REPORT ON

VULCAN SOUTH

GROUNDWATER IMPACT ASSESSMENT

For: Vitrinite Pty Ltd

Project number: 4027

Date: 14/03/2022

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Prepared for

Vitrinite Pty Ltd

1. Introduction

hydrogeologist.com.au has been engaged by Mining & Energy Technical Services Pty Ltd (METServe) to prepare a groundwater impact assessment to support an Environmental Authority (EA) application for Vulcan South (VS) (the Project). The Project is proposed to be developed by Vitrinite Pty. Ltd., owner of Qld Coal Aust No.1 Pty. Ltd. and Queensland Coking Coal Pty. Ltd. (Vitrinite), and is located:

- north of Dysart and approximately 35 km south of Moranbah in Queensland's Bowen Basin; and
- to the immediate west of the BHP Billiton Mitsubishi Alliance (BMA) Saraji Mine and Peak Downs Mine.

The Project location is presented in Figure 1.1.

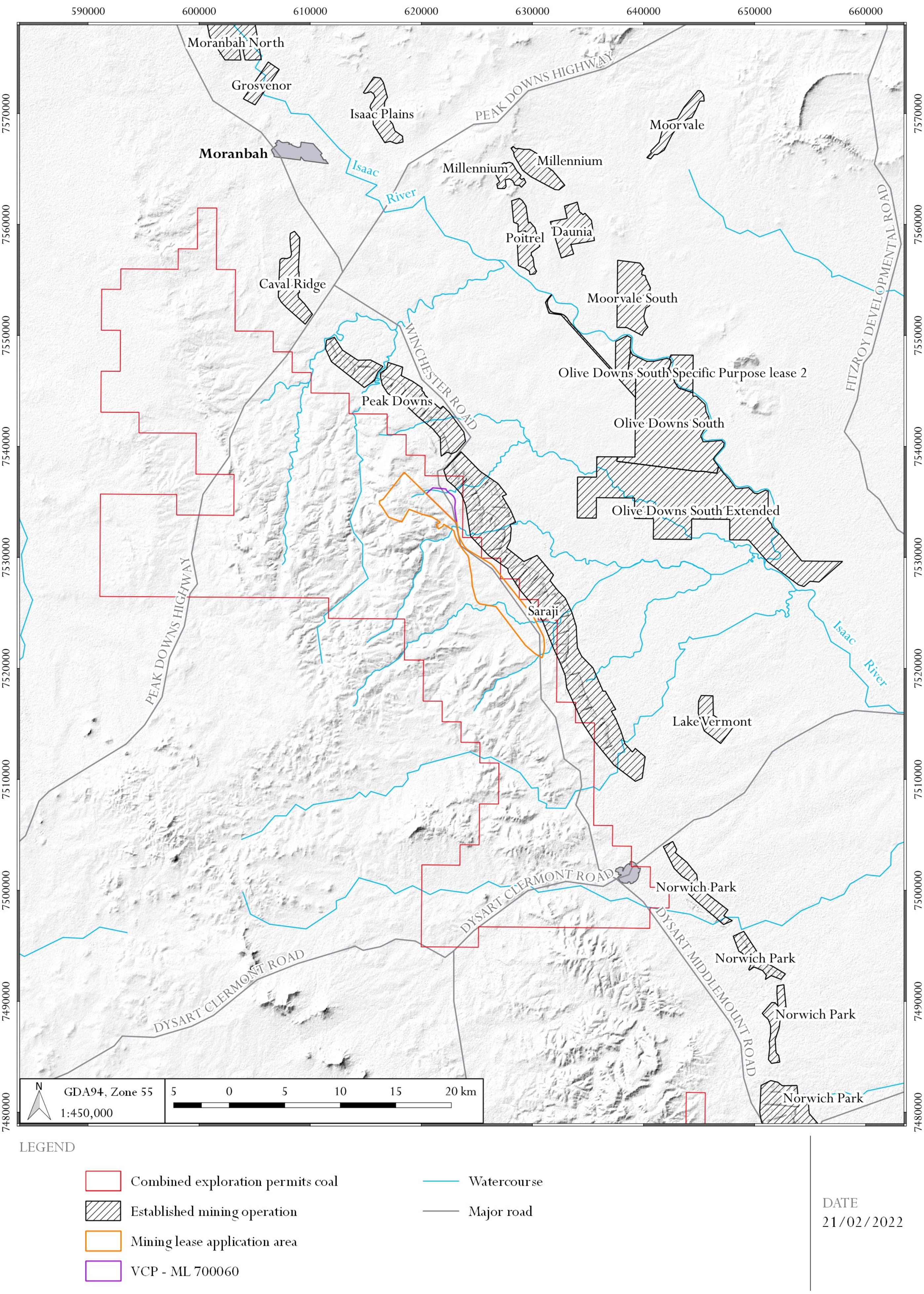
METServe has been engaged by Vitrinite to manage the environmental approval process for the Project. Vitrinite has commissioned environmental assessment work for the purposes of preparing a mining lease application (MLA) and EA application. The groundwater impact assessment will also support the likely referral of the Project to the Commonwealth Department of the Environment and Energy (DoEE) under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

1.1. Background

The Project is located immediately to the south of Vitrinite's coal mine, the Vulcan Coal Mine (VCM), which is located on ML700060 (Figure 1.1). The proposed MLA boundary (the Project area) abuts ML700060, however proposed activities for VS and VCM will be implemented separately.

The Vulcan hard coking coal target has been defined and selected for open cut development via three separate open cut pits that form the primary mining focus of the Project (i.e. Vulcan North pit, Vulcan Main pit, and Vulcan South pit). The Project will operate for approximately nine years, including primary rehabilitation works, following a two year construction period and will extract approximately 13.5 million tonnes (Mt) of ROM coal consisting predominantly of hard coking coal with an incidental thermal secondary product at a rate of up to 1.95 million tonnes per annum (Mtpa). The Project will target the Alex and multiple Dysart Lower coal seams. Truck and shovel mining operations will be employed to develop the pits.

Ex-pit waste rock dumps will be established prior to commencing in-pit dumping activities that will continue for the life of the operation. Ancillary infrastructure, including a Run of Mine (ROM) pad, modular coal handling and preparation plant (CHPP), rail loop and train load-out facility (TLO), Mine Infrastructure Area (MIA), offices, roads and surface water management infrastructure will be established to support the operation. In-pit dumping will fill the majority of the pit volumes during operations with the remaining final voids to be backfilled upon cessation of mining, resulting in the establishment of low waste rock dump landforms over the former pit areas. The initial Ex-pit waste rock dump will be rehabilitated in-situ.



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Project location and surrounding mines

FIGURE No.
1.1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
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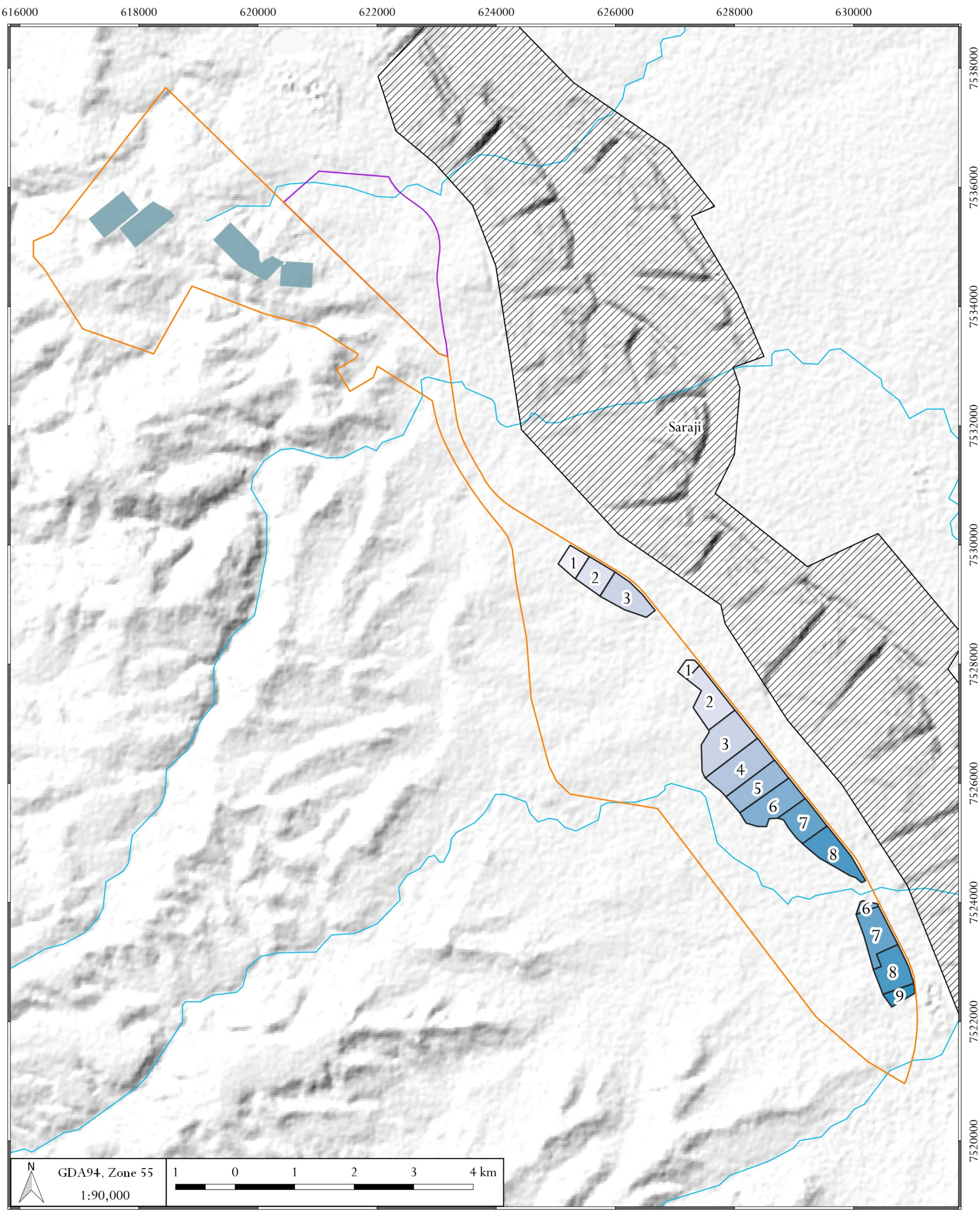
The Project includes a small-scale highwall mining trial program in the north of the Project area. The trial will involve the establishment of four highwall mining benches across a number of hillsides to facilitate extraction of coal utilising a highwall miner. The highwall mining trial will target up to 750 kt of coal which will be transported by truck to the CHPP via a dedicated haul road. The highwall mining trial is scheduled to be completed within the first year of mining operations.

The open cut mining footprint will cover a total area of approximately 477 hectares (ha). The annual mine progression for the Project is shown in Figure 1.2 along with the proposed MLA area, which for the purpose of this assessment is referred to as the Project area.

hydrogeologist.com.au (2019) established a groundwater monitoring network across the Project area in June 2019 to support the Project (Appendix A). The groundwater monitoring network was equipped with data loggers to enable high frequency (daily) groundwater level measurements to be captured. On-going monitoring and sampling of the groundwater monitoring network is being carried out to further supplement the groundwater level and quality data included in this groundwater impact assessment. The monitoring and sampling of the groundwater monitoring network is planned for and carried out in consideration of the Queensland Monitoring and Sampling Manual (Department of Environment and Science, 2018a).



LEGEND

Vulcan South mine progression (Year):

1 2 3 4 5 6 7 8 9

Established mining operation
Mining lease application area
Highwall mining area
VCP - ML 700060

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Vulcan South - mine progression

FIGURE No.
1.2

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006. Based on or contains data provided by the State of Queensland [2019]
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1.2. Objectives and scope

The objective of the assessment is to identify and assess the Project groundwater impacts in a robust manner that meets the expectations of multiple stakeholders. These stakeholders include the Queensland Government, the Commonwealth Government, surrounding landholders, and mining companies. The scope of work defines the following distinct activities which have been compiled into the groundwater impact assessment to support Project approval:

- Review existing geological and hydrogeological information in the public domain and from private investigations.
- Describe the following components of the groundwater regime:
  - geology and stratigraphy, locally and regionally, including faulting;
  - aquifer types (confined / unconfined), hydraulic characteristics and connectivity;
  - depth to, and thickness of aquifers and their transmissivity;
  - relationship between local and regional groundwater flows;
  - groundwater flow directions and discharge;
  - groundwater quality and chemistry;
  - sources of recharge and recharge rates for each aquifer; and
  - surface water interactions and potential groundwater dependent ecosystems (GDEs).
- Determine the local environmental values and water quality objectives of the groundwater resource in accordance with the Environmental Protection (Water) Policy 2009 (EPP Water) (Department of Environment and Heritage Protection, 2011), the Queensland Water Quality Guidelines (Department of Environment and Heritage Protection, 2009), and the ANZECC Water Quality Guidelines (AWQG, 2018).
- Develop a calibrated numerical groundwater model to predict potential drawdown of all relevant aquifers. The groundwater impact assessment should:
  - present the conceptualisation of the hydrogeological system, including assumptions and limitations;
  - define each hydrogeological or hydrostratigraphic unit including storage, flow, connectivity, recharge / discharge pathways and the predicted changes likely to occur as a result of the Project;
  - simulate the Project and predict groundwater level drawdown or depressurisation in each hydrostratigraphic unit during the Project and post closure;
  - predict the volumes of groundwater reporting to each pit as seepage or inflow including proportions from each hydrostratigraphic unit;
  - predict residual groundwater levels and recovery rates in each hydrostratigraphic unit during post closure; and
  - include an assessment of the quality of, and risks inherent in, the data used and modelling, which may require sensitivity analysis.
- Predict and present impacts on environmental values, including identified third party landholder bores and potential GDEs.
- Predict and present impacts on potential interactions and connectivity between surface waters and groundwaters.
- Predict and present drawdown impacts during operations and post mining resulting from the Project.
- Predict and present cumulative drawdown impacts with other existing, known or reasonably foreseeable projects in the region during and post mining.
- Propose an ongoing groundwater management strategy including monitoring of the established bore monitoring network, any measures to manage or mitigate potential impacts and a program for the review and update of the numerical model.
- Describe potential impacts on groundwater quality from the Project (e.g. spills, contaminants).

1.3. Data and information sources

Data and information used for the purposes of this assessment has been obtained from the following sources:

- proponent provided information from METServe and Vitrinite;
- reports and publications as listed in Section 9 of this report;
- groundwater assessments from nearby mines including:
  - Caval Ridge Mine (URS, 2009);
  - Saraji Mine (AECOM, 2016); and
  - Olive Downs Coal Project (HydroSimulations, 2018).
- relevant Bowen Basin publications including:
  - CSIRO (2002);
  - Arrow Energy (2012);
  - URS (2012); and
  - Arrow Energy (2016).
- publicly available datasets including:
  - Australian Bureau of Meteorology (BoM) weather and climate data (Bureau of Meteorology, 2016);
  - Scientific Information for Land Owners (SILO) rainfall and evaporation (https://www.longpaddock.qld.gov.au/silo/);
  - Groundwater Dependent Ecosystems Atlas (GDE Atlas, BOM, 2018) (http://www.bom.gov.au/water/groundwater/gde/);
  - QLD globe (https://qldglobe.information.qld.gov.au/); and
  - Queensland Springs Database (https://data.qld.gov.au/dataset/springs/resource/4cdc89ef-b583-446e-a5c7-0836a91a3767).
- spatial mapping data from the Queensland spatial catalogue (QSpatial) (http://qldspatial.information.qld.gov.au/catalogue/custom/index.page).

2. Regulatory framework

hydrogeologist.com.au have considered the Project description and activities proposed against the various legislation and guidelines produced by the Queensland and Commonwealth Governments. Relevant legislation is described below.

2.1. Queensland

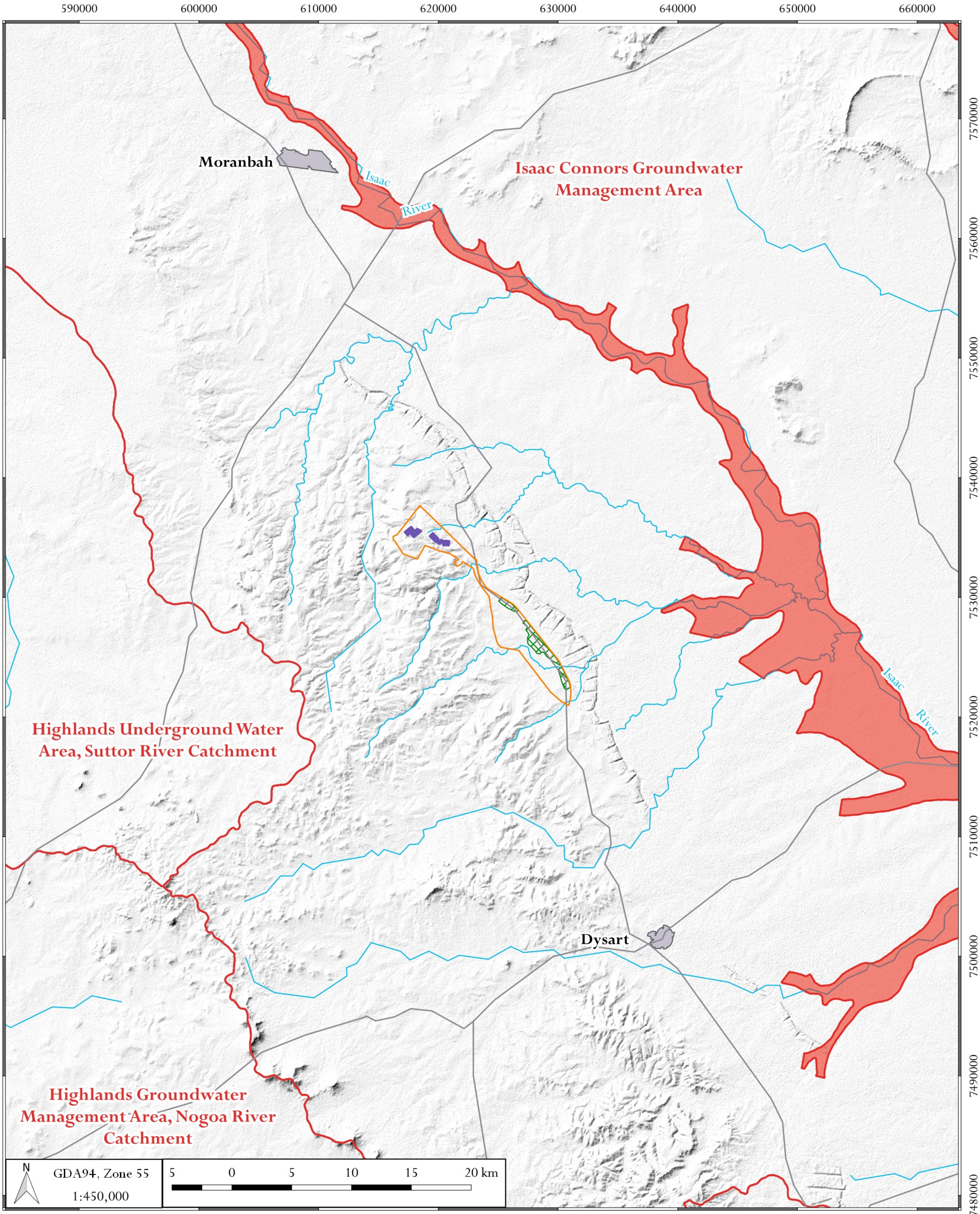
2.1.1. Water Act 2000

The *Water Act 2000* (Water Act), supported by the subordinate Water Regulation 2016, is the primary legislation regulating groundwater resources in Queensland. The purpose of the Water Act is to advance sustainable management and efficient use of water resources by establishing a system for planning, allocation and use of water. The Water Act is enacted under a framework of catchment specific Water Plans.

Water resources within the Project area are covered by the Water Plan (Fitzroy Basin) 2011 (Queensland Government, 2014) (Water Plan). The Water Plan covers surface waters (zone WQ1301) associated with the Isaac River, and groundwaters (zone WQ1310) of the Fitzroy Basin. Section 7 of the Water Plan defines the groundwater units and groundwater sub-areas areas, including the Isaac Connors groundwater management area, as follows:

> *(3) The Isaac Connors groundwater management area consists of the following (also each a groundwater unit)—*
>
> *(a) Isaac Connors Groundwater Unit 1, containing the aquifers of the Quaternary alluvium;*
>
> *(b) Isaac Connors Groundwater Unit 2, containing all subartesian aquifers within the Isaac Connors groundwater management area other than the aquifers included in Isaac Connors Groundwater Unit 1.*
>
> *(4) The area of Isaac Connors Groundwater Unit 1 shown on map E in schedule 4 is the Isaac Connors Alluvium groundwater sub-area for this plan.*

Map E, in Schedule 4, is reproduced as Figure 2.1 in this report. Figure 2.1 indicates that the Isaac Connors Alluvium groundwater sub-area is limited to the Isaac River and those parts of its tributaries that are adjacent to the confluence with the Isaac River. The Project area is approximately 20 km to the west of the Isaac River (Figure 2.1) and is well outside the Isaac Connors Groundwater Unit 1. It is assessed by **hydrogeologist.com.au** that the proposed open pits would drain groundwater from the Isaac Connors Groundwater Unit 2, that is the sub-artesian aquifers within the Isaac Connors groundwater management area. This interpretation is confirmed by the general absence of Quaternary alluvium near the proposed open pits and more broadly within the Project area, as discussed in Sections 4 and 5 of this report.



LEGEND

- Isaac Connors Alluvium Groundwater Sub-Area
- Groundwater management area
- Proposed pit
- Highwall mining area
- Mining lease application area
- Watercourse
- Major road

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Groundwater management areas and units

FIGURE No.
2.1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
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2.1.2. Environmental Protection Act 1994

The quality of Queensland waters is protected under the Environmental Protection (Water) Policy 2009 (EPP Water) (Department of Environment and Heritage Protection, 2011).The EPP Water achieves the objective of the *Environmental Protection Act 1994* (EP Act) to protect Queensland waters whilst supporting ecologically sustainable development. Queensland waters include waters in rivers, streams, wetlands, lakes, aquifers, estuaries, and coastal areas.

The Isaac River Sub-basin Environmental Values and Water Quality Objectives (2011) is made pursuant to the provisions of the EPP Water, which is subordinate legislation under the EP Act. The EPP Water provides a framework for identifying environmental values (EVs) for Queensland waters, and deciding the water quality objectives (WQOs) to protect or enhance the EV. The Isaac River Sub-basin Environmental Values and Water Quality Objectives (2011) contains EV (Section 2, Table 1) and WQO for waters (including groundwaters) in the Isaac River Sub-basin.

For Isaac River groundwaters, the EVs selected for protection are as follows:

- aquatic ecosystems;
- irrigation;
- farm supply/use;
- stock water;
- primary recreation;
- drinking water; and
- cultural and spiritual.

The draft water quality guidelines (Department of Environment and Science, 2018b) inform the development of water quality guidelines to enhance or protect the ‘aquatic ecosystem’ EV for Queensland waters, in accordance with the provisions of the EPP Water. The draft guidelines (Department of Environment and Science, 2018b) outline protocols for comparing test site water quality against relevant WQO recognised under the EPP Water.

Section 2.7 of the Queensland Water Quality Guidelines (Department of Environment and Heritage Protection, 2009) provides guidance on the approach taken to identify EV, water quality indicators and guidelines (as a basis for WQO) in groundwaters. Where local EV and WQO have been scheduled under the EPP Water for groundwaters, these are the applicable reference source for decision making.

In the absence of scheduled data, the EPP Water identifies applicable EV and potential sources for water quality guidelines to inform decision making. The EP Act identifies that groundwater quality is an EV to be protected and therefore the groundwater quality should be maintained within the range of natural quality variations. Natural quality variations should be established through baseline characterisation.

In the absence of scheduled data, the default management intent is that there should be ‘no change’ to the natural variation in groundwater quality. From the Queensland Water Quality Guidelines (Department of Environment and Heritage Protection, 2009), no change in the natural variation in groundwater quality is deemed to have occurred if there are no detectable changes to the 20^{th}, 50^{th} and 80^{th} percentiles of the natural distribution of values. Where review of local data indicates that some groundwater systems are clearly impacted, then in these cases, the management intent would be to improve quality, and more stringent percentiles may be used to derive guideline values.

Generally, the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (AWQG, 2018) should apply to the quality of both surface waters and groundwaters since the EVs which they protect relate to above-ground uses (e.g. irrigation, drinking water, farm animal or fish production and maintenance of aquatic ecosystems). Hence groundwater should be managed in such a way that when there is a surface expression of groundwater, whether from natural seepages or from bores, it will not cause the established WQO for these waters to be exceeded, nor compromise their designated EV (an important exception is stygofauna).

