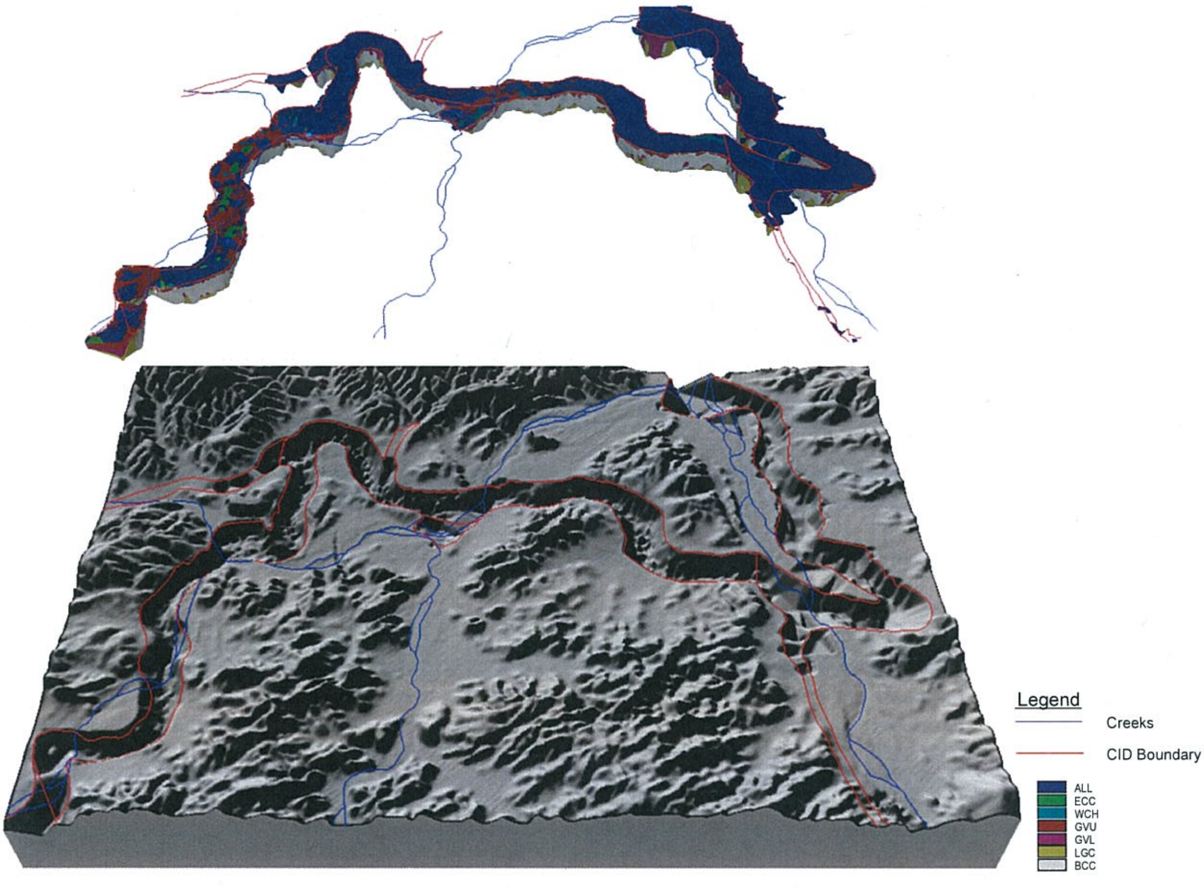
Water Resource Evaluation / Projects & Development

Yandicoogina 2013 Groundwater Model Setup and Calibration

December 2013

RTIO-PR-0733863



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1. Introduction

Rio Tinto Iron Ore (RTIO) developed a numerical groundwater model in 2008 for Yandicoogina Operations (Yandi). The model was developed for the 45C licence application and assessing dewatering requirements for the site. The model domain was limited to mining and dewatering at Junction Central and Junction South East.

As part of Yandi's expansion work (below water table mining at Junction South West (JSW) is to commence in 2014 and Billiards South (BS) is undergoing a pre-feasibility study) the model domain needed to be extended to minimise boundary effects from dewatering in the Channel Iron Deposit (CID). Based on the 2008 model, the new model domain was extended to the west and north and updated with the alluvium layer defined in the 2010 regional groundwater model (RTIO-PDE-0078850). The number of model layer was also increased from 7 to 15 to refine the geology from RTIO Vulcan geology block model for JSW and BS. The model was calibrated against observed hydrographs from 1998.

This report presents the model setup and calibration of the new model. The intent of the model is to predict water table level for the medium-term-plan (MTP), assess what if's scenarios and set dewatering targets for Operations.

Numerical Groundwater Model.

2. Numerical Model Code

The modelling code selected to simulate the groundwater flow condition at Yandicoogina was MODSURFACT version 3.0. MODSURFACT is an enhanced version of the widely used United States Geological Survey MODFLOW. MODSURFACT was used mainly to overcome the numerical instability associated with MODFLOW rewetting of dry cells, and better representation of dewatering wells with Fractured Well Package. The solver selected was PCG5 with adaptive time stepping. MODSURFACT was developed by HydroGeoLogic, Inc. The pre- and post-processor used was Visual MODFLOW version 4.3 developed by Schlumberger Water Services.

3. Model Setup

The numerical model domain extends 25.5 km north-south and 30km east-west to cover the CID areas and minimise model boundary effects (Figure 1).

MODSURFACT is a finite-difference numerical code that requires the model domain to be discretised into three-dimensional blocks that broadly represent the rock mass within it. The model setup consists of 425 rows, 491 columns and15 layers. Irregular grids were used to capture the required hydrogeological details, maintain numerical stability, and minimise model runtime. The smallest grid measures 31m x 32m and the largest blocks measures 509m x 750m (Figure 1). The top of layer 1 was assigned the elevations of the surface topography and the bottom layer is flat at 250mRL. Variable layer thicknesses were used to capture the geology in the CID as shown on Figures 2 and 3.

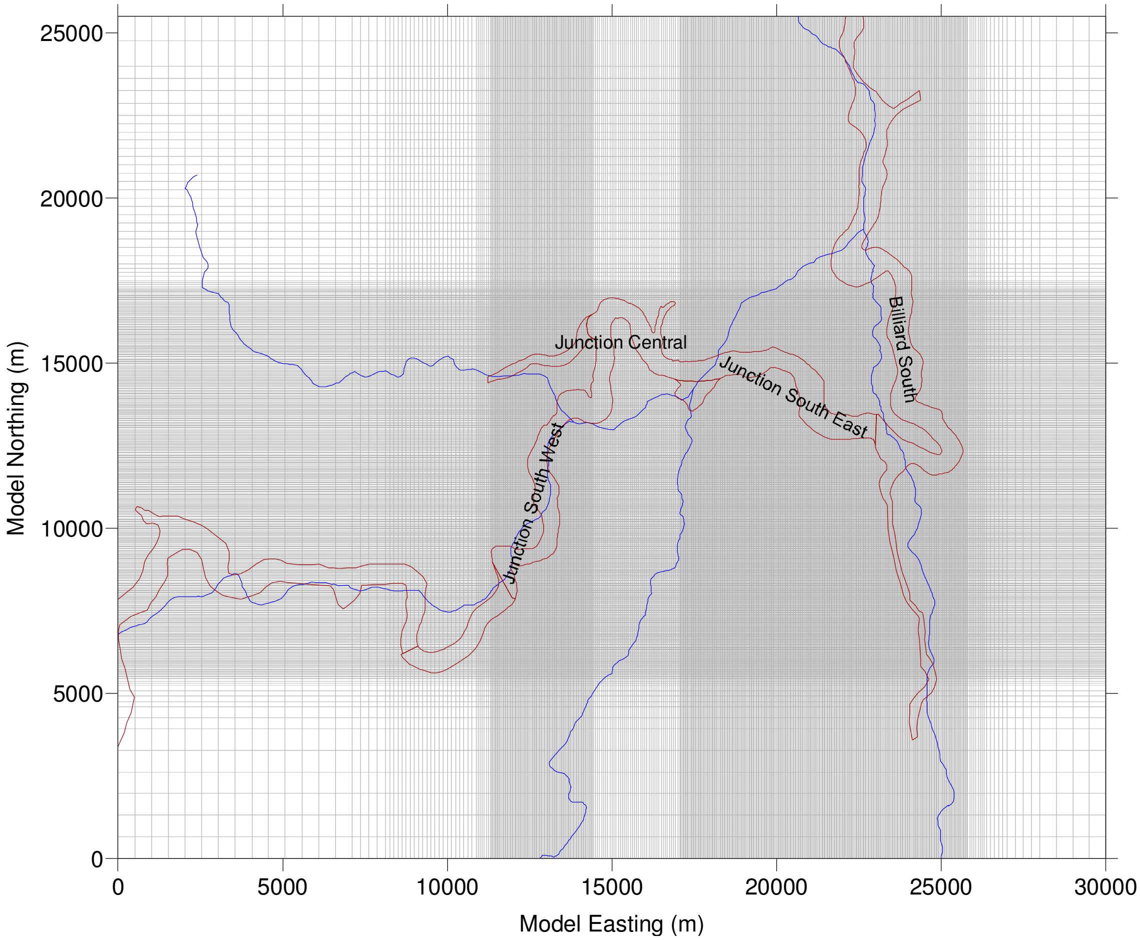


Figure 1   Model Domain and Discretisation.

