June 2018

ELIWANA MINING PROJECT

Numerical Groundwater Model Development and Calibration Report

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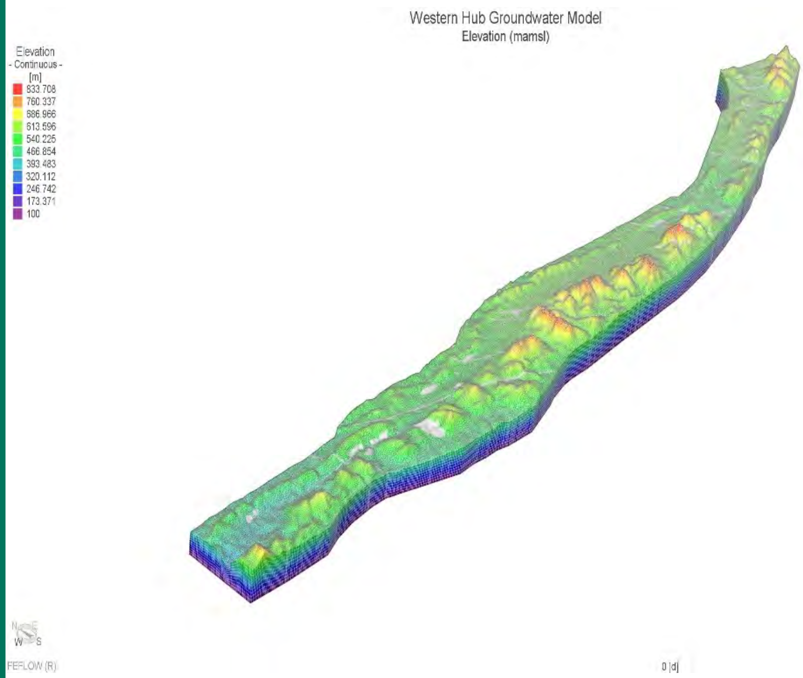

Report Number. 1671484-003-R-Rev4

Distribution:

1 Electronic Copy - Fortescue
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REPORT

Golder Associates

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1.0 INTRODUCTION

A numerical model has been constructed by Golder Associates Pty Ltd (Golder) for Fortescue Metals Group Ltd (Fortescue) to represent the conceptual groundwater system of the Eliwana Mining Project (the Project) study area as presented in the project Hydrogeological Conceptual Model Report (Golder, 2017a).

The purpose of building the model was to develop a predictive tool that can be used to estimate dewatering and water supply requirements for the Eliwana mine development. The numerical model was also developed to be used to assess potential impacts to the environment and other groundwater users as a result of the proposed mine development.

The steady state Eliwana Groundwater Model (EWGM) was developed, calibrated and tested for sensitivity based on the principles outlined in the Australian Groundwater Modelling Guidelines (Barnett 2012).

The previous version of this report (1671484-003-R-Rev1) has been updated to incorporate changes which have been made to the previous version of the EWGM. These changes include extension of the model domain to the west and south to incorporate proposed mine pits which were not part of the original mine plan, changes to the distribution of recharge across the model, the incorporation of mineralised zones within the ore bodies and changes to the model grid structure to reduce run times. As a consequence of these changes, the calibration of the model has also necessarily been updated and the results of the latest calibration of the model are presented in this version of the report.

2.0 GROUNDWATER MODEL DEVELOPMENT

2.1 Modelling Objectives

The objective of this work was to develop a robust numerical groundwater model which is consistent with the conceptualisation of the hydrogeology of the Wester Hub project area. The model was constructed with the intent that it would be used as a predictive tool to assess the following:

- Mine Dewatering – The model will be used to simulate mine dewatering according to a preliminary life of mine plan provided by Fortescue. The results of pit dewatering modelling will provide input into dewatering wellfield and water management design, including estimates of preliminary well numbers, locations, depths and abstraction rates to facilitate mining.
- Project Water Balance – The model will be used to simulate water supply abstraction from the Wittenoom Aquifer to meet any deficit in project water demand not met by abstraction for dewatering.
- Potential Impacts – The model will be used to assess potential impacts to the environment as a result of dewatering and abstraction of groundwater to meet project demand. The model will be used to assess the magnitude of groundwater level drawdown at and surrounding the site allowing the evaluation of any potential reduction in groundwater supply to surrounding users or the environment (i.e. groundwater dependant ecosystems).

A sensitivity analysis was carried out on the steady state version of the EWGM to provide an indication of the hydrogeological parameters likely to play an important role in the alignment between the modelled and observed behaviour.

It should be recognised that, over time, more groundwater data will become available which will likely enhance the understanding of the groundwater system and therefore the model should be tested on an ongoing basis and where it no longer replicates the observed conditions, it may need to be updated.

2.2 Summary of Mining Plan

A summary of Fortescue's proposed mining plan for the Project is provided below and is based on the document (Prelim Mine Plan (04-05-2017).xls):

- The mining plan comprises extraction of ore from a series of pits (Figure 1) between 2019 and 2036.
- Dewatering will be required where mining extends below the pre-development water table (BWT)

- The total water demand for project operations during the life of mining (processing, construction and camp supply) ranges between around 120 and 190 L/s.

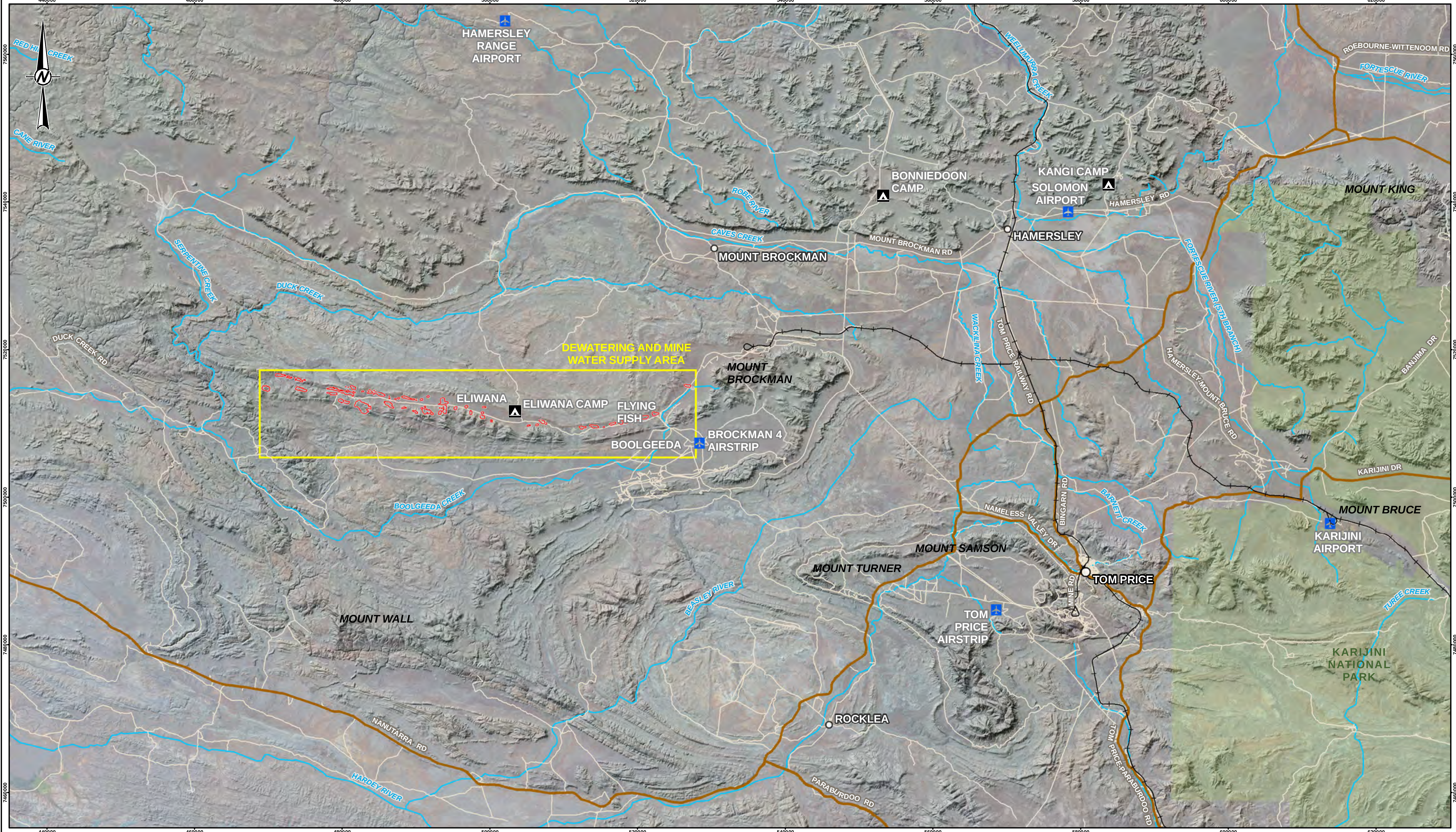
2.3 Summary of Hydrogeological Conceptual Model

The EWGM was developed based on the hydrogeological conceptual model established for the Eliwana mining area (Golder, 2017a). The conceptual model consists of *a set of assumptions* that has allowed the hydrogeology area to be represented by a simplified, yet robust numerical model which will be used to meet the predictive modelling objectives for the Project. These *assumptions* are really experience-based judgements made by the Golder study team based on the available field data, existing knowledge of the Project area and other mining activities currently being carried out in surrounding areas.

2.3.1 Geology and Aquifers

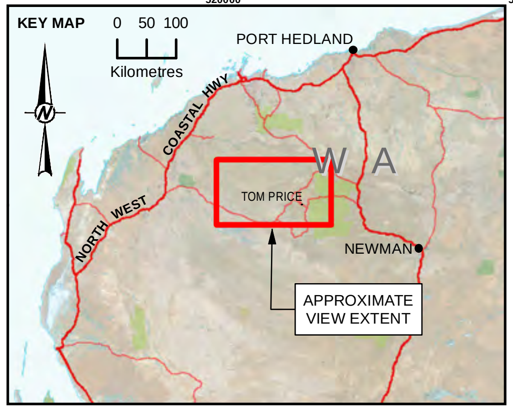
The model domain has been discretised into fifteen geological zones based on the Leapfrog geological block model supplied by Fortescue. The geological zones were used as a basis for the hydrogeological zones assumed in the model. These zones are consistent with the stratigraphic nomenclature of the Mount Bruce Supergroup comprising the Hamersley and Fortescue Groups and the hydro-stratigraphy based on the lithology descriptions as presented in Figure 2. By retaining all geological boundaries within the numerical model, Fortescue will have the ability to test hypotheses with respect to aquifer boundary conditions and hydrogeological properties as the conceptual understanding improves with time.

The model only includes basement lithologies and does not include a specific zone or layer representing the overlying regolith (Cainozoic sediments and detritals). The layers in the model which represent the basement lithologies were simply extended to surface for model simplicity. This was considered an appropriate simplification due to the limited amount or complete absence of saturated regolith present in the Project area. Saturtion of the regolith does occur, in places predominantly along the valley floor, overlying the Wittenoom Formation. However, since the saturated layers representing the Wittenoom Aquifer have been modelled to exist to surface, groundwater flow in this zone is simulated, however it has not discretely been represented in the model as an individual zone or layer.



LEGEND

- PIT SHELL
- CAMP SITE
- AIRPORT / AIRSTRIP
- EXISTING RAIL
- MAIN ROAD
- ACCESS ROAD / TRACK
- DRAINAGE



0 5 10 15 20
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NOTE:
1. COORDINATE SYSTEM: GDA 1994 MGA ZONE 50

REFERENCES:
1. ROADS © WESTERN AUSTRALIAN LAND INFORMATION AUTHORITY TRADING AS LANDGATE (2018)
2. INSET BASE DATA SOURCED FROM STREET PRO DATA 2009
3. AERIAL IMAGE AND TOPOGRAPHY SOURCED FROM GEOSCIENCE AUSTRALIA - ACRES LANDSAT MOSAIC
4. DRAINAGE © DEPARTMENT OF WATER

CLIENT
FORTESCUE METALS GROUP

CONSULTANT
GOLDER

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PREPARED	MS
REVIEWED	MJB
APPROVED	MJB

PROJECT
ELIWANA MINING PROJECT - NUMERICAL GROUNDWATER MODEL DEVELOPMENT AND CALIBRATION

TITLE
PROPOSED ELIWANA MINING PROJECT LOCATIONS

PROJECT NO.	CONTROL	REV.	FIGURE
1671484	003 R	4	1

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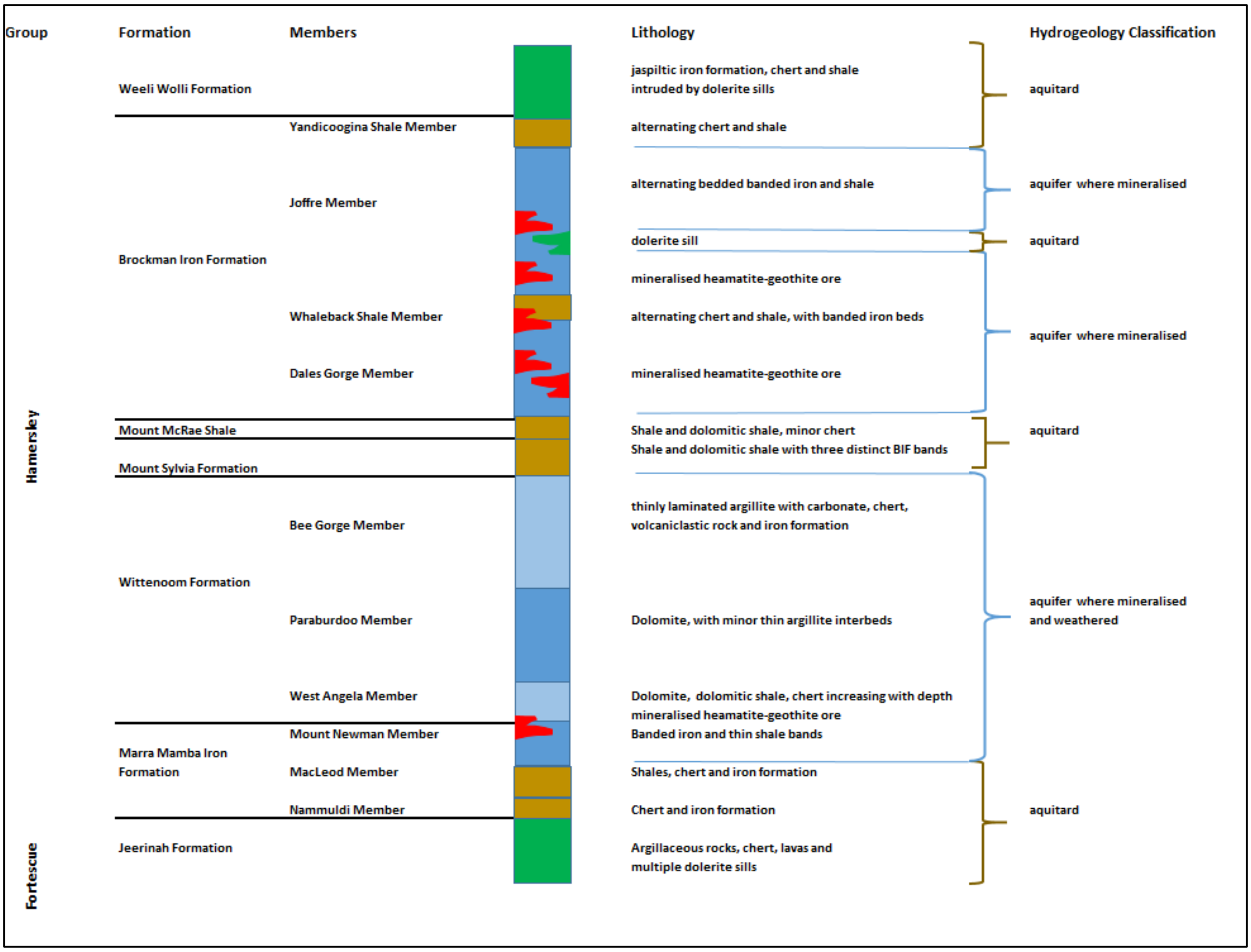


Figure 2: Stratigraphy, lithology and conceptual hydro-stratigraphic units of Project area

The distribution of the geological units at ground surface within the model domain is shown in Figure 3.