The Department of Regional Development, Manufacturing and Water (DRDMW) Groundwater Database (GWDB) contains groundwater quality data from registered groundwater bores. Where sufficient data exist, water quality guidelines are developed at aquifer/sub-aquifer level based on existing conditions, using groundwater quality data sourced from the DRDMW GWDB or from local monitoring data. Following the definition and mapping of chemistry zones, the groundwater quality data are used to calculate a range of percentiles for available indicators for each chemistry zone.

Where there is potential for groundwater to be impacted by activities such as mining, it is important to acquire localised reference (or baseline) data prior to commencement of the activity. In this situation, the local pre-development data would be used as reference data. Where the groundwater quality is slightly disturbed due to anthropogenic contamination or from naturally occurring groundwater chemistry, the slightly disturbed waters guideline applies. Where groundwater is moderately or highly disturbed, more stringent percentiles may be applied as follows:

- high ecological value (HEV) groundwaters guideline: 20/50/80th percentiles of the waters in the sub-aquifer chemistry zones;
- slightly disturbed (SD) groundwaters guideline: 20/40/70th percentiles of the waters in the sub-aquifer chemistry zones; and
- waters potentially impacted by human activities – guideline: no change to the 20/50/80th percentiles of local pre-development data.

2.1.3. Environmental authority

The Queensland guideline (Department of Environment and Science, 2016) provides information to those preparing a site-specific application for a new EA (site-specific application) or an application to amend an EA (amendment application) for resource projects or activities that are carried out on one or more resource tenures (e.g. mineral development licence or mining lease); and involve the exercise of underground water rights (or a change to the exercise of underground water rights).

Section 126A of the EP Act (State of Queensland 2019, n.d.) outlines the mandatory information that must be included within a groundwater assessment. It requires that groundwater assessments must state the following:

- *any proposed exercise of underground water rights during the period in which resource activities will be carried out under the relevant tenure;*
- *the areas in which underground water rights are proposed to be exercised;*
- *for each aquifer affected, or likely to be affected by the exercise of underground water rights, include:*
    - *a description of the aquifer;*
    - *an analysis of the movement of underground water to and from the aquifer, including how the aquifer interacts with other aquifers and surface water;*
    - *a description of the area of the aquifer where the water level is predicted to decline because of the exercise of underground water rights; and*
    - *the predicted quantities of water to be taken or interfered with because of the exercise of underground water rights during the period in which resource activities are carried out.*
- *the environmental values that will, or may, be affected by the exercise of underground water rights and the nature and extent of the impacts on the environmental values;*
- *any impacts on the quality of groundwater that will, or may, happen because of the exercise of underground water rights during or after the period in which resource activities are carried out; and*
- *strategies for avoiding, mitigating or managing the predicted impacts on the environmental values or predicted impacts on the quality of groundwater.*

EAs are administered by a range of Queensland Government and local government agencies. The agency that administers an EA is called the administering authority and for this Project it is the Department of Environment and Science (DES).

2.2. Commonwealth

The EPBC Act is administered by the DoEE and is designed to protect national environmental assets, known as Matters of National Environmental Significance (MNES). Under the 2013 amendment to the EPBC Act, impacts on groundwater resources, in relation to coal seam gas (CSG) development and large coal mining development were included, and are known as the 'water trigger'.

A project may be declared a controlled action by the DoEE, with water resources being one of the controlling provisions. The Independent Expert Scientific Committee (IESC) is a statutory body under the EPBC Act that provides scientific advice to the DoEE and relevant state ministers on CSG or large coal mining development proposals. Guidelines have been developed in order to assist the IESC in reviewing these proposals. Whilst the Project is not considered to be a large coal mining development, the IESC information requirements checklist is presented in Table 2-1, with details on where aspects have been addressed and documented within the report.

Table 2-1 IESC information requirements checklist

Information requirements	Section addressed
Description of the proposal	
Provide a regional overview of the proposed project area including a description of the: ▪ *geological basin;* ▪ *coal resource;* ▪ *surface water catchments;* ▪ *groundwater systems;* ▪ *water-dependent assets; and* ▪ *past, present and reasonably foreseeable coal mining and CSG developments.*	Sections 3, 4, 5, 5.7.2
Describe the statutory context, including information on the proposal's status within the regulatory assessment process and any applicable water management policies or regulations.	Section 2
Describe the proposal's location, purpose, scale, duration, disturbance area, and the means by which it is likely to have a significant impact on water resources and water-dependent assets.	Sections 1, 5.9, 6.2, 7
Describe how impacted water resources are currently being regulated under state or Commonwealth law, including whether there are any applicable standard conditions.	Section 2
Risk assessment	
Identify and assess all potential environmental risks to water resources and water-related assets, and their possible impacts. In selecting a risk assessment approach consideration should be given to the complexity of the project, and the probability and potential consequences of risks.	Section 6
Assess risks following the implementation of any proposed mitigation and management options to determine if these will reduce risks to an acceptable level based on the identified environmental objectives.	Section 7
Incorporate causal mechanisms and pathways identified in the risk assessment in conceptual and numerical modelling. Use the results of these models to update the risk assessment.	Section 6
The risk assessment should include an assessment of: ▪ *all potential cumulative impacts which could affect water resources and water-related assets; and* ▪ *mitigation and management options which the proponent could implement to reduce these impacts.*	Section 6
Groundwater – Context and Conceptualisation	
Describe and map geology at an appropriate level of horizontal and vertical resolution including: ▪ *definition of the geological sequence(s) in the area, with names and descriptions of the formations and accompanying surface geology, cross-sections and any relevant field data; and.* ▪ *geological maps appropriately annotated with symbols that denote fault type, throw and the parts of sequences the faults intersect or displace.*	Section 4

Information requirements	Section addressed
Define and describe or characterise significant geological structures (e.g. faults, folds, intrusives) and associated fracturing in the area and their influence on groundwater – particularly groundwater flow, discharge or recharge. ▪ *Site-specific studies (e.g. geophysical, coring / wireline logging etc.) should give consideration to characterising and detailing the local stress regime and fault structure (e.g. damage zone size, open/closed along fault plane, presence of clay/shale smear, fault jogs or splays).* ▪ *Discussion on how this fits into the fault's potential influence on regional-scale groundwater conditions should also be included.*	Sections 4, 5, 5.9.1
Provide site-specific values for hydraulic parameters (e.g. vertical and horizontal hydraulic conductivity and specific yield or specific storage characteristics including the data from which these parameters were derived) for each relevant hydrogeological unit. In situ observations of these parameters should be sufficient to characterise the heterogeneity of these properties for modelling.	Sections 5, 5.4
Provide time series level and water quality data representative of seasonal and climatic cycles	Sections 5.3, 5.8
Provide data to demonstrate the varying depths to the hydrogeological units and associated standing water levels or potentiometric heads, including direction of groundwater flow, contour maps, and hydrographs. All boreholes used to provide this data should have been surveyed.	Section 5.5.5
Provide hydrochemical (e.g. acidity/alkalinity, electrical conductivity, metals, and major ions) and environmental tracer (e.g. stable isotopes of water, tritium, helium, strontium isotopes, etc.) characterisation to identify sources of water, recharge rates, transit times in aquifers, connectivity between geological units and groundwater discharge locations.	Section 5.8
Describe the likely recharge, discharge and flow pathways for all hydrogeological units likely to be impacted by the proposed development.	Section 5.5.4
Assess the frequency (and time lags if any), location, volume and direction of interactions between water resources, including surface water/groundwater connectivity, inter-aquifer connectivity and connectivity with sea water.	Sections 5.5 and 5.6
Groundwater – Analytical and Numerical Modelling	
Provide a detailed description of all analytical and/or numerical models used, and any methods and evidence (e.g. expert opinion, analogue sites) employed in addition to modelling.	Section 6.1, Appendix C
Undertake groundwater modelling in accordance with the Australian Groundwater Modelling Guidelines (Barnett et al. 2012), including independent peer review.	Section 6.1, Appendix C
Calibrate models with adequate monitoring data, ideally with calibration targets related to model prediction (e.g. use baseflow calibration targets where predicting changes to baseflow).	Section 0, Appendix C
Describe each hydrogeological unit as incorporated in the groundwater model, including the thickness, storage and hydraulic characteristics, and linkages between units, if any.	Appendix C
Describe the existing recharge/discharge pathways of the units and the changes that are predicted to occur upon commencement, throughout, and after completion of the proposed project.	Sections 5.5.4, 6, Appendix C
Describe the various stages of the proposed project (construction, operation and rehabilitation) and their incorporation into the groundwater model. Provide predictions of water level and/or pressure declines and recovery in each hydrogeological unit for the life of the project and beyond, including surface contour maps for all hydrogeological units.	Sections 1, Appendix C
Identify the volumes of water predicted to be taken annually with an indication of the proportion supplied from each hydrogeological unit.	Section 6.2.1, Appendix C
Undertake model verification with past and/or existing site monitoring data.	Appendix C
Provide an explanation of the model conceptualisation of the hydrogeological system or systems, including multiple conceptual models if appropriate. Key assumptions and model limitations and any consequences should also be described.	Section 5.9
Consider a variety of boundary conditions across the model domain, including constant head or general head boundaries, river cells and drains, to enable a comparison of groundwater model outputs to seasonal field observations.	Appendix C
Undertake sensitivity analysis and uncertainty analysis of boundary conditions and hydraulic and storage parameters, and justify the conditions applied in the final groundwater model (see Middlemis and Peeters [in press]).	Section 6.2.4, Appendix C
Provide an assessment of the quality of, and risks and uncertainty inherent in, the data used to establish baseline conditions and in modelling, particularly with respect to predicted potential impact scenarios.	Appendix C

Information requirements	Section addressed
Undertake an uncertainty analysis of model construction, data, conceptualisation and predictions (see Middlemis and Peeters [in press]).	Appendix C
Provide a program for review and update of models as more data and information become available, including reporting requirements.	Section 7
Provide information on the magnitude and time for maximum drawdown and post-development drawdown equilibrium to be reached.	Section 6.2.3
Groundwater – Impacts to Water Resources and Water-dependent Assets	
Provide an assessment of the potential impacts of the proposal, including how impacts are predicted to change over time and any residual long-term impacts. Consider and describe: ▪ *any hydrogeological units that will be directly or indirectly dewatered or depressurised, including the extent of impact on hydrological interactions between water resources, surface water/groundwater connectivity, interaquifer connectivity and connectivity with sea water;* ▪ *the effects of dewatering and depressurisation (including lateral effects) on water resources, water-dependent assets, groundwater, flow direction and surface topography, including resultant impacts on the groundwater balance;* ▪ *the potential impacts on hydraulic and storage properties of hydrogeological units, including changes in storage, potential for physical transmission of water within and between units, and estimates of likelihood of leakage of contaminants through hydrogeological units;* ▪ *the possible fracturing of and other damage to confining layers; and* ▪ *for each relevant hydrogeological unit, the proportional increase in groundwater use and impacts as a consequence of the proposed project, including an assessment of any consequential increase in demand for groundwater from towns or other industries resulting from associated population or economic growth due to the proposal.*	Section 6
Describe the water resources and water-dependent assets that will be directly impacted by mining or CSG operations, including hydrogeological units that will be exposed/partially removed by open cut mining and/or underground mining.	Sections 5, 5.7.2, 6
For each potentially impacted water resource, provide a clear description of the impact to the resource, the resultant impact to any water-dependent assets dependent on the resource, and the consequence or significance of the impact.	Section 6
Describe existing water quality guidelines, environmental flow objectives and other requirements (e.g. water planning rules) for the groundwater basin(s) within which the development proposal is based.	Sections 2 5.8.3, 5.8.4
Provide an assessment of the cumulative impact of the proposal on groundwater when all developments (past, present and/or reasonably foreseeable) are considered in combination.	Section 6
Describe proposed mitigation and management actions for each significant impact identified, including any proposed mitigation or offset measures for long-term impacts post mining.	Section 7
Provide a description and assessment of the adequacy of proposed measures to prevent/minimise impacts on water resources and water-dependent assets.	Section 7
Groundwater – Data and Monitoring	
Provide sufficient data on physical aquifer parameters and hydrogeochemistry to establish pre-development conditions, including fluctuations in groundwater levels at time intervals relevant to aquifer processes.	Section 5
Develop and describe a robust groundwater monitoring program using dedicated groundwater monitoring wells – including nested arrays where there may be connectivity between hydrogeological units – and targeting specific aquifers, providing an understanding of the groundwater regime, recharge and discharge processes and identifying changes over time.	Section 5
Develop and describe proposed targeted field programs to address key areas of uncertainty, such as the hydraulic connectivity between geological formations, the sources of groundwater sustaining GDEs, the hydraulic properties of significant faults, fracture networks and aquitards in the impacted system, etc., where appropriate.	Section 7
Provide long-term groundwater monitoring data, including a comprehensive assessment of all relevant chemical parameters to inform changes in groundwater quality and detect potential contamination events.	Section 5.8
Ensure water quality monitoring complies with relevant National Water Quality Management Strategy (NWQMS) guidelines (ANZECC/ARMCANZ 2000) and relevant legislated state protocols (e.g. QLD Government 2013).	Section 5.8

Information requirements	Section addressed
Cumulative Impacts – Context and Conceptualisation	
Provide cumulative impact analysis with sufficient geographic and temporal boundaries to include all potentially significant water-related impacts.	Section 6, Appendix C
Consider all past, present and reasonably foreseeable actions, including development proposals, programs and policies that are likely to impact on the water resources of concern in the cumulative impact analysis. Where a proposed project is located within the area of a bioregional assessment consider the results of the bioregional assessment.	Section 6, Appendix C
Cumulative Impacts – Impact	
Provide an assessment of the condition of affected water resources which includes: ▪ *identification of all water resources likely to be cumulatively impacted by the proposed development;* ▪ *a description of the current condition and quality of water resources and information on condition trends;* ▪ *identification of ecological characteristics, processes, conditions, trends and values of water resources;* ▪ *adequate water and salt balances; and,* ▪ *identification of potential thresholds for each water resource and its likely response to change and capacity to withstand adverse impacts (e.g. altered water quality, drawdown).*	Section 6, Appendix C
Assess the cumulative impacts to water resources considering: ▪ *the full extent of potential impacts from the proposed project, (including whether there are alternative options for infrastructure and mine configurations which could reduce impacts), and encompassing all linkages, including both direct and indirect links, operating upstream, downstream, vertically and laterally;* ▪ *all stages of the development, including exploration, operations and post closure/decommissioning;* ▪ *appropriately robust, repeatable and transparent methods;* ▪ *the likely spatial magnitude and timeframe over which impacts will occur, and significance of cumulative impacts; and* ▪ *opportunities to work with other water users to avoid, minimise or mitigate potential cumulative impacts.*	Section 6, Appendix C
Cumulative Impacts – Mitigation, Monitoring and Management	
Identify modifications or alternatives to avoid, minimise or mitigate potential cumulative impacts. Evidence of the likely success of these measures (e.g. case studies) should be provided.	Section 7
Identify cumulative impact environmental objectives.	Section 7
Identify measures to detect and monitor cumulative impacts, pre and post development, and assess the success of mitigation strategies.	Section 7
Describe appropriate reporting mechanisms.	Section 7
Propose adaptive management measures and management responses.	Section 7

3. Baseline conditions

3.1. Climate

Climate plays a major role in defining two characteristics of groundwater systems; recharge and evapotranspiration. The BoM (2016) classifies the climate of a particular area using multiple criteria – temperature and humidity, amount of seasonal rainfall and type of vegetation. Based on these criteria, the Project area can be characterised as subtropical, with mostly hot dry summers and mild winters. In terms of rainfall, the Project area is classified as summer rainfall dominant with the majority of the rain falling between November and March.

In order to establish the long-term rainfall and evapotranspiration trend, the following data were used:

- data from BoM Station 035019, located at Clermont Post Office (approximately 70 km southwest of the Project area), the closest site suitable for long-term monthly statistics with rainfall data available from 1870 and evaporation from 1979; and
- data from synthetic (interpolated) SILO data (Jeffrey *et al.*, 2001).

At the Clermont Post Office (BoM Station 035019), mean annual potential evaporation (2,080 mm, evaporation if unlimited water is available) greatly exceeds mean rainfall (658 mm). Further, mean potential evaporation exceeds mean rainfall for every month and may limit groundwater recharge from rainfall (Figure 3.1). Hence, on a monthly basis, it is likely that only episodic, or large and persistent rainfall has the potential to generate groundwater recharge. Approximately 70% of the average annual rainfall occurs between November and March, with January and February traditionally the wettest month, and August and September the driest months (Figure 3.1).

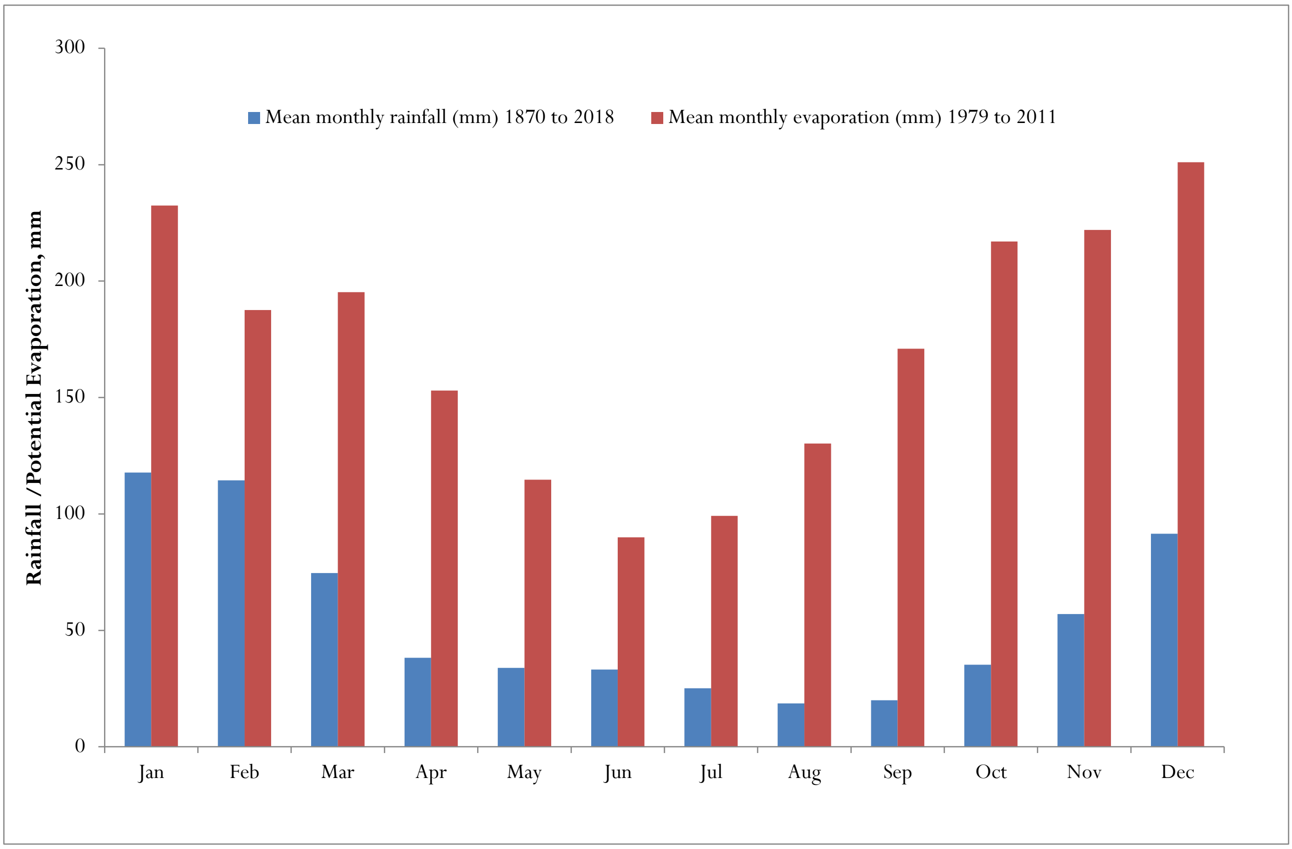


Figure 3.1 Rainfall and evaporation at Clermont Post Office (Station 035019)

Monthly patched point SILO rainfall data, adjacent to the Project area, were obtained from the Long Paddock website (https://www.longpaddock.qld.gov.au/silo/) in August 2019. SILO is a database of Australian climate data from 1889 to the present. It provides continuous daily meteorological datasets for a range of climate variables in ready-to-use formats suitable for biophysical modelling, research, and climate applications. The datasets are constructed from observational data obtained from BoM. SILO interpolates rainfall and evaporation records from available stations to a selected point. Consistent with data from Clermont Post Office (BoM Station 035019), mean annual potential evaporation for the SILO data (2,013 mm) greatly exceeds mean rainfall (582 mm). Further, mean potential evaporation exceeds mean rainfall for every month for the SILO data.

The cumulative rainfall departure (CRD) from monthly mean is another useful qualitative tool to show periods of rainfall that are wetter or dryer than average conditions. Figure 3.2 shows both total monthly rainfall (blue bars on the left axis) and the CRD (red curve) on the right axis for data between January 1901 to July 2019. Wetter than average periods are shown by an increasing trend in CRD; conversely, drier than average periods are shown by a decreasing trend. Notable observations from Figure 3.2 include the following:

- drier than average conditions between 1918-1950, 1960-73 and 2001-2007;
- above average rainfall between 1953-1960, 1973-1979, 2007-2012; and
- a relatively average rainfall period since 2012.

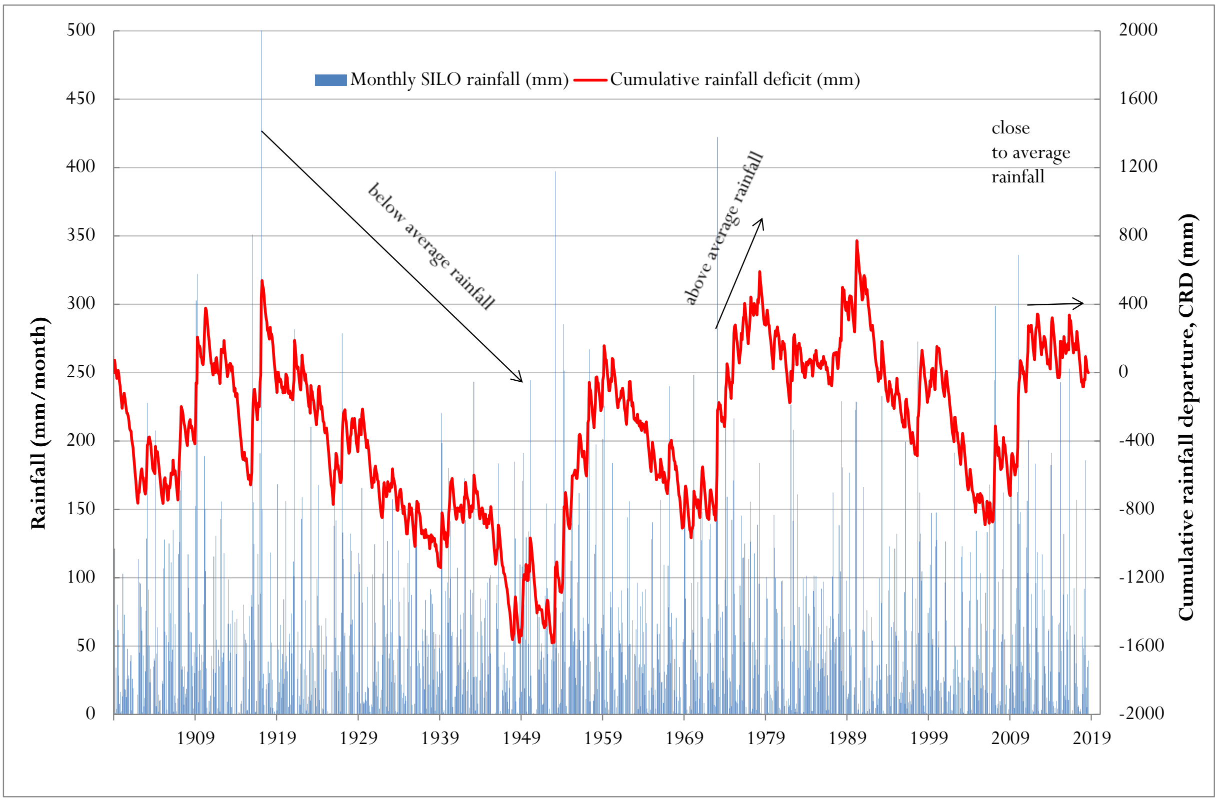


Figure 3.2 Monthly SILO rainfall and CRD

3.2. Topography and drainage

The Project area slopes from the Harrow Range in the west to the Isaac River east of the Project area (Figure 3.3). Surface elevations reach approximately 500 mAHD approximately 25 km to the west of the Project area. The surface elevation within the Project area is generally between 380 mAHD in the north, and 200 mAHD in the south.