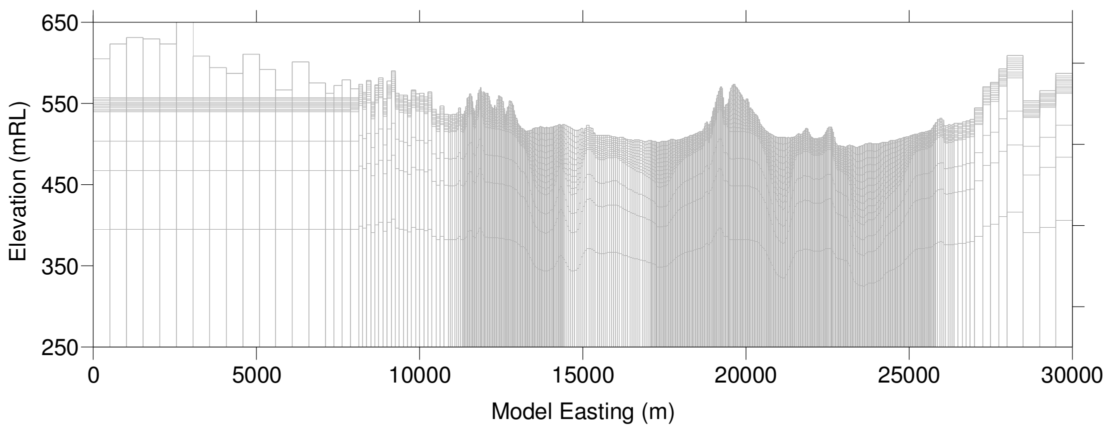


Figure 2   Vertical Discretisation – East West Cross-Section along 13984mN.

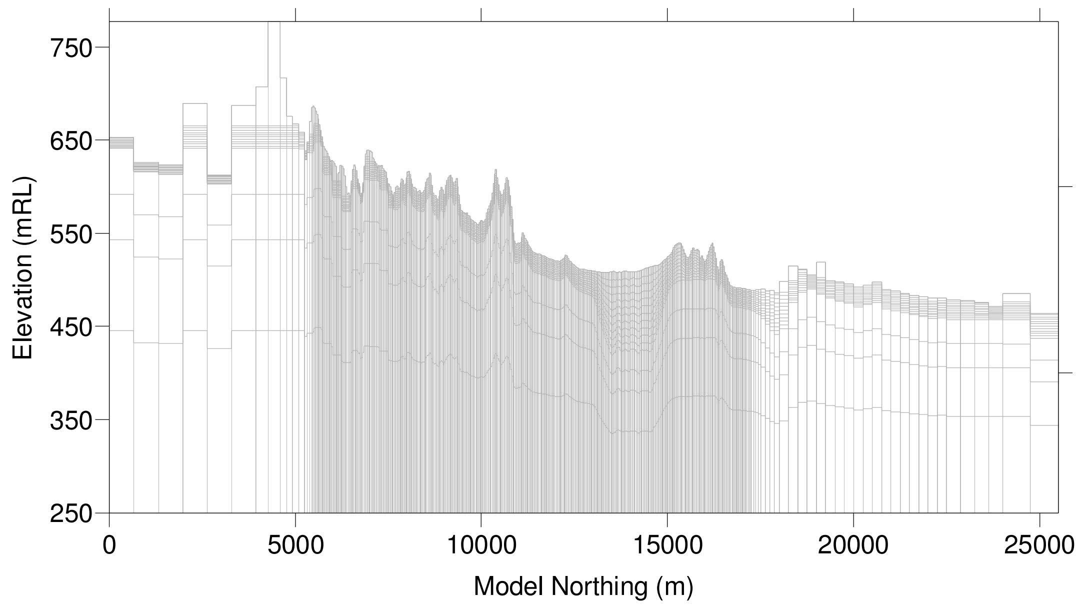


Figure 3 Vertical Discretisation – North South Cross-Section along 21015mE.

The hydrostratigraphic units were based on geo-stratigraphical interpretations consisting of the alluvial, eastern clay conglomerate (ECC), weathered channel deposit (WCH), goethite vitreous upper (GVU) and goethite vitreous lower (GVL), limonitic goethite clay (LGC), basal clay conglomerate (BCC), Weeli Wolli Formation and Brockman Iron Formation resource drilling database and Vulcan geology block model.

Figures 4 and 5 show the distribution of the hydrostratigraphic units in layers 1, 5, 10 and 15 and Figures 6 and 7 show cross-sectional views. The hydraulic characteristics of these materials were initially estimated from aquifer test pumping conducted mainly within the CID and adjusted through calibration to long term pumping. Outside the CID, the thicknesses of the alluvial and weathered basement were broadly assumed due to limited available data. As the Weeli Wolli Formation and the Brockman Iron Formation within the model domain is fractured, these domains were assumed permeable and modelled as equivalent porous media.

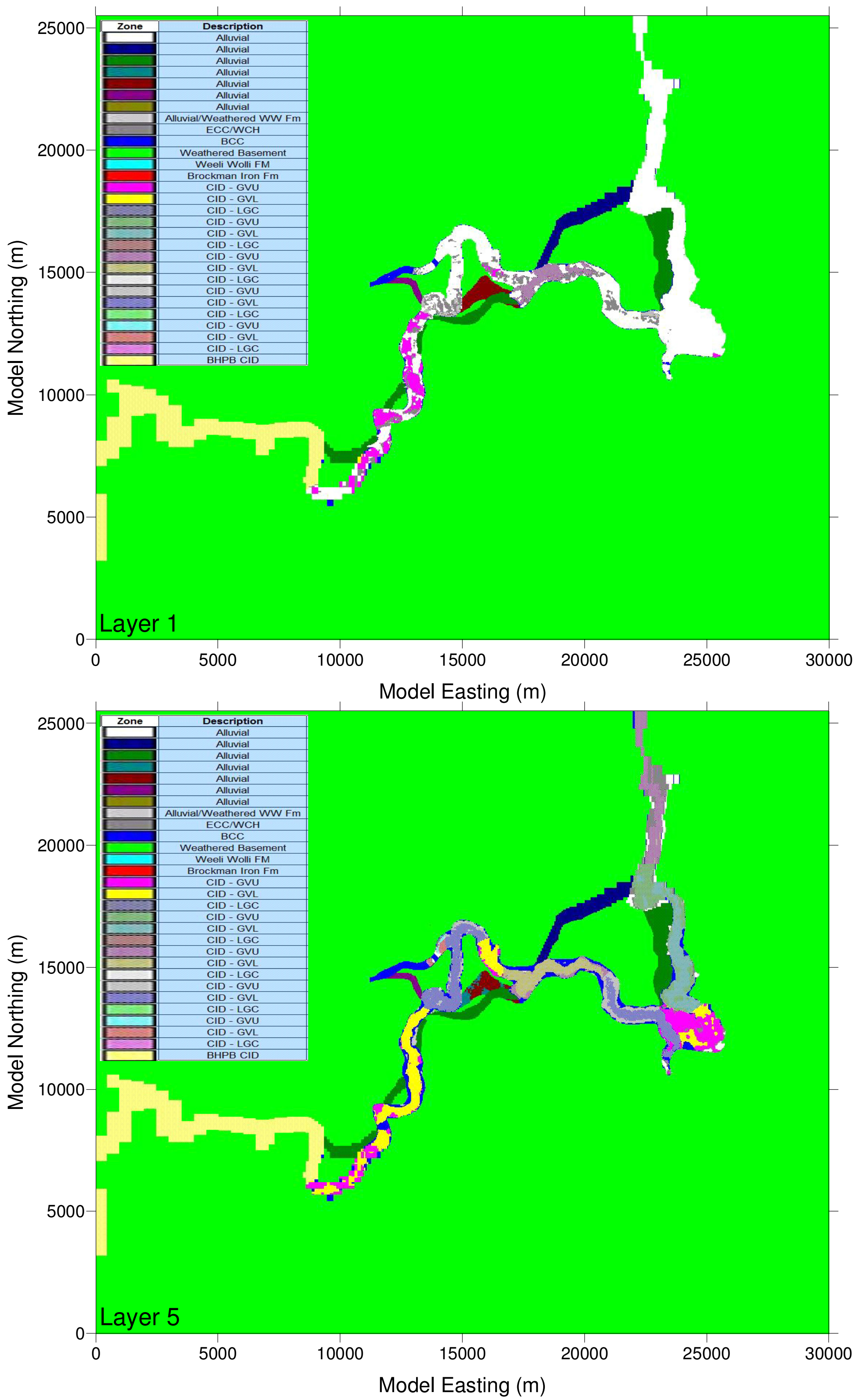


Figure 4 Hydraulic Parameter Zones – Plan View (Layer 1 and 5).