There are three main aquifers for consideration with respect to dewatering and water supply planning as detailed below:

- The **Wittenoom Aquifer** comprising the mineralised Bee George, Paraburdoo and West Angelas Members of the Wittenoom Formation (dolomite, banded iron and minor chert) and the overlying detritals and Cainozoic sediments, where saturated
- The mineralised **Marra Mamba Aquifer** comprising the upper mineralised Mount Newman Member of the Marra Mamba Formation and
- The mineralised **Brockman Aquifer** characterised by enrichment of the parent banded iron formation within the mineralised Brockman Iron Formation members; that is, the ore body. Within this environment, groundwater replaces the silicate and carbonate gangue minerals with goethite, resulting in an aquifer with higher porosity and permeability.

The current conceptualisation of the Project's aquifers is that the Wittenoom and Mount Newman Aquifers form a single, hydrogeologically continuous aquifer. The differentiation in nomenclature was chosen herein to highlight that each hydrostratigraphic unit within the model can be parametrised on an individual basis. This feature of the groundwater model allows the modelling of groundwater abstraction for water supply to be targeted to a single aquifer (and the geological members which make up each aquifer) rather than grouping these features into a single, broad and inflexible, aquifer designation.

The strata is documented to dip at 30-45° consistently with various thicknesses. The basement geology is crossed by dolerite dykes that are inferred to be impermeable and are characterised as groundwater boundaries. A detailed description of the conceptual model is contained in Golder (2017a).

The depth of mineralisation varies across the project area as does the availability of drill hole data from which the distribution of mineralisation is based. The mineralised zones represented in the EWGM have been based on the mineralisation shells included in the leapfrog model provided by Fortescue.

2.3.2 Groundwater Sub Catchments and Initial Heads

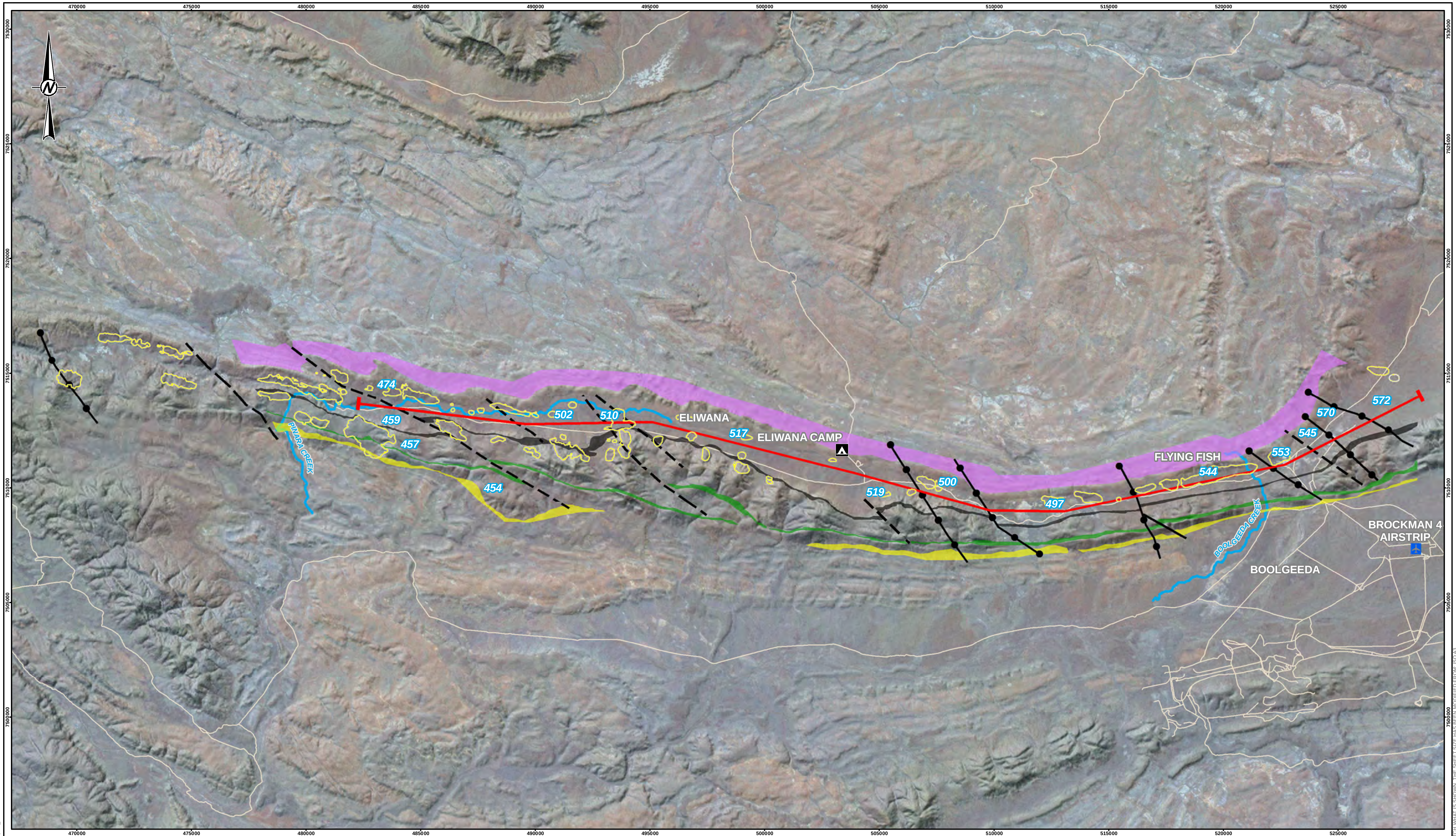
The groundwater system is known to be compartmentalised by low permeability dolerite dykes running north-south, and relatively low permeability strata running east-west along strike. These cause the aquifers to be divided into groundwater sub-catchments. The sub-catchments receive rainfall-recharge via surface infiltration along the valley where creek lines coincide with shallow depths to the water table. Discharge of groundwater on a sub catchments level may occur either through internal transfer through the dolerite dykes (very minor) or through evapotranspiration from groundwater dependant ecosystems (GDEs). The amount of recharge and discharge is expected to be insignificant in comparison with total groundwater storage within each groundwater sub catchment, and may only be of significance for impact assessment if the identified (potential) GDEs mapped by Fortescue can be shown to be groundwater dependent.

Groundwater levels within the sub-catchments were estimated using depth to groundwater measurements obtained in mineral exploration boreholes across the Project area (Golder, 2017a). For the most part, measured groundwater levels indicate very flat hydraulic gradients, separated by large level changes either side of NW-SE trending lineaments mapped as dolerite dykes where basement rocks outcrop to the north or south of the valley.

Eleven sub catchments were inferred in the Project area by their approximate head elevation in relative metres above Australian Height Datum (Table 1). The highest groundwater elevation is in the east at 570 m AHD and the lowest is in the west at 460 m AHD. The distribution of these sub catchments is shown in Figure 3 (plan view) and Figure 4 (long section through the valley floor). Compartmentalisation of the sub catchments has been demonstrated from test pumping responses in certain areas (Golder, 2017a). Other areas could be refined by future testing pumping and larger scale pumping of the aquifer (dewatering) which will allow a more definitive statement on the extent and distribution of groundwater compartments.

Table 1: Groundwater sub-catchments

Groundwater Sub-Catchment	Aquifer	Mean Groundwater Level (m AHD)
572*	Wittenoom	572
570*	Wittenoom	570
545	Wittenoom	545
Grunters	Wittenoom	553
544	Wittenoom	544
497	Wittenoom	497
Kenny Bore	Wittenoom	500
Ren Bore	Wittenoom	517-519
EWPB002	Wittenoom	510
502*	Wittenoom	502
Talisman	Wittenoom	474
Broadway East	Wittenoom	459
Westend	Mineralised Brockman	457
Westend J6	Mineralised Brockman	454



LEGEND

473	INTERPRETED GROUNDWATER LEVEL (m AHD)		LONG SECTIONG LOCATION
	CAMP SITE		INTERPRETED DYKE
	AIRPORT / AIRSTRIP		INTERPRETED FAULT
	ACCESS ROAD / TRACK		DOLERITE SILL
	MAJOR DRAINAGE		JEERINAH FORMATION
	PIT SHELL		MOUNT MCCRAE SHALE
			YANDICOOGINA SHALE

0 1 2 3 4 5

1:160,000 KILOMETRES

NOTE:
1. COORDINATE SYSTEM: GDA 1994 MGA ZONE 50

REFERENCES:
1. AERIAL IMAGERY AND ROADS © WESTERN AUSTRALIAN LAND INFORMATION AUTHORITY TRADING AS LANDGATE (2018)
2. VEGETATION DATA MAPPING AND DRAINAGE SUPPLIED BY CLIENT
3. INSET IMAGE AND TOPOGRAPHY SOURCED FROM GEOSCIENCE AUSTRALIA

CLIENT
FORTESCUE METALS GROUP

CONSULTANT
GOLDER

YYYY-MM-DD	2018-06-12
DESIGNED	MJB
PREPARED	MS
REVIEWED	MJB
APPROVED	MJB

PROJECT
ELIWANA MINING PROJECT - HYDROGEOLOGICAL CONCEPTUAL MODEL

TITLE
PLAN VIEW OF LONG SECTION

PROJECT NO.	CONTROL	REV.	FIGURE
1671484	003 R	4	3

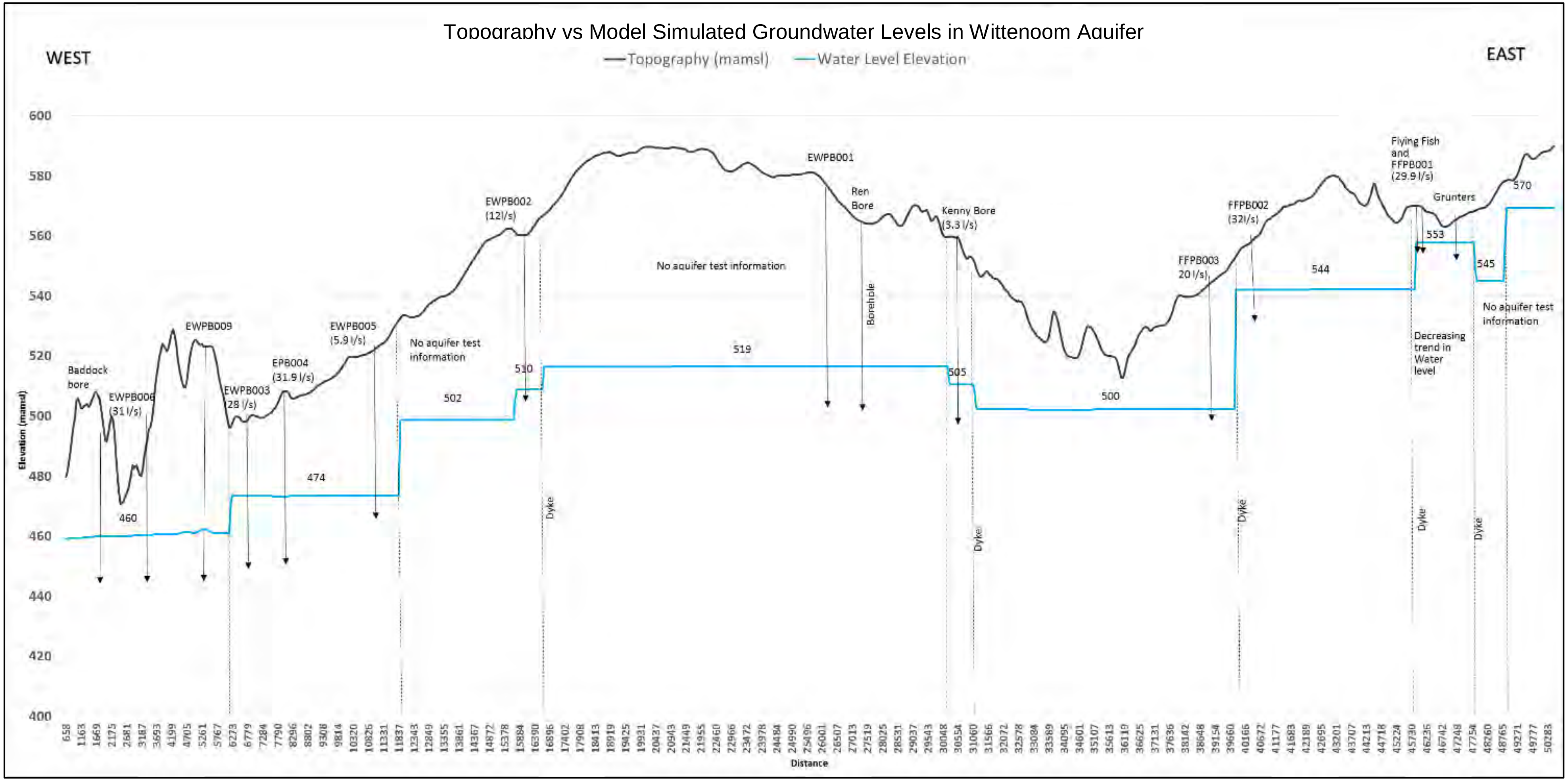


Figure 4: Groundwater Sub Catchments (Long Section through Valley)

2.3.3 Initial Heads

Initial piezometric heads across the project area were derived from open hole measurements of water level from RC mineral drilling. Most of these boreholes were drilled in to mineralised ore bodies within the valley and where those holes were sufficiently deep enough they would intersect either the Wittenoom Aquifer or mineralised Brockman Aquifer. From these groundwater levels the different compartments have been identified by plotting the topography versus water level elevation on a scatterplot (Figure 5). The red lines indicate the different compartments identified in the conceptual phase of the project. The highest groundwater elevation is in the east at 570 m AHD and the lowest in the west at 460 m AHD.

