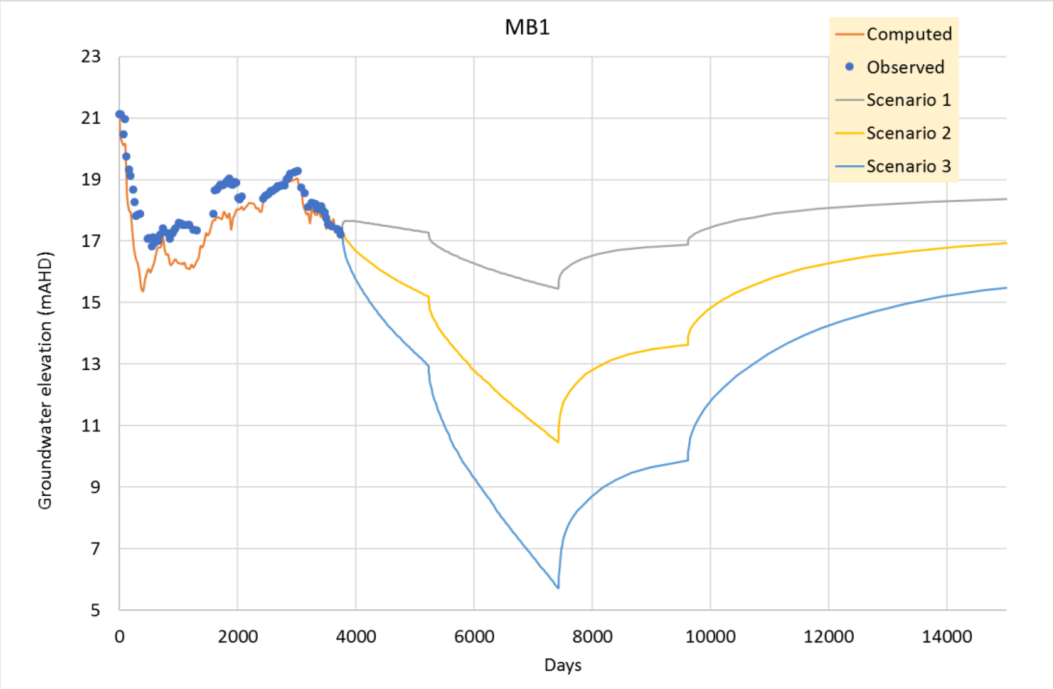
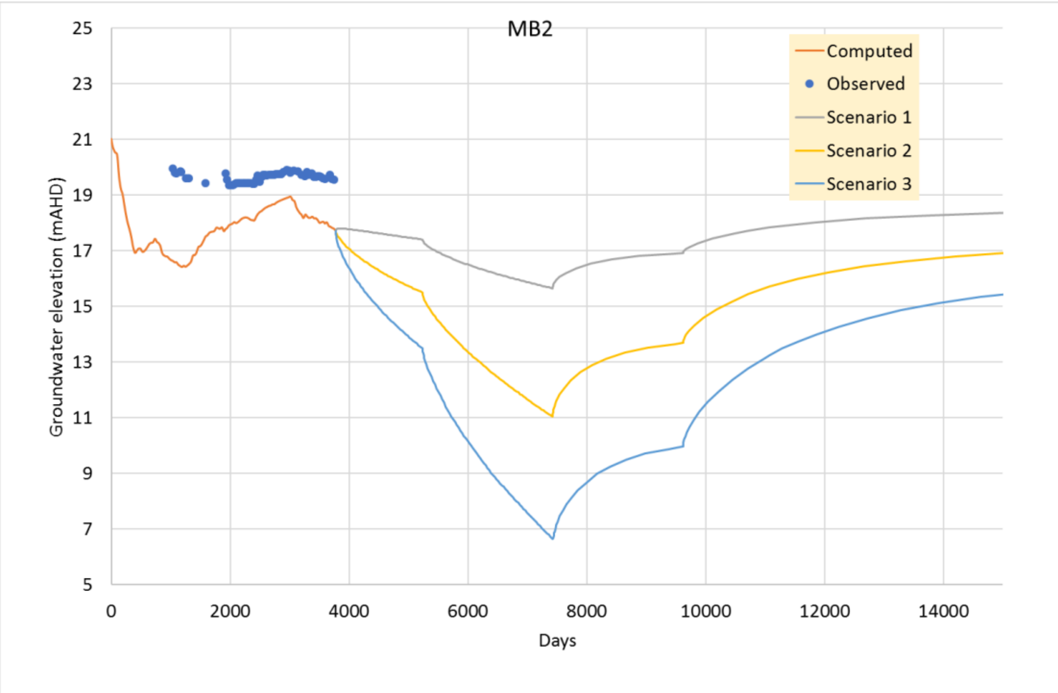