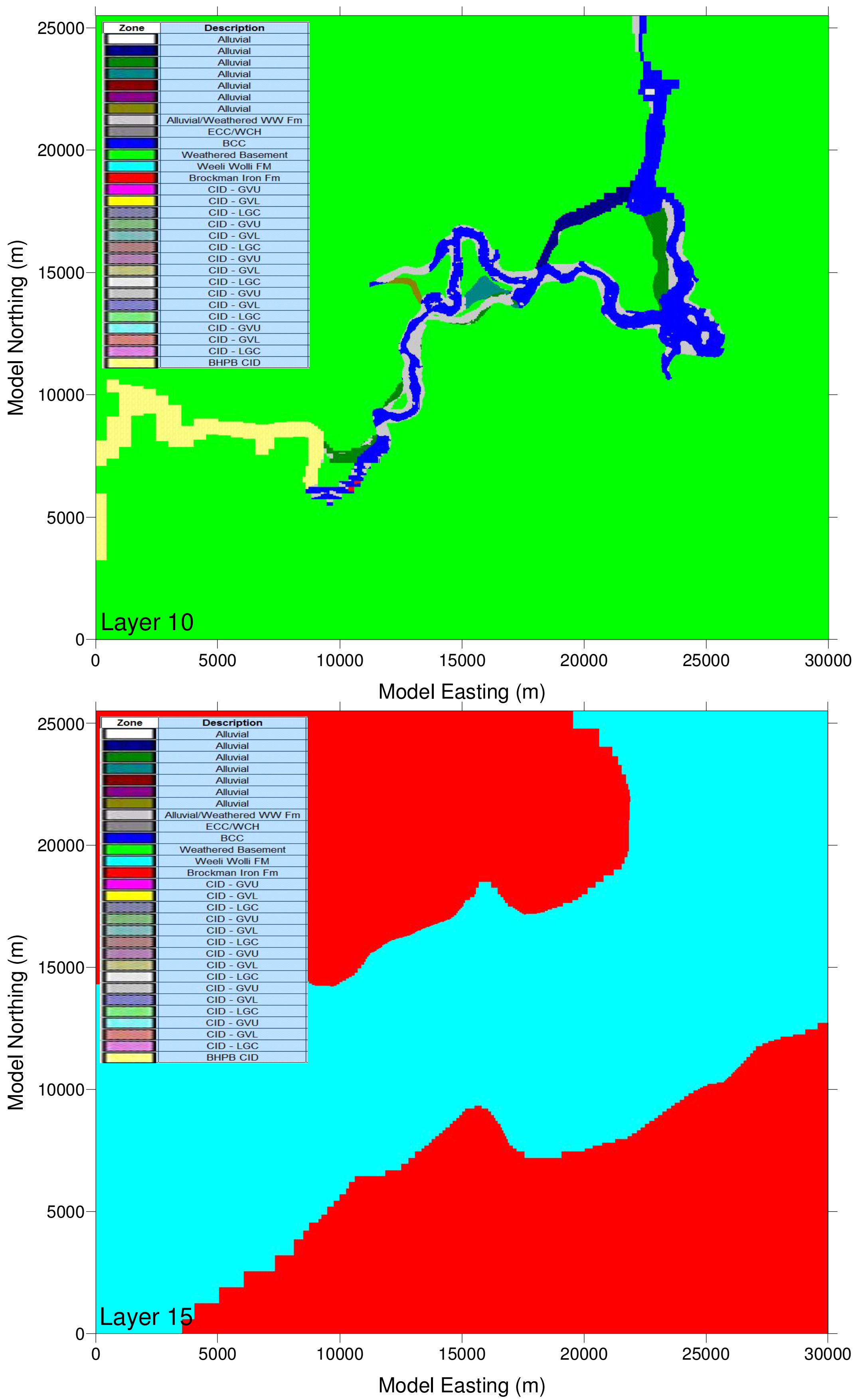


Figure 5 Hydraulic Parameter Zones – Plan View (Layer 1 and 5).

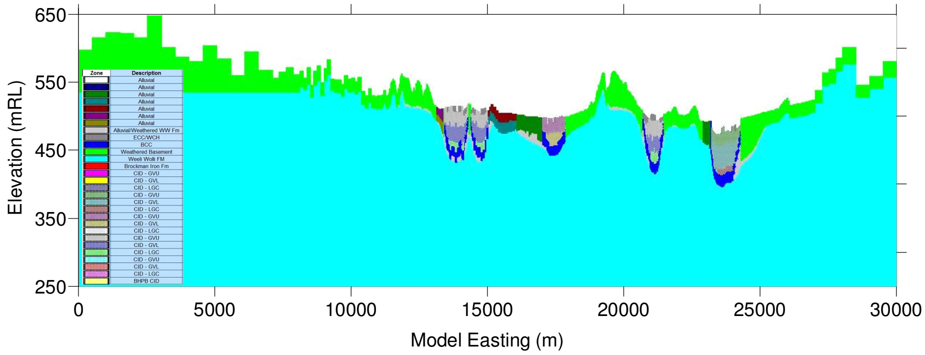


Figure 6   Hydraulic Parameter Zones – East West Cross-Section along 13984mN (looking north).

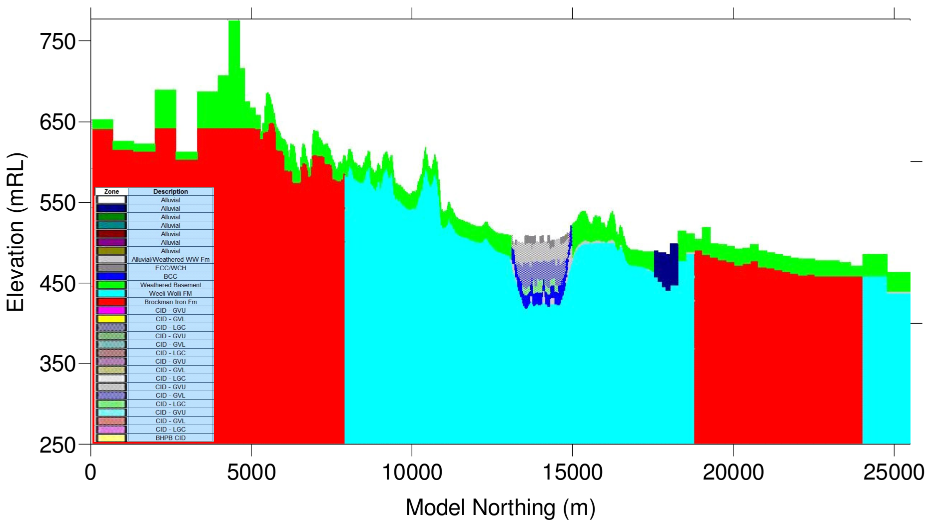


Figure 7   Hydraulic Parameter Zones – North South Cross-Section along 21015mE (looking west).

No-flow boundary condition was assigned to the model boundaries to represent the relatively impermeable Weeli Wolli Formation and Brockman Iron Formation outside the model domain except in the CID. Constant head boundary condition was assigned to the CID upgradient of the mine and MODFLOW drain cells were assigned to the CID down gradient of the mine as shown on Figure 8. This approach facilitates regional groundwater to flow from the west and south to the north-north-east matching observations. MODFLOW drain cells were also used in the mined out area at Junction Central to represent in-pit sump pumping.

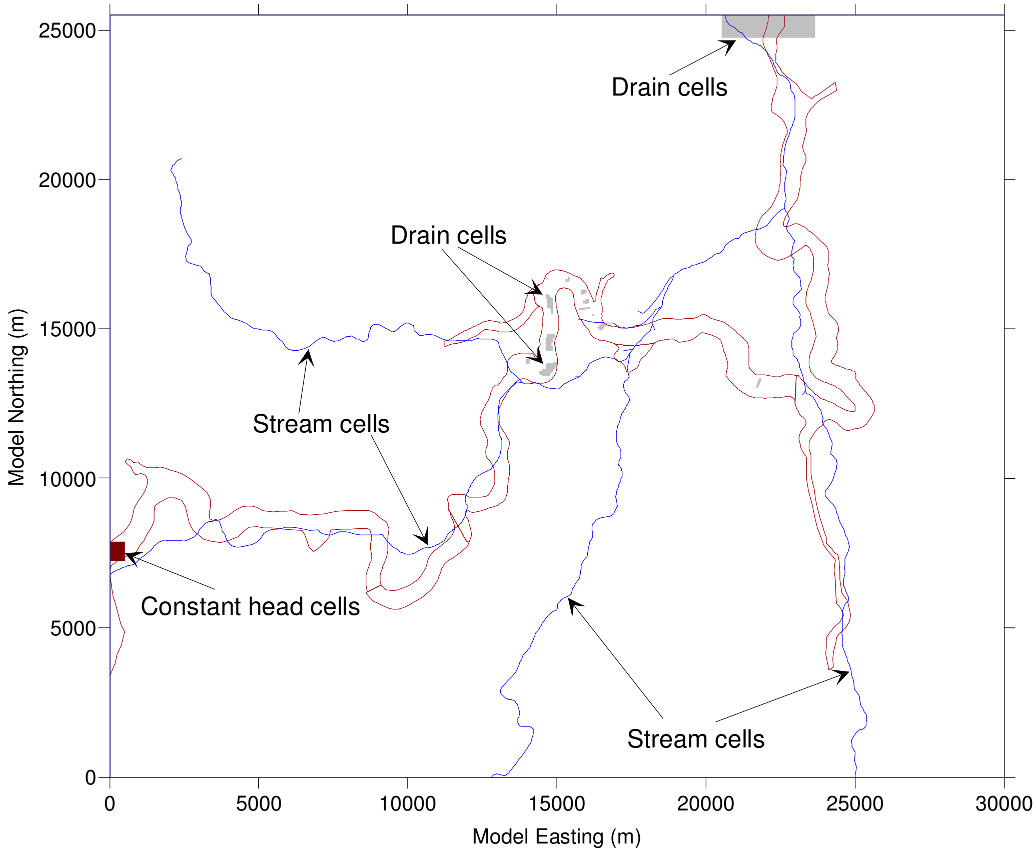


Figure 8 Model Boundary Conditions.

Direct rainfall recharge is represented in the model by MODFLOW recharge cells with selection that recharge enters the highest saturated layer i.e. cells that contain the water table. As direct rainfall recharge to the water table potentially occurs when it rains, measured rainfall were used to temporally vary monthly recharge rates assigned to the MODFLOW recharge cells. This simplified approach scaled the monthly measured rainfall and assumes all infiltration assigned enters the water table. Figure 9 shows the recharge zones assigned to the model based on surface geology and geomorphology. Although this approach is not very accurate in an arid environment, it serves as an approximation of seasonal rainfall recharge.