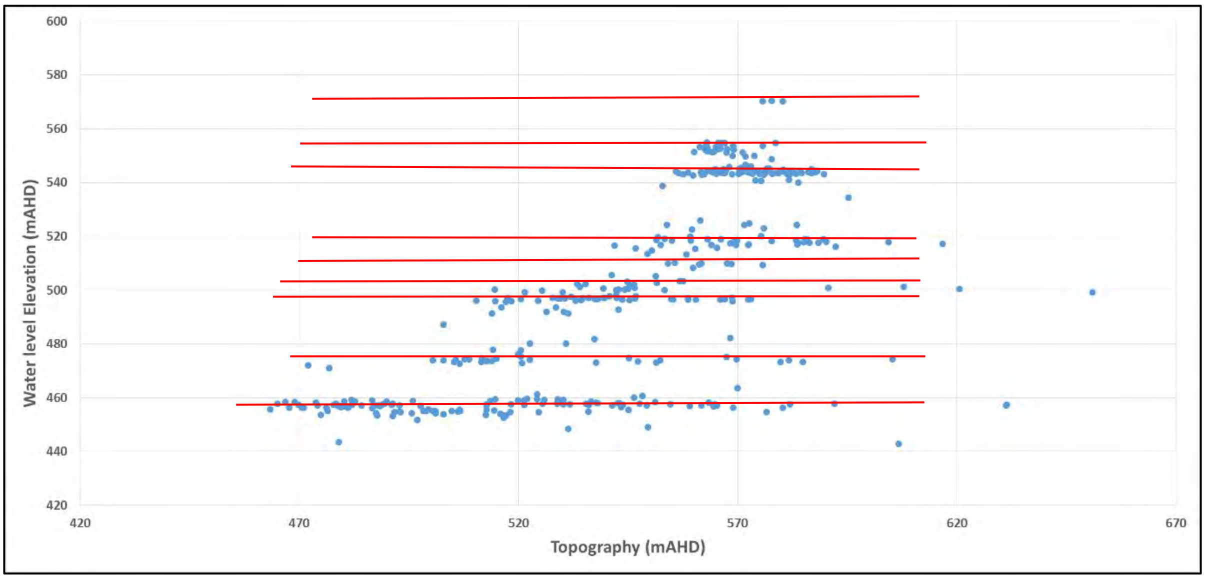


Figure 5: Scatterplot showing topography versus observed water level elevation

2.3.4 Recharge

As discussed in Golder (2017a), recharge was only considered a factor in the water balance of seven sub catchments; those with water level of less than 30 m bgl. Within other catchments, where depth to groundwater is >30m bgl the unsaturated zone is assumed to possess sufficient moisture deficit such that no recharge is discernible.

2.3.5 Data input summary and assumptions

A summary of the data utilised in the development of the model is presented below (Table 2).

Table 2: Data summary

Input Parameter	Scale	Source, Parameter or Assumption Description	Data Uncertainty
Topography (DEM)	1:50 000	The topographic elevations were interpolated from the 5 m contour data sourced from Geoscience Australia	Low
Rivers, streams, drainages	1:50 000	Obtained from GIS shape files. STREET PRO DATA 2009	Low
Geology	1:250 000	Geological map provided by FMG, geophysics, drill logs and LEAPFROG model provided by FMG.	Low
Mine Layout (Pits)		Pit shells provided in dxf format and life of mine plan provided in excel spreadsheet by Fortescue	Low
Boreholes and pumping rates		Aquifer testing program was completed by Fortescue on production boreholes and older water supply boreholes (Step tests, constant rate and slug tests)	Moderate
Steady State Modelling Parameters – Flow Model			
Boundary conditions		The model domain is aligned with geological boundaries identified by Fortescue in the LEAPFROG model such as geological contacts and dolerite dykes.	Moderate
Recharge		Initial values described in and constrained through steady state model calibration. Applied only across valley areas (Wittenoom Formation) where a combination of shallower groundwater levels and higher hydraulic conductivities would permit recharge. Lack of long term monitoring data.	High
Hydraulic Conductivity		Initial ranges are described in Section 3.6.	Moderate
Aquifer thickness		Aquifer thickness for the Brockman Iron Formation was based on the depth of mineralisation included in the Leapfrog Model as based on resource definition drilling. The thickness of the Wittenoom Formation aquifer was not restricted due to a lack of data.	Moderate
Transient State Modelling Parameters			
Initial Hydraulic Heads		Initial heads reflect steady state hydraulic heads, 36 hydraulic heads were available from the drilling program in combination with the production and observation boreholes. RC drilling hydraulic heads assisted with the conceptual understanding	Moderate
Specific Yield		The ratio of the volume of water that drains by gravity to that of the total volume of the saturated porous medium.	Moderate

3.0 NUMERICAL FLOW MODEL DEVELOPMENT

3.1 Modelling Packages

The code selected for conducting the modelling of the Project study area is FEFLOW, developed by the WASY Institute for Water Resources Planning and Systems Research Ltd Berlin, Germany. A Leapfrog model was developed for the study area encompassing the entire model boundary. The coupling between Leapfrog and FEFLOW was used to develop the FEFLOW model. Each stratigraphic unit in the Leapfrog geology model was transferred and retained in the FEFLOW model as separate hydrostratigraphic units. Images of the Leapfrog model are presented in Figure 6. The dip of the geological units was kept intact with the Leapfrog-FEFLOW coupling tool. Aquifer parameters were then applied to each geological unit consistent with the values outlined in the hydrogeological model (Golder, 2017a).

3.2 Modelled Area

The aerial extent of the EWGM was based on the extent of the Leapfrog model with the exception that the model was extended further south such that all pit shells fell within the modelled domain. The model boundary is shown in Figure 8.

3.2.1 Model Top and Base boundary

It is assumed that the base of the model is impermeable, the top of the model is represented by the supplied DEM topography (Figure 11).

3.2.2 Model Layers

The model comprises 10 layers of variable thickness, reflecting the conceptual hydrogeological model developed, specifically a sequence of unconfined aquifers. These layers was selected to best represent the dip of the geological model with depth. The average thickness of the layers is approximately 50 m.

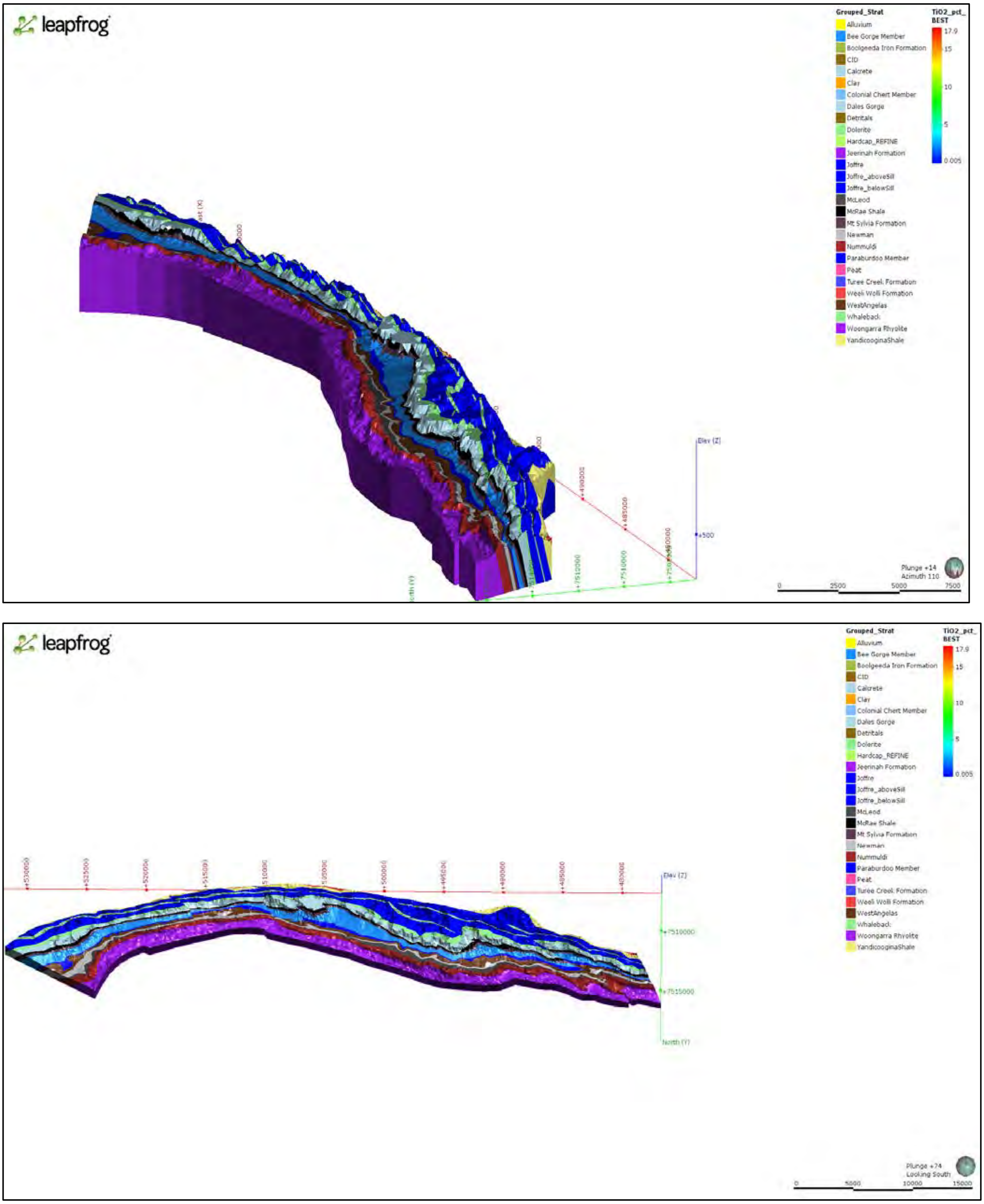


Figure 6: Leapfrog images of geological model

3.3 Construction of Finite Element Grid

The EWGM encompasses a total area of 284.3 km^2 (approximately 50 km × 5.5 km). A finite element network (grid) was designed to provide a high resolution of the numerical solution, while at the same time accommodating the large model area. The finite element grid is based on a super element mesh constructed across the area and shown in Figure 7. The super element mesh contains the main important features of the conceptual model, e.g. the surface expression of the main hydrostratigraphic aquifer units, structures and production borehole positions.

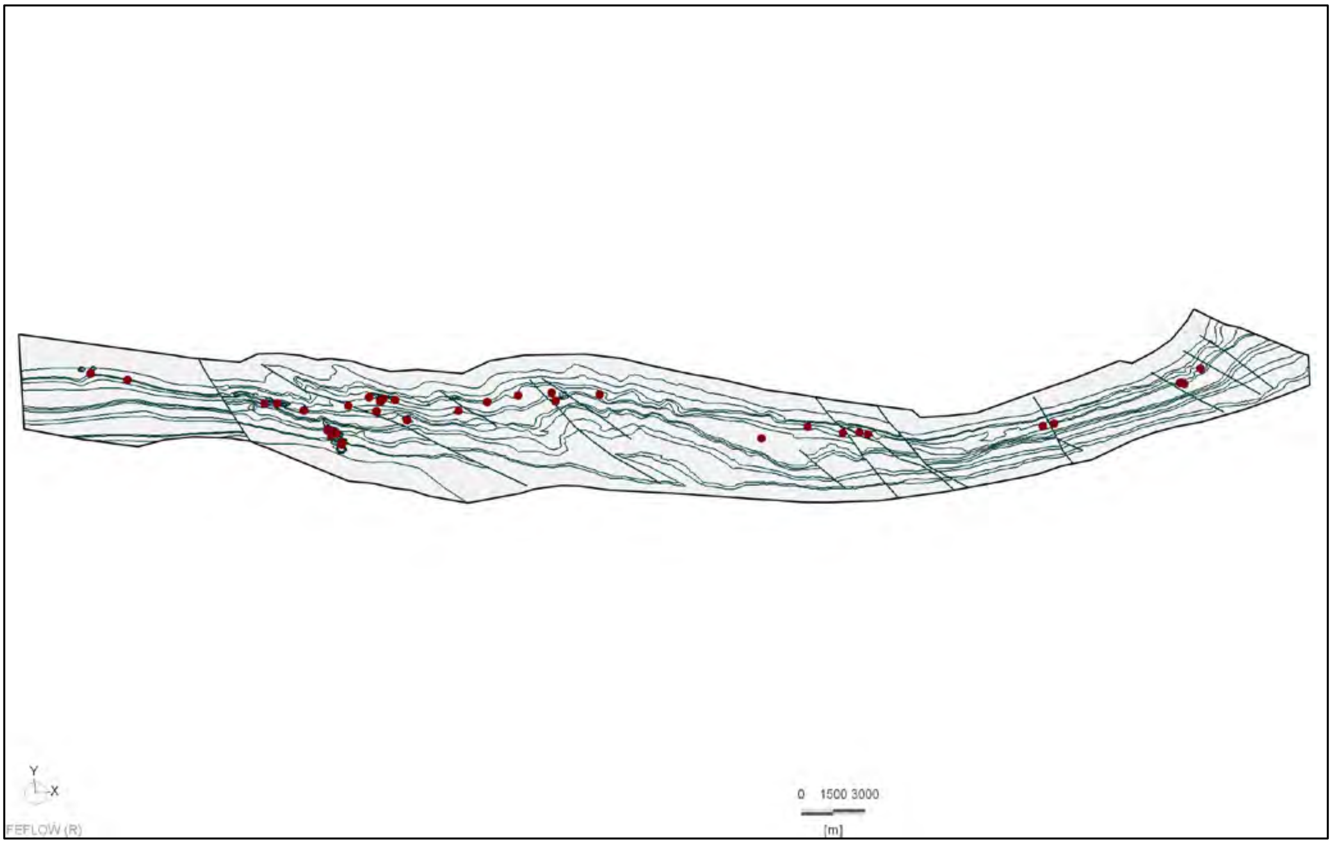


Figure 7: Super Element Mesh constructed for EWGM

The finite element grid was compiled using the FEFLOW pre-processing software, which facilitated the construction of 6-noded triangular prism elements over the area of investigation as shown in Figure 8 and Figure 9. The triangular grid consists of 1,175,800 elements and 655,930 nodes. The positions of the hydrogeological units, dykes, boreholes and pits areas below the groundwater level are incorporated in the modelling grid.