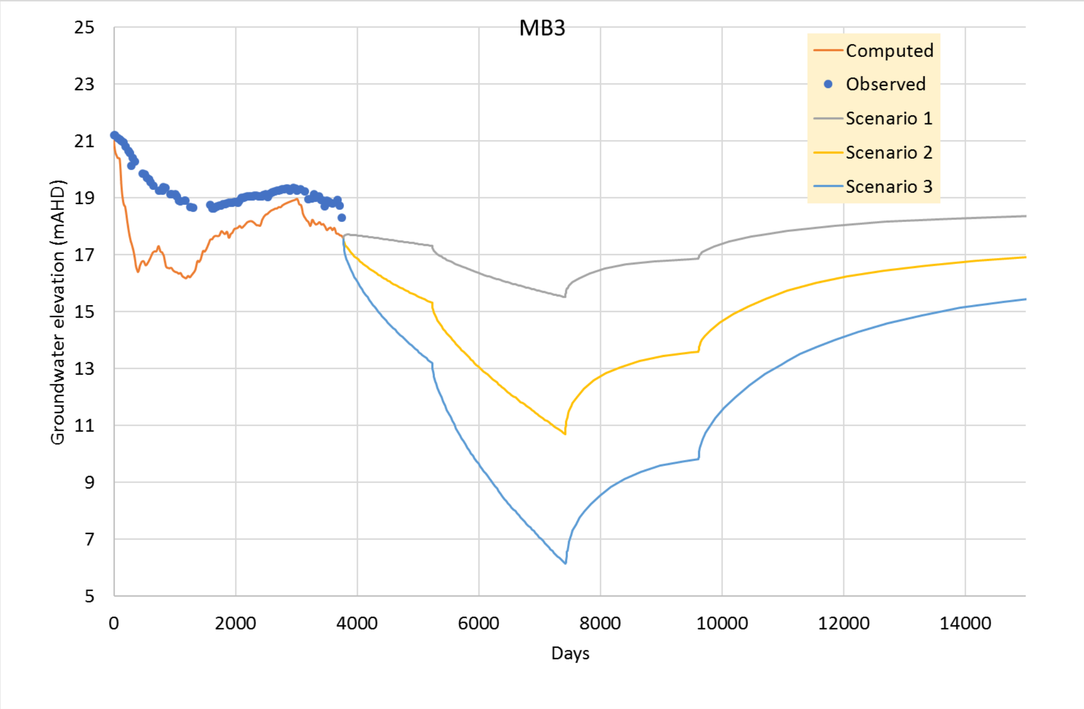