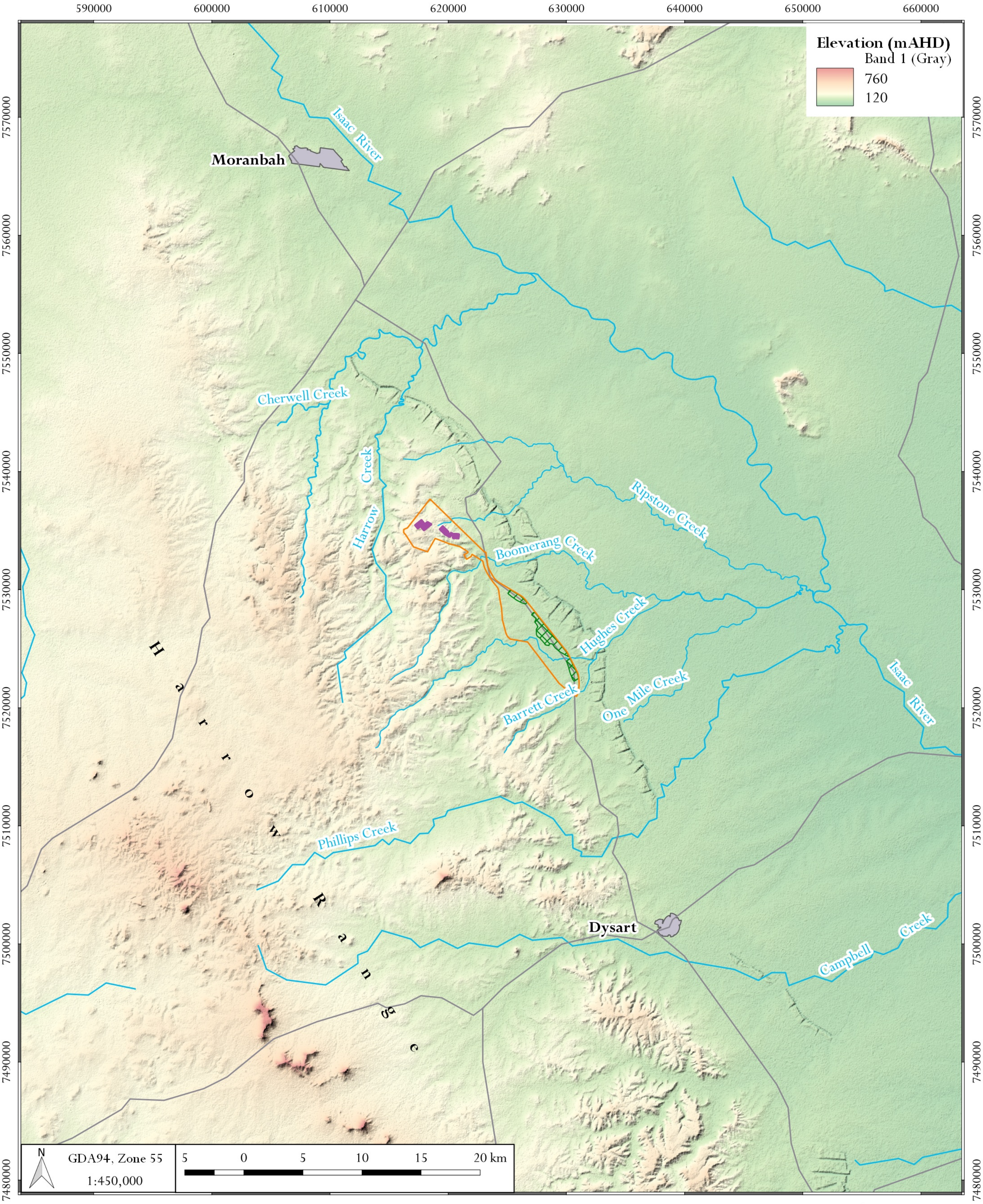
The Project area is surrounded by a number of ephemeral catchments (Figure 3.3) which drain from west to east, including the following creeks:

- Harrow Creek;
- Boomerang Creek;
- Hughes Creek;
- Barrett Creek;
- Phillips Creek; and
- Campbell Creek.

A tributary of Ripstone Creek flows through the Project area to the north-east, extending through the neighbouring BMA Saraji Mine. Boomerang Creek and a tributary of Hughes Creek flow through the central and southern parts of the Project area from west to east. Barrett Creek flows through the southernmost extent of the Project area.

A number of surface water diversions have been constructed in association with the existing coal mines to the east of the Project area. These include diversions on Ripstone Creek, Harrow Creek, Boomerang Creek and Hughes Creek. These diversions are all located downstream of the Project area and have been constructed by BMA. Surface water flow data captured and maintained by BMA indicates these creeks are all ephemeral.

The ephemeral creeks surrounding the Project area have limited flow, and typically only discharge after heavy rainfall events. The largest local surface water catchment near the Project area is Phillips Creek (10 kms to the south of the Project area), which flows into the Isaac River. The confluence of these two surface water systems is located approximately 20 km to the east of the Project area.



LEGEND

- Proposed pit
- Highwall mining area
- Mining lease application area
- Watercourse
- Major road

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Topography and drainage

FIGURE No.
3.3

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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Whilst Hughes Creek and Boomerang Creek are much closer to the proposed pits, Phillips Creek (some 10 kms to the south) is the only watercourse with publicly available stream flow data. Figure 3.4 and Figure 3.5 are from the DRDMW Water Monitoring Information Portal (WMIP) ([https://water-monitoring.information.qld.gov.au/)](https://water-monitoring.information.qld.gov.au/), visited on 10 September 2019).

Figure 3.4 shows discharge and water level data for the historic gauging station (130409a) on Phillips Creek at Tayglen. Figure 3.4 shows that flows within Phillips Creek are ephemeral, with short-duration flows generally occurring over the summer months. Based on daily flow data between 1968 and 1988, Figure 3.5 shows that Phillips Creek flows less than 25 % of the time, with less than 10% probability of flows exceeding 0.1 m^3/s (8.64 ML/day) and less than 2% probability of flows exceeding 10 m^3/s (864 ML/day).

The reader is directed to the Vulcan South– Surface Water Assessment (WRM, 2022) report for further information analysis and impact assessment regarding surface water systems in the Project area.

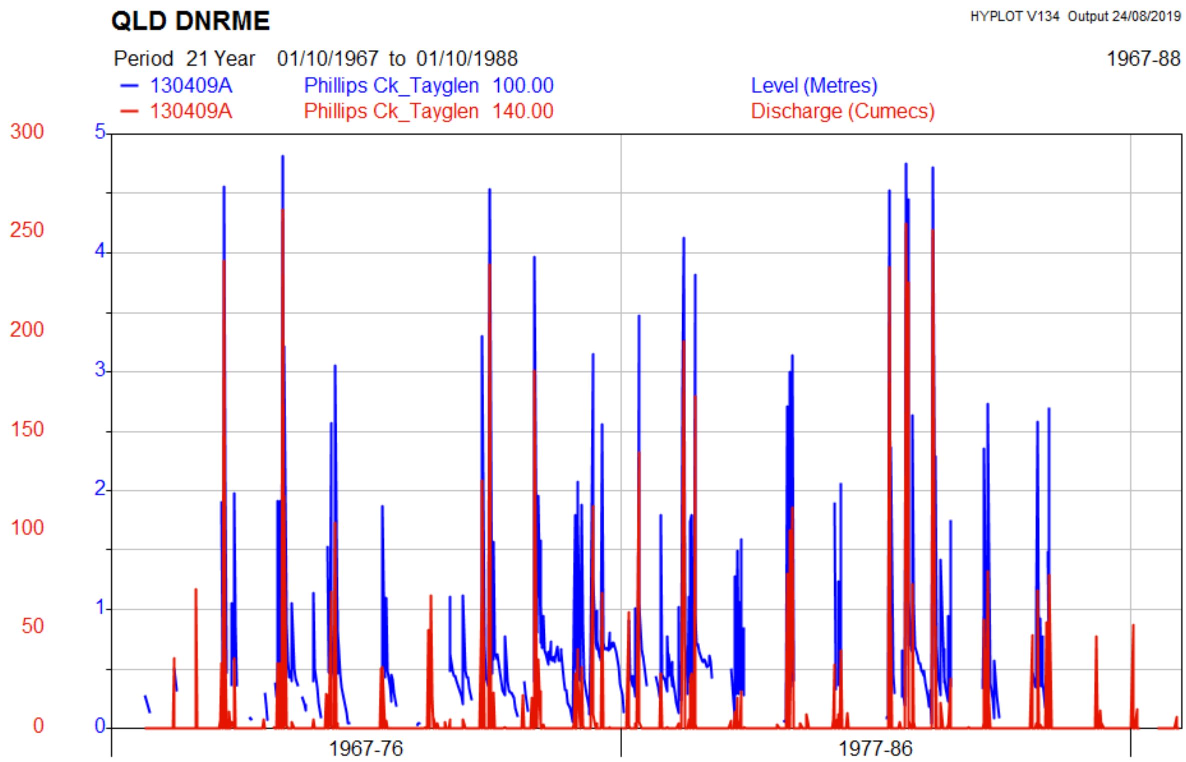


Figure 3.4 Discharge and water level, Phillips Creek at Tayglen (from DRDMW Water Monitoring Information Portal)

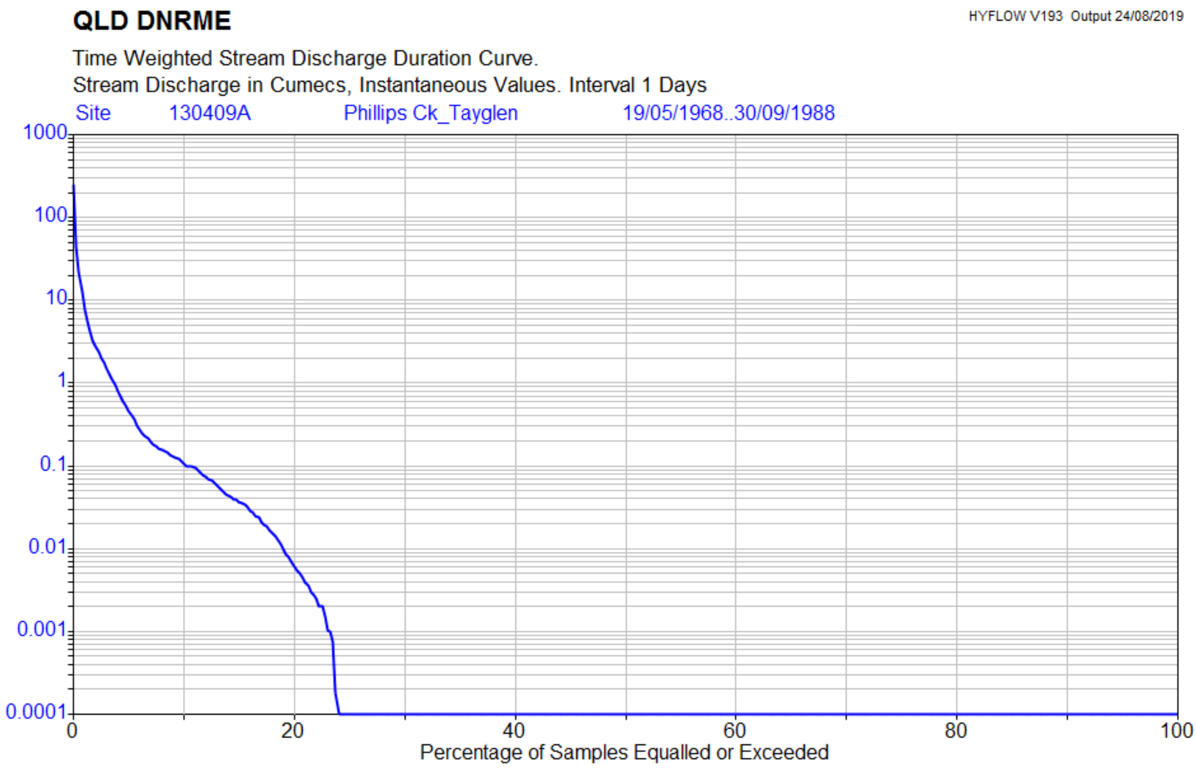


Figure 3.5 Daily flow duration, Phillips Creek at Tayglen (from DRDMW Water Monitoring Information Portal)

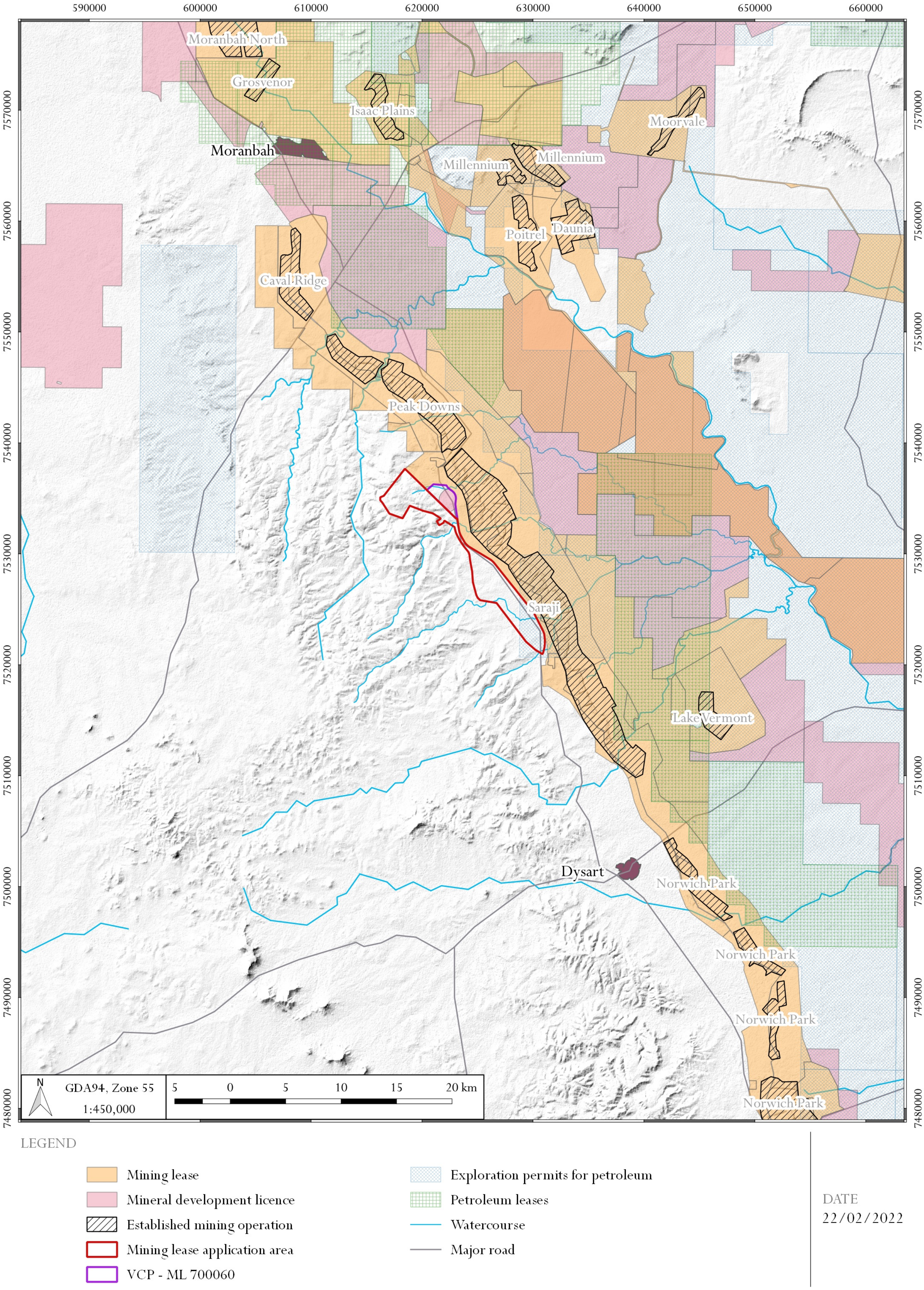
3.3. Land use

Land use is dominated by coal exploration and mining, beef cattle grazing, and CSG exploration and operations. Figure 3.6 shows the distribution of mineral development licences (MDLs) and mining leases (MLs) in the region. Figure 3.6 also shows the petroleum leases and exploration permits for petroleum in the region relating to CSG.

The individual coal mines in close proximity to the Project area are the BMA Saraji Mine and BMA Peak Downs Mine. Caval Ridge Mine is located to the north of Peak Downs Mine and Norwich Park Mine is located to the south of Saraji Mine. These series of coal mines are owned by BMA, however Norwich Park Mine is currently in care and maintenance.

Peak Downs Mine and Saraji Mine commenced coal production in the early 1970s with mining extending some 50 km in length and 2 km to 5 km in width. The mines generally follow the strike of the coal seams within the Moranbah Coal Measures and the mines extract coal seams that are stratigraphically higher than the coal seams to be mined as part of the Project.

Lake Vermont Mine is located to the south-east of Saraji Mine and is owned by the Jellinbah Group. Lake Vermont Mine currently has a production capacity of 8 Mtpa and was last expanded in 2012/2013.



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Mining tenure

FIGURE No.
3.6

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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4. Geology

4.1. Regional geology

The Bowen Basin is an elongated, north-south trending structure that extends from central Queensland to the south beneath the Surat Basin, and into New South Wales where it connects with the Gunnedah Basin and Sydney Basin. The Bowen Basin covers an area of approximately 200,000 km^2, from Collinsville in the north to Rolleston in the south (AECOM, 2016; Arrow Energy, 2016; URS, 2012) and contains Permian to Triassic age sediments with a maximum thickness of about 9,000 m (OGIA, 2016). The Bowen Basin evolved above a basement of Early Palaeozoic metamorphic and sedimentary rocks of the Drummond Basin and Anakie Block (CSIRO, 2002).

The Bowen Basin is divided into a number of structural elements which comprise north north-west to south south-east trending platforms / shelves, separated by sedimentary troughs. The Project area is located on the western limb of the northern Bowen Basin, a northerly plunging syncline, and at the southern end of the Collinsville Shelf (AECOM, 2016). The major basin elements and structure are shown in Figure 4.1. The general Project area is represented by the red rectangle in Figure 4.1.

The depositional history of the Bowen Basin is complex and individual formations are not always laterally extensive or easy to correlate across the basin. Deposition in the basin began during the Early Permian, with river and lake sediments and volcanics being deposited in the east, and a thick succession of coals and non-marine sedimentary rocks in the west (Geoscience Australia, 2019; AECOM, 2016). These sediments were then overlain by mostly fine-grained sediments such as mudstone and siltstone of marine origin (OGIA, 2016).

The Back Creek Group is regionally developed and consists of generally fine grained clastic sediments; but is lithologically variable and comprises four formations: the Tiverton, Gebbie, Blenheim and Exmoor, in ascending stratigraphic order (AECOM, 2016). A sag phase (post-extension thermal subsidence) during the mid-Permian resulted in basin-wide marine transgression and regression cycles for the remainder of the Middle Permian and much of the Late Permian (AECOM, 2016).

The Late Permian resulted in reactivation of the volcanic arc (uplift of the New England Orogeny) and westward thrusting in the New England Orogeny, which altered the Bowen Basin into a foreland basin. The resultant infill allowed for widespread, coal-forming alluvial and delta plain depositional environments, preserved as the equivalents of the Blackwater Group. The northern half of the basin saw eastward prograding deltas combined with major axial fluvial systems which resulted in the deposition of the upper delta plain Moranbah Coal Measures and equivalents (lower delta plain German Creek Formation and the MacMillan Formation), (AECOM, 2016). The non-marine deposition of the Fort Cooper Coal Measures and equivalents (Burngrove and Fairhill Formations) then followed.

Subsequent subdued volcanic activity in the east may have produced the basin-wide peat forming environments of the prograding alluvial and delta depositional systems that resulted in the Rangal Coal Measures (AECOM, 2016).

Compressive deformation of the Bowen Basin units occurred during the Middle to Late Triassic period, resulting in regional uplift and erosion, folding of sediments and strike-slip movement along faults to accommodate contraction. This led to a series of north-south trending faults with (generally) westward directed thrusts, which bound the eastern margin of the Bowen Basin.

Sedimentation in the basin was terminated by the Middle to Late Triassic (AECOM, 2016). Cainozoic post-basin faulting and subsequent Tertiary basin development (i.e. the Duaringa Basin) occurred concordantly with the emplacement of post-Triassic-aged intrusions (Main Range Volcanics) as the entire basin was subjected to a long period of deep weathering where lateritic profiles were strongly developed. Terrestrial Tertiary deposits are widespread, where basalt and associated intermediate and acid rocks are found over large areas across the Bowen Basin (AECOM, 2016). The Permian and Triassic sediments are thus covered by a thin veneer of unconsolidated to semi-consolidated Cainozoic sediments (Tertiary to Quaternary alluvium and colluvium); (HydroSimulations, 2018). The alluvial sediments are localised along rivers and creeks. Volcanic intrusions and extrusions (i.e. basalt) are also present within the region, but not in the Project area.

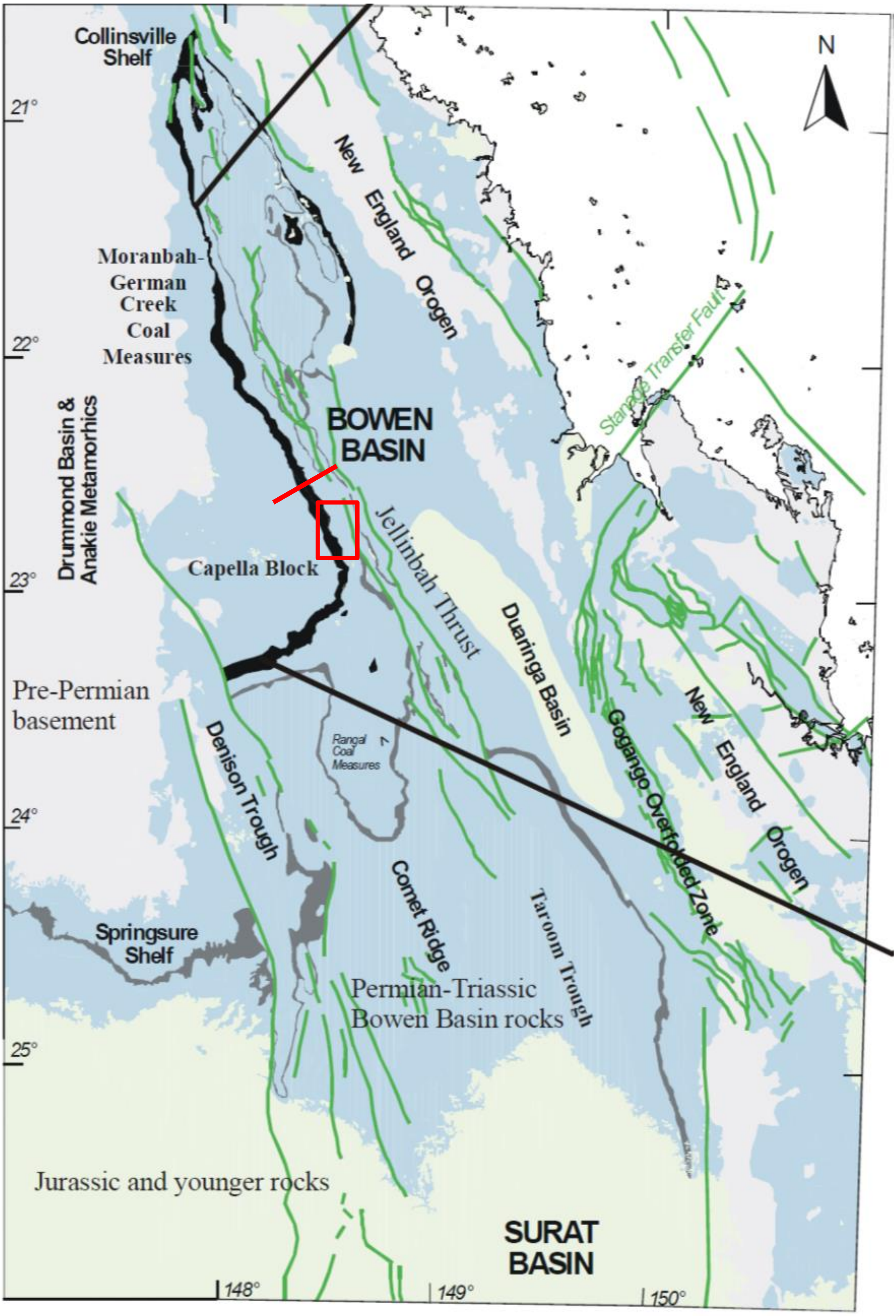


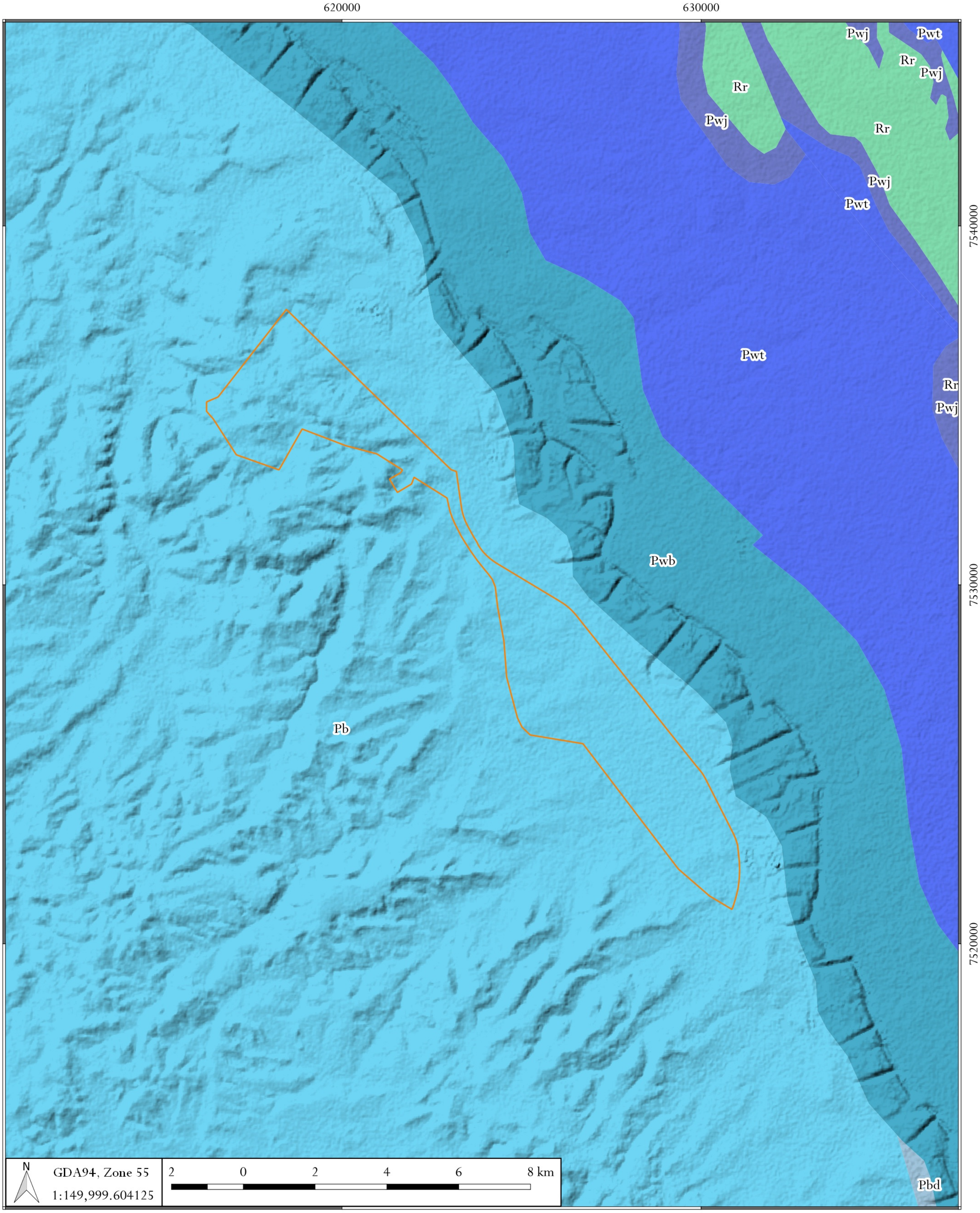
Figure 4.1 Major basin elements and regional faults (green lines) after CSIRO, 2002

Note: Figure 4.2 inset area is shown in red

A detailed description of the Bowen Basin development and stratigraphy is provided by CSIRO (2002); in particular a detailed account is given on the Moranbah Coal Measures / German Creek Coal Measures within the western limb of the central Bowen Basin.