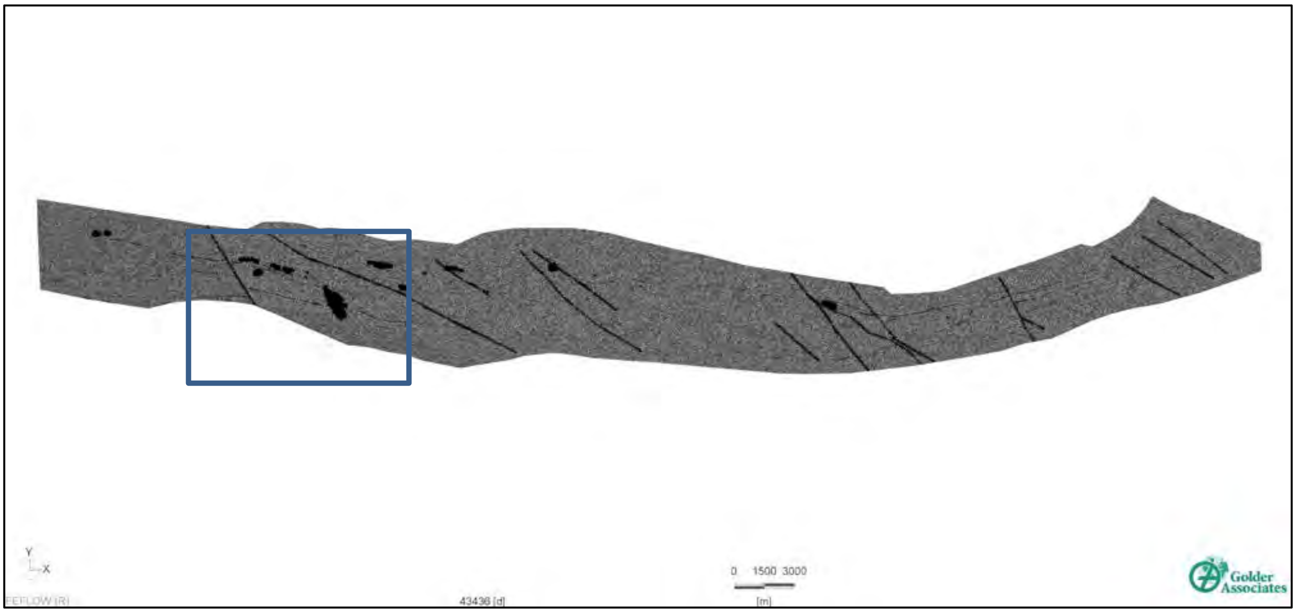


Figure 8: Finite element network with zoomed areas

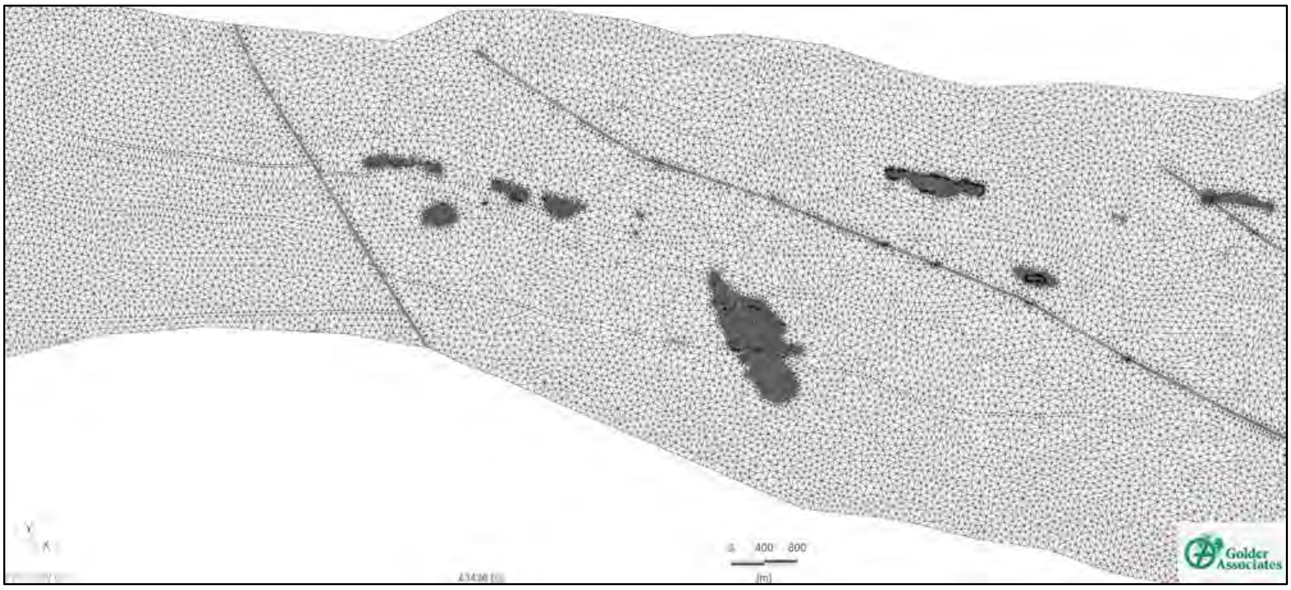


Figure 9: Zoomed finite element network referred to in previous figure, showing additional discretisation around boreholes, pits and dykes.

3.4 Boundary Conditions

Boundary conditions express the way the considered domain interacts with its environment. In other words, they express the conditions of known water flux, or known variables, such as groundwater head. Different boundary conditions result in different solutions hence the importance of stating the correct boundary conditions. Boundary conditions in a groundwater flow model can be specified either as:

- Dirichlet Type (or constant head) boundary conditions, or
- Neuman Type (or specified flux, including "no flux") boundary conditions, and
- Or a mixture of the above.

3.4.1 Model Perimeter (External) Boundaries

The northern boundary of the model coincides with the contact between the Fortescue and Hamersley Group. The upper Fortescue Group formation is considered to be a no-flow boundary owing to abundant dolerite sills. The southern boundary of the model coincides with the contact between the Brockman Iron and Weeli Wolli Formation. This boundary is also considered to be a no-flow boundary with abundant dolerite sills. The eastern boundary of the site coincides with a dolerite dyke identified in the hydrogeological conceptual model (Golder, 2017a) and as such was also assigned a no flow boundary. Due to the absence of an identified dyke or geological structure which could be assigned a no-flow boundary, a constant head boundary, equal to the water level elevation within the relevant groundwater sub catchment, was applied at the western boundary of the model.

A summary of the boundary conditions assigned to the model perimeter is provided in Table 3.

Table 3: Boundary conditions

Boundary	Topographical Feature	Boundary Condition
Northern Boundary	Geological Contact	Neumann special case (No flow boundary condition)
Southern Boundary	Geological Contact	Neumann special case (No flow boundary condition)
Western Boundary	Dolerite Dyke	Dirichlet BC = Water level Elevation (Water is permitted to leave the model at this boundary)
Eastern Boundary	Dolerite Dyke	Neumann special case (No flow boundary condition)

3.4.2 Internal model boundaries

Due to the compartmentalised nature of the groundwater system, the only mechanism for groundwater discharge is through evapotranspiration (vegetation within groundwater dependant ecosystems) or surface seepage (along creek lines). Boundary conditions were applied at the locations where potential GDEs have been mapped (Figure 10). These boundaries are activated in circumstances where groundwater levels are within 15 m bgl and permit groundwater to be removed from the system as discussed in the conceptual model report.

The constant head boundaries representing the potential GDEs have been constrained so that water can only discharge from the system – a reversal of the hydraulic gradient back towards the aquifer from the surface system would therefore not allow water to enter the aquifer. This therefore represents a true “drain type” boundary condition (Dirichlet Type I boundary condition).