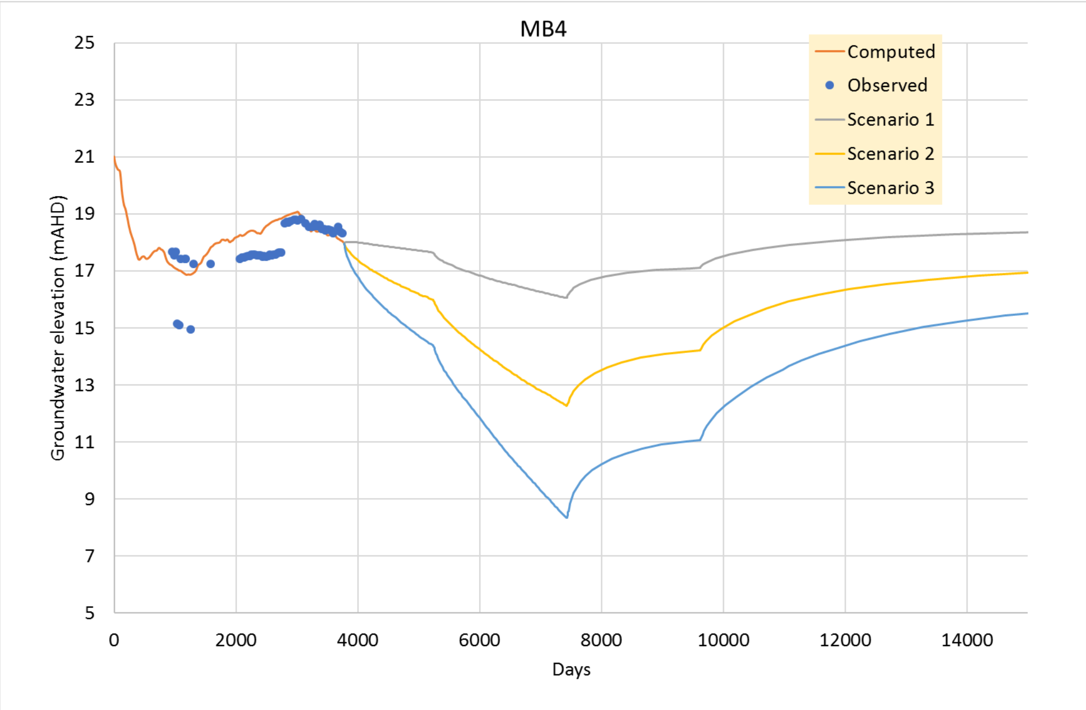
Figure A.4: Validation hydrographs (PEST parameters)