Regionally, the stratigraphic sequence is summarised by URS (2012) as follows: *the Permo-Triassic sediments of the Bowen Basin are overlain by a thin covering of unconsolidated Quaternary alluvium and colluvium, poorly consolidated Tertiary aged sediments of the Suttor and Duaringa Formations and, in places, remnants of Tertiary basalt flows. The Triassic Rewan Group underlies the Tertiary sediments and, in places, a number of outcrops of the Moolayember Formation and Clematis Sandstone can be found. The Permian Blackwater Group, coal measures and associated overburden and interburden are located below the Triassic strata and overly the Back Creek Group*. Figure 4.2 shows the Bowen Basin solid geology in and around the Project area. Near the Project area, because of the easterly dip, the Permian Black Creek Group, Moranbah Coal Measures, Fort Cooper Coal Measures and Rangal Coal Measures sub-crop from west to east.

The Permian coal measures occur as stratified sequences of interbedded and consolidated sandstone, siltstone, mudstone, and coal with the coal measures outcropping to the east and west of the Isaac River.



LEGEND

Geology solid

- Pb - Back Creek Group
- Pbd - German Creek Formation
- Pwb - Moranbah Coal Measures
- Pwj - Rangal Coal Measures, Bandanna Fmt.
- Pwt - Fair Hill Fmt., Fort Cooper Coal Measures
- Rr - Rewan Group

Mining lease application area

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Regional Bowen Basin solid geology

FIGURE No.
4.2

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4.2. Local geology

Cross-section D-D' of URS (2012) extends near the Project area and is reproduced as Figure 4.3. The section extends from the west/south-west to the east/north-east and the approximate location of the section is shown as a red line in Figure 4.1. The Project area would plot between ~140,000 m and ~142,000 m on the section, characterised by sub-cropping Moranbah Coal Measures beneath the Tertiary and Quaternary sediments. Beneath the Moranbah Coal Measures, the Back Creek Group forms the Permian basement and outcrops to the west of the site. The Triassic units (notably the Rewan Group) are absent locally and occur further to the east. The local surface geology is shown in Figure 4.4.

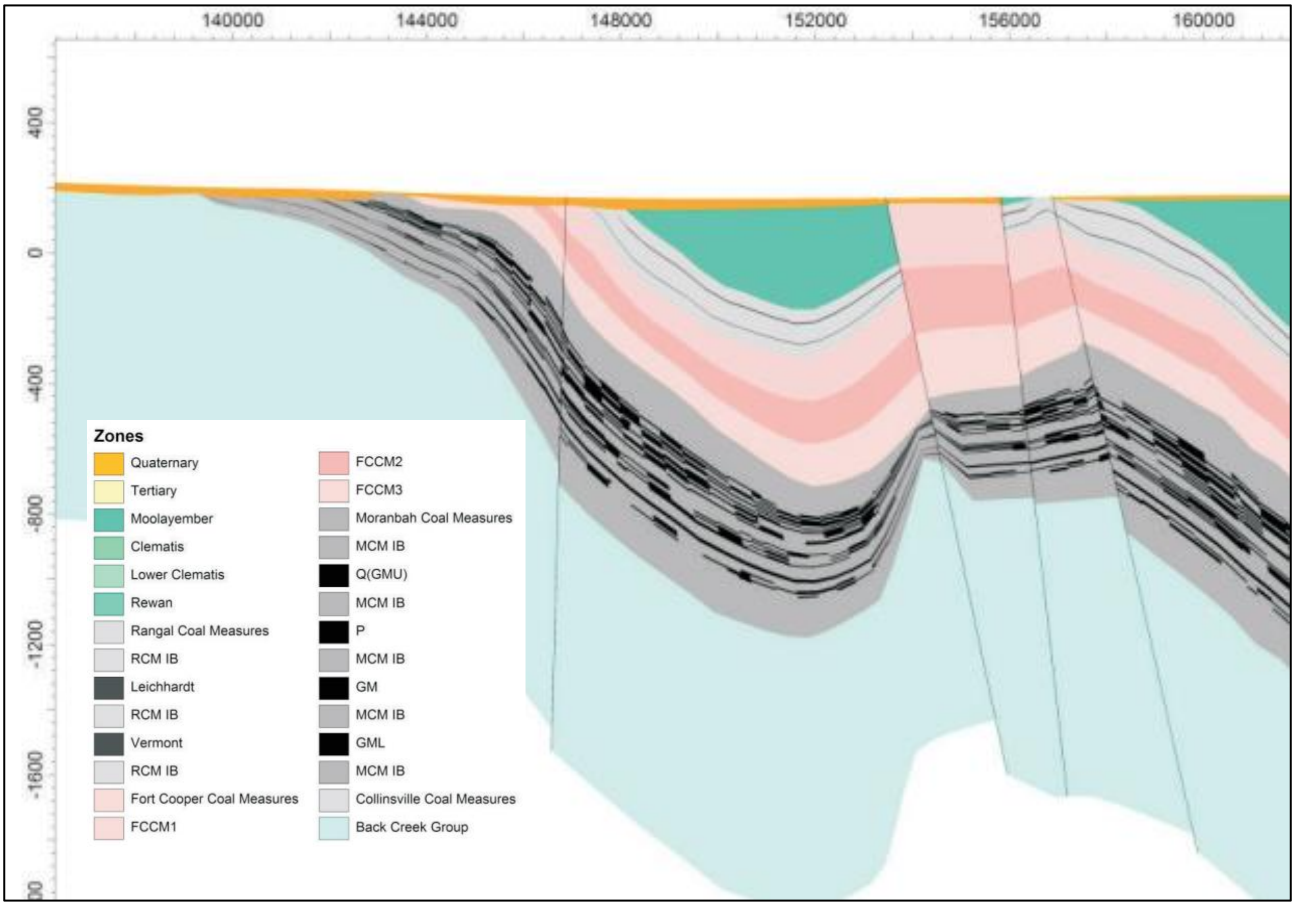
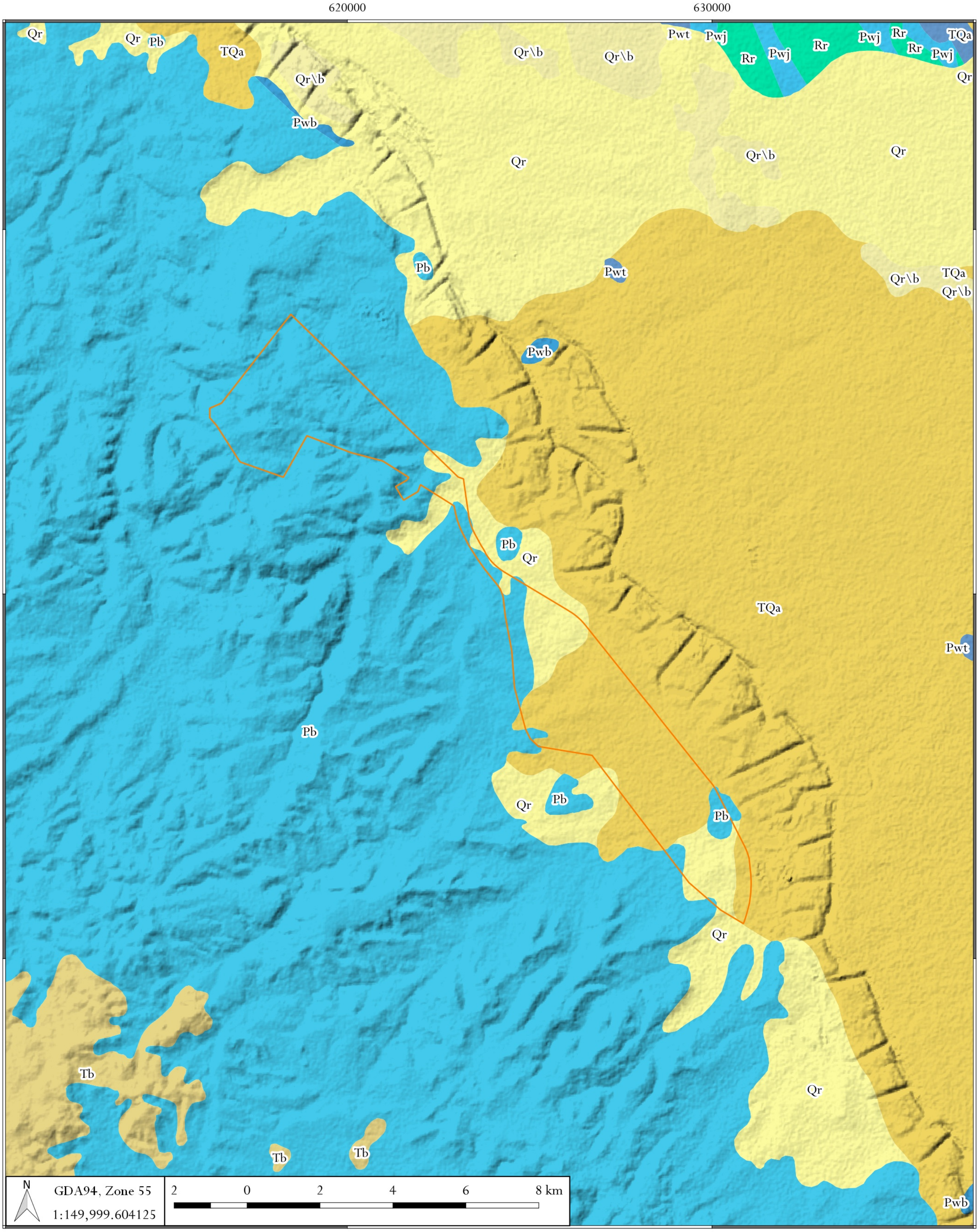


Figure 4.3 Cross-section D-D' from URS (2012)



LEGEND

Geology - surface

- Pb - Back Creek Group
- Pwt - Fort Cooper Coal Measures
- Pwb - Moranbah Coal Measures
- Qr\b - Colluvium
- Qr - Colluvium
- Pwj - Rangal Coal Measures
- Rr - Rewan Group
- Tb - Basalt
- TQa - Alluvium
- Mining lease application area

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Local surface geology

FIGURE No.
4.4

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4.2.1. Quaternary alluvium

Quaternary alluvium is mapped in excess of 10 kms to the north and south of the Project area associated with Cherwell Creek and Phillips Creek, respectively. None of these mapped Quaternary alluvium deposits are, however, recognised in Figure 2.1 nor shown in Figure 4.4. Figure 2.1 indicates that the Isaac Connors Alluvium groundwater sub-area is limited to the Isaac River and those parts of its tributaries that are adjacent to the confluence with the Isaac River. In general, the Quaternary alluvium, where present, is associated with the larger ephemeral surface drainage features in the catchment, such as the Isaac River.

The alluvium comprises irregular sequences of unconsolidated clay, silt, sand, and gravel. The Quaternary alluvium sediments are variable in thickness, elongated, irregular, and lensoidal (URS, 2012). This is due to the meandering and braided nature of the depositional environment that includes cross-cutting and reworking of older alluvial deposits. The alluvium is also considered to be heterogeneous due to the irregular nature of the bedrock and clayey composition (Arrow Energy, 2016).

The Quaternary alluvial sediments (in excess of 10 kms) to the south-east of the Project area are reported to have a maximum thickness of 25 m at Phillips Creek (AGE, 2007 in AECOM, 2016) as a result of infilling a paleo-channel carved through Tertiary sediments and into the underlying Permian coal measures. Similar thicknesses of alluvial sediments are understood to occur along the Isaac River, east of the Project area.

4.2.2. Tertiary sediments

The Tertiary aged sediments are mapped as present in the southern portion of the Project area (see TQa in Figure 4.4). These are generally described as clay, silt, sand, gravel and colluvial and residual deposits with a predominantly clay matrix. AECOM (2016) refer to the Tertiary aged sediments as heterogeneously distributed lensoidal sand deposits separated by a low permeability clay-rich matrix. Tertiary sediments comprise unconsolidated to consolidated fluvial sediments which include clay, silty clay, sandy clay, clayey sand, sand and gravel with clay predominant (AECOM, 2016). Typically, these sediments are less than 15 m thick although the Tertiary sediments have been reported up to 57 m thick at Saraji Mine. The presence of paleo-channels and lensing of units within the Tertiary sediments prevent correlation of discrete units; individual units are laterally discontinuous with varied thickness (AECOM, 2016).

The Duaringa Formation is mapped 10 km to the south-east of Saraji Mine and contains mudstone and siltstone (i.e. low permeability strata). The Duaringa Formation is more of a laterally extensive Tertiary stratigraphic unit that is mappable and correlatable over a larger area of the Bowen Basin to the east.

Weathering of the Tertiary sediments is evident (AGE, 2011 in AECOM, (2016)) and the lithologies can vary from heavily leached, mottled white and maroon clays to sandy clays.

A basal sand and gravel sequence has been identified beneath the clay rich matrix in the western limb of the Bowen Basin. Comprising medium to coarse grained sands and fine gravels, the basal sand and gravel sequence has a maximum thickness of approximately 3 m and is considered to be locally continuous. The basal Tertiary sequence indicates the presence of a laterally discontinuous paleo-channel system assumed to be related to a proto-Phillips Creek system (AECOM, 2016).

At the Olive Downs Coal Project located approximately 20 km to the north-east, lithological logs indicate that the Cainozoic (Quaternary to Tertiary aged) alluvium comprises heterogeneous, fine to coarse grained sands interspersed with lenses of clays and gravels. These sediments, while spatially variable, generally comprise four main lithologic sequences including:

- upper soil and clay layer (up to 10 m thick);
- sand and sandy clay unit (3 m to 15 m thick);
- sand and gravel unit (up to 8 m thick); and
- basal clay unit (> 1 m thick).

At the Olive Downs Coal Project, the heterogeneity of the Cainozoic sediments was observed in surface geophysics (transient electromagnetics) with discrete areas of the alluvium, correlating to clayey / less permeable zones (HydroSimulations, 2018). HydroSimulations (2018) also found that Cainozoic aged sediments comprise much of the surficial regolith material at the site, including alluvium and colluvium.

The Tertiary sediments are defined by an unconformable boundary with the underlying Permian coal measures which characterises the Permian topography prior to deposition of the Tertiary sediments (AECOM, 2016).

hydrogeologist.com.au (2019) drilled and constructed several groundwater monitoring bores within the Project area. **hydrogeologist.com.au** (2019) used the term "*weathered Permian*" to describe the lithology intersected above the fresh Permian coal measures and those rocks considered equivalent to the regolith described by (HydroSimulations, 2018). It is assessed by **hydrogeologist.com.au** that within the Project area, the lithology intersected above the fresh Permian coal measures does not constitute Tertiary aged sediments, rather a weathering profile that had developed during the Tertiary on the Permian strata. There was no evidence of an unconformable horizon in the drill hole observations and the material intersected, graded from highly weathered, generally clay bound material at the surface through to the unweathered Permian coal measures that typically occurred between 1 m to 20 m below ground level.

4.2.3. Permian coal measures

Blackwater Group

Coal seams within the Permian coal measures of the Blackwater Group form the main economic resource of the numerous mines in the region (HydroSimulations, 2018). In increasing depth (age) order, the major coal measures of the Blackwater Group include the:

- Rangal Coal Measures;
- Fort Cooper Coal Measures; and
- Moranbah Coal Measures.

The Permian coal measures occur as stratified sequences of interbedded and consolidated sandstone, siltstone, mudstone, and coal. Four major coal "superseams", that occur for more than 200 km along the western limb of the Bowen Basin, were recognised by CSIRO (2002). The superseams (Figure 4.5) in stratigraphic order from oldest to youngest are:

- Lower Superseam (Goonyella Lower – Dysart - German Creek Seams);
- Middle Superseam (Goonyella Middle - Harrow Creek – Aquila Seams);
- P-Superseam (P Seams – Pleiades Seam) and 'P-tuff' a regional tuffaceous unit; and
- Upper Superseam (Goonyella Upper Seams).

The Project area is in the "middle tile" of CSIRO (2002) where the lower seams of the Moranbah Coal Measures are mined. Here, the lowest Dysart seams are the stratigraphic equivalents of the Goonyella Lower seam to the north and the German Creek seam to the south (Figure 4.5).

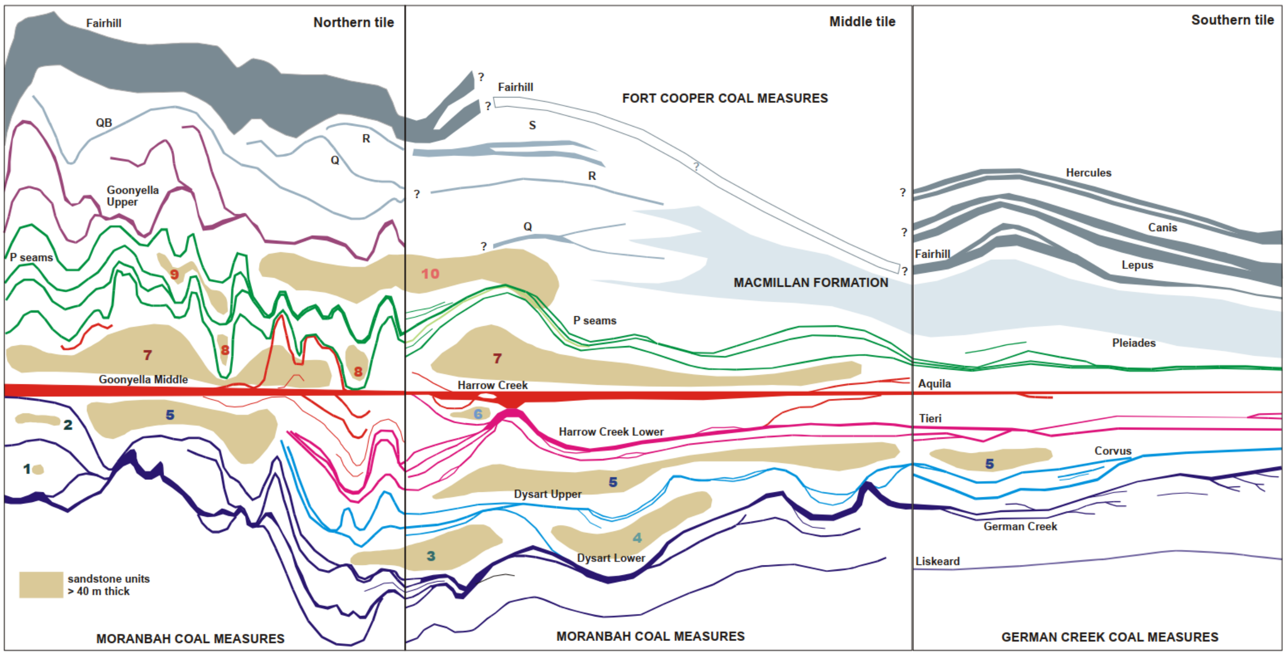


Figure 4.5 Regional correlation sections showing the "superseams", after CSIRO, 2002

The sequence of coal seams in the Moranbah Coal Measures have a cumulative coal thickness of 20 m to 30 m in the north, progressively thinning to the south. Near the Project area the cumulative thickness of coal appears to be between 5 m and 15 m (CSIRO, 2002).

The three open cut pits are targeting the ALEX and Dysart Lower-Lower (DLL) coal seam of the Moranbah Coal Measures. Outcropping at surface to the west of the Project is the basal section of the Moranbah Coal Measures, locally mapped by Vitrinite as a sequence of sandstones and siltstones. This sequence is capped in a resistant, quartzose medium to coarse grained sandstone, locally referred to as the Mesa Sandstone due to the characteristic mesa plateaus that have formed in the region. The base unit of the Moranbah Coal Measures is locally referred to as the Mesa Siltstone (Tom O'Malley, Vitrinite, per.comm., 2019).

The ALEX coal seam is about 1 m thick of high quality and low ash content, overlying approximately 2 m of siltstone and a very thickly bedded medium sandstone locally referred to as the Mesa Sandstone which grades into the Mesa Siltstone. The DLL consists of a 2.5 m thick seam with four plies; and a separate basal ply, with high ash and good quality coal. An additional 1 m thick coal seam makes the entire sequence to be mined approximately 3.5 m thick. The regional sediments dip approximately eastward at about 4° in the Project area (Tom O'Malley, Vitrinite, per.comm., 2019).

East of the Project area, at the Saraji Mine, the Permian coal measures are generally undisturbed and have a gentle regional dip of 2° to 5° towards the east (AECOM, 2016). Minor faults are mapped within the existing Saraji Mine which locally steepen the coal seams to approximately 9° to 10°. The Saraji South Fault is located south of the Saraji Mine, near Phillips Creek. The Saraji South Fault is a high angle, north north-west trending normal fault, with throws mapped between 10 m and 50 m (AGE, 2011 in AECOM, (2016)). The Downs Creek Fault is a north north-west trending normal fault with a maximum throw of 60 m and is located south of the Project area, near Lotus Creek Road.

At Saraji Mine, the Permian coal measures comprise overburden of sandstone, siltstone, claystone, mudstone, coal, coal parting materials and sub-coal (underburden) strata. The Moranbah Coal Measures include the Dysart series, Harrow Creek group, P, Q and R coal seams. Of these, the Harrow Creek Upper (H16) and Dysart Lower (D24 and D14) coal seams are mined at Saraji Mine (AECOM, 2016). The H16 seam is the uppermost of the two targeted coal seams and sub-crops to the west of the Saraji Mine with an easterly dip.