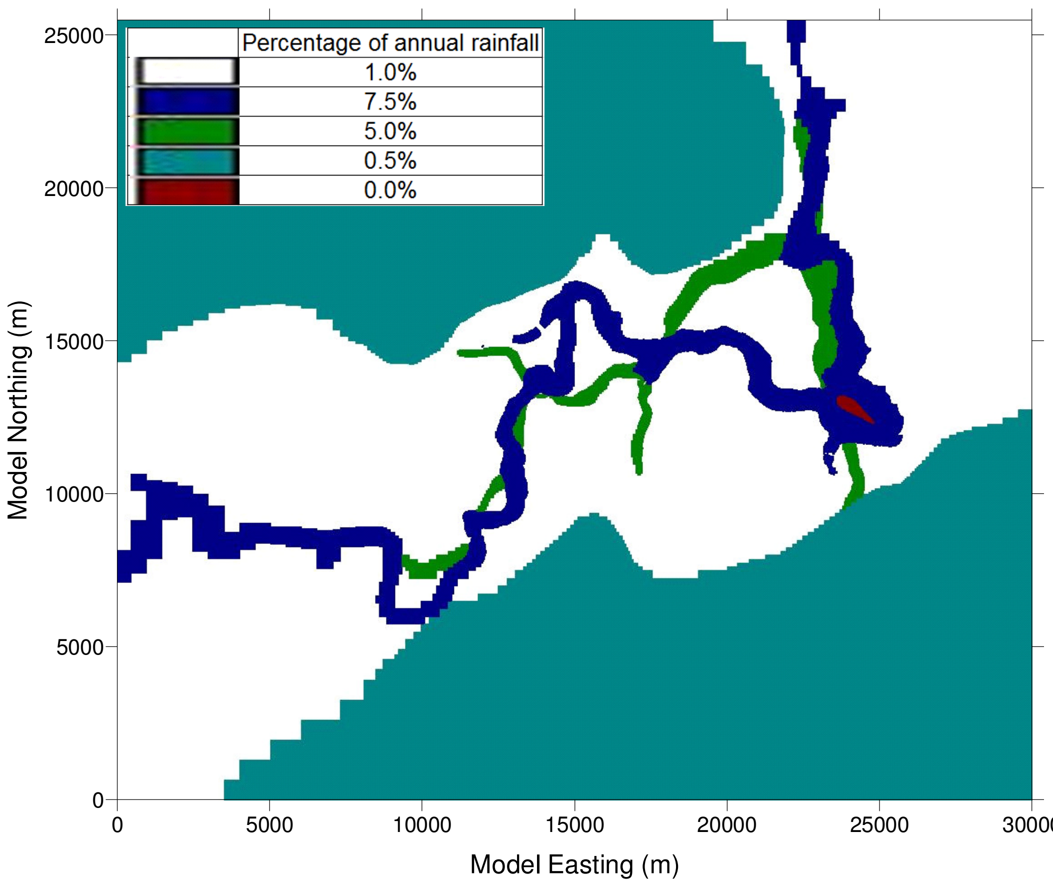


Figure 9 Recharge Zones.

Indirect rainfall recharge from leakage from the creeks was modelled with MODFLOW stream cells. The use of stream cells accounts for losses and gains along the creek i.e. leakage upstream results in reduction in stream flow downstream. This is important in the model because Marillana Creek intersects the CID at a number of places where leakage potentially occurs. Dewatering in the CID has the potential to induce more leakage and hence lessen the amount of water that moves downstream and be available downstream. The rate of leakage is controlled by the streambed conductance of the stream cells. The variability and lack of measured values of the conductance between the creeks and the underlying aquifers has resulted in the trial and error adjustment of the streambed conductance in the model calibration. A uniform rectangular stream width of

5m was assumed and a manning roughness coefficient of 0.093 was used to calculate the stage height for all the creeks. Stream cells were assigned to Marillana, Weeli Wolli, Yandicoogina, Phil's creeks and all the 7 discharge outlets as shown on Figure 10.

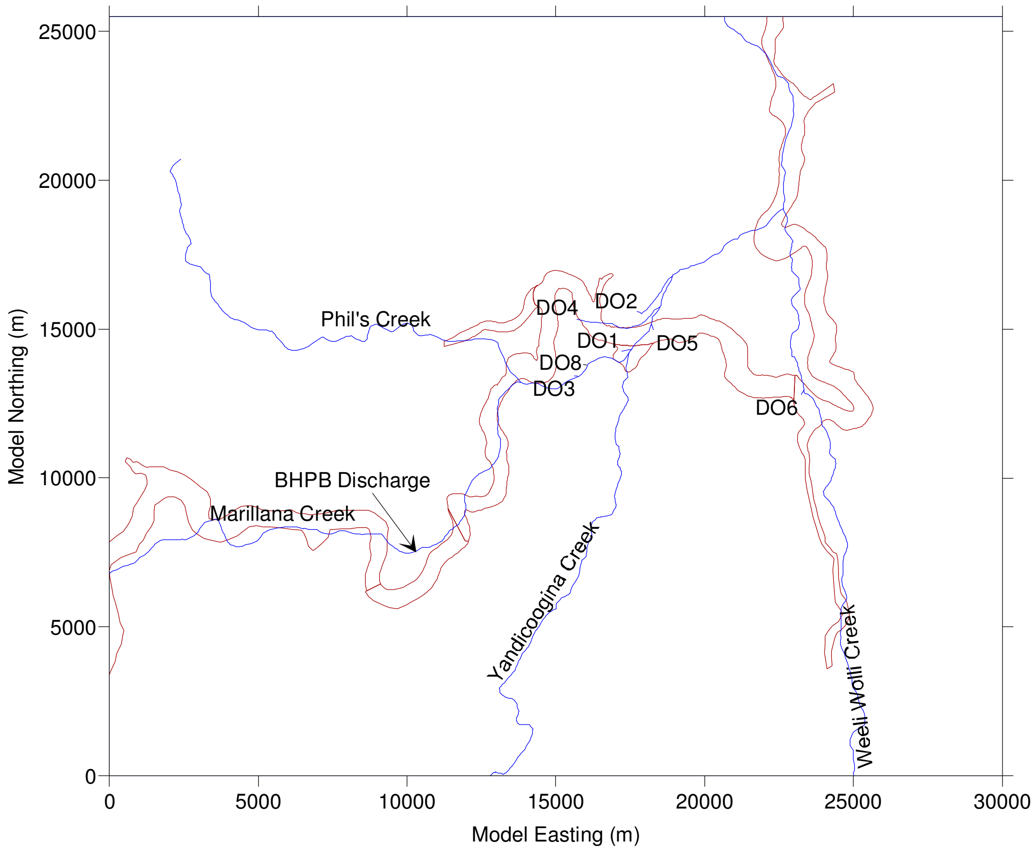


Figure 10 MODFLOW Stream Cells.

Measured discharge rates from Yandi's discharge outlets were assigned to the highest upstream stream cells in the model. Scaled catchment runoff for Yandicoogina and Phil's creeks were assigned to the highest upstream stream cells. Discharge from BHPB Yandi was added to the scaled catchment runoff upstream of the discharge location. Inflow into Weeli Wolli Creek at the model boundary was modelled by scaling measured flows at Tarina Gauging Station to account for losses from the station to the numerical model boundary. Bank storage was not modelled.

Evapotranspiration represents the loss of water through uptake by plants. The zoning of the evapotranspiration cells in the model is similar to the recharge cell zoning where groundwater is shallow. This assumes the area with higher recharge has denser vegetation and hence higher evapotranspiration. Extinction depths between 2m to 5m for the evapotranspiration cells were used to broadly represent the effective root depths of the native vegetation. MODFLOW assumes a simplistic approach of linearly reducing the assigned evapotranspiration rate to zero at the extinction depth. An evapotranspiration rate of 2,500 mm a year was assumed. Figure 11 shows the zones.