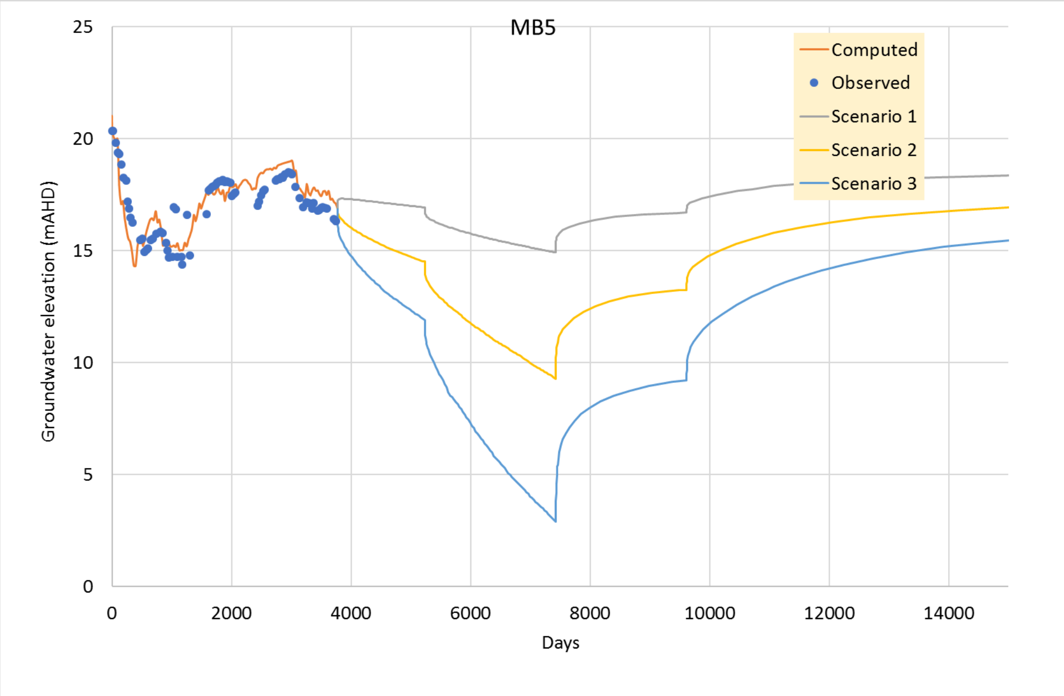
Appendix B. Hydrographs

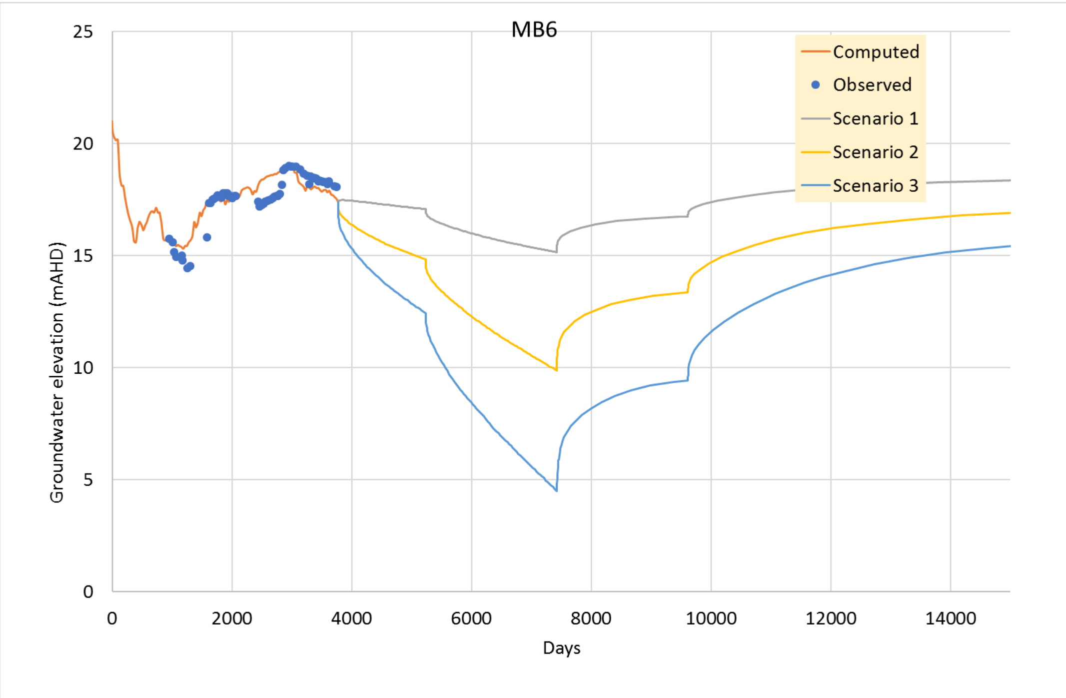




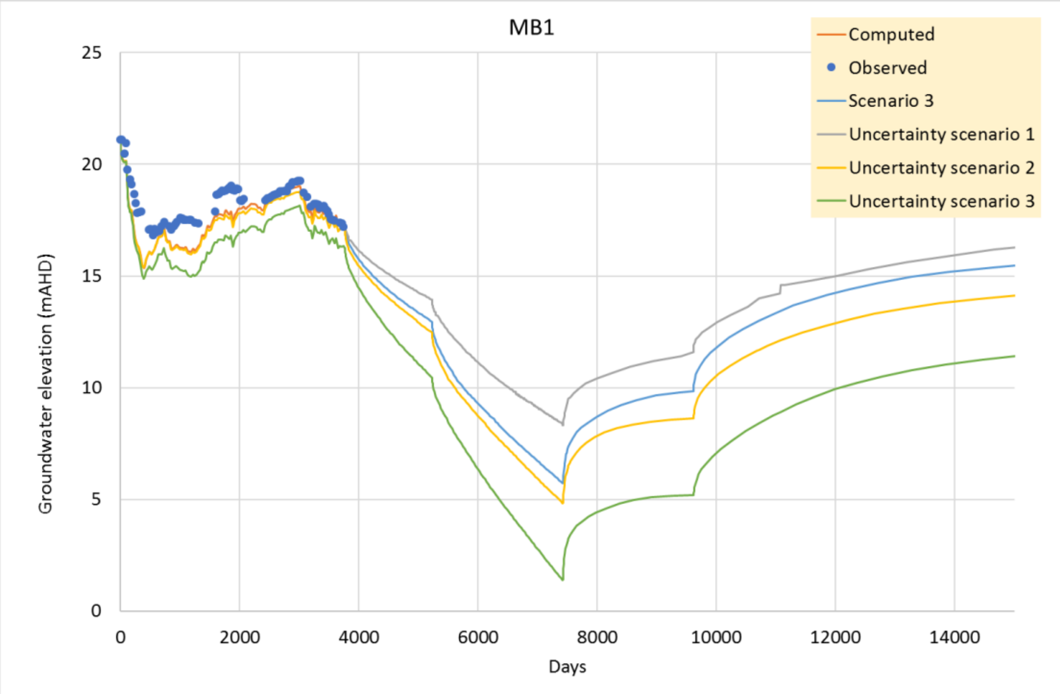

MB3
Computed
Observed
Scenario 1
Scenario 2
Scenario 3
Groundwater elevation (mAHD)
25
23
21
19
17
15
13