Near the Caval Ridge Mine, the Permian coal measures generally dip from west to east, at between 3° and 6°. The sequence within the northern extension of the Peak Downs Mine (located to the south of the Caval Ridge Mine and to the north of Saraji Mine) shows considerable deformation with strata dipping to 30° and along strike flexures in excess of 10°. Faulting and seam splitting is common, producing local steepening of the coal seams (over 10°). Minor faulting occurs in the seams in the Caval Ridge Mine area. Vertical displacement along faults ranges from less than 1 m to 36 m along the regional Harrow Creek Fault in the Peak Downs Mine (URS, 2009). Near the Olive Downs Coal Project, the coal measures dip around 7° to the east, which steepens in the south to 15° (HydroSimulations, 2018).

Back Creek Group

The Back Creek Group outcrops within and to the west of the Project area (Figure 4.4). The local interpretation of the Back Creek Group is on-going (Tom O'Malley Vitrinite, per.comm., 2019). The Exmoor and Blenheim Formations of the Back Creek Group are currently interpreted to be conformably underlying the Moranbah Coal Measures. The top of the Exmoor Formation is characterised by prominent coarse-grained siliceous boulder sandstone in outcrop, whilst the top of the Blenheim Formation is easily identifiable by the stratigraphic marker of the fossiliferous and worm burrowed sandstone, locally termed the Worm Burrow Sandstone.

Coal seams within the Back Creek Group include the MAY coal seam that has been interpreted to be within the Dingo Siltstone of the Exmoor Formation, and the Matilda (MAT) coal seam within the MAT Siltstone of the Blenheim Formation. The MAT coal seam is the target coal seam in the Highwall Mining area. The stratigraphic interpretation of these coal seams and the Back Creek Group has not been fully assessed; interpretations are ongoing as more information is gathered (Tom O'Malley Vitrinite, per.comm., 2019).

5. Hydrogeology

An aquifer is generally defined as a geological unit that can transmit and store significant quantities of groundwater. Within the region, the Quaternary alluvium, Tertiary sediments, and Permian coal measures yield low volumes of groundwater and hence they would not typically be classified as aquifers in most hydrogeological settings. In reality, they would be called either poor aquifers or aquitards. However, there may be individual lithological units within these formations that have higher hydraulic conductivities than the intervening units, and as groundwater in these formations are to be assessed for the determination of impact, they are referred to as aquifers for the purposes of this report. This approach is consistent with URS (2009) and URS (2012), AECOM (2016) and HydroSimulations (2018).

5.1. Regional hydro-stratigraphy

The regional and local geology are described in Sections 4.1 and 4.2, respectively. Near the Project area, the Tertiary Suttor Formation, Duaringa Formation, Tertiary basalt, Triassic Rewan Group, Moolayember Formation and Clematis Sandstone are all absent. In addition, the Permian Rangal Coal Measures and Fort Cooper Coal Measures are also absent locally (Table 5-1).

Hence the interpretation of **hydrogeologist.com.au** of the local hydrostratigraphy, consistent with HydroSimulations (2018), URS (2012) and AECOM (2016), includes isolated Quaternary alluvium, older Tertiary sediments, colluvial sediments and weathered Permian coal measures; and unweathered or fresh Permian coal measures.

Table 5-1 Interpreted regional and local hydro-stratigraphy

Period	Group	Unit	Regional	Local
Quaternary		alluvium	✓	✗ only at isolated places
Tertiary		regolith*	✓	✓
		Suttor & Duaringa Formations	✓	✗
		basalts	✓	✗
Triassic		Moolayember Formation	✓	✗
		Clematis Sandstone	✓	✗
		Rewan Group	✓	✗
Permian	Blackwater Group	Rangal Coal Measures	✓	✗
		Fort Cooper Coal Measures	✓	✗
		Moranbah Coal Measures and	✓	✓
	Back Creek Group	German Creek Formation	✓	✗
	Back Creek Group Exmoor Formation	Dingo Sandstone	✓	✓
		Dingo Siltstone	✓	✓
		Wallaby Hill Sandstone	✓	✓

Note: The regolith concept of HydroSimulations (2018) is adopted for the weathered Permian coal measures.

5.2. Local hydrogeology

The following section defines the hydro-stratigraphic units for the Project. AECOM's (2016) hydro-stratigraphy of the Saraji Mine is reproduced as Table 5-2. The Project area is to the west of, and at a higher elevation than Saraji Mine and other mines to the east. Occupying a higher position in the landscape significantly affects the local hydrogeology, as several units listed by AECOM (2016) are absent, while others may, in places, be unsaturated. This is because under topographically higher elevations, the groundwater table is generally deeper than that observed at Saraji Mine, and the Permian coal measures are at shallower depths due to their dip to the east.

Table 5-2 Hydro-stratigraphy of the Saraji Mine, after AECOM (2016)

Age	Stratigraphic unit	Lithology	Aquifer type
Quaternary	Alluvium	Clay, silts, sand, gravel, floodplain alluvium	Unconfined (aquifer)
Tertiary	Sediments	Clay, silt, sand, gravel, colluvium, fluvial and lacustrine deposits including cross-bedded quartz sandstone, conglomerate, claystone	Aquitard
	Duaringa Formation	Mudstone, sandstone, conglomerate, siltstone, oil, shale, lignite, and basalt	Aquitard
Unconformity			
Late Permian	Fort Cooper Coal Measures	Coal, brown and green sandstone, conglomerate, carbonaceous shale, tuff	Confined aquifer (coal) and confining unit (interburden)
	Moranbah Coal Measures	Coal, sandstone, siltstone, mudstone, carbonaceous mudstone	Confined aquifer (coal) and confining unit (interburden)
Middle Permian	Back Creek Group	Sandstone, siltstone, carbonaceous shale, minor coal and sandy coquinite	Confining unit

The following sections define the hydrogeology of the various hydro-stratigraphic units for the Project and further discuss groundwater flow, quality, and the hydraulic characteristics. The local hydro-stratigraphic units are listed as follows:

- Quaternary alluvium;
- Tertiary sediments; and
- Permian coal measures.

5.2.1. Quaternary alluvium

Although Quaternary alluvium was not observed during the drilling of local monitoring bores (Section 5.3), nor mapped in close proximity to the open pits proposed by the Project, it is important as a regional hydro-stratigraphic unit and is described here following the observations made by URS (2009) and URS (2012), AECOM (2016) and HydroSimulations (2018). Quaternary alluvium is mapped (Figure 4.4) near both the northern and southern boundaries of the Project area associated with Cherwell Creek and Phillips Creek, respectively.

The Quaternary alluvium is recognised to occur as discrete channels associated with the present day, larger surface water systems such as the Isaac River and some of its tributaries. Where it exists, the Quaternary alluvium forms an unconfined aquifer of limited lateral extent. Due to the semi-arid climate, the ephemeral nature of the stream flow, and spatial discontinuity of the more permeable sand and gravel layers, the groundwater resource in the Quaternary alluvium is not abundant and groundwater only occurs in isolated areas (URS, 2012). The alluvial sediments are often unsaturated and, where they are saturated, are generally disconnected laterally.

HydroSimulations (2018), (Figure 4-4, not reproduced in this report) shows interpreted alluvium near the Olive Downs Coal Project, based on a geophysical (transient electromagnetic, TEM) survey. The results indicate that all Quaternary alluvium is associated with the Isaac River, and near its confluence with Phillips Creek and Ripstone Creek. No Quaternary alluvium is shown near, or to the west of Saraji Mine. These observations are also confirmed by Figure 4.4 which indicates a general absence of Quaternary alluvium near the Project area. In addition, a review of bore data by AECOM (2016) indicated several bores were drilled in close proximity to Phillips Creek but only a few of these bores intersected the Quaternary alluvium; and some of these were reported to be drilled dry. The other bores drilled along the creek were constructed in the Tertiary sediments below and adjacent to the alluvial sediments.

5.2.2. Tertiary sediments

Tertiary sediments have been mapped in the southern portion of the Project area and at Saraji Mine. These sediments consist of lenses of palaeochannel gravels and sands separated by sandy silts, sandy clays and clays (URS, 2009) with thicknesses near the Caval Ridge Mine up to 30 m. The silts and clays are densely compacted, hard, and generally dry. Potential for groundwater, however, exists within sandy and gravely sections, and represents an unconfined to confined aquifer depending on location. Most of the clean sand and gravel lenses are permeable but are of limited lateral and vertical extent (URS, 2009). Historically, mining issues associated with Tertiary sediment derived groundwater at the Peak Downs Mine appear limited to pit wall stability rather than ongoing problems with groundwater inflow. This generally indicates low hydraulic conductivity and limited lateral extent of the more permeable areas (URS, 2009).

HydroSimulations (2018) found that near the Olive Downs Coal Project, the surficial regolith material covering much of the site comprises Cainozoic (Quaternary to Tertiary) aged sediments, including alluvium and colluvium. Older alluvial (TQa in geological maps and Figure 4.4) sediments are distributed extensively across the region, and colluvium and residual deposits (Qr and Qr\b) occur within isolated patches to the north. No Quaternary alluvium is shown near or to the west of Saraji Mine. Site drilling logs indicate the sequences exhibit similar geological characteristics and have therefore been grouped as 'regolith' by (HydroSimulations, 2018).

HydroSimulations (2018) summarised regolith as:

"*Based on site geological logs, the regolith comprises a heterogeneous distribution of fine to coarse grained sand, clay, sandstone and claystone. The regolith material is generally 15 m to 45 m thick. The units are all recorded as being highly weathered, with the depth of weathering extending to around 50 m below ground level (mbgl), into the underlying coal measures*".

As described in Section 4.2.2, **hydrogeologist.com.au** use the term "*weathered Permian*" to describe the lithology intersected above the fresh Permian coal measures and those rocks are considered equivalent to the regolith of (HydroSimulations, 2018). There was no evidence of an unconformable horizon in the drill holes and the material intersected was highly weathered, generally clay bound material down to the top of the unweathered Permian coal measures. It was assessed by **hydrogeologist.com.au** that the lithology intersected above the fresh Permian coal measures in the Project area did not constitute Tertiary aged sediments, rather a weathering profile that had developed during the Tertiary on the Permian strata. Within the monitoring bores drilled for the Project, the depth of weathering typically occurred between 1 m to 20 m below ground level and the weathered profile was generally unsaturated.

Hence, whether the strata are Tertiary sediments or weathered Permian regolith is not of significance in the saturated groundwater flow context as much of the strata are unsaturated beneath the Project area and nearby at Saraji Mine (AECOM, 2016). To this end, it is recognised that locally there are no Tertiary sediments in the vicinity of the proposed open pits, however the weathered profile or regolith intersected is highly likely to have similar hydraulic properties to the majority of the Tertiary sediments described and documented at other sites within the region, that is clayey in nature, of low permeability and of limited saturation. The term Tertiary sediments from here on refers to a mix of specific Tertiary aged sediments and the weathered zone or regolith material that has formed on top the Permian coal measures.

The Tertiary sediments outcrop beneath most of the Project area and to the east (Figure 4.4). The Tertiary sediments, where saturated, form an unconfined unit, although confinement (due to the generally low hydraulic conductivity) is possible deep into the regolith.

5.2.3. Permian coal measures

Throughout the Bowen Basin, the coal seams are considered to be poor aquifers within the Permian coal measures, and the adjacent overburden and interburden sediments generally considered as aquitards. Accordingly, AECOM (2016) hydrogeologically divided the Permian coal measures into non-coal-bearing over- and inter-burden units and coal seams. URS (2009) noted, in the context of overall low yields and therefore low hydraulic conductivity, that historical mining issues with groundwater in the Permian coal measures at Peak Downs Mine appear to have been limited to pit wall stability rather than ongoing problems with groundwater inflow, indicating the generally low hydraulic conductivities of the Permian coal measures on site.

The coal seams generally are considered dual-porosity strata where primary-porosity is provided by the matrix and a secondary porosity is the result of the presence of fractures (joints and cleats). Natural cleats within the coal seams are likely the dominant space for groundwater storage; the main pathway for groundwater movement is dependent on fracture interconnectivity (URS, (2009) and AECOM, (2016)). The coal seam aquifers are generally confined above and below by the low permeability inter- and overburden (AECOM, 2016).

The non-coal-bearing overburden and interburden units comprise claystone, mudstone, sandstone, siltstone, and shale. These low permeability rock types are not recognised for their high groundwater potential. They can, however, provide localised supplies of variable, generally low yielding and poor quality groundwater (AECOM, 2016). The overburden and interburden rocks in several mines in the northern Bowen Basin (e.g. Broadlea Coal Mine, Burton Mine and Ellensfield Coal Mine) have been described as essentially impervious to groundwater movement (AGE, 2007 in AECOM, 2016).

The target coal seams at the Saraji Mine are the Harrow Creek Upper seam and the Dysart Lower seams of the Moranbah Coal Measures and these seams form confined aquifers. These seams are laterally extensive along the western and eastern margins of the Bowen Basin and within the Project area but with varying thickness.

Within the Project area, the targeted ALEX and DLL coal seams of the Moranbah Coal Measures are regarded as poor aquifers (because of their limited thickness) and the interburden (including over- and under-burden) as aquitards. Groundwater in the ALEX and DLL coal seams are expected to be confined from above by overburden and the regolith and from underneath by the interburden.

The Back Creek Group comprises sandstone, siltstone, shale and minor coal; and is considered a semi-pervious lower boundary for groundwater flow to the overlying Blackwater Group (URS, 2012). The Back Creek Group is normally considered as the base layer for numerical models (the base of a model, by definition is impervious). The Exmoor Formation of the Back Creek Group is locally mapped by Vitrinite as the Dingo Sandstone, Dingo Siltstone and Wallaby Hill Sandstone (from top down), but contains recognised and laterally extensive coal seams (MAY and MAT seams) that, together with the sandstones, can potentially form poor aquifers similar to those interpreted in the Blackwater Group.

The German Creek Coal Measures are considered to be part of the Back Creek Group according to the Australian Stratigraphic Units Database (https://asud.ga.gov.au/search-stratigraphic-units/results/7142, visited on 14 August 2019). The stratigraphic relationships are shown in Table 5-2.

5.3. Groundwater monitoring network

In June 2019, eight monitoring bores were drilled in the Project area (see Section 1.1) with four bores drilled to the east in nearby ML700060 (as part of the VCM). Monitoring bore MB13 was drilled in early 2021 for the VCM. Table 5-3 summarises the location, target unit and construction details for each monitoring bore (**hydrogeologist.com.au**, 2019) which forms the groundwater monitoring network. The bores are shown in Figure 5.1 along with the registered groundwater bores associated with the DRDMW GWDB. MB06 and MB10 are nested monitoring bores drilled on the same site.

Table 5-3 Vulcan South monitoring bores – construction details from hydrogeologist.com.au (2019)

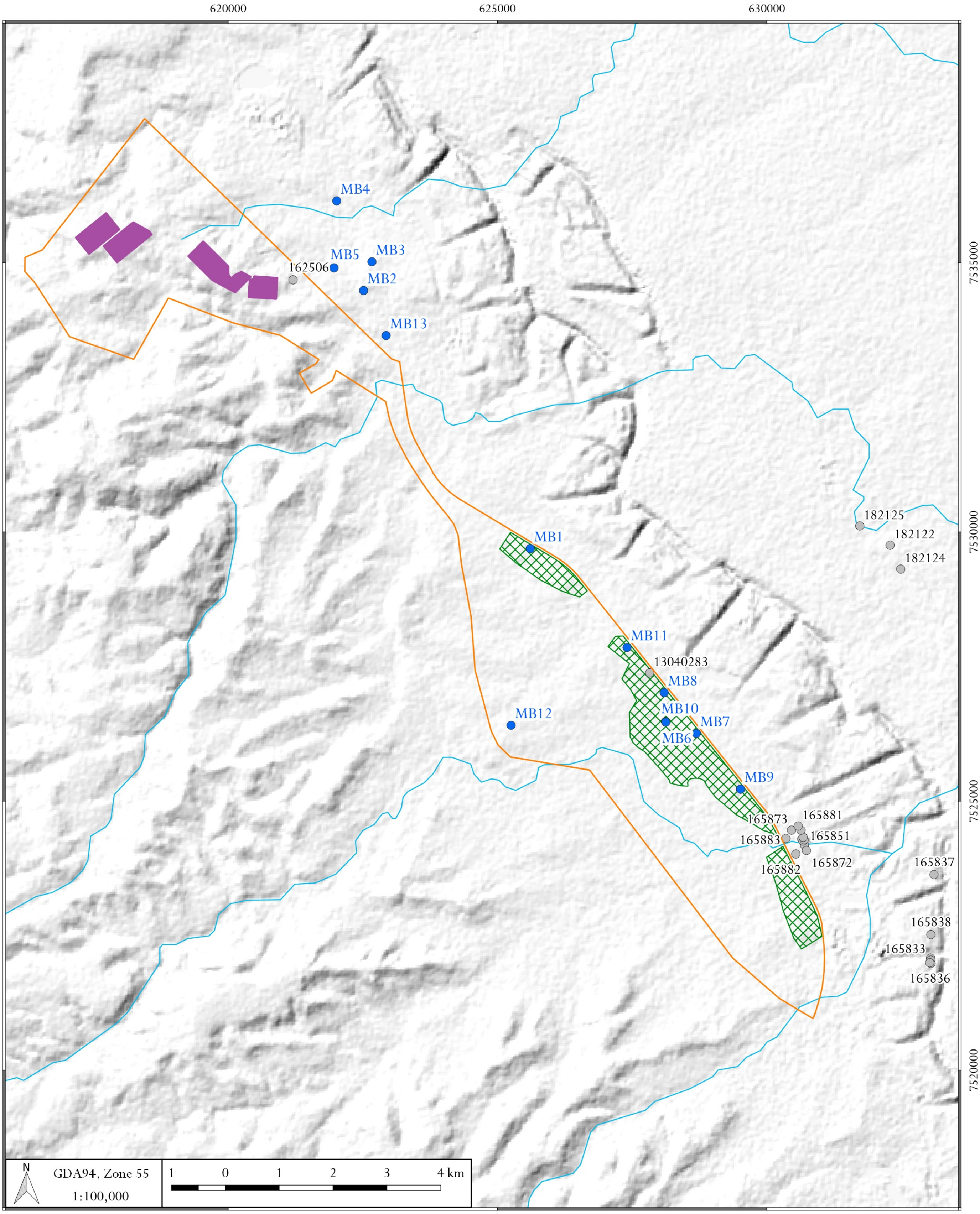
ID	Area	Easting	Northing	Target unit	Casing height (maGL)	Hole depth (mbGL)	Screen interval (mbGL)	Airlift yield (L/min)	Casing elevation (mAHD)
MB01	Project	625606	7529691	DLL coal seam	0.70	24.9	21.9 – 24.9	Dry	222.91
MB02	VCM	622513	7534483	DLL coal seam	0.71	12.0	9.0 – 12.0	Dry	254.69
MB03	VCM	622668	7535017	DLL coal seam	0.70	33.8	30.8 – 33.8	<0.1	257.68
MB04	VCM	622014	7536148	DLL coal seam	0.71	21.5	18.5 – 21.5	1	243.28
MB05	VCM	621964	7534905	MAT coal seam	0.77	40.9	37.9 – 40.9	0.5	252.70
MB06	Project	628119	7526476	Weathered Permian	0.70	24.6	21.6 – 24.6	Dry	214.61
MB07	Project	628691	7526258	Weathered Permian	0.67	43.0	40.0 – 43.0	0.1	215.99
MB08	Project	628092	7527015	Weathered Permian	0.70	24.0	21.0 – 24.0	Dry	212.24
MB09	Project	629511	7525222	DLL coal seam	0.65	34.4	31.4 – 34.4	0.1	208.98
MB10	Project	628123	7526469	DLL coal seam	0.70	40.3	37.3 – 40.3	<0.1	214.60
MB11	Project	627403	7527854	DLL coal seam	0.70	29.9	26.9 – 29.9	Dry	225.66
MB12	Project	625251	7526409	Back Creek Group	0.66	38.2	32.2 – 38.2	1	241.43
MB13	VCM	622931	7533648	MAT coal seam	0.63	36.92	33.5 – 36.5	Unknown	223.13

Notes: Easting and northing coordinates are in GDA94, Zone 55

maGL – metres above ground level

mbGL – metres below ground level

The DLL coal seam (Dysart Lower Lower) is in the Mesa Siltstone (Lower Moranbah Coal measures); the MAT seam is in the Dingo Siltstone of the Exmoor Formation (Back Creek Group).



LEGEND

- Monitoring bore
- Registered bore
- Proposed pit
- Highwall mining area
- Mining lease application area

DATE
23/02/2022

hydrogeologist.com.au

Vulcan South - Groundwater Impact Assessment (4027)

Groundwater monitoring bore network

FIGURE No.
5.1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
Based on or contains data provided by the State of Queensland [2019]
Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\05_01_4027_Vulcan South_Groundwater monitoring bore network.qgz

5.3.1. Rationale

The groundwater monitoring network was established based on available information relating to the general understanding of groundwater flow conditions (west to east), the coal resource and general geology of the region and the available mining and exploration tenure. The rationale for locating the monitoring bores was to have an upstream and downstream bore plus an understanding of groundwater conditions within the Project area and to the north and south. The groundwater within the Permian coal measures is often brackish to saline which restricts the environmental value of the groundwater (Section 5.8.3) which is typically limited livestock watering and industrial use.

The Project area monitoring bores were designed to target the Permian coal measures and the Tertiary sediments as there is no mapped Quaternary alluvium within or in close proximity to the Project area. A number of the Project area monitoring bores targeting the Permian coal measures and the Tertiary sediments were dry.

The target coal seams of the Moranbah Coal Measures (Section 4.2.3) generally strike in a north north-west to south south-east orientation and dip to the east. This local orientation of geology spatially constrains the groundwater monitoring network to the west of proposed Vulcan pits. As a result, monitoring bore MB12 has been constructed within the Back Creek Group (see Section 4.2.3 and Section 5.2.3). The Back Creek Group underlies the Moranbah Coal Measures. The general groundwater flow conditions are from west to east and a suitable upstream monitoring site in the target coal seam(s) was not able to be practically established. However, it is assessed that MB12 will be able to provide an appropriate site for the monitoring of drawdown that may propagate through the Back Creek Group extending to the west of the Vulcan pits. There is no mining development upstream of the Vulcan pits.

The Project area is adjacent to existing mining leases which are operated by BMA. The establishment of Project specific groundwater monitoring bores on the BMA mining leases to the east (Figure 3.6) is not practical or achievable therefore mining tenure has spatially constrained the groundwater monitoring network to the east of proposed Vulcan pits. Monitoring bores MB01, and MB06 through to MB11 were all located and designed on existing cleared drill pads (to minimise land and vegetation clearances). The monitoring bores were spatially distributed so far as was reasonably practical to do so to provide an adequate spatial spread of the data. At the time of monitoring bore installation, the mine plan was not available for consideration.

The VCM groundwater monitoring bores were located in association with ML700060 to the north and to the immediate east of the Project area. The spatial constraints associated with local geology and mining tenure also affected the location of the VCM groundwater monitoring bores.

Subsequent to installing the monitoring bores, the mine plan was provided, and it is clear that a significant number of the Project area monitoring bores will be disturbed by mining operations. Prior to this disturbance occurring, replacement monitoring bores will be established in locations which provide an adequate spatial distribution in the target formation and will enable long term monitoring. Any replacement monitoring bore will also need to consider potential contaminant sources.

The groundwater monitoring network is considered to be fit for purpose for this assessment. Future changes to the network or the monitoring plan will be needed which are planned for and outlined in a proposed adaptive management strategy (see Section 7.1).

5.3.2. Current monitoring plan

All of the groundwater monitoring bores installed in 2019 (**hydrogeologist.com.au**, 2019) now form the groundwater monitoring network. A total of six monitoring bores were dry after drilling and construction, indicating that these bores are constructed above the regional groundwater table. The presence of dry holes provides useful information in conceptualising the groundwater system.

Groundwater level monitoring

The groundwater level monitoring of the groundwater monitoring network has been carried out monthly (for the first six months) then quarterly thereafter, and all monitoring bores were equipped with data loggers or pressure transducers, which automatically collect readings every four hours. The use of dataloggers will continue as part of on-going groundwater level monitoring. The manual groundwater level measurements collected at the site are summarised in Table 5-4.

From Table 5-4 it is observed that the groundwater elevations are generally between 180 mAHD and 220 mAHD in the southern portion of the Project area, and 230 mAHD to 240 mAHD in the north. The depth to groundwater measurements indicate that the depth to groundwater in the southern portion of the Project area is between 20 m to 35 m below ground level. Groundwater elevations are generally a subdued reflection of topography, that is deep beneath high land elevation (hills) and shallow beneath low land elevation (valleys).

In some instances (e.g. MB03), the depth to groundwater measurement collected after airlift development was influenced by the drilling and construction process, and in other instances the low permeability of the intersected formation (e.g. MB12). For this reason, the earlier measurements in Table 5-4 may not be representative.