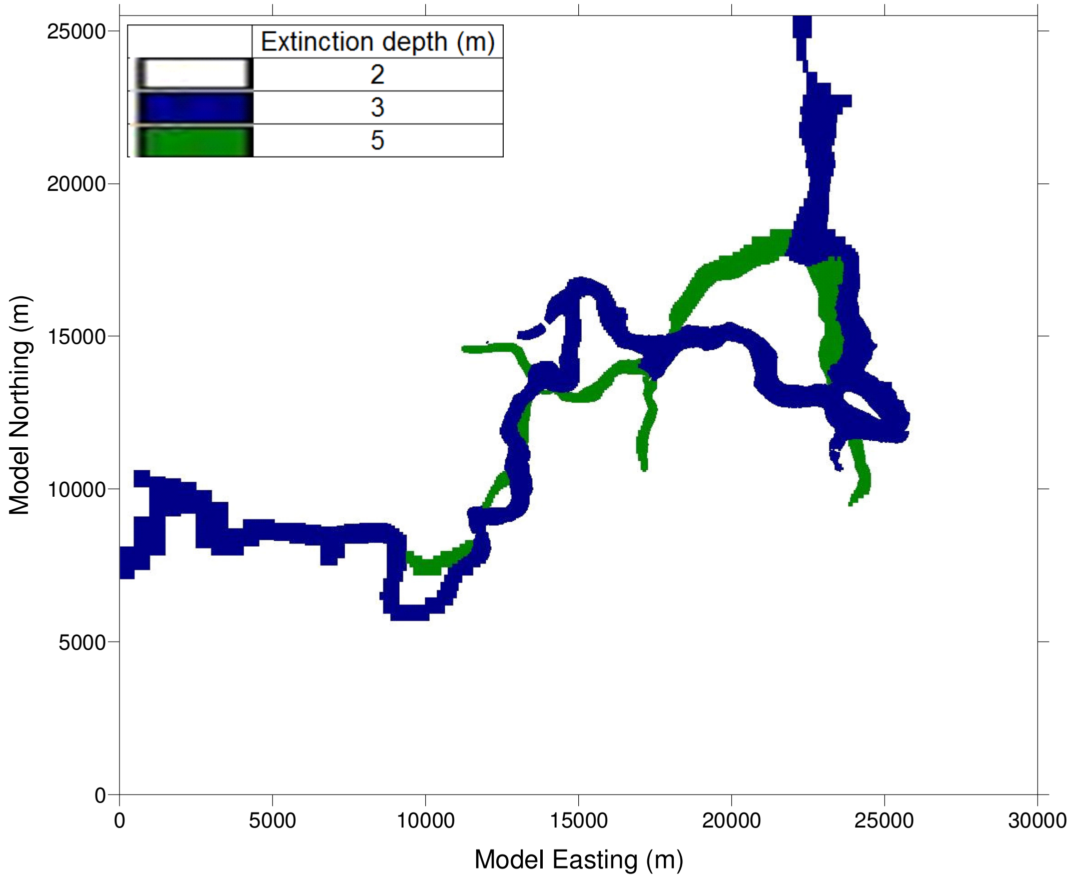


Figure 11 Evapotranspiration Zones.

MODSURFACT Fractured Well Package was used to model abstraction and injection from and to wells. The package treats the screened section as a highly conductive zone, similar to the behaviour of an actual screen section, in computing inflows into the well from each aquifers intersected. Measured abstraction and injection rates since 1998 were reduced to monthly rates and assigned to the model. The screened intervals were simplified to include the GVL and the LGC layers, however, if these layers are thin then the screened intervals were extended to include the GVU and/or the BCC layers. This assumes that the LGC, being most permeable, can effectively drain the upper layers. Figure 12 shows the location of the dewatering and injection bores assigned to the model since 1998.

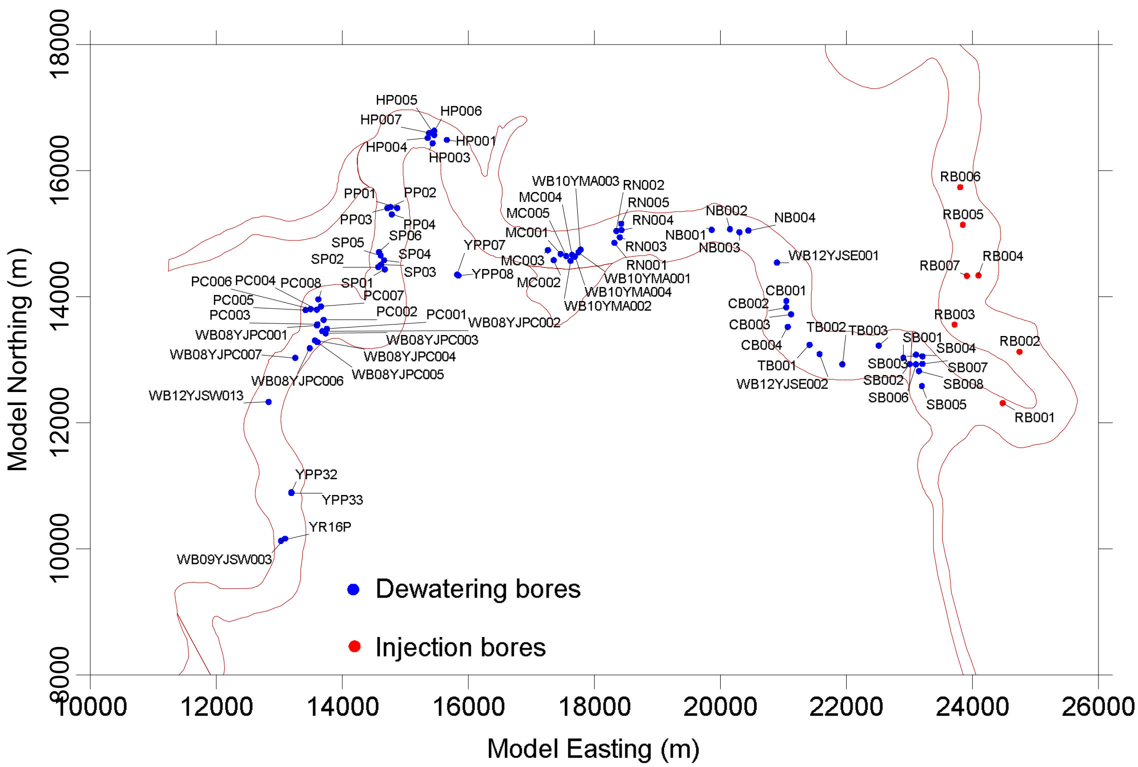


Figure 12 Dewatering and Injection Bores (1998 to 2013).

Model Calibration

4. Steady-State Calibration

The model steady-state calibration process adopted involved the establishment of a water level condition consistent with pre-abstraction water level. Groundwater in steady-state assumes a state of equilibrium where inflows equal outflows i.e. no storage gain or loss. The dynamic nature of the system to recharge meant that only quasi steady-state conditions exist. The purpose is to establish an initial/starting water level for the transient calibration. Water levels measured pre-1998 was used as target for the steady-state calibration. Hydraulic conductivity and boundary conditions were adjusted in the calibration process.

Table 1 lists the scaling factors applied to the measured monthly rainfall and Table 2 lists the extinction depths required to calibrate the model.

Table 1 Recharge Zones and Scaling Factors.

Zone	Description	Percentage of annual rainfall
1	Weeli Wolli Formation	1%
2	Channel Iron Deposit	7.5%
3	Alluvial	5%
4	Brockman Iron Formation	0.5%
5	Low permeability WW Fm	0%

Table 2 Evapotranspiration Zones Rates and Extinction Depths.

Zone	Descriptions	Extinction Depth (m)
1	Weeli Wolli Formation/Brockman Iron Formation/Low permeability WW Fm	2
2	Channel Iron Deposit	3
3	Alluvial	5

Figure 13 shows the simulated steady-state water table and Table 3 lists the mass balance within the model domain.

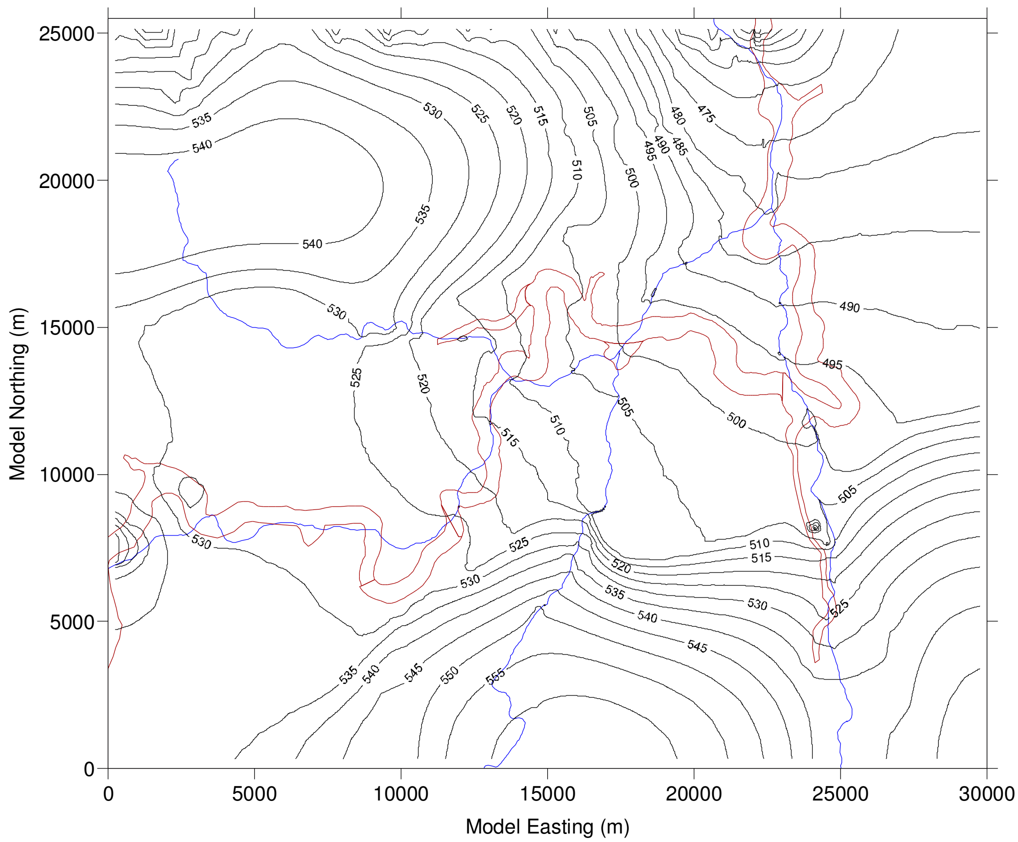


Figure 13   Simulated Steady-State Water Table (mRL).

Table 3   Steady-State Water Balance Summary.