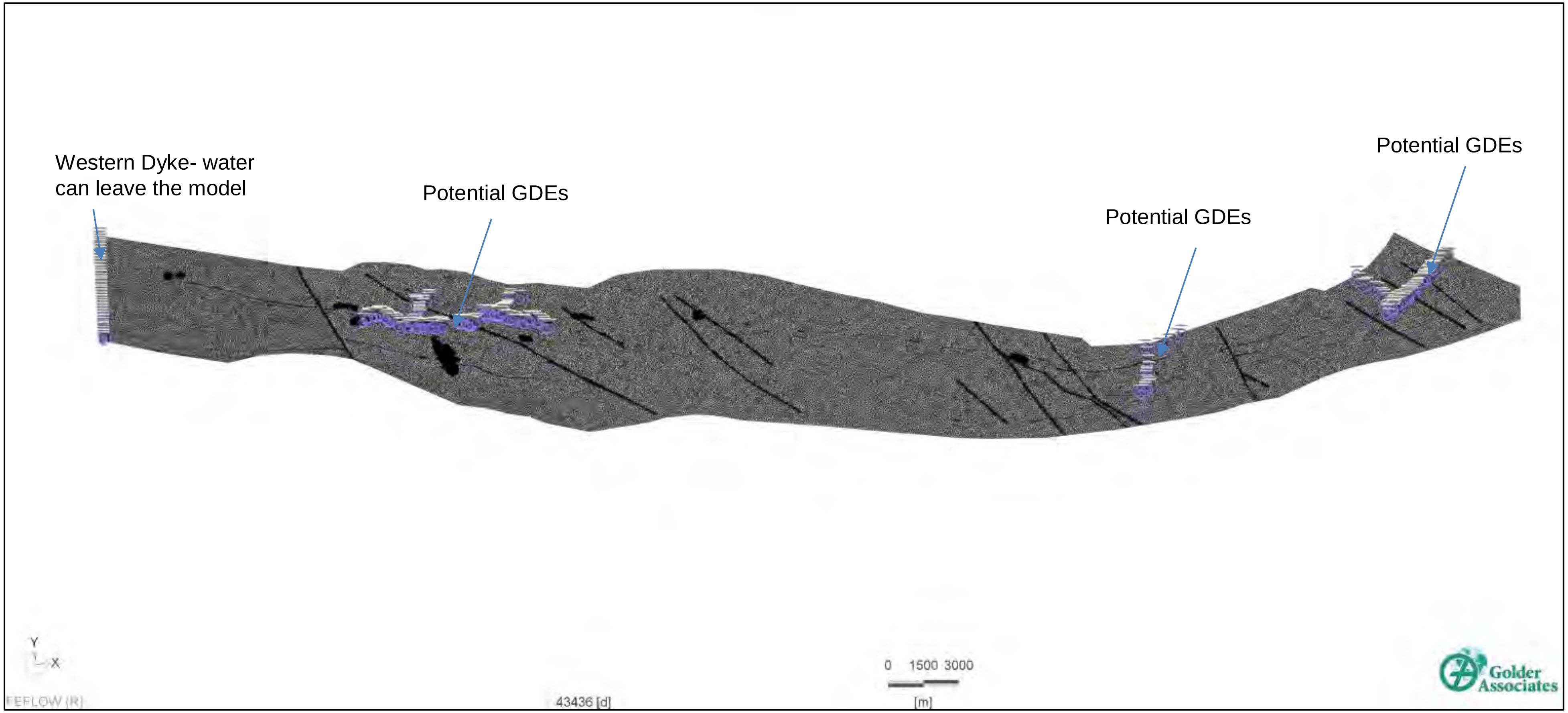


Figure 10: Internal model boundaries

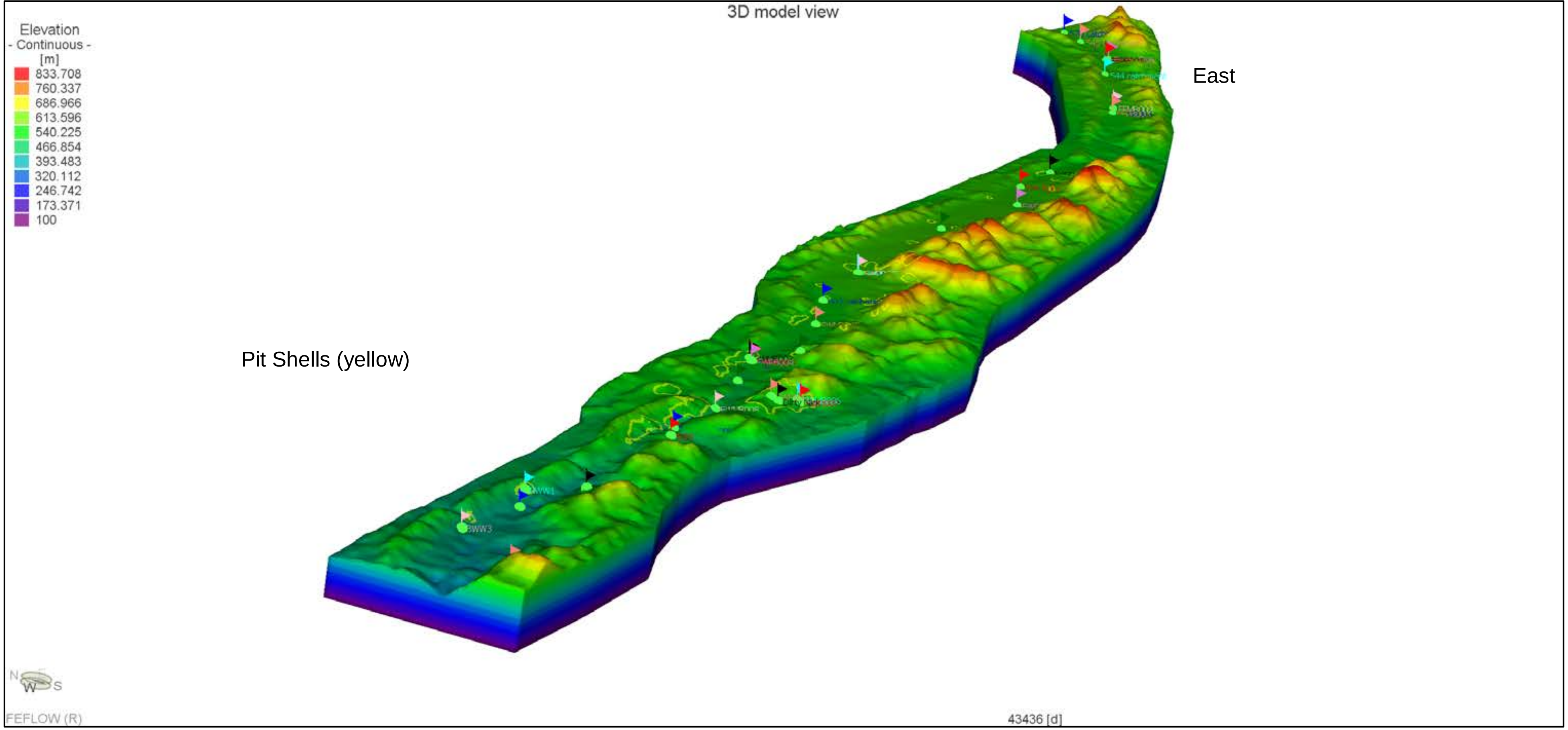


Figure 11: 3D model elevation

3.5 Aquifer Hydraulic Conductivity and Storativity

The images below show the conversion of stratigraphic layering in the Leapfrog model into hydrostratigraphic layers in the EWGM (Figure 12 and Figure 13). The aquifer transmissivity (hydraulic conductivity × aquifer thickness) and specific yield of each hydrostratigraphic unit was initially assigned based on generic parameters for the Pilbara (using the combined experiences of the Golder Project Team) and aquifer testing. Table 4 shows the initial generic range of initial values used in the model.

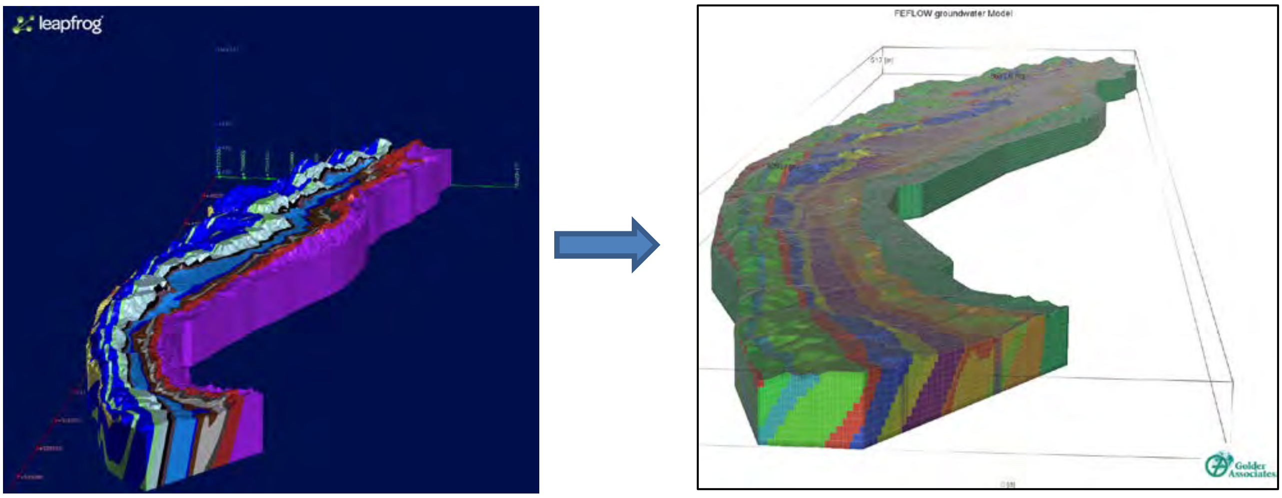


Figure 12: Leapfrog model to FEFLOW model

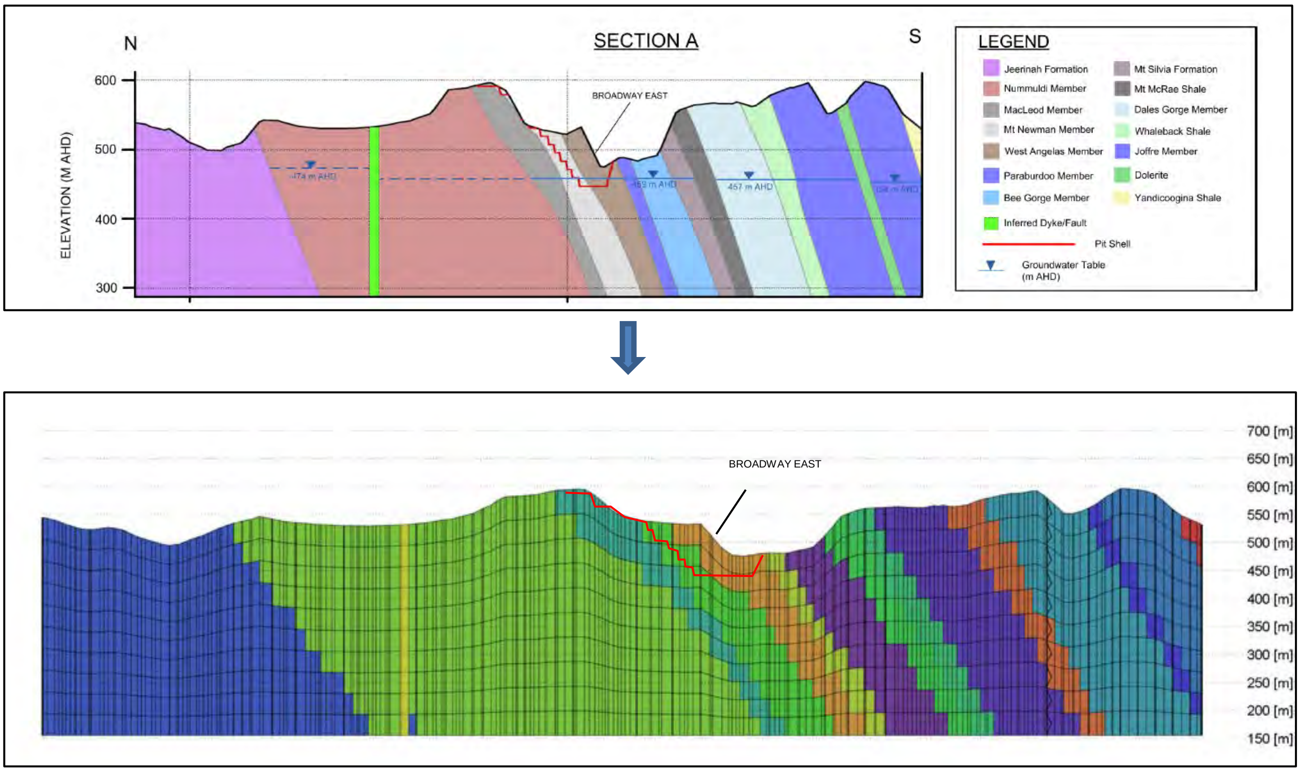


Figure 13: Conceptual Leapfrog Model NS Section A vs FEFLOW section of same NS section

Table 4: Initial generic K values and Sy values

Formation	Member	Hydro-Stratigraphy	Lithology	FMG Pumping Testing		Generic Parameters			
						K (m/day)		Specific Yield	
				K m/day	Sy	Mineralised	Unmineralised	Mineralised	Unmineralised
Weeli Wolli		Aquitard	jaspilitic banded iron and dolerite sills			0.01	0.001	0.01	0.001
Brockman Iron			banded iron, carbonates and shale	1.1-1.6		1-6	0.001-0.01	0.2	0.01
	Yandicoogina	Mineralised Brockman Aquifer	alternating chert and shale				0.001-0.01		
	Joffre above sill		interbedded chert and banded iron and shale	5.8	0.005	1-6	0.001-0.005	0.2	0.005
	Dolerite sill	Aquitard	dolerite and dykes cutting through dolomites			0.01	0.001-0.01	0.01	0.001
	Joffre Below Sill	Mineralised Brockman Aquifer	interbedded chert and banded iron and shale			1-6	0.001-0.01	0.2	0.01
	Whaleback Shale		shale with alternating banded iron			1-6	0.001-0.01	0.2	0.01
	Dales Gorge		alternating banded iron and shale bands			1-6	0.001-0.01	0.2	0.01
Mount McRae Shale		Aquitard	graphitic and chloritic shale with upper cherty banded iron bed			0.01	0.001	0.01	0.001
Mount Sylvia		Aquitard	laminated mudstone, chert and dolomite with three main banded iron beds			1	0.01	0.01	0.001
Wittenoom Formation				3.1-19.7	0.001	1-6	0.01-0.1		
	Bee Gorge	Wittenoom Aquifer	laminated fissile argillite, tuff, pyroclastic turbidite, iron formation			1-6	0.01-0.1	0.05	0.01
	Paraburdoo		massive dolomite, with thin chert and argillaceous rocks	4.5-48.5	0.04-0.07	10-40	0.01-0.1	0.1	0.01
	West Angela		massive to shaley dolomite with increasing chert with depth			1-10	0.01-0.1	0.05	0.01
Marra Mamba Iron	Mount Newman		banded iron formation with interbedded carbonate and thin shale	4.8	0.001	1-6	0.01-0.1	0.2	0.01
	MacLeod	Aquitard	banded iron, chert, and interbedded carbonate and shale			NA	0.001-0.01	NA	0.001
	Nammuldi	Aquitard	cherty banded iron with thin shales			NA	0.001-0.01	NA	0.001
Jeerinah		Aquitard	fissile shale and dolerite sills			NA	0.001	NA	0.001

3.6 Recharge and Discharge

Recharge was applied across the model to each hydrostratigraphic unit with a hydraulic conductivity > 0.01 m/d in layer 1 of the model (i.e. at surface). This method of assigning recharge results in recharge only being applied to the Wittenoom Aquifer and other hydrostratigraphic units in the model which have been assigned mineralised parameters within layer 1. All other areas in the model have been applied a zero recharge. This is considered appropriate since recharge in these areas is unlikely due to a combination of low hydraulic conductivity and the water table being present at significant depths (i.e. up to 100 m bgl).

Discharge from the model is allowed to occur through the constrained boundary conditions used to represent the potential GDEs and also the western boundary of the model. Due to the compartmentalisation of aquifers into sub catchments, the balance between recharge and discharge within each sub catchment forms the greatest influence on the calibration of steady state heads within the model.

3.7 Steady state calibration

According to the conceptual model for the system, the calculated head distribution (hx, hy, hz) is dependent upon the recharge from rainfall, hydraulic conductivity and boundary conditions. For a given hydraulic conductivity value (or transmissivity value) and set of boundary conditions specified, the head distribution across the aquifer can be obtained for a specific recharge value. This simulated head distribution can then be compared to the measured head distribution and the recharge values, with the hydraulic conductivity distribution altered until an acceptable correspondence between measured and simulated heads is obtained. With the model structure in place the steady state calibration of the model was undertaken.

A three dimensional steady state groundwater flow model representing the study area was constructed to represent pre-mining groundwater flow conditions. These conditions then serve as the initial conditions for the transient simulations of groundwater flow associated with mine development.

The three dimensional groundwater flow equation on which FEFLOW modelling is based upon is provided below:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)\pm W=S\frac{\partial h}{\partial t}$$

Where: h: Hydraulic Head [L]

Kx, Ky, Kz = Hydraulic conductivity [L/T]

S = storage coefficient

T = Time [T]

W = Source and sinks [L/T]

3.7.1 Recharge specified in model

The calibrated recharge applied to the model area was 3 mm per annum (1% of mean annual rainfall). This value is consistent with the range identified in the hydrogeological conceptual model (Golder, 2017a) which estimated a range of 0.5 to 1.0 % of mean annual rainfall based on analytical groundwater sub catchment water balances. As described above this recharge was only applied across the low lying areas along the valley (Wittenoom Formation) and the mineralised zones (zones with k > 0.01 m/d), other areas in the model have been applied a zero recharge. The model takes into account losses due to evapotranspiration from the GDEs through the boundary conditions imposed.

3.7.2 K values obtained by model calibration

The range of hydraulic conductivity (k) values obtained from model calibration appear to be within the lower ranges of the generic conductivity values provided in Table 5**.** Plan views and 3D views of the recharge and k-values used the model are provided below in Figure 14 and Figure 15.