11
9
7
5
0
2000
4000
6000
8000
10000
12000
14000
Days

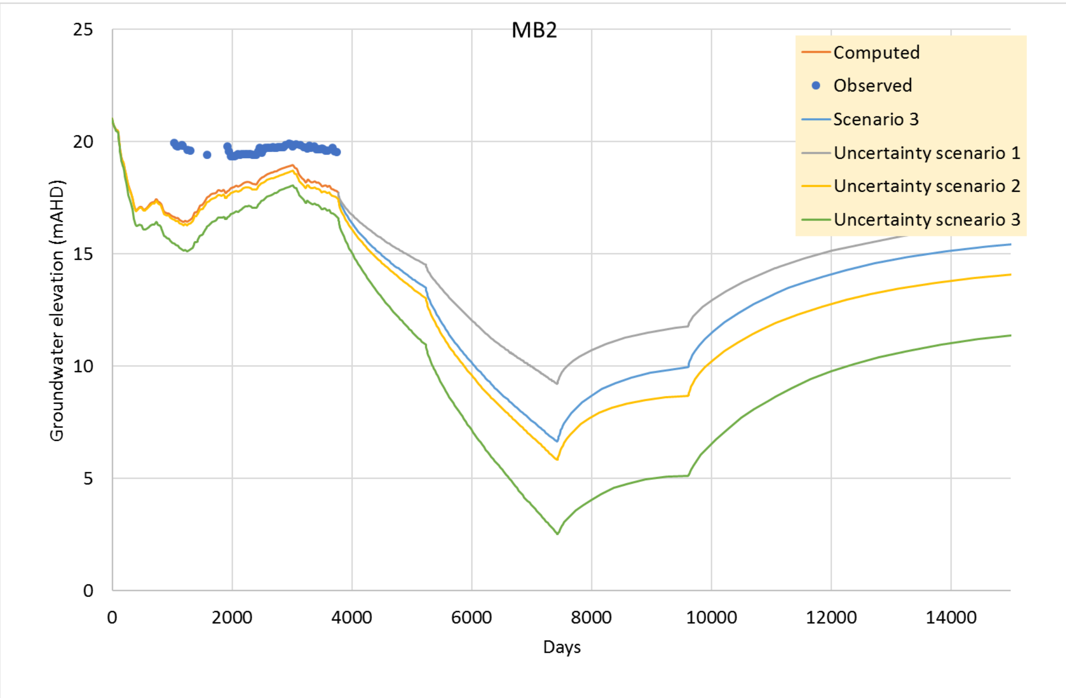

MB4
Computed
Observed
Scenario 1
Scenario 2
Scenario 3
Groundwater elevation (mAHD)
25
23
21
19
17
15
13
11
9
7
5
0
2000
4000
6000
8000
10000
12000
14000
Days