	Volume In		Volume Out	
	Total (m3/d)	**% of Total**	**Total (m3/d)**	**% of Total**
Stream Leakage	107,319	92	62,729	54
Recharge	1,403	1	0	0
ET	0	0	35,196	30
Constant Head	7663	7	7	0
Drain Cells	0	0	18,425	16
Total	**116,385**	**100**	**116,350**	**100**

5. Transient calibration

Following an acceptable match of the simulated steady-state water table with pre-abstraction water levels, the steady-state model was converted to the transient model by activating all transient parameters and boundary conditions. Historical abstraction, injection and discharge rates, and water levels from observation bores from January 1998 to July 2013 were used in the calibration – a period of 14.5 years.

Monthly stress periods were used to capture the changes in abstraction, injection and recharge rates. Scaling factors for rainfall recharge and stream flows from the steady-state calibration were adopted in the transient calibration. Specific yield and specific storage of each of the hydrostratigraphic units were adjusted, within bounds, in the transient calibration. Calibration was done by comparing simulated hydrographs with measured hydrographs. Figure 14 shows the locations of the calibration bores. Both quantitative (water level matching) and qualitative (trend matching) methods were used to guide the model calibration. Any changes to hydraulic conductivity and boundary conditions require recalibration of the steady-state model. Figures 15 to 18 show simulated versus observed hydrographs in the calibration bores. Observed values are represented by the green dots and simulated hydrographs by the blue lines.

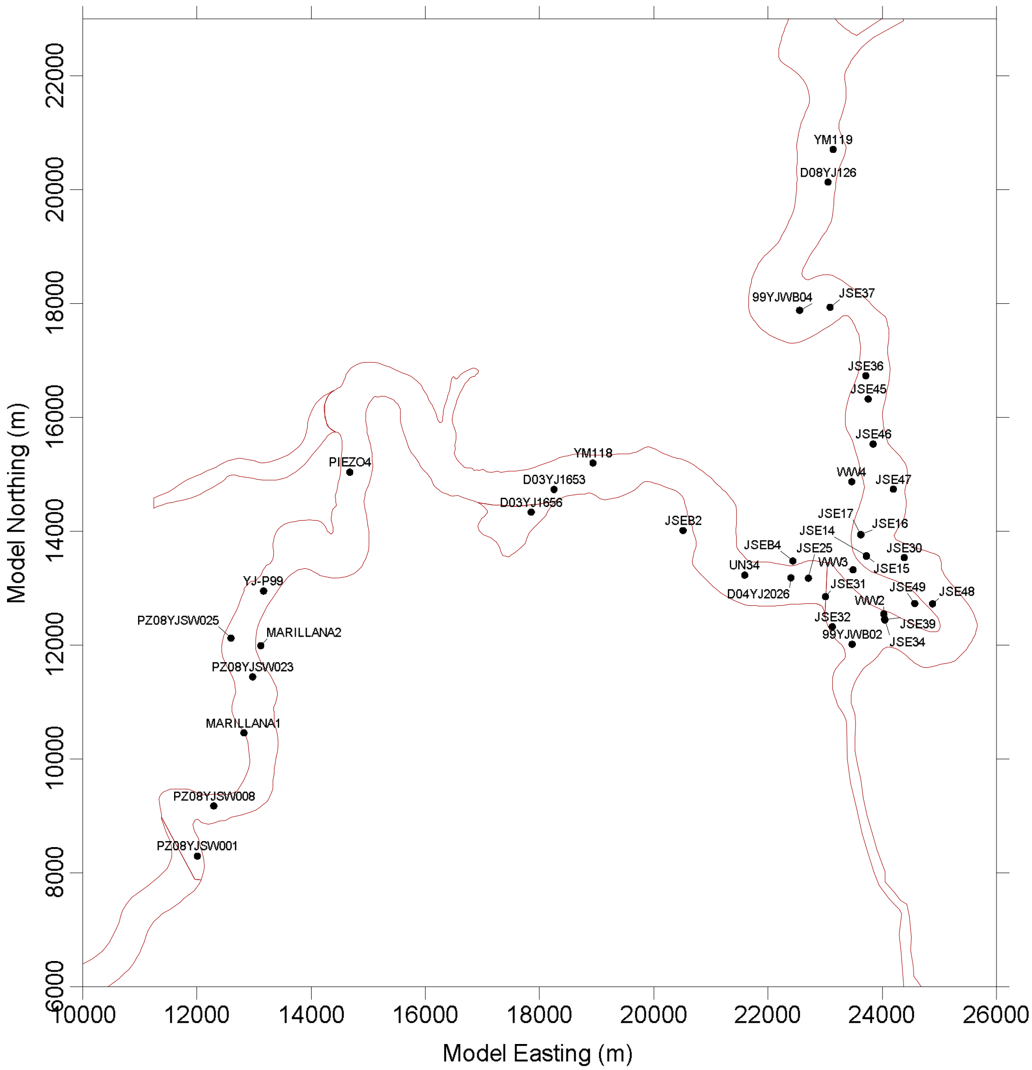


Figure 14 Location of Calibration bores.

Figure 15 Transient Calibration - Observed versus Calculated Heads.

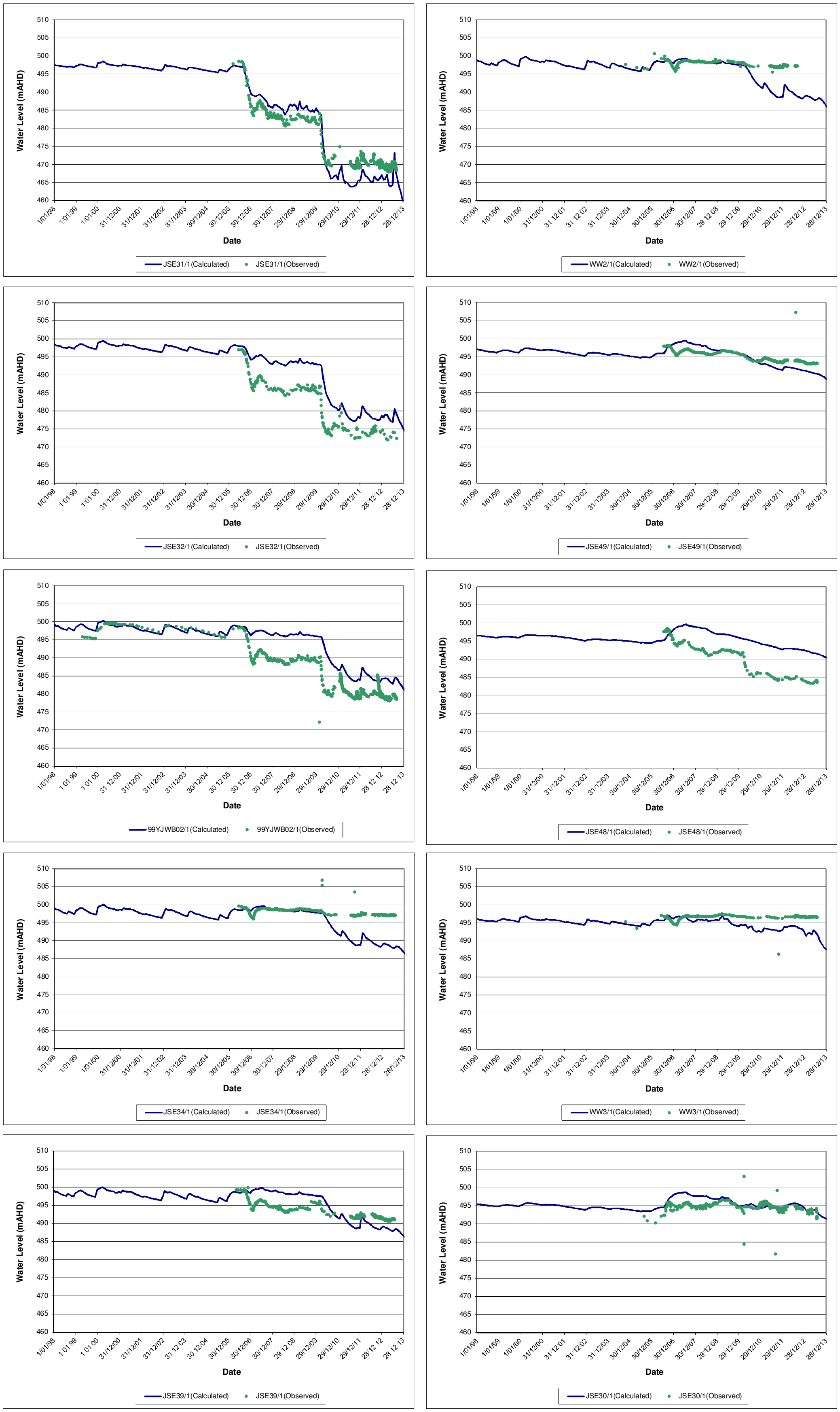


Figure 16 Transient Calibration - Observed versus Calculated Heads.