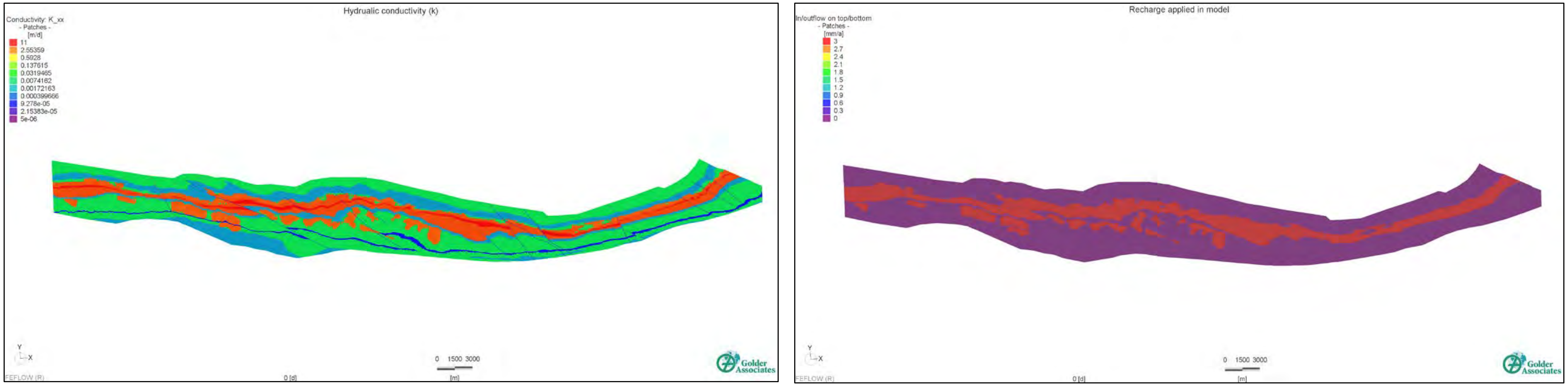


Figure 14: Plan views of the hydraulic conductivity and recharge zones applied in the model

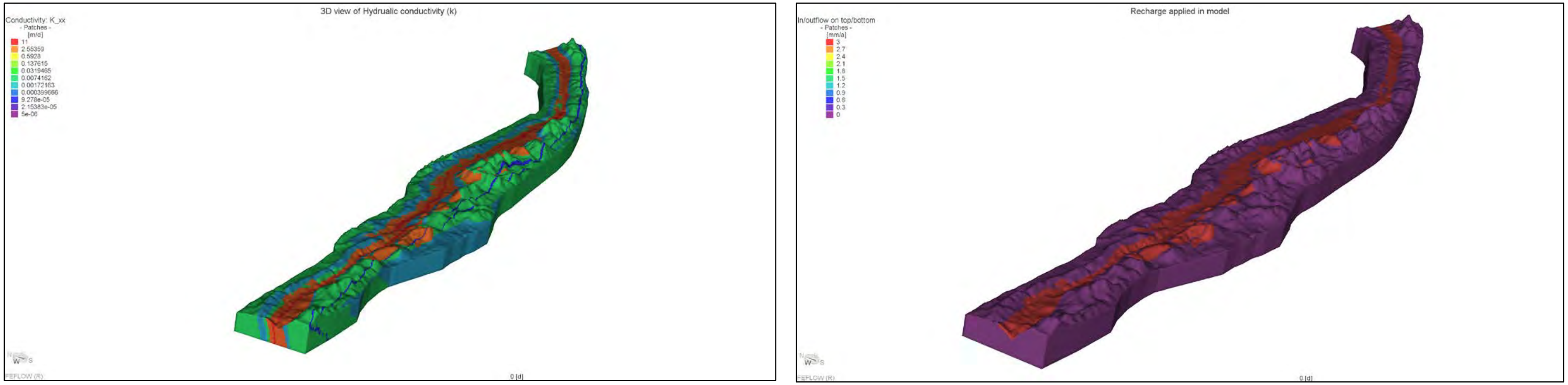


Figure 15: 3D views of the hydraulic conductivity and recharge zones applied in the model

Table 5: Calibrated K values used in model

Formation	Member	Hydro-Stratigraphy	Lithology	FMG Pumping Testing (Mineralised Zones Only)		Generic Parameters Hydraulic Conductivity (m/day)		Steady State Calibration (best fit) Hydraulic Conductivity (m/day)	
				K m/day	Sy	Mineralised	Unmineralised	Mineralised	Unmineralised
Weeli Wolli		Aquitard	jaspilitic banded iron and dolerite sills			0.01	0.001	NA	0.001
Brockman Iron Formation	Yandicoogina	Mineralised Brockman Aquifer	alternating chert and shale	1.1 – 5.8	0.005		0.001-0.01	NA	0.001
	Joffre above sill		interbedded chert and banded iron and shale			1-6	0.001-0.005	6	0.01
	Dolerite sill	Aquitard	dolerite and dykes cutting through dolomites			0.01	0.001-0.01	NA	0.0001
	Joffre Below Sill	Mineralised Brockman Aquifer	interbedded chert and banded iron and shale			1-6	0.001-0.01	6	0.01
	Whaleback Shale		shale with alternating banded iron			1-6	0.001-0.01	6	0.01
	Dales Gorge		alternating banded iron and shale bands			1-6	0.001-0.01	6	0.01
Mount McRae Shale		Aquitard	graphitic and chloritic shale with upper cherty banded iron bed			0.01	0.001	NA	0.001
Mount Sylvia		Aquitard	laminated mudstone, chert and dolomite with three main banded iron beds			1	0.01	NA	0.001
Wittenoom Formation	Bee Gorge	Wittenoom Aquifer	laminated fissile argillite, tuff, pyroclastic turbidite, iron formation	3.1-48.5	0.04-0.07	1-6	0.01-0.1	5	NA
	Paraburdoo		massive dolomite, with thin chert and argillaceous rocks			10-40	0.01-0.1	11	NA
	West Angela		massive to shaley dolomite with increasing chert with depth			1-10	0.01-0.1	5	NA
Marra Mamba Iron Formation	Mount Newman	Mineralised Marra Mamba Aquifer	banded iron formation with interbedded carbonate and thin shale	4.8	0.001	1-6	0.01-0.1	4	0.01
	MacLeod	Aquitard	banded iron, chert, and interbedded carbonate and shale			NA	0.001-0.01	NA	0.001
	Nammuldi	Aquitard	cherty banded iron with thin shales			NA	0.001-0.01	NA	0.001
Jeerinah		Aquitard	Fissile shale and dolerite sills			NA	0.001	NA	0.01
Faults / Dolerite Dykes		Aquitard						NA	0.000005 – 0.0001

3.7.3 Steady state results

Calibration is the process of identifying a suitable set of hydraulic parameters, boundary conditions and stresses that best describes the observed hydraulic heads or fluxes within a defined catchment. Under steady state conditions the groundwater flow equation is reduced to exclude storativity and only transmissivity (or hydraulic conductivity) and recharge are considered in the calibration process.

The suitability of the calibrations was evaluated for five criteria:

- Residual error (m): < 10% of the model thickness
- Absolute residual (m): <10% of the model thickness
- Root mean square error (m): <10% of the model thickness
- Scaled root mean squared error: <5% (Barnett, 2012)
- Correlation: >0.95.

The general principles outlined in the Australian Groundwater Modelling Guidelines (Barnett, 2012) were followed for calibration of the model. The difference between the simulated and the observed hydraulic head (residual) was calculated for each target (Table 6). The error in the calibration was expressed by three common methods: the mean error (ME), the mean absolute error (MAE) and the root mean squared (RMS) error and the scaled root mean squared (SRMS) error. The ME is the mean difference between measured (WLm) and simulated (WLs) water levels:

$$ME = 1/n \ \Sigma \ (WLm - WLs)_i$$

For i=1 to n, the number of calibration targets.

A small ME is not necessarily an indication of a good calibration, because negative and positive residuals, even if large, can cancel each other out, resulting in a small ME. The MAE addresses this as the mean of the absolute value of the differences in measured and simulated water levels:

$$MAE = 1/n \ \Sigma \ | (WLm - WLs)_i |.$$

The RMS error is the squared differences in measured and simulated water levels.

$$RMS = \sqrt{[1/n \ \Sigma \ (WLm - WLs)_i^2]}.$$

In keeping with standard practice, the RMS error was evaluated as a ratio to the total water level change across the model domain. If the ratio is small, the errors are only a small part of the overall model response.

The SRMS is the RMS divided by the range of measured heads expressed as a percentage:

$$SRMS = RMS / \Delta H$$

Where ΔH = range of measured groundwater elevations across the modelled domain.

The ME, MAE, RMS and SRMS errors were calculated using observed groundwater levels, and were 0.6 m, 4.9 m, 6.0 m and 3.2%, respectively. The SRMS error of 3.2 % of the range of water level change across the model domain which is consistent with an acceptable calibration (< 5%) as suggested by Barnett (2012). All other measures of calibration suitability ME, MAE and RMS were less than 10% of the model thickness further supporting that an acceptable calibration has been achieved. A table of points used, the observed groundwater level, modelled predicted level, and the above calibration statistic measures are provided in Table 6.

The observed groundwater levels were plotted against the simulated water levels in a scatter plot (Figure 16 and Figure 17). Deviations from the straight line indicating a perfect match between the observed and simulated values should be randomly distributed indicating that there is no bias towards over or under predicting the groundwater levels. A correlation coefficient of 99% was obtained between the simulated and observed groundwater elevations.

A 3D view of the Steady State Hydraulic Head is shown in Figure 18.

Table 6: Steady State Results

Observation Point	Observed head (mamsl)	Simulated Head (mamsl)	Absolute Error (m) MAE	Error (m) ME	Square Error (m)
570 catchment	570.3	553.1	17.2	17.2	295.7
545 catchment	544.9	550.1	5.2	-5.2	27.5
FFPB001	550.3	544.9	5.3	5.3	28.3
FFMB001	550.2	544.9	5.3	5.3	27.9
Flying Fish	550.6	544.9	5.7	5.7	32.0
FFPB002	543.5	536.6	6.9	6.9	48.1
FFMB002	543.5	536.6	6.9	6.9	47.6
544 catchment	543.9	536.6	7.3	7.3	52.6
FFMB003	497.5	494.4	3.1	3.1	9.7
FFPB003	497.4	494.4	3.0	3.0	9.2
Kenny Bore	501.0	509.9	9.0	-9.0	80.5
Ren Bore	519.0	519.9	0.9	-0.9	0.8
EWPB001	519.6	519.9	0.4	-0.4	0.1
518 catchment	518.2	519.9	1.7	-1.7	2.7
EWPB002	509.8	518.3	8.5	-8.5	72.0
EWMB002	509.8	518.3	8.5	-8.5	72.0
502 catchment	502.5	504.8	2.3	-2.3	5.4
EWMB005	479.2	480.4	1.2	-1.2	1.5
EWMB003	474.1	480.1	6.0	-6.0	36.4
EWMB004	473.8	480.1	6.3	-6.3	40.1
EWPB004	473.3	480.1	6.8	-6.8	46.2
EWMB009	465.0	457.0	7.9	7.9	63.0
EWMB008	458.6	456.6	2.1	2.1	4.2
Baddock bore	455.4	458.9	3.6	-3.6	12.6
EWPB007	456.7	455.8	0.9	0.9	0.8
EWMB006	457.3	458.9	1.6	-1.6	2.5
Dirty Nick	457.1	458.9	1.8	-1.8	3.2
EWD007	453.3	458.9	5.6	-5.6	31.7
EWPB05	453.4	458.9	5.5	-5.5	30.2
Westside	474.0	475.2	1.2	-1.2	1.5
BWW3	384.8	385.1	0.3	-0.3	0.1
BWW1	394.0	385.6	8.4	8.4	70.3
Reef Bore	393.9	385.2	8.7	8.7	75.2
P4	387.2	385.6	1.6	1.6	2.5
P3	393.3	385.6	7.7	7.7	59.0
BWS	454.8	456.4	1.6	-1.6	2.5
AVERAGE	483.6	483.1	4.9	0.6	36.0
MINIMUM	384.8	385.1	0.3	-9.0	0.1
MAXIMUM	570.3	553.1	17.2	17.2	295.7
Correlation	99.3		RMS		**6.0**
			SRMS		**3.2%**