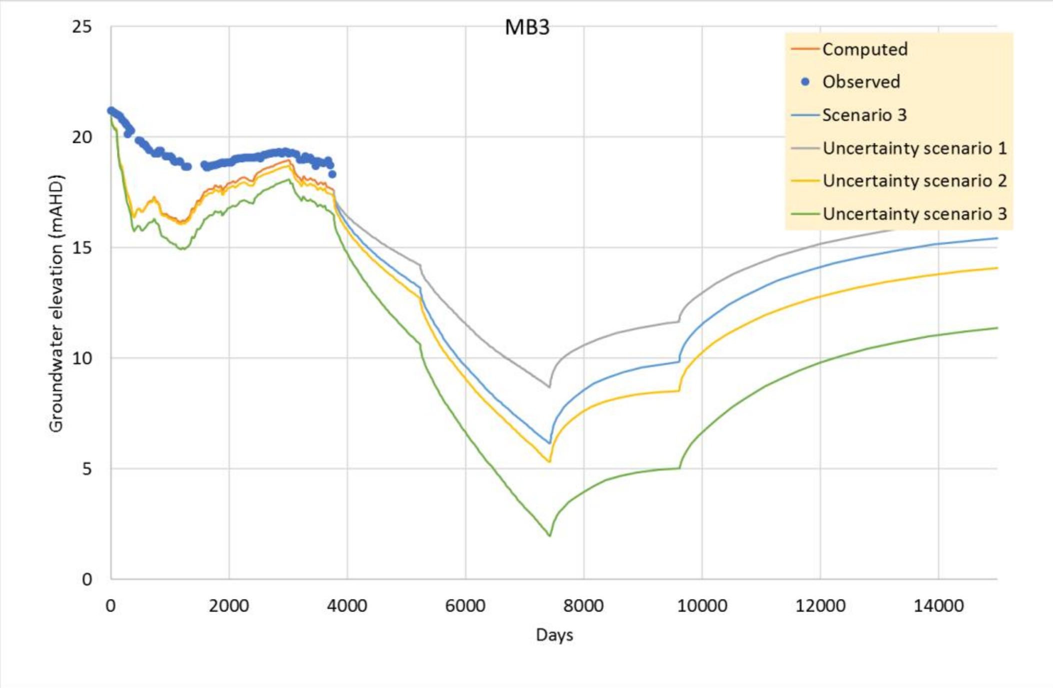

MB5
Computed
Observed
Scenario 1
Scenario 2
Scenario 3
Groundwater elevation (mAHD)
Days
0
5
10
15
20
25
0
2000
4000
6000
8000
10000
12000
14000