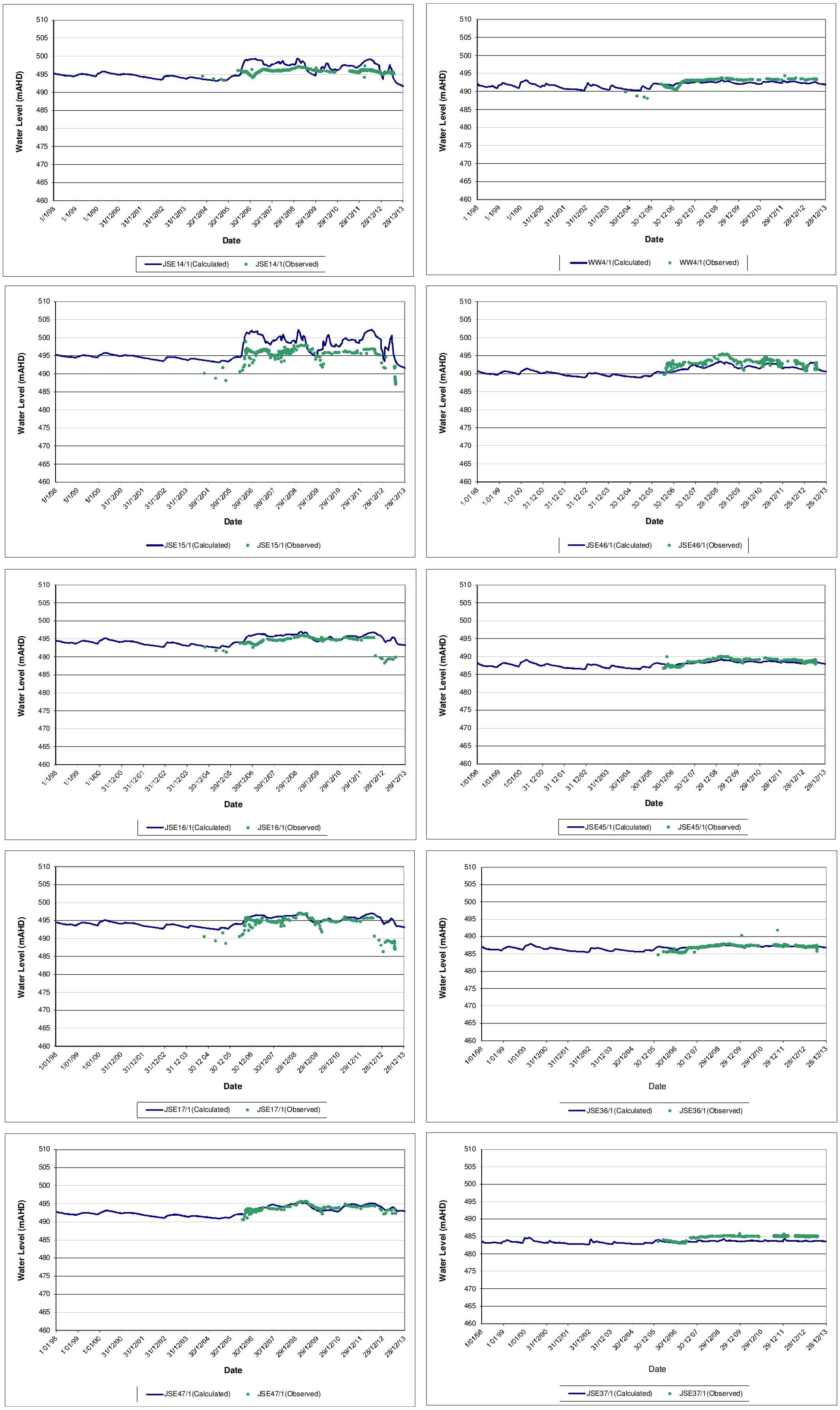


Figure 17 Transient Calibration - Observed versus Calculated Heads.

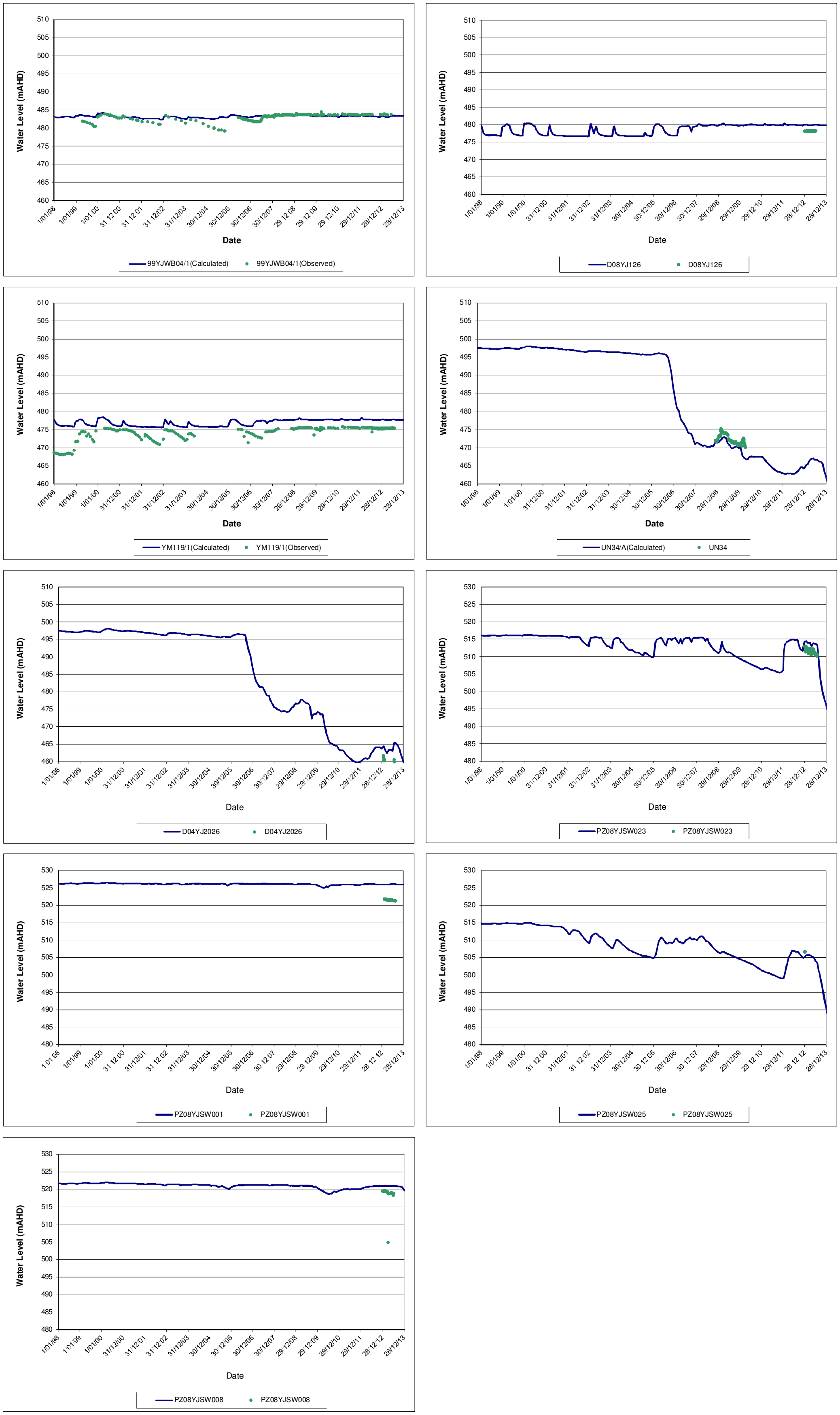


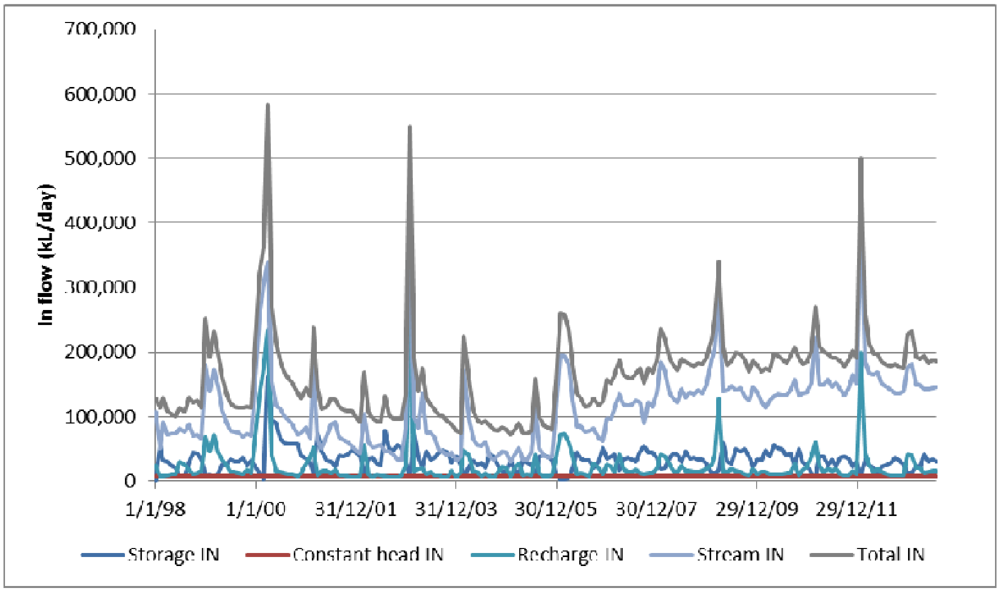
Figure 18 Transient Calibration - Observed versus Calculated Heads.

Table 4 lists the hydraulic parameters derived from the model calibration (F3D_TrCal14ext_2013d.vmf). The hydraulic parameters were generally similar to the previous model.

Table 4 Hydraulic Parameters of Zones.