Figure 5.2 shows the groundwater elevation hydrographs at the six monitoring bores (note that the hydrographs for MB04 or MB05 overlap) over a 12 month period from June 2019 through to September 2021. Except for the spikes in data observed at MB04, MB05 and MB12, the groundwater elevation hydrographs demonstrate a static system with no or very little (~centimetre magnitude) temporal variations in groundwater level. The notable spikes in data in mid-July, mid-August and mid-September are associated with the monthly groundwater sampling events. The bores with the spikes (MB04, MB05 and MB12) are constructed within low hydraulic conductivity formations and the groundwater is slow to recover following purging.

Table 5-4 Summary of manual groundwater level measurements

Site ID	Casing elevation (mAHD)	SWL														
		Jun 2019	Jul 2019	Aug 2019	Sep 2019	Oct 2019	Dec 2019	Mar 2020	Jun 2020	Aug 2020	Oct 2020	Dec 2020	Mar 2021	May 2021	Jul 2021	Sep 2021
MB1	222.91	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
MB2	254.69	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
MB3	257.68	239.38	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
MB4	243.28	237.47	237.58	237.45	237.18	237.75	238.13	237.53	237.53	236.76	236.54	236.37	236.58	236.61	236.53	236.41
MB5	252.70	238.17	238.01	237.99	238.23	238.69	238.55	238.10	227.77	235.95	236.62	236.53	236.37	236.72	236.41	236.04
MB6	214.61	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
MB7	215.99	181.19	179.71	179.77	179.79	180.31	180.12	180.40	189.79	179.92	179.87	179.91	179.99	179.91	179.96	180.03
MB8	212.24	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
MB9	208.98	181.57	181.34	181.36	181.39	181.81	181.48	182.12	181.88	181.24	180.98	181.29	181.35	181.33	181.32	181.43
MB10	214.60	182.09	182.15	182.20	182.29	183.04	183.00	183.04	188.10	182.49	182.50	182.55	182.60	182.56	182.61	182.65
MB11	225.66	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
MB12	241.43	215.36	216.22	216.41	216.66	218.00	218.39	216.94	215.71	216.55	216.56	216.53	215.85	215.60	215.61	214.85
MB13	223.13	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	209.12	208.53	208.49	208.63

Notes: *Easting and northing coordinates are in GDA94, Zone 55 from differential GPS*

SWL – standing water level

mAHD – metres above Australian Height Datum from differential GPS

mbTOC – metres below top of casing (PVC)

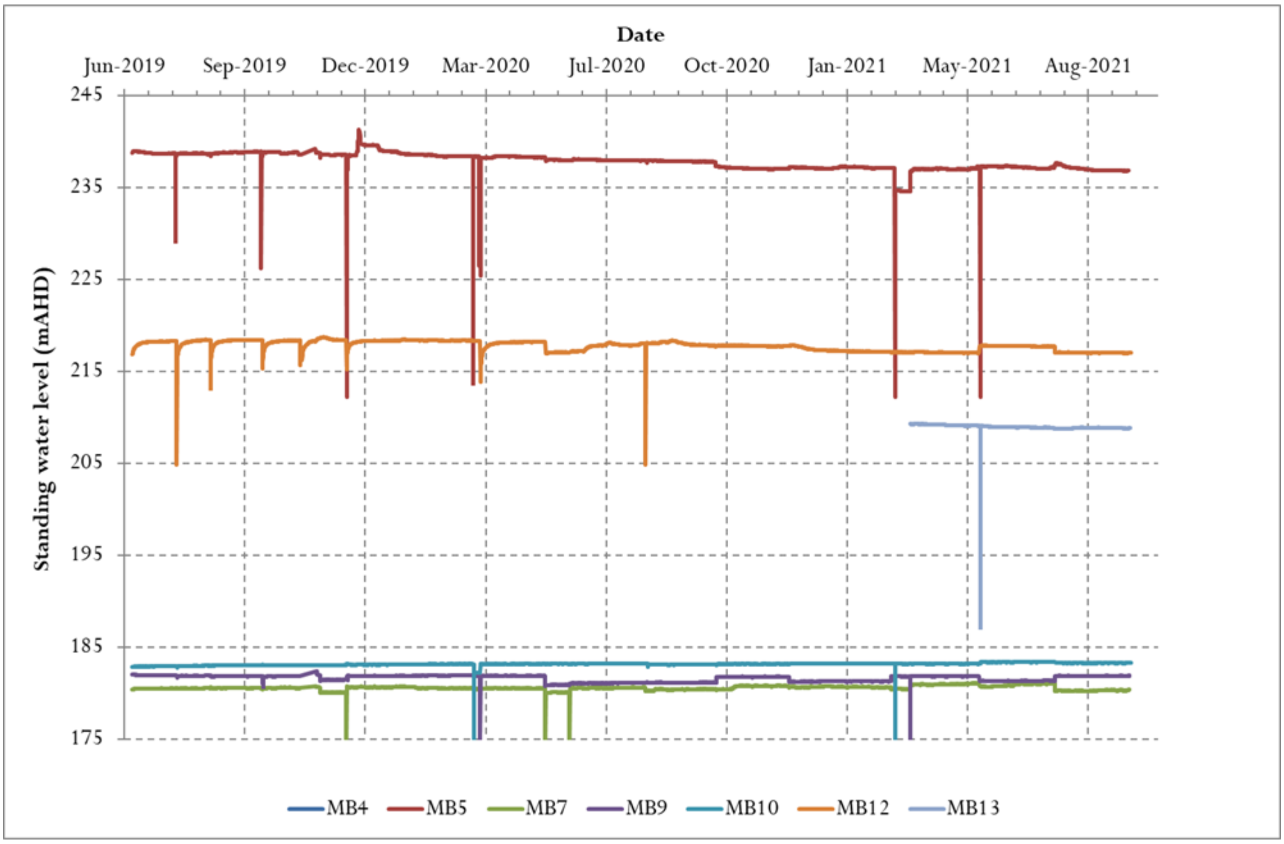


Figure 5.2 Groundwater hydrographs for Vulcan South monitoring bores

Groundwater sampling

Groundwater sampling is also regularly carried out (monthly for the first six months then quarterly thereafter) across the monitoring network to collect representative samples for baseline characterisation and for the derivation of trigger levels and contaminant limits (DES, 2021). The groundwater quality parameters monitored are consistent with those provided in Appendix A, which have been developed in consideration of the DES (2017) Guideline: Model mining conditions. The monitoring and sampling of the groundwater monitoring network is planned for and carried out in consideration of the Queensland Monitoring and Sampling Manual (DES, 2018a).

At the time of completing this report, results from eight monthly monitoring rounds are available. DES (2021) recommend at least eight groundwater samples be taken over a 12-month period to establish a robust baseline in order to derive site-specific triggers or limits for groundwater quality. Further sampling of the groundwater monitoring network will be carried out to further add to the dataset used derive interim trigger values. The derivation of trigger values will be carried out in consideration of DES (2021). Section 5.8 provides further discussion on groundwater quality including site specific data.

5.4. Hydraulic properties

Hydraulic testing in the form of slug testing and constant head testing was performed on the Project groundwater monitoring network summarised in Table 5-3. Slug testing (falling head tests) was completed on the monitoring bores recording a groundwater level, whereas constant head testing was completed on the dry monitoring bores. The recovery curve method was carried out for MB12 given the slow recovery response following sampling. The results of the testing are provided in Appendix B and are summarised below in Table 5-5.

Table 5-5 Summary of hydraulic testing from the Vulcan South monitoring bores

Site ID	Area	Target unit	Test method	Hydraulic conductivity (m/d)
MB01	Project	DLL coal seam	Constant head	3.9×10^{-2}
MB02	VCM	DLL coal seam	Constant head	5.3×10^{-2}
MB03	VCM	DLL coal seam	Constant head	3.2×10^{-2}
MB04	VCM	DLL coal seam	Slug test (Hvorslev, 1951)	9.7×10^{-2}
MB05	VCM	MAT coal seam	Slug test (Hvorslev, 1951)	2.4×10^{-2}
MB06	Project	Weathered Permian	Constant head	>0.1
MB07	Project	Weathered Permian	Slug test (Hvorslev, 1951)	0.21
MB08	Project	Weathered Permian	Constant head	>0.1
MB09	Project	DLL coal seam	Slug test (Hvorslev, 1951)	2.0×10^{-2}
MB10	Project	DLL coal seam	Slug test (Hvorslev, 1951)	0.41
MB11	Project	DLL coal seam	Constant head	2.9×10^{-2}
MB12	Project	Back Creek Group	Recovery test	2.8×10^{-4}

For two of the dry monitoring bores (MB06 and MB08) the rate at which the bore accepted water was higher than the rate it could be fed in. Therefore, it is assumed that the hydraulic conductivity of the intersected lithology at these monitoring bores is higher than 0.1 m/d.

The hydraulic testing of the monitoring bores indicates that generally the highest hydraulic conductivities are for the weathered Permian, moderate values for the DLL and MAT coal seams and the lowest results are for the Permian underburden. The following order of magnitude is observed in relation to hydraulic conductivities:

- Weathered Permian: low 10^{-1} m/d;
- DLL and MAT coal seams: 10^{-2} m/d; and
- Permian underburden: 10^{-4} m/d.

The horizontal hydraulic conductivities collated from various studies in the Moranbah-Dysart region are summarised in Table 5-6. Spatial variability, local geology, the different methods used to acquire data and uncertainties in interpretation explain the wide range of values which in some instances cover three or four orders of magnitude. Notwithstanding the above, the results in Table 5-5 are consistent with the description of the hydrogeology (Sections 5.1 and 5.2) and the majority of hydraulic conductivity ranges presented in Table 5-6.

Table 5-6 Horizontal hydraulic conductivity estimates (m/d) from studies in the Moranbah-Dysart region

Formation	URS (2009)	URS (2012)*	CDM Smith (2013)*	URS (2014)	AECOM (2016)	HydroSim. (2018)	Arrow (2016)
Quaternary alluvium	0.09 to 0.4	2.5 to 250	0.09 to 100	0.001	1×10^{-3}	2×10^{-1} to 9	1×10^{-2} to 1.5
Tertiary sediments/ regolith	-	0.1 to 10**	-	-	1×10^{-3} to 1×10^{-2}	1×10^{-1} to 6×10^{-1}	0.1 to 1
Triassic (Rewan F.)	-	5×10^{-4} to 5×10^{-2}	1×10^{-5} to 1×10^{-1}	-	-	2×10^{-6} to 5×10^{-3}	-
Permian coal measures	-	1×10^{-4} to 5×10^{-2}	-	-	-	-	0.2 to 1
Permian coal seams	1×10^{-2} to 5×10^{-1}	-	1×10^{-6} to 5	0.002 to 0.16	1×10^{-3} to 1×10^{-2}	5×10^{-4} to 1×10^{-1}	-
Permian interburden	2×10^{-2} to 3×10^{-2}	-	1×10^{-4} to 1×10^{-1}	-	-	6×10^{-7} to 6×10^{-3}	-
Permian Back Creek Group	-	1×10^{-4} to 1×10^{-2}	1×10^{-3} to 1×10^{-2}	-	-	-	-

*Note: *Collated data from literature ** (0.005 to 0.5 m/d for Duaringa Formation)*

The following sections provide commentary on the hydraulic parameters collated in Table 5-6.

Quaternary alluvium

Because of its thin saturated thickness (where it exists and is saturated) the Quaternary alluvium on its own would rarely form an aquifer. Rather, in combination with the underlying Tertiary sediments or Permian coal measures it may form a poor aquifer. The values reported by AECOM (2016) for the Quaternary alluvium appear to be low while the upper end of the reported values URS (2012) and CDM Smith (2013) appear high. The remaining data suggest a horizontal hydraulic conductivity in the order of 1×10^{-1} m/d to 1×10^{0} m/d, consistent with a (poor) aquifer. No Quaternary alluvium was intersected within the monitoring bore network and therefore Project specific data is unavailable.

Tertiary sediments

As discussed in Section 4.2.2, on-site observations during the construction of the Vulcan South monitoring bores indicate that the lithology intersected above the fresh Permian coal measures did not constitute Tertiary aged sediments, rather a weathering profile that had developed during the Tertiary on the Permian coal measures. As stated in Section 5.2.2, for the purposes of this report, Tertiary sediments are defined as a mix of specific Tertiary aged sediments and the weathered zone or regolith material.

For a mix of specific Tertiary aged sediments and the weathered zone or regolith, hydraulic conductivities in the order of 10^{-1} m/d appear reasonable (as provided by HydroSimulations, 2018, and Arrow Energy, 2016; in Table 5-6).

Permian coal measures

Throughout the Bowen Basin, the Permian coal seams are understood to be the main water bearing horizon within the Permian coal measures and the confining overburden, underburden and interburden strata are considered to be aquitards. Table 5-6 therefore lists the horizontal hydraulic conductivities for the coal measures (coal and over- and interburden), coal seams only, and interburden (including overburden) only.

The coal seams are considered dual-porosity strata where primary-porosity is provided by the matrix and a secondary porosity is the result of the presence of fractures (joints and cleats). These secondary porosity features within the coal seams likely dominate groundwater storage; and the main pathway for groundwater movement is dependent on the interconnectivity of these fractures (URS, 2009 and AECOM, 2016). Hence the hydraulic conductivity of the coal seams is expected to vary considerably spatially and also decrease with increasing depth of burial as the fractures close under increasing overburden pressure (HydroSimulations, 2018).

For the reasons listed above, the horizontal hydraulic conductivities in Table 5-6 cover a wide range. A range between 1×10^{-2} m/d and 1×10^{-1} m/d appears to be reasonable and consistent with the descriptions provided in Section 4.2.3 for the upper coal seams. For the interburden, a range between 1×10^{-5} m/d and 1×10^{-3} m/d appears to be realistic. For the coal measures (coal seams and inter- and overburden together), horizontal hydraulic conductivities between 1×10^{-4} m/d and 1×10^{-2} m/d appear to be reasonable. For the Permian Back Creek Group, horizontal hydraulic conductivities between 1×10^{-4} m/d and 1×10^{-2} m/d appear to be realistic and consistent with the material descriptions provided.

5.5. Groundwater flow, recharge, and discharge

5.5.1. Quaternary alluvium

AECOM (2016) and HydroSimulations (2018) suggest that the Quaternary alluvium is recharged primarily from creek flow events and by the infiltration of rainfall (and overland flow, where alluvium is exposed and no substantial clay barriers occur).

The mechanism of recharge described above is presented in Figure 5.3 below. The schematic represents a surface water system or creek within the Project area. There is very little Quaternary alluvium that has developed along the creek and a nominal thickness of 2 m is presented in this diagram. Given the ephemeral nature of the system, the creek is more often dry and, if present, the Quaternary alluvium is generally unsaturated. The groundwater table beneath the creek occurs at depth (greater than 10 m below ground level) and forms part of the regional groundwater table. If the local system has the ability to store water following a flow event and sub-surface conditions allow the stored water to infiltrate past the vegetation root zone, then this surface water flow may provide recharge to the groundwater system. This would be observed as localised mounding beneath the creeks and surface water systems. Otherwise, diffuse rainfall recharge would be expected to occur over a large area but at low rates.

The alluvial sediments may discharge to underlying Tertiary sediments and/or sub-cropping coal seams, especially during and immediately after periods of creek flow. Other discharge mechanisms from the alluvium include evapotranspiration (AECOM, 2016) where the water table is shallow, i.e. outside the Project area and near the Isaac River.

Groundwater flow, where and when the alluvium is present and saturated, is expected to follow topography. For example, groundwater in the alluvium follows the down-stream flow gradient of the Isaac River, with south-easterly flow gradients (HydroSimulations, 2018).

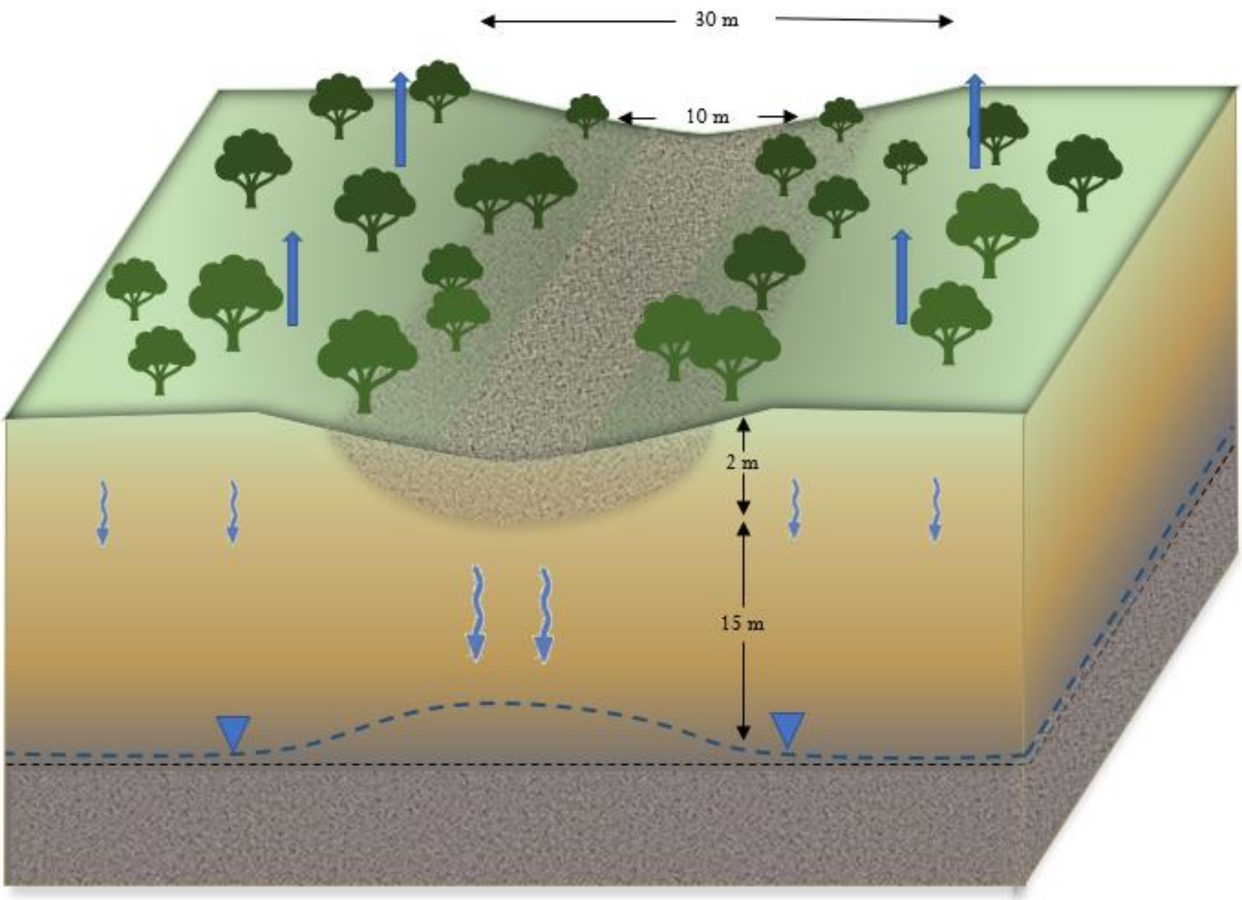


Figure 5.3 Schematic diagram of recharge processes

5.5.2. Tertiary sediments

Recharge to the Tertiary sediments is likely from creek flow (losing ephemeral streams) events and, where there is no Quaternary alluvium beneath surface water systems, from surface infiltration of rainfall and overland flow. Recharge may also occur by downward vertical seepage from overlying Quaternary alluvium (URS, 2009) where the alluvium is present. Given the clayey nature of the Tertiary sediments it would be expected that recharge rates would be very low.

Discharge from the Tertiary sediments, where they outcrop and the water table is shallow, may occur through evapotranspiration. The Tertiary sediments may also discharge to the Permian coal measures as, in general, there is a downward vertical hydraulic gradient between the Tertiary sediments and Permian coal measures.

Observations from open pits at Saraji Mine (AECOM, 2016) indicate that groundwater discharges relatively slowly from the sandy horizons within the Tertiary sediments. Based on these observations, the Tertiary sediments were considered by AECOM (2016) to contain a series of poorly connected aquifers of low to moderate permeability, with drainage from the upper to lower aquifers delayed by lower permeability horizons. Groundwater ingress rates are low as evaporation rates are higher than the seepage rate, hence groundwater does not report directly or require management in the pits (AECOM, 2016).

As for the Quaternary alluvium, groundwater flow in the Tertiary sediments is expected to follow topography and surface water drainage patterns. Groundwater levels within the Tertiary sediments from monitoring bores near the Saraji Mine were reported to be at depths shallower than the recorded water strikes from drilling and installation, interpreted by AECOM (2016) to indicate that groundwater is semi-confined to confined by the clayey sediments in the upper sections of the sequence (AECOM, 2016).

5.5.3. Permian coal measures

Within the Project area and in the vicinity of the proposed open pits, the Permian coal measures are known to be partially unsaturated and site-specific monitoring bores (i.e. MB01, MB02, MB03 and MB11) have confirmed this. Figure 5.4 illustrates how the Permian coal measures change in the vicinity of the proposed Vulcan main pit from unsaturated to partially saturated in the north-west, to unconfined and eventually to fully saturated and confined in the south-east.

As for the Tertiary sediments, groundwater recharge to the Permian coal measures is likely from creek flow (losing ephemeral streams) events where there are no Cainozoic sediments beneath surface water systems; and from surface infiltration of rainfall and overland flow, where the Permian coal measures are exposed, and no substantial clay barriers occur in the shallow sub-surface. Recharge may also occur from overlying Cainozoic sediments under downward vertical hydraulic gradient and along faults and other structural features (AECOM, 2016).

Discharge from the Permian coal measures, where they outcrop and the water table is shallow, may occur through evapotranspiration or along faults and by groundwater extraction from bores and mine dewatering/depressurisation (AECOM, 2016; HydroSimulations, 2018). For the shallower coal measures, groundwater elevations are generally at or below groundwater elevations within the overlying unconfined sediments, indicating a downward hydraulic gradient. However, with increased depth of cover and pressure, the hydraulic gradient within the Permian coal measures may reverse, coinciding with a decrease in hydraulic conductivity with depth (HydroSimulations, 2018).

As for the Cainozoic sediments, groundwater flow in the Permian coal measures is expected to follow topography and surface water drainage patterns, although the similarity to surface water drainage for the deeper confined units will be less pronounced than that for a shallow unconfined aquifer. Within the Permian coal measures, due to the low hydraulic conductivity of the interburden material, groundwater would largely flow along the bedding planes of the coal seams (HydroSimulations, 2018). In the vicinity of active mine dewatering sites, groundwater would flow into the pits but the spatial extent of the interference zone of individual pits would be limited because of the low hydraulic conductivity and storativity of the coal measures.

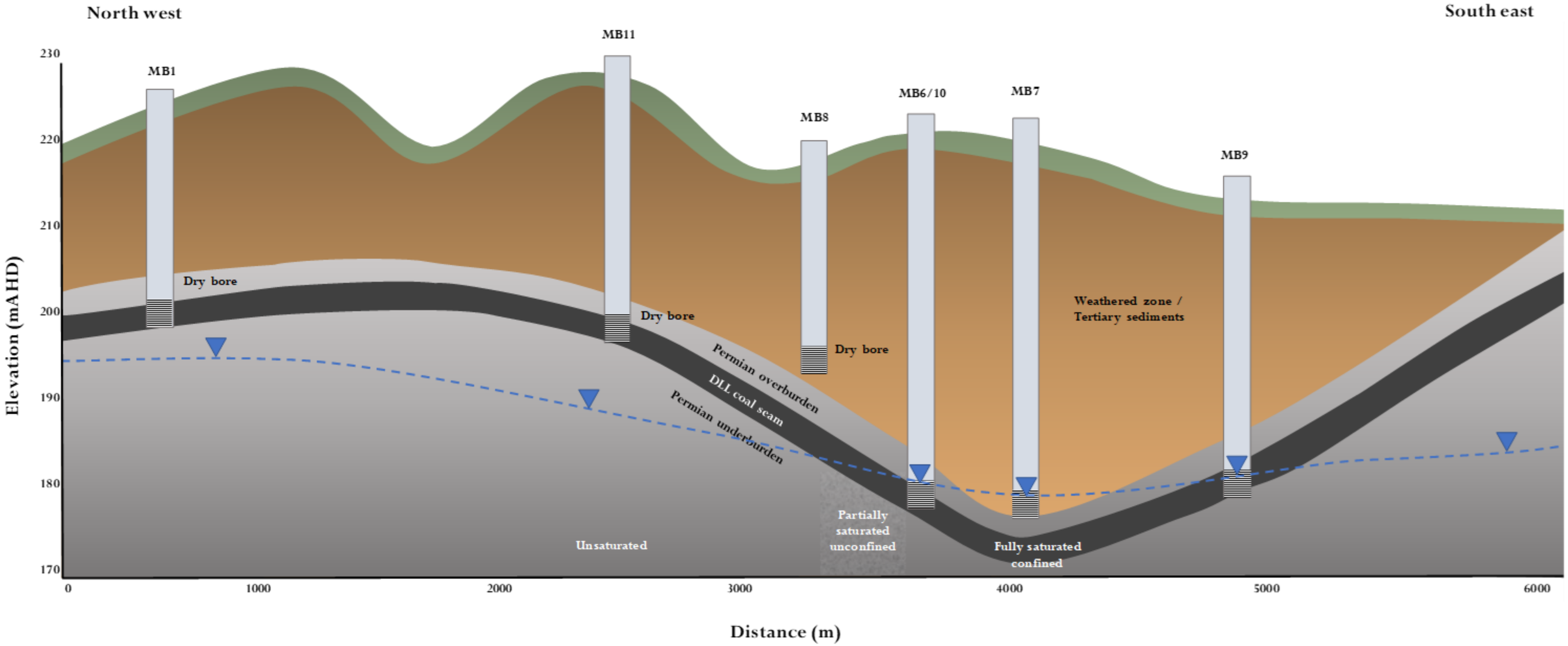


Figure 5.4 Saturation extent of the Permian coal measures in the Project area (looking north-east)

5.5.4. Recharge and discharge rates

While the literature generally agrees on the recharge and discharge mechanisms, the rates of recharge and discharge vary significantly. AECOM (2016) used a preliminary recharge rate of 1.43 mm/yr for the Quaternary alluvium and 0.89 mm/yr for the rest of the model domain. URS (2012) and Arrow (2016) used a minimum of 1 mm/yr for Triassic/Permian strata and "*more for alluvium*" (Arrow Energy, 2016).