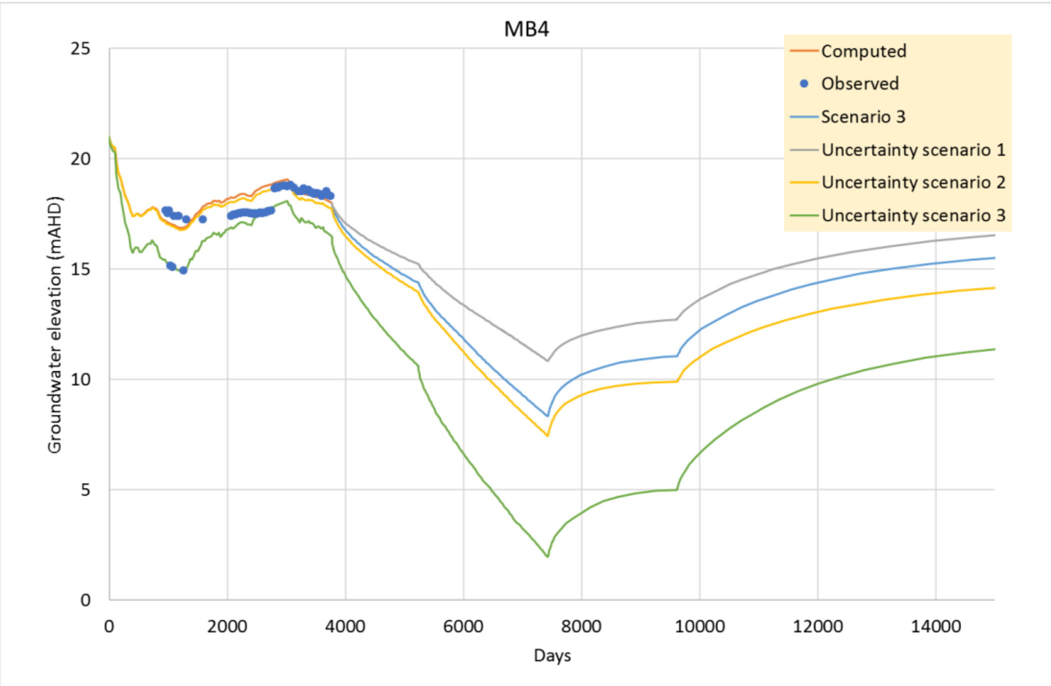

MB6
Computed
Observed
Scenario 1
Scenario 2
Scenario 3
Groundwater elevation (mAHD)
Days
0
5
10
15
20
25
0
2000
4000
6000
8000
10000
12000
14000

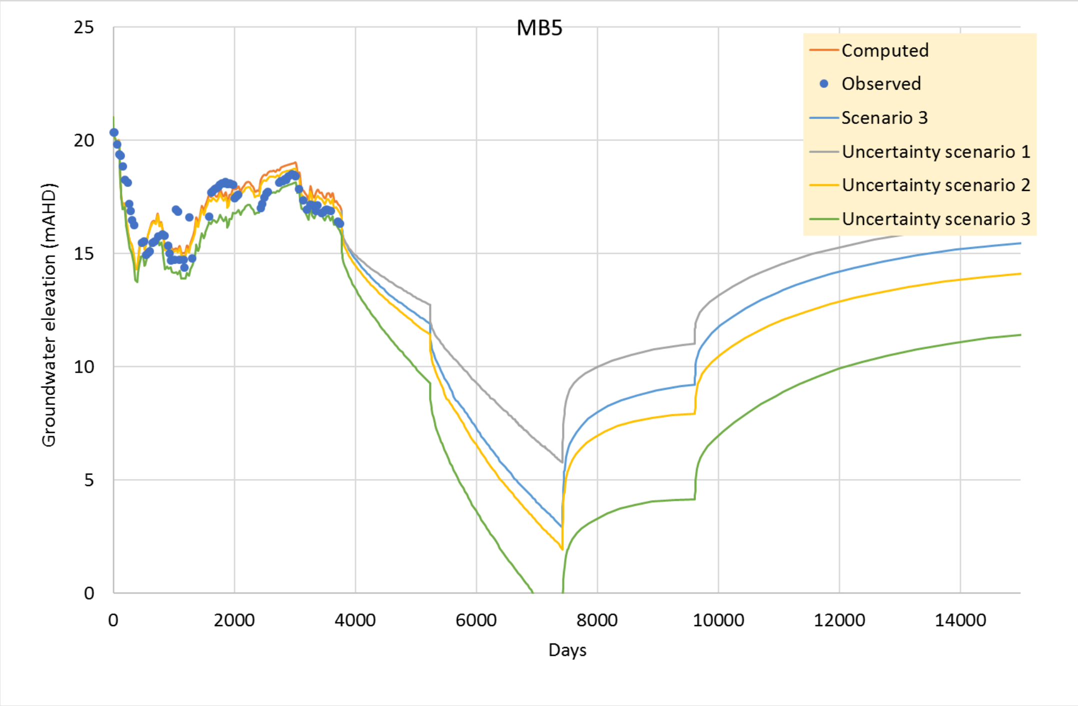
Appendix C. Uncertainty analysis hydrographs