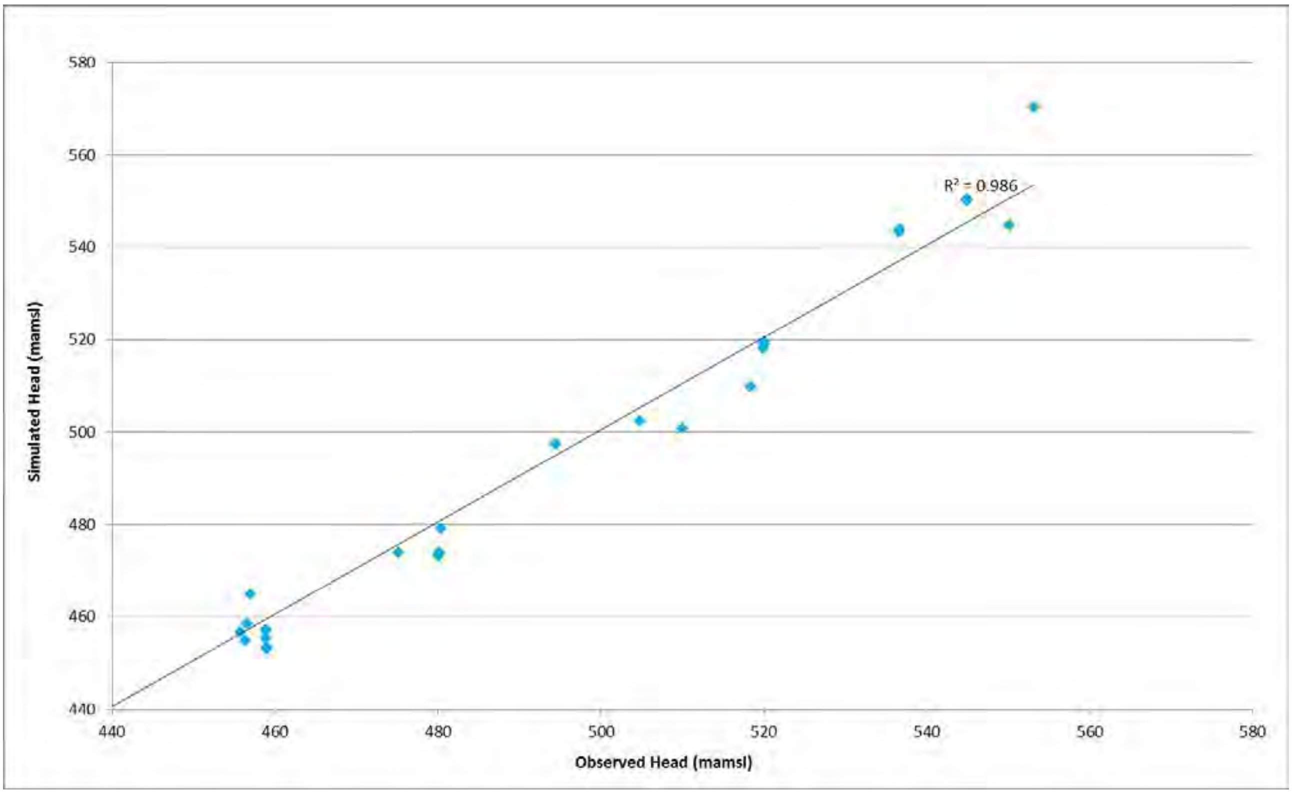


Figure 16: Scatterplot of simulated versus measured groundwater level

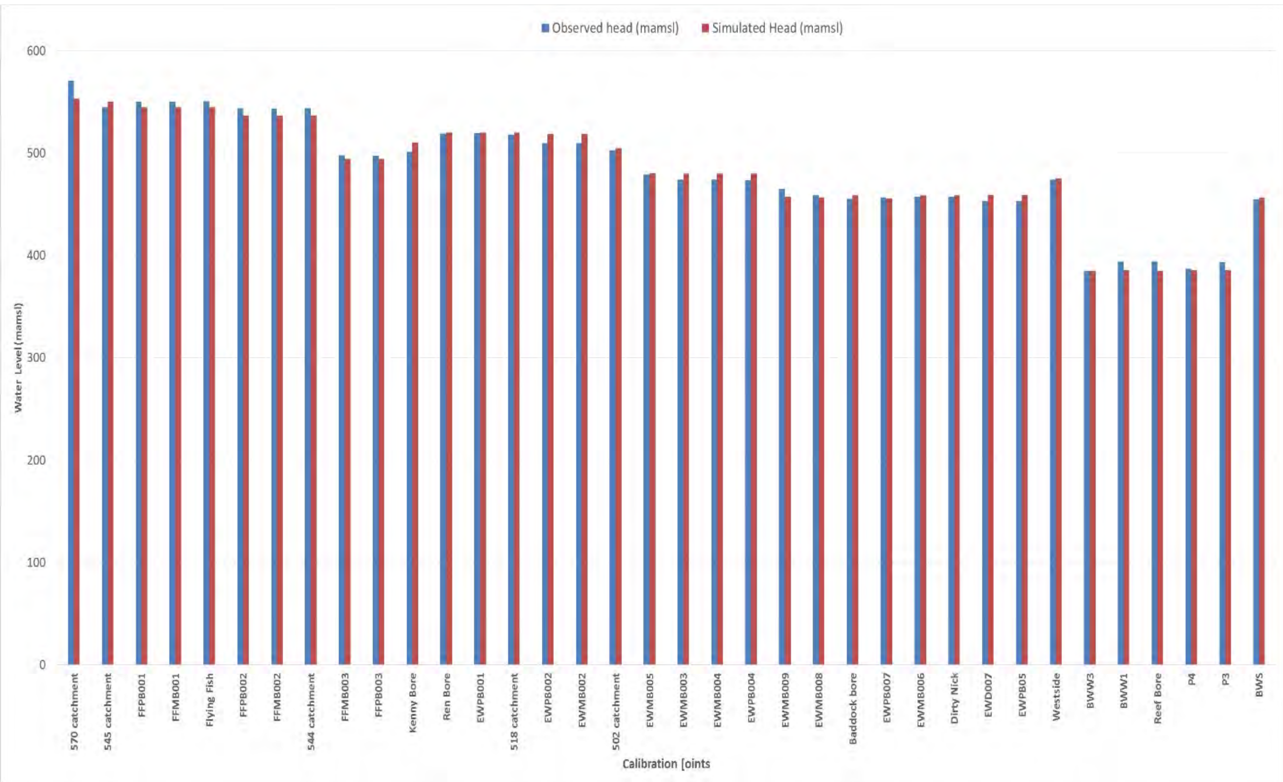


Figure 17: Bar –Chart of simulated versus measured groundwater level

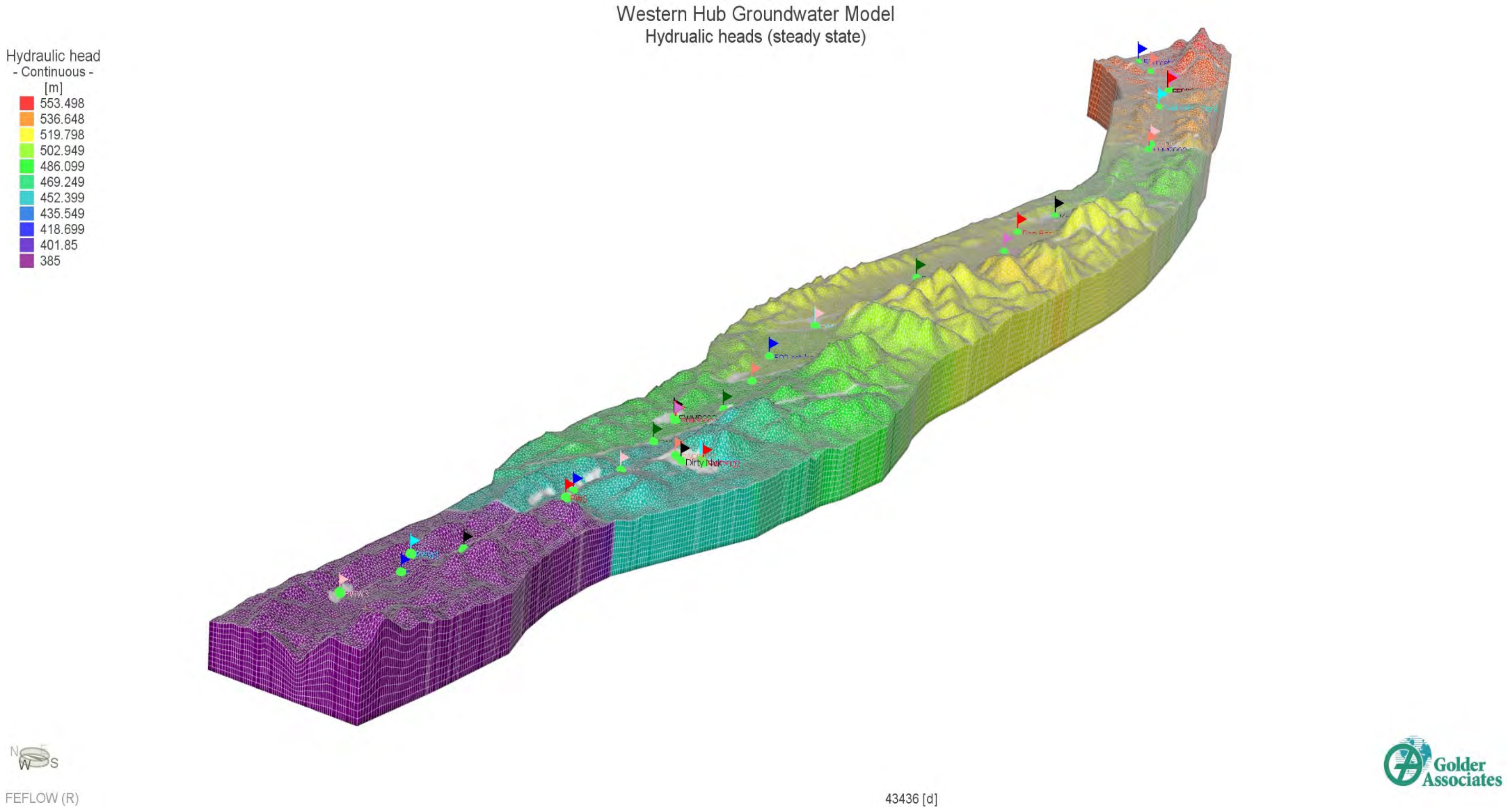


Figure 18: 3D Steady state model calibration of water level elevation

3.7.4 Steady state water balance

A steady-state water balance has been developed using the results of the FEFLOW model calibration (Table 7). The water balance error was 0.0% was obtained which is compliant with the suggested criteria provided by Barnett (2012) of <1%.

Table 7: Steady state water balance components

Pre Development Steady State: Feflow Model				
Component		Inflow (ML/a)	Outflow (ML/a)	Cumulative Balance (ML/a)
1	Effective recharge from precipitation	215	0	**215**
2	Water losses from western boundary	0	-38	**177**
3	Water losses from potential GDEs	0	-177	**0**
Total		**215**	**-215**	**0**
Balance Error (%)				**0.0%**

The results of the water balance indicate that the majority (82%) of water discharged from the model is by way of evapotranspiration from potential GDEs across the Project area. This is consistent with the hydrogeological conceptualisation of the groundwater system (Golder, 2017a) which suggests that these groundwater sub catchments are isolated 'buckets' where very little transfer of water occurs laterally between catchments. Therefore, the majority of discharge from the model must occur internally, within individual sub catchments.

3.7.5 Steady State sensitivity analysis

An assessment was undertaken of the sensitivity of the model to changes in the calibrated values of hydraulic conductivity and recharge. Sensitivity model runs included halving and doubling both the hydraulic conductivity and the recharge values in the model (total of 4 additional model runs). The sensitivity of each model run was assessed by comparison of the SRMS values from the sensitivity run with that of the calibrated run.

Since the model will be used (in the future) to assess the potential impacts of dewatering and water supply abstraction on the availability of the groundwater to potential GDEs, it is considered appropriate to use the estimated groundwater discharge rate at potential GDEs as an indicator of model sensitivity.

The results of the sensitivity analysis are shown in Figure 19 and Figure 20 (hydraulic conductivity) and Figure 21 and Figure 22 (recharge).

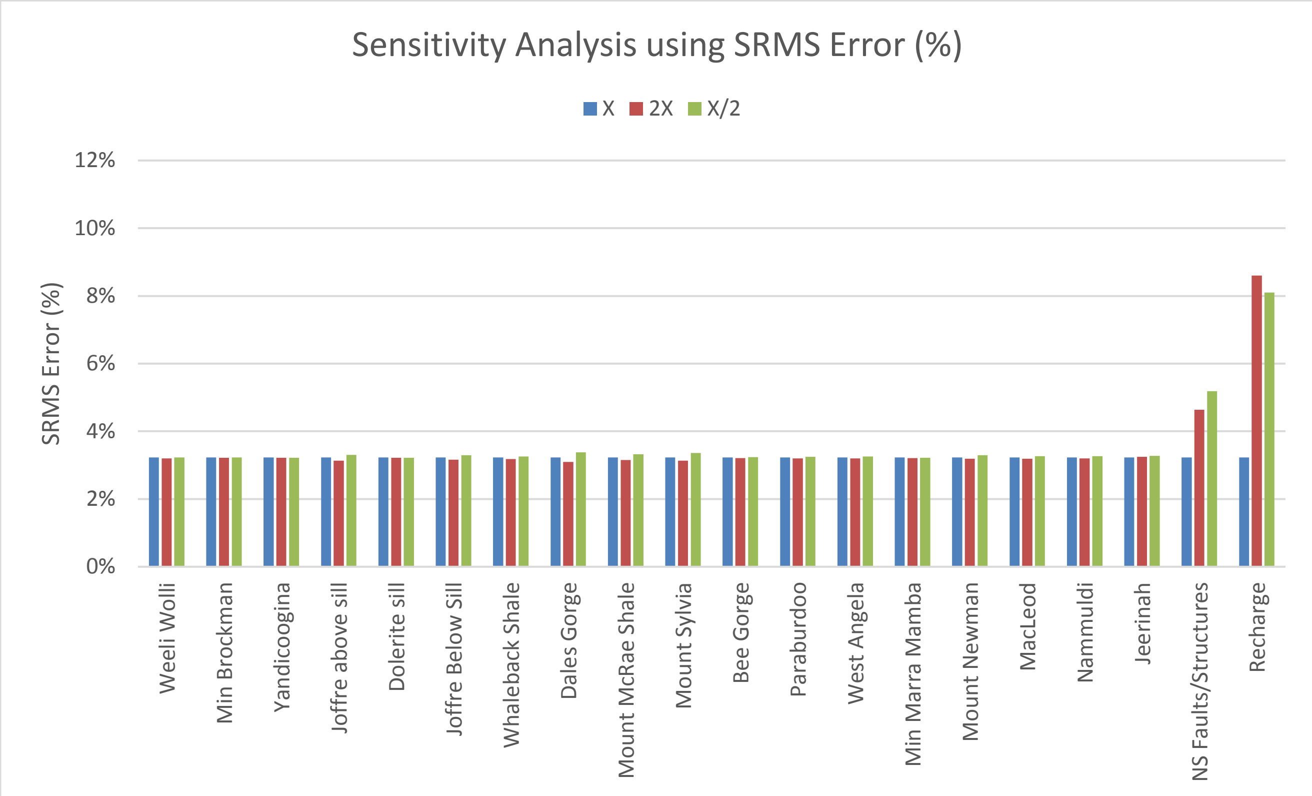


Figure 19: Results of Sensitivity Analysis – Hydraulic conductivity based on SRMS Error %

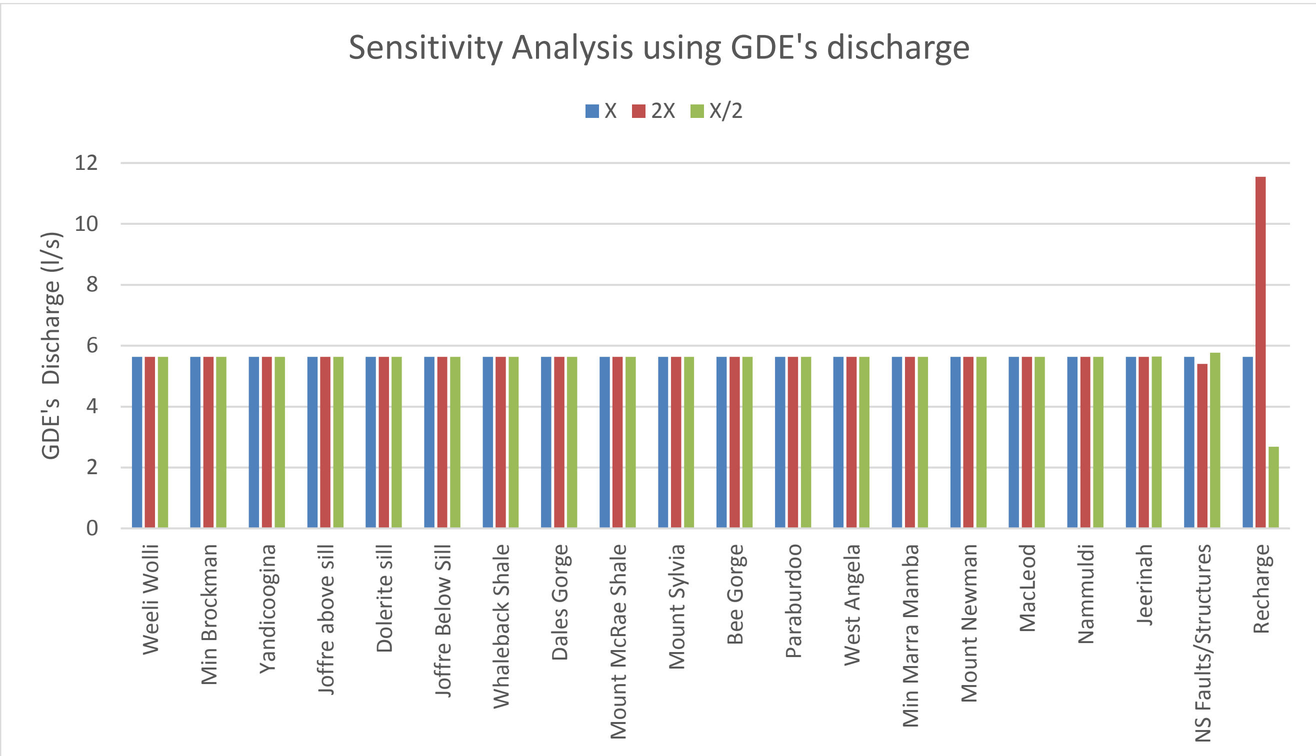


Figure 20: Results of Sensitivity Analysis – Hydraulic conductivity based on discharge to potential GDEs