HydroSimulations (2018) used model calibrated recharge rates of 2.8 mm/yr to 5.1 mm/yr for the Quaternary alluvium, 0.15 mm/yr for Tertiary sediments and 0.06 mm/yr for outcropping Permian coal measures. These recharge rates are summarised in Table 5-7 together with indicative long-term average recharge/rainfall percentages.

Table 5-7 Estimates of recharge rates (mm/yr)

Reference	Quaternary alluvium	Tertiary sediments	Permian coal measures
AECOM (2016)	1.43 (0.2%)	0.89 (0.1%)	0.89 (0.1%)
URS (2012)	>1 (>0.1%)	1 (0.1%)	1 (0.1%)
HydroSimulations (2018)	2.8 – 5.1 (0.4% - 0.7%)	0.15 (0.02%)	0.06 (0.009%)

Note: Value in brackets is the percent of recharge assuming an annual rainfall of 660 mm/yr.

HydroSimulations (2018) also refer to recharge rates used in Arrow Energy's Bowen Gas Project and other nearby projects (not sighted during the preparation of this report). According to HydroSimulations (2018), recharge at Lake Vermont was simulated as the equivalent of 2% mean annual rainfall and at Isaac Plains it was simulated as 0.5% (mean annual rainfall) to alluvium and 0.25% (mean annual rainfall) elsewhere. For the Arrow Energy Bowen Gas Project, recharge to the Quaternary alluvium was simulated as 1 mm/yr to 3 mm/yr (low recharge scenario) or 9 mm/yr to 27 mm/yr (high recharge scenario). Recharge was simulated as 0.3 mm/yr or 3 mm/yr for Tertiary sediments, 0 mm/yr for the Rewan Group and 0.33 mm/yr to 3 mm/yr for outcropping Permian coal measures.

For discharge, URS (2012) and Arrow (2016) modelled the difference between potential and actual evapotranspiration with an extinction depth of 10 m in their respective numerical models. HydroSimulations (2018) applied maximum potential evaporation rates using actual evapotranspiration values with an average value (600 mm/yr) used as the transient calibration evapotranspiration rate. Extinction depths were set to 2 m below ground across the model domain.

5.5.5. Groundwater flow

Based on the literature reviewed in this report, and published groundwater contour maps, horizontal (lateral) regional groundwater flow is expected to follow the same patterns as topography and the surface water drainage from all hydrogeological units, although the resemblance to surface water drainage for the deeper confined units will be less pronounced than that for the shallow unconfined aquifer.

URS (2012) presented regional groundwater elevations (not reproduced in this report) for the Permian Blackwater Group. Average groundwater "levels" (i.e. elevations) were used to create the map, both from non-coal units and coal seams, hence both temporal and vertical changes (within the Blackwater Group) in groundwater elevation were disregarded. URS (2012) indicated, in general, flow from the west (north-west) to the east (south-east) mimicking the surface water drainage pattern. URS (2012) commented that groundwater flow may also be constrained by major N-S strike fault systems. The interpretation of **hydrogeologist.com.au** is that there may be an indication for such influence on groundwater flow, however, it is difficult to say with certainty at the scale provided.

Groundwater contours by AGE 2012a (a memorandum on predicted inflows and drawdown for the Saraji East Underground Mine) in AECOM (2016; Saraji Mine) indicate a generally west to east flow pattern, similar to the URS (2012; Bowen Gas Project) interpretation. The pre-mining groundwater contours are model generated, and the elevations are typically up to 20 m different to the regional contours presented by URS.

Figure 5.5 shows composite groundwater elevation contours, prepared by **hydrogeologist.com.au**. The groundwater elevation contours are based on 412 individual datapoints collated from the DRDMW GWDB, site specific monitoring bores and Project exploration drill holes and groundwater elevations summarised as part of neighbouring projects (AECOM, 2016). For each datapoint, the depth to groundwater measurements were considered and corrected to an elevation based on surveyed or reported elevations or derived from an STRM (one second) digital elevation model (DEM). Notwithstanding that, the contours represented in Figure 5.5 are a composite groundwater elevation map (groundwater elevations from different times and from various hydro-stratigraphic units), it clearly indicates groundwater flow to the east within the Project area. To the east of the Project area, the inferred direction of groundwater flow turns to the south-east and eventually follows the alignment of the Isaac River, in agreement with the findings of HydroSimulations (2018).

Based on the literature reviewed and presented in this report, horizontal (lateral) regional groundwater flow is expected to follow the same patterns as topography and the surface water drainage for all hydrogeological units, although the resemblance to surface water drainage for the deeper confined units will be less pronounced as for the shallow unconfined groundwater systems. Near the Project area, the statement above would suggest a west to east groundwater flow, and this is consistent with the data assessed.

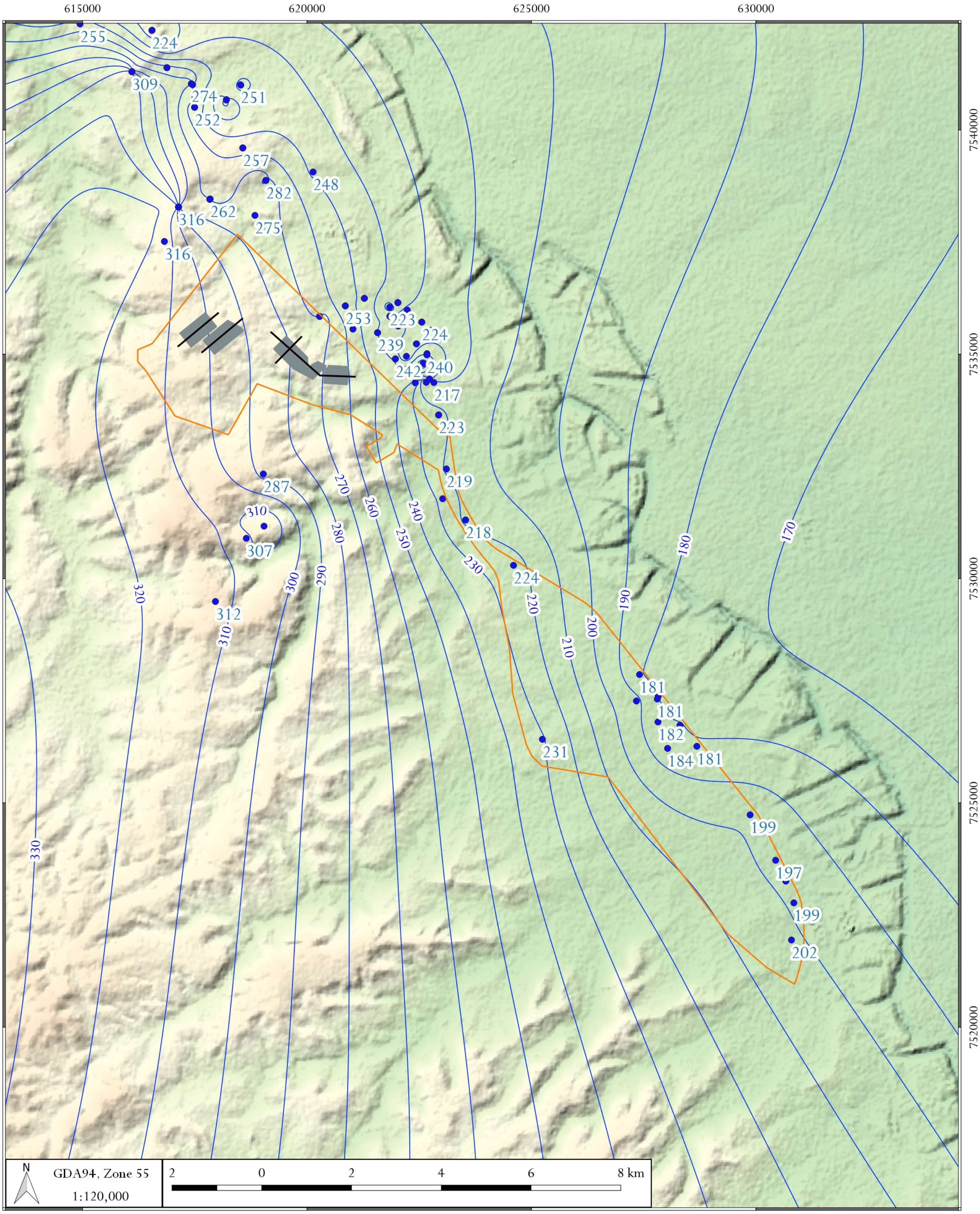
Vertically, the highest groundwater elevations were measured in the Quaternary and Tertiary units and upper Permian coal seams. Groundwater elevations also appear to decrease with the depth within the coal seams (URS, 2009 and AECOM, 2016). Vertical hydraulic gradients, where reported, are downward, suggesting potential downward leakage between the hydrogeological units (although HydroSimulations (2018) reported a single observation deep in the Permian where the vertical hydraulic gradient within the Permian coal measures reversed, coinciding with a decrease in hydraulic conductivity with depth). Groundwater elevations measured by AECOM (2016) in nested bores indicate downward hydraulic gradients in all measured bores between the Tertiary and Permian units and within the Permian units in all but one bore. These observations are consistent with those made by HydroSimulations (2018).

Highwall Mining Area

Within the Highwall Mining area the groundwater elevation contours are between 260 mAHD and 310 mAHD (Figure 5.5). Assessment of topographic data, the structure contours for the floor of the MAT coal seam and the groundwater elevation contours has been carried out to determine whether the highwall mining associated with the Project will intersect groundwater during operation.

A series of four cross-sections have been generated to demonstrate the relationship between the MAT seam floor and the groundwater contours (Figure 5.6). The cross-sections clearly demonstrate that the groundwater contours are typically greater than 10 m below the floor of the MAT coal seam in the Highwall Mining area. This has been confirmed by a number of coal exploration drill holes located within the Highwall Mining area that have been reported as dry during and after drilling.

On this basis it is assessed that the highwall mining proposed as part of the Project will not interact with groundwater. For impact assessment purposes the Highwall Mining area will no longer be discussed in this report.



LEGEND

Groundwater elevation contours (mAHD):

contours compiled by hydrogeologist.com.au

Groundwater elevation data point

Highwall mining area

Location of section (see Fig. 5.6)

Mining lease application area

DATE
22/02/2022

hydrogeologist.com.au

Vulcan South - Groundwater Impact Assessment (4027)

Groundwater elevation contours

FIGURE No.
5.5

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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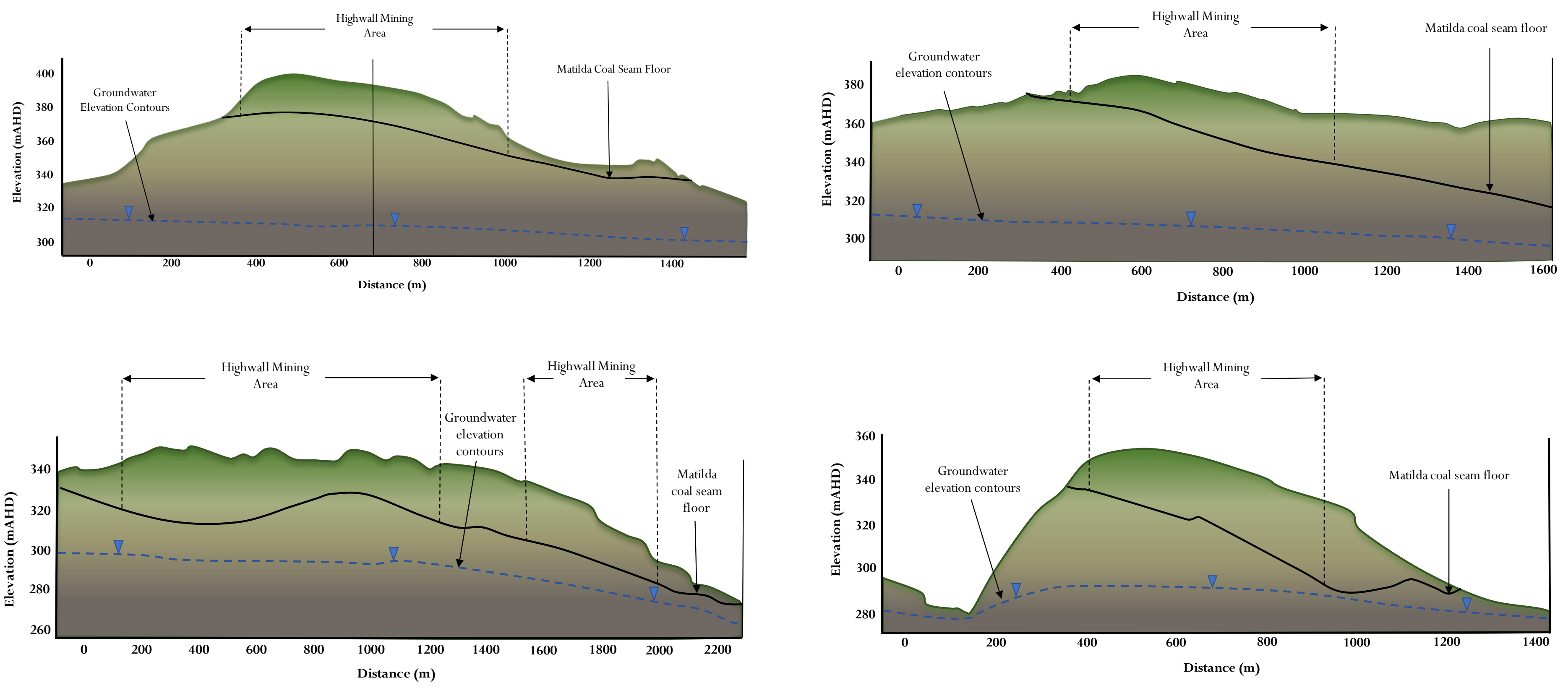


Figure 5.6 Highwall Mining area cross-sections

Effect of mining

AECOM (2016) noted that:

"Groundwater levels in the alluvium (MB2), Tertiary (PZ02A and PZ04A) and Permian (MB31, MB33 to MB37) strata, measured over time, do not indicate any impacts of mine dewatering even though coal mining at Saraji Mine has been undertaken since 1974". The monitoring bores referred to above are located between 600 m (MB2) and 1,500 m (MB33 and MB34) of the existing Saraji Mine open cut pits. The monitoring data would indicate that the zone of influence (or interference) is restricted to an area immediately adjacent to the open cut pit. This is likely due to low permeability of the mined strata and Permian overburden. AECOM (2016) therefore considered that the long term mine activities do not markedly impact on regional groundwater resources.

hydrogeologist.com.au concurs with this interpretation. The low hydraulic conductivity / transmissivity for most units, combined with low storage, would result in mine interference zones limited in lateral extent, except in areas where secondary porosity (fractures) opened extensive preferential pathways in the coal seams.

Structural control

CSIRO (2002) presents the distribution of faults, dykes and sills within the Project area and this is reproduced as Figure 5.7. In Figure 5.7 red lines represent thrust faults with > 3m throw, blue lines indicate normal fault with 1 m to 3 m throw, and turquoise lines show normal faults with > 3 m throw; purple rectangles signify inferred basement structures. The approximate location of the Project area is indicated on the figure to show the location relative to the Jellinbah Thrust Fault Zone and the structures mapped at Saraji Mine and Peak Downs Mine. The proposed open pits may be influenced to some degree by local structure mapped at the adjacent Saraji Mine.

The main geological structure in the region is the Jellinbah Thrust Fault Zone. The Jellinbah Thrust Fault Zone is highly faulted with several easterly dipping thrust faults. It is a north-west trending zone of thrust faults with throws in the order of 100 m to 500 m (URS, 2012). The Olive Downs Coal Project (HydroSimulations, 2018) is located within the Jellinbah Thrust Fault Zone and discusses several regional fault structures with a dominant north-north-west trend, including the Iffley Fault Zone (up to 100 m displacement). On the western side of the Olive Downs Coal Project is the Isaac Thrust Fault, which has up to 500 m vertical displacement.

The Jellinbah Thrust Fault Zone is truncated by the Tertiary unconformity, with little to no fault activity during the Cainozoic (CSIRO, 2002 and HydroSimulations, 2018). Faulting can result in higher permeabilities within strata parallel with the fault plane, and lower permeabilities within strata perpendicular to the fault plane. However; this can be dependent on whether faults are currently active or not. Faulting has been inactive within the Bowen Basin for over 140 million years, indicating that the fault zones are less likely to act as conduits to flow (HydroSimulations, 2018). This relates to filling of the fractured pore spaces over time through hydrothermal alteration and mineralisation. Drill core logs from the Olive Downs Coal Project show that where fractures and faults have been geologically logged, many fractures are "healed" with calcite and siderite. This indicates that, although the system is a fractured network, many of the existing fractures are cemented with the likely effect of reducing effective permeability when compared to any open fracture network.

The behaviour of faults was also assessed as part of the Bowen Gas Project using the movement of water and gas across a series of faults utilising stable isotope and water quality analyses. Higher gas production rates were observed on either side of a major fault, with differences in isotopic compositions of produced water for wells north and south of a major fault line at similar depths, implying little communication across the fault boundary, and suggesting that the fault acts as a barrier to water and gas flow. The results of the study showed that compartmentalisation was evident and that this was due to the structural geology (faulting) in the basin (HydroSimulations, 2018).

The Jellinbah Thrust Fault Zone occurs some 10 km to 15 km to the east of the proposed open pits and would be very unlikely to influence groundwater flow on a local scale. On a regional scale, however, the presence of the Jellinbah Thrust Fault Zone would act as a low permeability zone in the regional flow system of the Permian strata. The experience of **hydrogeologist.com.au**, with the Jellinbah Thrust Fault Zone, is that lateral groundwater flow within the fault zone is to the east (north-east). To the west of the fault zone, the presence of 'dense' groundwater head/elevation contours suggest a steep horizontal hydraulic gradient while to the east of fault zone the gradient is flatter, indicating that the fault zone is acting as an impediment, i.e. the hydraulic conductivity of the fault zone is lower than that of the host rocks.

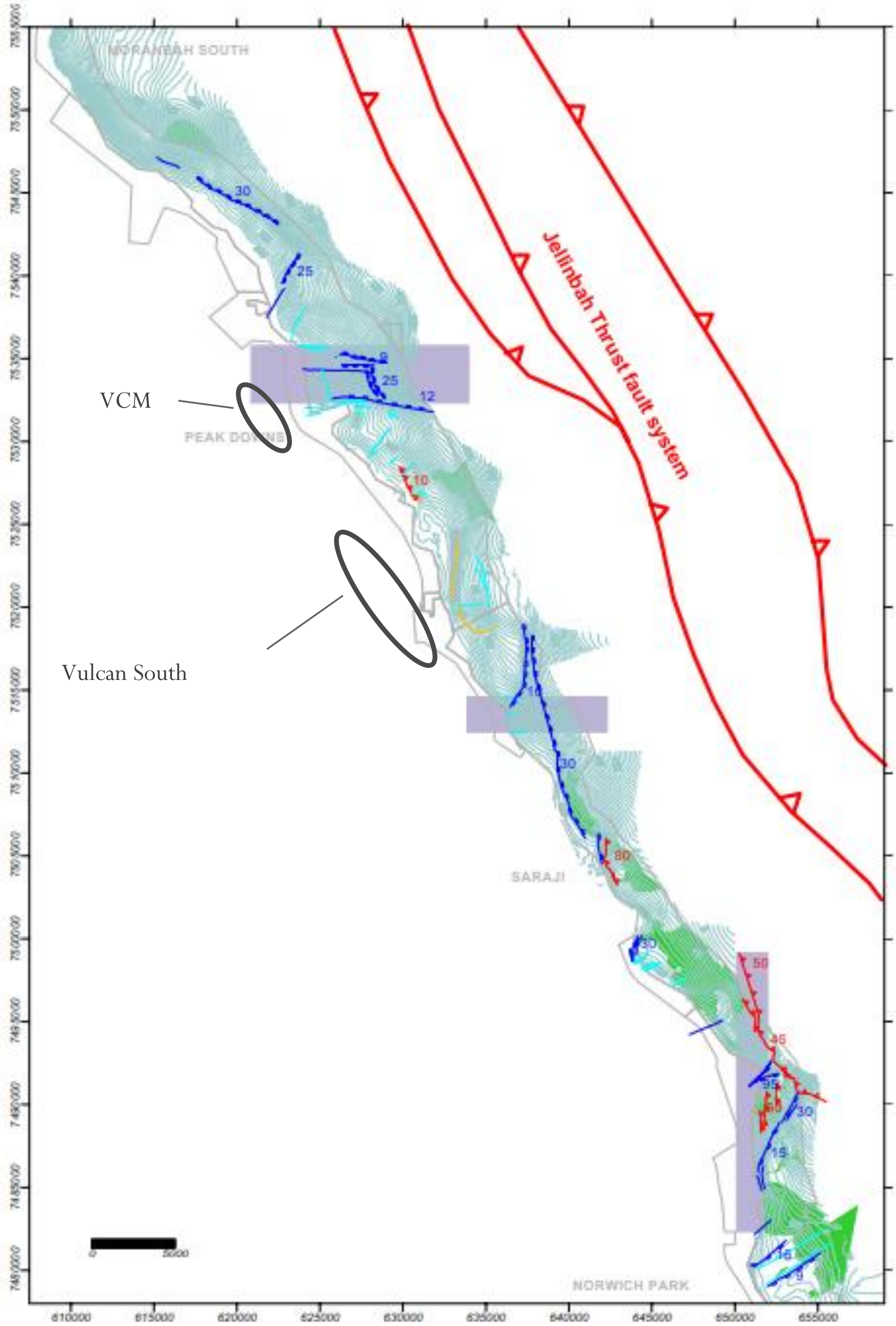


Figure 5.7 Faults with >1 m throw mapped in the Dysart seam of the Middle Tile, after CSIRO (2002)

5.6. Surface-groundwater interaction

Surface-groundwater interaction was investigated for the Olive Downs Coal Project (HydroSimulations, 2018), approximately 20 km to the north-east of the Project area. Despite the distance between the projects, the assessment appears to be directly transferable because the numerical groundwater model domain of HydroSimulations (2018) extends westward sufficiently enough to cover all important watercourses in the Project area.

In addition, HydroSimulations (2018) have:

- developed a conceptual hydrogeological model that is consistent with that presented in this report in Section 5.9;
- addressed surface water-groundwater interaction with the same or similar modelling tools used and described in Section 5.6;
- relied on a dataset almost identical to that available for this report because the most important stream gauging station, Phillips Creek at Tayglen (Figure 3.3) was closed in late 1988 (https://water-monitoring.information.qld.gov.au/, visited 21 August 2019); and
- the groundwater report and model of HydroSimulations (2018) appears to be the most recent and comprehensive groundwater assessment in the vicinity of the Project area.

Further, a careful evaluation of the differences between the Olive Downs Coal Project and the Project area suggests that surface and groundwater interact to a lesser degree at the Project area than at Olive Downs Coal Project:

- the Project area is to the west and at higher elevation than the Olive Downs Coal Project, resulting in generally deeper groundwater table and less flow in the watercourses than those at the Olive Downs Coal Project;
- the Quaternary alluvium of the Isaac River, through which most surface-groundwater interaction at the Olive Downs Coal Project occurs, is absent in the Project area; and
- the importance of the Isaac River (and its associated alluvium) on the groundwater regime of the Project area is significantly less, not just because of the distance, but because of the Jellinbah Thrust Fault Zone which is situated in between the Isaac River and the Project area, compartmentalising groundwater flow in the Permian strata.