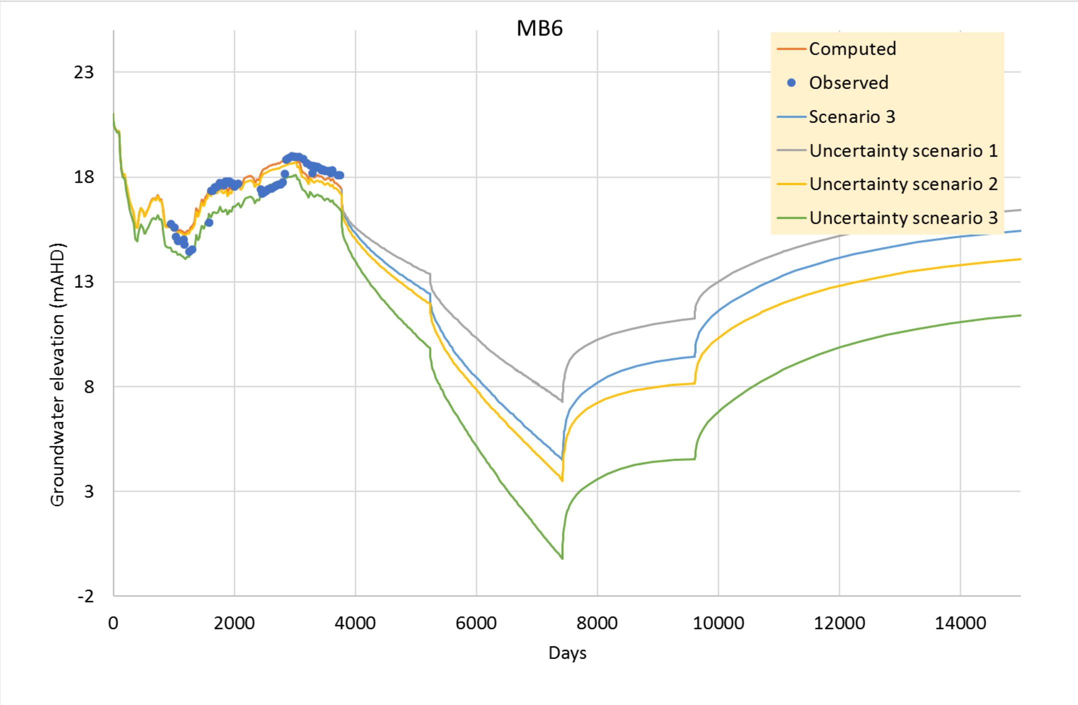





MB3
Computed
Observed
Scenario 3
Uncertainty scenario 1
Uncertainty scenario 2
Uncertainty scenario 3
Groundwater elevation (mAHD)
Days
0
5
10
15
20
25
0
2000
4000
6000
8000
10000
12000
14000


MB4
Computed
Observed
Scenario 3
Uncertainty scenario 1
Uncertainty scenario 2
Uncertainty scenario 3
Groundwater elevation (mAHD)
Days
0
5
10
15
20
25
0
2000
4000
6000
8000
10000
12000
14000


MB5
Groundwater elevation (mAHD)
Days
Computed
Observed
Scenario 3
Uncertainty scenario 1
Uncertainty scenario 2
Uncertainty scenario 3


MB6
Groundwater elevation (mAHD)
Days
Computed
Observed
Scenario 3
Uncertainty scenario 1
Uncertainty scenario 2
Uncertainty scneario 3