Zone	Description	Kx (m/d)	Ky (m/d)	Kz (m/d)	Sy (-)	Ss (1/m)
	Alluvial	20	20	2	0.1	0.0001
	Alluvial	10	10	2	0.1	0.0001
	Alluvial	20	20	4	0.1	0.0001
	Alluvial	50	50	10	0.3	0.0001
	Alluvial	20	20	4	0.3	0.0001
	Alluvial	20	20	4	0.1	0.0001
	Alluvial	1	1	0.01	0.05	0.00001
	Alluvial/Weathered WW Fm	1	1	0.01	0.05	0.00001
	ECC/WCH	1	1	0.1	0.1	0.0001
	BCC	1	1	0.2	0.01	0.000001
	Weathered Basement	1	1	0.1	0.05	0.0001
	Weeli Wolli FM	1	1	0.01	0.01	0.000001
	Brockman Iron Fm	0.01	0.01	0.01	0.001	0.000001
	CID - GVU	1	1	0.2	0.005	0.000001
	CID - GVL	5	5	1	0.01	0.000001
	CID - LGC	10	10	2	0.02	0.000001
	CID - GVU	2	2	0.5	0.01	0.000001
	CID - GVL	10	10	5	0.05	0.000001
	CID - LGC	20	20	10	0.1	0.00001
	CID - GVU	2	2	0.5	0.01	0.000001
	CID - GVL	10	10	5	0.05	0.000001
	CID - LGC	20	20	10	0.1	0.000001
	CID - GVU	5	5	2	0.1	0.000001
	CID - GVL	20	20	4	0.2	0.000001
	CID - LGC	70	70	30	0.3	0.000001
	CID - GVU	5	5	2	0.01	0.000001
	CID - GVL	20	20	4	0.05	0.000001
	CID - LGC	50	50	10	0.1	0.000001
	BHPB CID	10	10	5	0.1	0.00001

Water balance from the transient calibration indicates that increased dewatering at Yandi increased leakage from the creeks and evapotranspiration was slightly higher possibly due to the increased water in the creeks as shown in Figure 19.



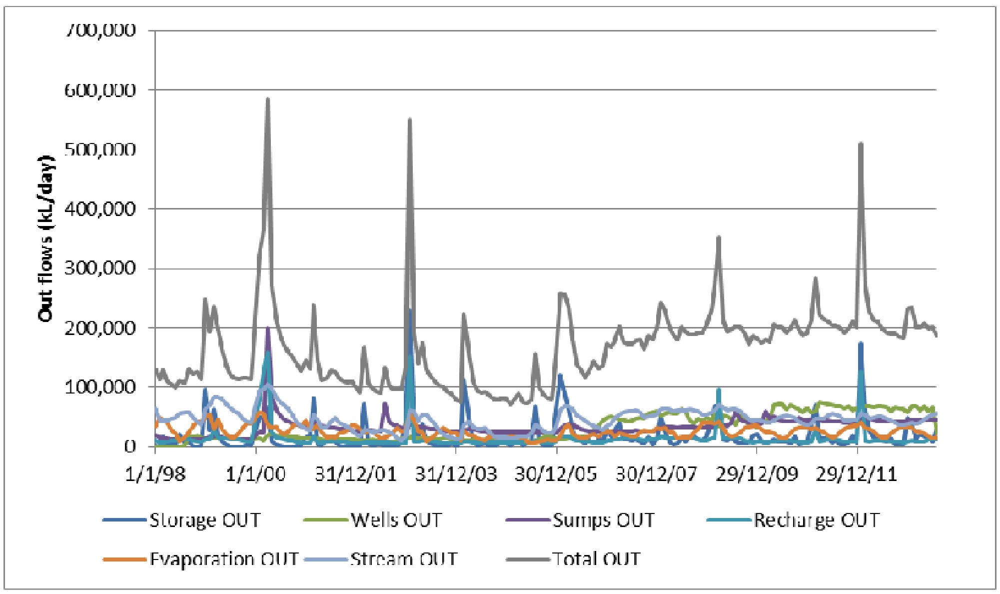


Figure 19 Transient Calibration Mass Balance.

Figure 20 shows the percentage discrepancy errors from the transient model calibration simulation. Percentage discrepancy error below 5% is considered good for complex flow systems.

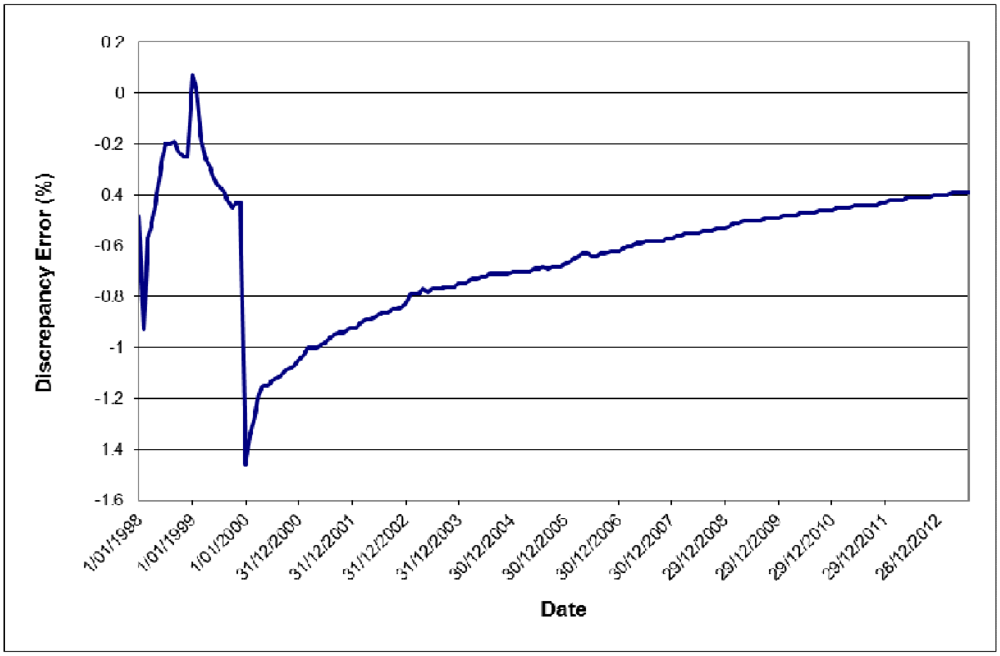


Figure 20   Transient Calibration - Discrepancy Errors.

6. Assumptions

A numerical model is a simplified representation of the real world. Assumptions are required in a numerical model due both to the inability to represent the subsurface accurately and to the simplified numerical representations of the varied and complex hydrogeologic processes. The assumptions made for the 2013 Yandi model include:

- The hydrostratigraphic units are coincident with the geo-stratigraphic units;
- The relative permeability of the GVU, GVL and LGC hydrostratigraphic units;
- The elevation of the base of the CID coincides with the end-of-hole elevation of the resource drilling logs;
- The materials below the resource drilling end of hole logs have similar hydraulic parameters as the basal clayey conglomerate;
- There is CID beneath the buffer zones of the creeks as interpreted from the resource drilling logs;
- Interpolating and/or extrapolating the symmetry of the CID beneath the creeks to fill in data gaps beneath the buffer zones;
- The calculated monthly abstraction rates assigned to the model are representative of the actual abstraction;
- The discretised screened intervals in the model are representative of the actual inflows into the production bore;
- In-pit sumps were adequately represented by MODFLOW drain cells by setting the elevation of the drain cells to the floor of the pit;

- The amount of water discharged into the WFC was completely recovered by the in-pit sumps or evaporated;
- The width of the creeks was fixed at 5.0m and a manning roughness coefficient of 0.093 accounts for the increased river stage when flows in the creeks increased;
- The slopes and elevations of the creeks can be computed from the topographical data;
- Conductances for the creek beds derived from model calibration are an accurate representation of the conductance between the creeks and the underlying water table aquifers;
- Scaling of monthly rainfall to represent infiltration to the water table is representative of the total rainfall recharge to the aquifers;
- The recharge zones used in the model can adequately account for the total recharge to the aquifers;
- Scaling of monthly rainfall in catchment upstream of BHPB discharge point is a good approximation of the flow in Marillana Creek upstream of the discharge point;
- Scaling of monthly rainfall in catchment upstream of Phil's and Yandicoogina creeks are good approximation of the flow in these creeks;
- Bank storage can be ignored;
- The evapotranspiration zones and extinction depths used in the model adequately account for the total loss of groundwater to the atmosphere;
- Recent interpretation of the pinching out of the Weeli Wolli Formation north, the CID and alluvium directly overlies the BIF and a large mineralised BIF occurs underneath the outwash has insignificant impacts on the model prediction.; and
- The higher in flows from the constant head boundaries along Marillana Creek provides a conservative approach to dewatering.

7. Model Limitations

According to the 2012 Australian Groundwater Modelling Guidelines confidence level classification, the Yandi numerical groundwater model can be classed as Class 3 model for 5 year model prediction. Longer term model prediction would lower the confidence level classification.

8. Summary

The Yandi 2008 numerical groundwater model domain was limited to mining and dewatering at Junction Central and Junction South East. As part of Yandi's expansion work to include Junction South West and Billiards South, the model domain was extended to minimise boundary effects from dewatering in these areas in the Channel Iron Deposit. The rebuild/update of the model included the alluvium layer defined in the

2010 regional groundwater model (RTIO-PDE-0078850). The number of model layer was increased from 7 to 15 to refine the geology from RTIO Vulcan geology block model.

The model was calibrated in steady-state and transient with abstraction, injection and discharge rates, and water levels from observation bores from January 1998 to July 2013. Both calibrations show the model is representative of the site and according to the 2012 Australian Groundwater Modelling Guidelines confidence level classification, the model can be classed as Class 3 for model prediction up to 5 years.

9. Recommendations

It is recommended that the model be:

- recalibrated at least once a year to maintain currency of the model; and
- refinement in the Oxbow and Billiards North areas for future model calibration.

References

Australian Government National Water Commission (2012), Australian groundwater modelling guidelines, Waterlines Report series No. 82.