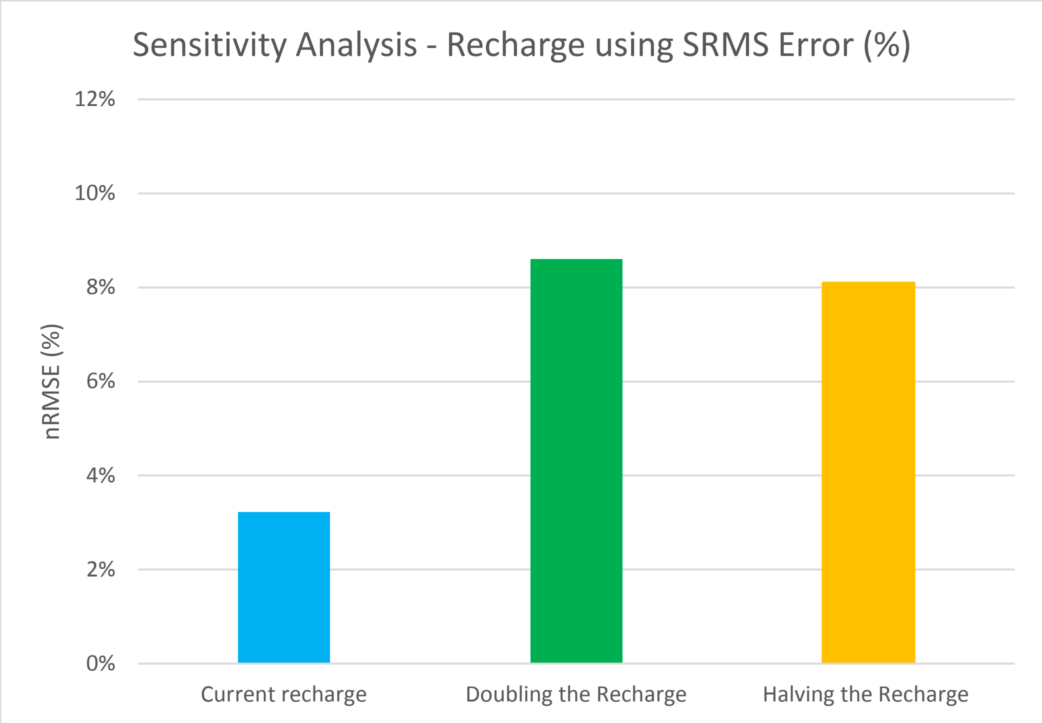


Figure 21: Results of Sensitivity Analysis – Recharge based on SRMS Error %

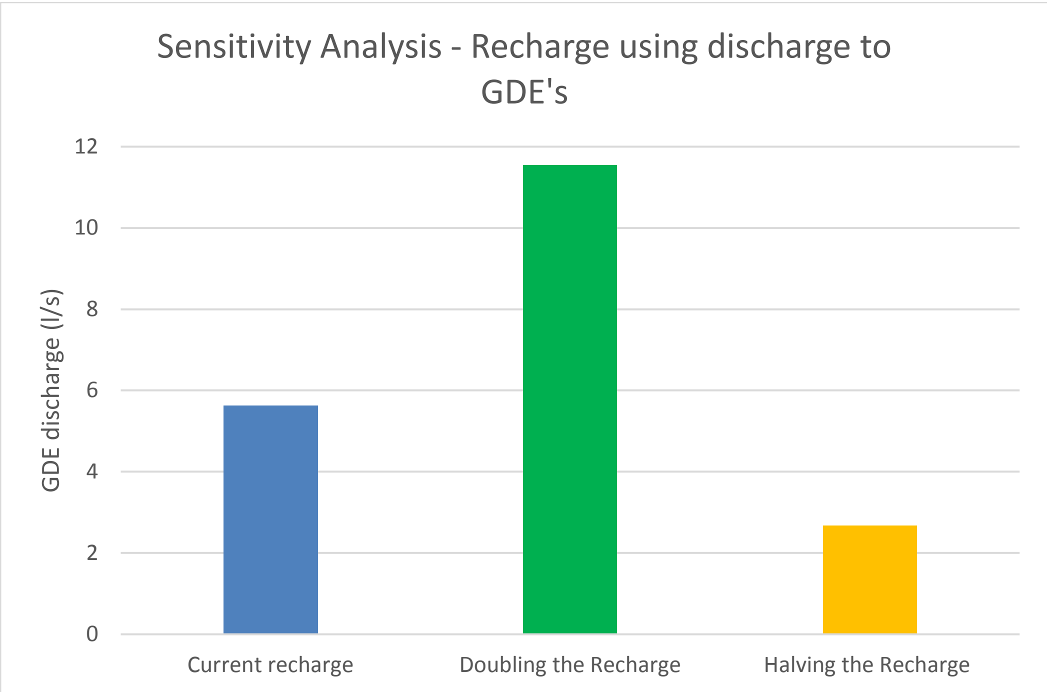


Figure 22: Results of Sensitivity Analysis – Recharge based on discharge to potential GDEs

The results show that the model's SRMS error is sensitive to the hydraulic conductivity of the faults and structures which separate the groundwater sub catchments but not the hydraulic conductivities assigned to the other hydrostratigraphic units represented in the model themselves. This is in agreement with the conceptualisation of the hydrogeology of the Project area (Golder 2017a) which requires low hydraulic conductivity values within these structures to maintain the observed head differences between them. Any change in the calibrated hydraulic conductivity of these structures would allow either not enough or too much groundwater to accumulate with individual sub catchments resulting in a deviation of the modelled groundwater level compared with that observed in the field.

The discharge of groundwater to potential GDEs is not sensitive to the modelled hydraulic conductivity. This indicates that changes in hydraulic conductivity do not significantly affect the calibrated groundwater levels for those sub catchments where potential GDEs are represented.

The sensitivity analysis shows that the model is sensitive to doubling and halving the calibrated recharge values. This is consistent with the project conceptualisation as movement between sub catchments is almost negligible meaning that applying varied recharge is akin to the “filling of a bucket with water”. If too much water is applied, the bucket fills too high, if not enough is applied, it does not fill high enough. This notion is also reflected where the discharge to potential GDEs increases/decreases proportionally to increases/decreases in applied recharge rates. An increase in recharge results in a higher groundwater level and a greater rate of discharge to the applied boundary conditions (GDEs). Lower recharge rates restrict the rate of discharge due to subdued groundwater levels.

Comparison of the rate of groundwater discharge to the boundary conditions representing the potential GDEs will provide a very useful tool for assessing impacts due to dewatering/water supply abstraction.

3.8 Transient Calibration

There is an absence of data across the Project area with which to perform transient calibration. Long term monitoring is limited in spatial extent and does not capture the response of groundwater levels to any recharge events. Furthermore, test pumping failed to adequately cause drawdown responses in monitoring bores (Golder, 2017a). It is anticipated that future water supply and dewatering activities will be critical in facilitating collection of transient data and allowing refinement of EWGM storage parameters.

3.8.1 Transient sensitivity analysis

In the absence of transient data, a range of Project aquifer (e.g. Wittenoom and Mineralised Brockman) specific yield parameters have been adopted to test the sensitivity of model predictions. A base case of 3%, lower bound of 1%, and upper bound of 7% specific yield have been adopted and are based on estimates of specific yield derived from test pumping results (Golder, 2017a).

4.0 PREDICTIONS

A total of six scenarios have been developed for the EWGM; the first three relate to a dewatering and water supply assessment and the final three to an impact assessment.

4.1 Water Supply and Dewatering Assessment

The following scenarios were simulated for water supply and dewatering; also providing an assessment of the likely range of the Project's water balance:

- Scenario 1 – Base case (3%) specific yield for Project Aquifers
- Scenario 2 - Minimum (1%) specific yield for Project Aquifers
- Scenario 3 – Maximum (7%) specific yield for Project Aquifers

The results of these simulations are presented in Golder (2017b) and summarised once more in Golder (2017c).

4.2 Impact Assessment

The following scenarios were simulated for the impact assessment:

- Scenario 4 – Minimum (1%) specific yield for Project Aquifers with accelerated mine plan (2018 – 2024)
- Scenario 5 - Maximum (7%) specific yield for Project Aquifers with accelerated mine plan (2018 – 2024)
- Scenario 6 – Minimum (1%) specific yield for Project Aquifers using 2036 groundwater levels predicted by Scenario 4 as initial heads. Simulation runs from 2036 – 2136.

These scenarios were developed to specifically target "worst case" impacts, and so simulating the range of specific yield parameters was not necessary. Scenario 4 provides the greatest magnitude of groundwater drawdown; Scenario 5 results in the greatest excess dewatering volume for disposal; and Scenario 6 simulates the longest groundwater recovery. The results of these simulations are presented in Golder (2017c).

5.0 UNCERTAINTY

A full discussion of the uncertainty regarding the hydrogeological conceptualisation and the EWGM is presented in Golder (2017c), following the impact assessment. A summary of this discussion is as follows:

- The numerical model was found to be most sensitive to the hydraulic conductivity of the dolerite dyke structures. The number, location and permeability of these would significantly impact steady state calibration and water balance.
- Alluvial material was omitted from the model for simplicity; however it is uncertain how this might impact potential throughflow between sub-catchments.
- Numerical model predictions were very sensitive (i.e. change significantly) to changes in storage parameters. Whilst it does not overly impact the time required to dewater a pit, it creates uncertainty regarding the water balance (e.g. magnitude of excess and deficit).

6.0 SUMMARY

A numerical groundwater model (EWGM) has been developed for the Eliwana Mining Project. The EWGM is based on the hydrogeological conceptualisation presented in Golder (2017a) and has been successful in achieving the objectives of:

- Simulating Mine Dewatering;
- Developing a Project Water Balance; and
- Assessing Potential Impacts

Key aspects of the development of the EWGM are as follows:

- Groundwater model boundaries have been selected based on mapped geological boundaries.
- The hydrostratigraphic units included in the FEFLOW model were created based on direct conversion of the geological layering/stratigraphy within the Leapfrog model for the Eliwana Mining area provided by Fortescue.
- Aquifer parameters and effective recharge were calibrated within the given ranges of generic parameters and aquifer testing results. Higher hydraulic conductivity values were applied to the mineralised zones of the Brockman Iron Formation and Marra Mamba Formation based on the mineralised shells in the Leapfrog model.
- The effective recharge is estimated to range from 0 to 1% of mean annual rainfall. Recharge is assumed to occur in the Wittenoom Formation and the mineralised areas of the Brockman and Marra Mamba Formations. In other areas zero recharge was applied.
- A good calibration in steady state of the hydraulic heads was achieved with a Normalised Root Mean Square Error of less than 5% (consistent with requirements as defined by Barnett, 2012).
- The model sensitivity was tested with the calculated discharge of the GDEs zones; as expected the model is sensitive to recharge and the hydraulic conductivity of the dolerite dykes.

No transient calibration data was available for the model development. Uncertainty regarding aquifer storage was therefore addressed in the model prediction stage, with a range of specific yield values (1%, 3% and 7%) adopted during the water supply and dewatering assessment. A ‘worst case’ approach was adopted for the impact assessment, where

- A low specific yield was used in the dewatering impact scenario;
- A high specific yield was used in the excess disposal impact scenario; and
- A low specific yield was used in the groundwater recovery scenario.

The results of the predictions are reported in Golder (2017b) and Golder (2017c); the Mine Dewatering and Water Supply report and the Groundwater Impact Assessment report respectively.

Uncertainty regarding the hydrogeological conceptualisation and parameterisation has been partly addressed through the steady state sensitivity and range of specific yield values utilised in the predictions. It is acknowledged that this uncertainty can be further reduced in time with additional groundwater level monitoring, particularly during periods of stress to the groundwater system (e.g. large recharge events of abstraction activities).

7.0 REFERENCES

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- Diersch H.J.G., "WASY Software ® FEFLOW: Finite Element Subsurface Flow&Transport Simulation System: Reference Manual". WASY Institute for Water Resources Planning and System Research Ltd, 2002, 292pp.
- Golder (2017a), Eliwana Mining Project - Hydrogeological Conceptual Model Report. Unpublished Report for Fortescue. Report number 1671484-002-R-Rev1, December 2017.
- Golder (2017b), Eliwana Mining Project – Dewatering and Water Supply Assessment. Unpublished Report for Fortescue. Report number 1671484-004-R-Rev2, December 2017.
- Golder(2017c), Eliwana Mining Project - Groundwater Impact Assessment, Report number 1671484-007-R-Rev3, December 2017

8.0 IMPORTANT INFORMATION

Your attention is drawn to the document titled – "Important Information Relating to this Report", which is included in Appendix A of this report. The statements presented in that document are intended to inform a reader of the report about its proper use. There are important limitations as to who can use the report and how it can be used. It is important that a reader of the report understands and has realistic expectations about those matters. The Important Information document does not alter the obligations Golder Associates has under the contract between it and its client.

Report Signature Page

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APPENDIX A

Important Information

IMPORTANT INFORMATION RELATING TO THIS REPORT

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Any uncertainty as to the extent to which this Report can be used or relied upon in any respect should be referred to Golder for clarification.

As a global, employee-owned organisation with over 50 years of experience, Golder Associates is driven by our purpose to engineer earth's development while preserving earth's integrity. We deliver solutions that help our clients achieve their sustainable development goals by providing a wide range of independent consulting, design and construction services in our specialist areas of earth, environment and energy.

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