The mechanism of recharge from surface water systems in the Project area is presented in Section 5.5.1 (Figure 5.3). The schematic represents a surface water system or creek within the region with little to no Quaternary alluvium development along the creek. The ephemeral nature of the surface water systems means that the creeks are dry for the majority of time and if present, the Quaternary alluvium would be unsaturated. The groundwater table beneath the creeks occurs within either the Tertiary sediments or Permian coal measures at depth (greater than 10 m below ground level) and forms part of the regional groundwater table. There is a significant thickness (generally greater than 10 m) of unsaturated material beneath the creek and above the groundwater table. For the reasons stated above, it is assessed that there is no significant surface-groundwater interaction in the Project area.

5.7. Groundwater use

Groundwater users in the vicinity of the Project area include mining companies (industrial use), private users (livestock beef cattle watering) and, potentially, GDEs (springs, surface water, stygofauna, wetlands etc).

5.7.1. Third party users

Third party groundwater use has been assessed through two mechanisms:

- consideration of the registered bores within 5 km of the numerical flow model domain on the DRDMW GWDB; and
- discussion with private landholders within 5 km of the proposed open pits.

The Groundwater Database – Queensland (DRDMW GWDB) stores registered water bore data from private water bores and Queensland Government groundwater investigation and monitoring bores. Data includes bore location, water levels, construction details, strata log and water quality. As such the DRDMW GWDB is the most reliable source of desktop information on groundwater use for the Project area.

Records within a 5 km distance of the numerical model domain (Section 6.1) extent were selected for subsequent analysis. Of the 83 DRDMW GWDB records within 5 km of the numerical flow model domain the following can be concluded:

- 65 (78%) are existing;
- 11 (13%) are abandoned and destroyed; and
- 7 (8%) are abandoned but still useable.

There are 69 records classifying bore use or purpose within 5 km of the numerical flow model domain. These records suggest that the overwhelming use of bores is for mining:

- 51 (74%) are for monitoring (41 for mine, 5 for petroleum or gas and 5 for sub-artesian monitoring);
- 14 (20%) are for water supply (these may be for mine supply or private supply as water supply is used as a broad term); and
- 4 (6%) are for investigation (stratigraphic, exploration or water resources investigation).

It is the experience of **hydrogeologist.com.au** that the name of a bore may also reveal its purpose, i.e. bore names containing long numbers, company abbreviations or sequences such as “MB” or “INV” or “PIEZO” are for monitoring or investigation while private bores are named after the farm or the owner. Of the 62 records with names available, 52 (84%) appear to be for the purpose of mine investigation and monitoring.

Groundwater quality is an important consideration for groundwater use because high salinity will generally preclude or limit certain uses. For this reason, groundwater salinity data was also analysed. For the 5 km vicinity of the numerical flow model domain, most of the groundwater salinity information in DRDMW GWDB is provided as field electrical conductivity (EC). Using the classification of Mayer *et al*. (2005) that is provided in Table 5-8, the 153 field EC records could be summarised as:

- none are fresh;
- one is marginal;
- 29 are brackish;
- 91 are saline; and
- 32 are highly saline.

The above statistics on field EC may somewhat be biased towards bores that are represented by several results (at different dates). The interpretation of **hydrogeologist.com.au** is that most bores in the vicinity of the Project area are for monitoring and investigation purposes (mostly for mining) and only a small fraction may be used for private groundwater use, probably for limited stock watering because of the high salinity of the groundwater.

The registered bores on the DRDMW GWDB are shown in Figure 5.1. It is clear that most registered bores are to the east and south-east and there are very few surrounding registered bores within close proximity of the Project. A private landholder bore (RN162506) is situated 300 m to the east of the Highwall Mining Area, the next closest private landholder bore is RN8606 which is located 3,000 m to the west of the Highwall Mining Area.

RN13040283, a Queensland government monitoring bore is located immediately to the east of the Vulcan main pit. The cluster of bores shown immediately to the east of the Vulcan main pit and Vulcan south pit have been drilled by BMA for the purposes of investigating and monitoring local water infrastructure.

Discussions have been held with the owners of the following property descriptions and Vitrinite to understand whether there are any groundwater bores on the property that may not be registered on the DRDMW GWDB:

- Lot 10 SP208611;
- Lot 2 SP296877;
- Lot 59 SP235297;
- Lot 7 CNS144;
- Lot 11 CNS394;
- Lot 14 CNS382; and
- Lot 9 SP235297.

The outcomes of the discussions indicate that there are no other groundwater supply bores in the Project area that are used by the local landholders. Potential impacts to third party groundwater users are discussed in Section 7.

5.7.2. Groundwater dependent ecosystems

A GDE is an ecosystem that requires access to groundwater on a permanent or intermittent basis to meet all, or some of its water requirements. For GDEs such as springs, wetlands, rivers and vegetation, groundwater plays an important role in sustaining aquatic and terrestrial ecosystems. A GDE therefore is a plant and/or animal community that is dependent on the availability of groundwater to maintain its structure and function.

The GDE Atlas (GDE Atlas, Bureau of Meteorology, 2016) was developed as a national dataset of Australian GDEs to inform groundwater planning and management. It is the first and only national inventory of GDEs in Australia. The GDE Atlas web-based mapping application allows the visualisation, analysis and downloading of GDE information for an area of interest (http://www.bom.gov.au/water/groundwater/gde/, visited 21 August 2019).

The GDE Atlas classifies ecosystems based on the potential for dependence on groundwater. Classification is based on multiple lines of scientific evidence, with categories for high, moderate, or low potential, allocated as follows:

- high potential for groundwater interaction (indicating a strong possibility the ecosystem is interacting with groundwater);
- moderate potential for groundwater interaction; or
- low potential for groundwater interaction (indicating it is relatively unlikely the ecosystem will be interacting with groundwater).

BOM (2018) maps areas for both aquatic and terrestrial GDE's and indicates that the following are mapped in the vicinity of the Project area:

- Aquatic GDEs rely on the surface expression of groundwater, including surface water ecosystems which may have a groundwater component such as rivers, wetlands, and springs. Aquatic GDEs associated with a number of separate water bodies along the Moranbah – Dysart Road, between Phillips Creek and Boomerang Creek and close to the Project area, are mapped as having a low, moderate or high potential to be associated with the surface expression of groundwater (Figure 5.8). These features all appear to be manmade impoundments associated with Saraji Mine or pastoral properties. Hughes Creek is mapped as having a moderate potential to be associated with the surface expression of groundwater.
- Terrestrial ecosystems rely on the subsurface presence of groundwater. This includes all vegetation ecosystems. Terrestrial GDEs to the west of Moranbah – Dysart Road are generally mapped as having a low to moderate potential to be dependent on the subsurface expression of groundwater (Figure 5.9). No subterranean GDEs (cave and aquifer ecosystems) have been identified by BOM, 2018 in the vicinity of the Project.

The depth to groundwater table map in Figure 5.10 was produced by subtracting the groundwater elevation grid (compiled and generated from publicly available information – see Figure 5.5) from the ground surface (SRTM data used for the regional area and LIDAR used for the local Project area) grid.

Figure 5.10 indicates that groundwater is generally between 5 m and 40 m deep in the area surrounding the proposed pits. The nearest areas with depth to groundwater less than 5 m (orange colours) are to the west and south of the Vulcan south pit. The area of shallow depth to groundwater to the west of the Vulcan south pit correlates with a moderate potential aquatic GDE associated with Hughes Creek (as presented in Figure 5.8).

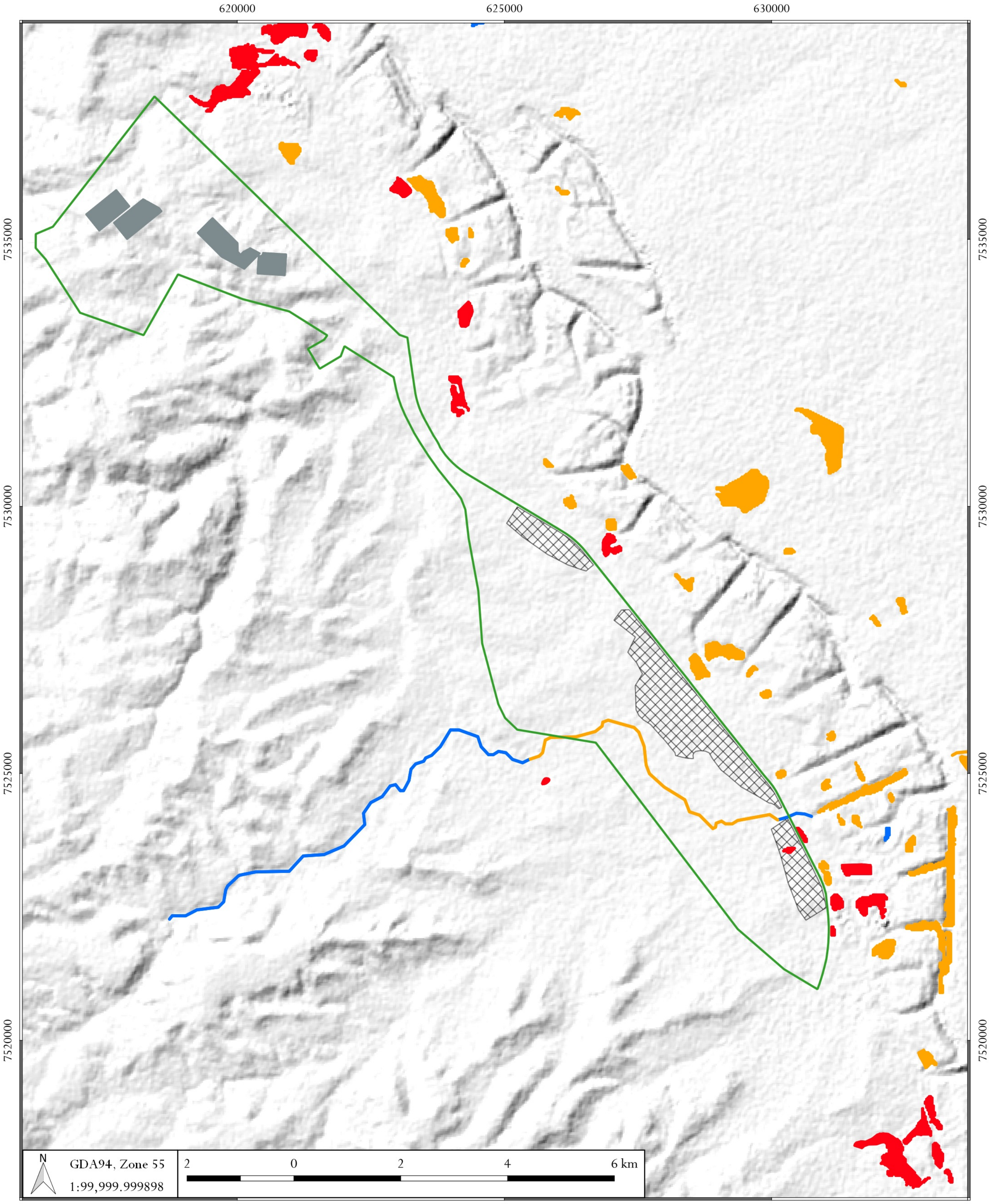
Aquatic GDEs with high or moderate potential for groundwater interaction are most likely to occur in areas where the seasonally high groundwater potentiometric heads are above or close to the corresponding surface water heads. This is necessary to maintain a hydraulic gradient from the groundwater to surface water, or at least have a hydraulically 'connected' system. In addition, groundwater in the Project area is brackish to saline and therefore unsuitable for the maintenance of freshwater GDEs (see Section 5.8 for further information on groundwater quality). It is the interpretation of **hydrogeologist.com.au** that it is highly unlikely for aquatic GDEs to be present within 1 km of the proposed pits.

In the experience of **hydrogeologist.com.au**, terrestrial GDEs with high or moderate potential for groundwater interaction are most likely to occur in areas where depth to groundwater is less than 10 m (i.e. the groundwater table is shallow, including alluvial deposits) and likely to be outside of the accessible reach of Eucalypt vegetation (Zolfaghar *et al*. 2014 in AECOM, (2016). There is an area of mapped terrestrial GDEs associated with Hughes Creek which is located within an area where the depth to groundwater is less than 10 m.

The reader is directed to the Vulcan South – Ecological Impact Assessment (METServe, 2022) report for further information regarding the presence of aquatic or terrestrial GDEs. Section 6.5 of this report discusses aquatic and terrestrial GDEs in relation to predicted groundwater impacts.

In addition, the Queensland Government maintains an inventory of identified springs in the Queensland Springs Database (https://data.qld.gov.au/dataset/springs/resource/4cdc89ef-b583-446e-a5c7-0836a91a3767, visited 21 August 2019) that can also be reviewed through QLD globe (https://qldglobe.information.qld.gov.au/). No springs have been identified in the vicinity of the Project area; with the nearest spring being situated at a distance greater than 100 km to the west.

A search of the EPBC Act 'Protected Matters Report' (http://www.environment.gov.au/epbc/pmst/index.html, visited 21 August 2019) found that there are no internationally or nationally important wetlands within 50 km of the Project area. Lake Elphinstone is the closest nationally important wetland, located approximately 100 km north of the Project area.



LEGEND

Aquatic groundwater dependent ecosystem:

- High potential GDE - from national assessment
- High potential GDE - from regional studies
- Moderate potential GDE - from national assessment
- Low potential GDE - from national assessment

- Proposed pit
- Highwall mining area
- Mining lease application area

DATE
22/02/2022

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Vulcan South - Groundwater Impact Assessment (4027)

Aquatic groundwater dependent ecosystems

FIGURE No.
5.8

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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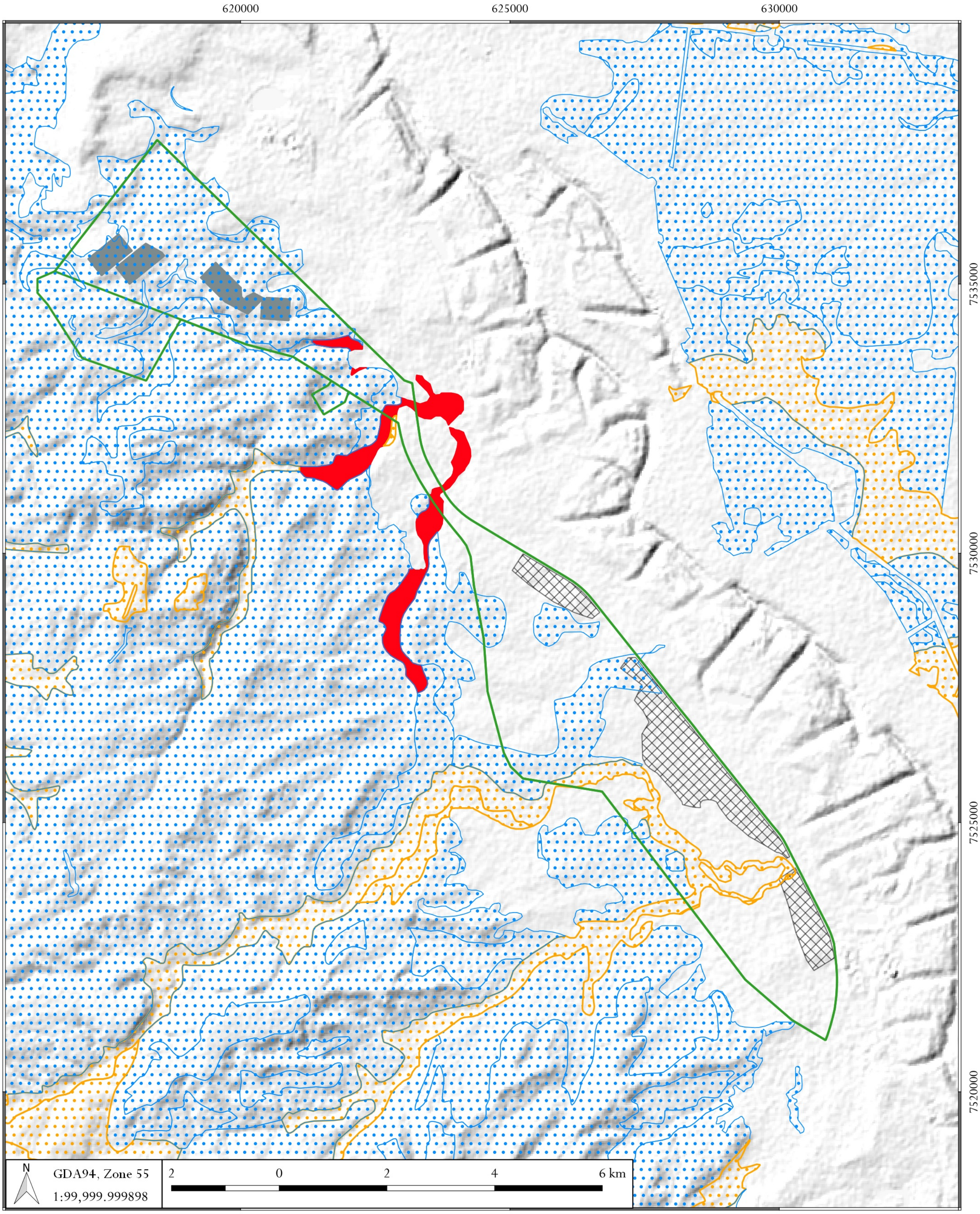

LEGEND

Terrestrial groundwater dependent ecosystem:

- High potential GDE - from national assessment
- Moderate potential GDE - from national assessment
- Moderate potential GDE - from regional studies
- Low potential GDE - from national assessment
- Proposed pit
- Highwall mining area
- Mining lease application area

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Vulcan South - Groundwater Impact Assessment (4027)

Terrestrial groundwater dependent ecosystems

FIGURE No.
5.9

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
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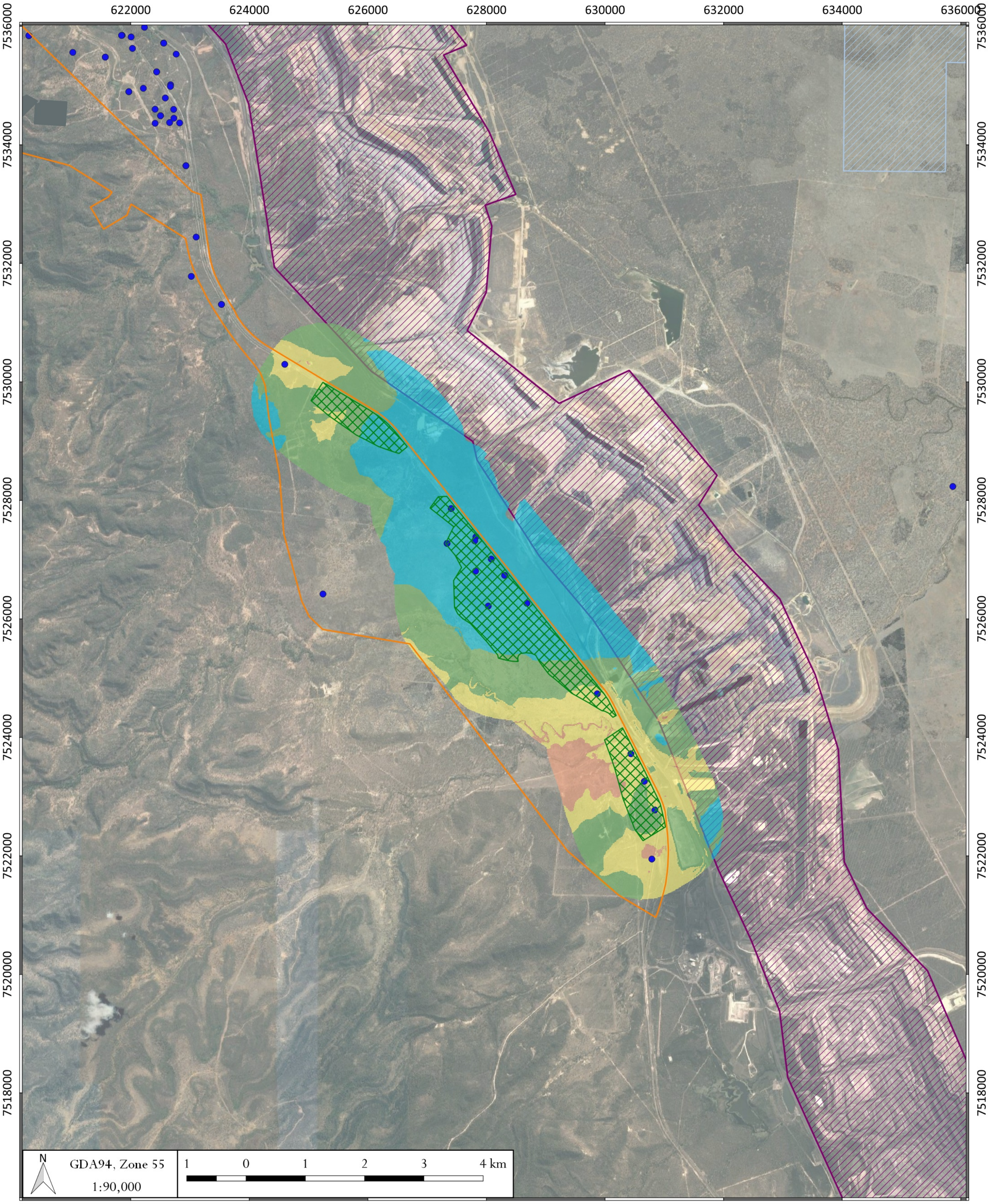

LEGEND

Depth to groundwater (m)

- <= 0
- 0 - 5
- 5 - 10
- 10 - 20
- 20 - 50

- Groundwater elevation data point
- Proposed pit
- Highwall mining area
- Mining lease application area
- Established mining operation

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22/02/2022

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Vulcan South - Groundwater Impact Assessment (4027)

Depth to groundwater

FIGURE No.
5.10

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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5.8. Groundwater quality

5.8.1. Site specific data

At the time of completing this report, fifteen rounds of analytical laboratory and field results were available from the groundwater monitoring network (see Section 5.3 and Table 5-3). The monitoring and sampling of the groundwater monitoring network is planned for and carried out in consideration of the Queensland Monitoring and Sampling Manual (DES, 2018a).

Groundwater salinity was classified by **hydrogeologist.com.au** (2019) using a system based on local experience. In this report, however, the classification of Mayer *et al*. (2005, http://www.water.wa.gov.au/water-topics/water-quality/managing-water-quality/understanding-salinity, visited on 11 March 2022) will be used because it is more widely used and contains more categories, especially a 'marginal' category between fresh- and brackish water (Table 5-8).

Table 5-8 Groundwater salinity classification based on Mayer *et al*. (2005)

Salinity status	EC* (µS/cm)	Description and use
Fresh	<750	Drinking and all irrigation
Marginal	750 – 1,500	Most irrigation, adverse effects on ecosystems become apparent
Brackish	1,500 – 3,000	Irrigation certain crops only; useful for most stock
Saline	3,000 – 15,000	Useful for most livestock
Highly saline	15,000–52,000	Very saline groundwater, limited use for certain livestock
Brine	>52,000	Seawater; some mining and industrial uses exist

*Note: *converted from total dissolved solids (TDS in mg/L) using a conversion factor of 0.67; rounded values*

The field EC and pH are summarised in Table 5-9 and Table 5-10. None of the samples are assessed as fresh or marginal, with all samples returning a field EC above 2,600 µS/cm and some above 20,000 µS/cm (MB12). Using the classification of Mayer *et al*. (2005), groundwater from the Project area is brackish (MB05); to saline (MB04, MB07, MB09, MB10 and MB13) to highly saline (MB12).

Some of the monitoring bores show variable water quality but this is likely the result of the groundwater still being influenced by drilling and construction during early sampling. For example, it is anticipated that initial sample results for MB04 and MB09 were not representative and these initial samples may have been impacted by the grouting process (fresh mix water with alkalinity from the cement) explaining the increase in salinity and decrease in pH since the first round of monitoring.

Table 5-9 Historical summary of field electrical conductivity (µS/cm)

Bore ID	Area	Jun 2019	Jul 2019	Aug 2019	Sep 2019	Oct 2019	Dec 2019	Mar 2020	Jun 2020	Aug 2020	Oct 2020	Dec 2020	Mar 2021	May 2021	Jul 2021	Sep 2021	Salinity status*
MB04	VCM	~~2,520~~	9,510	9,346	10,409	10,703	11,709	12,913	12,734	12,782	12,752	12,048	11,122	10,904	12,592	10,901	Saline
MB05	VCM	2,960	3,042	2,737	2,753	2,739	2,719	2,720	2,720#	2,840	2,757	2,754	2,651	2,858	2,712	2,625	Brackish to saline
MB07	Project	5,680	6,091	5,739	5,819	5,882	5,830	-	5,184	5,141	5,383	5,393	5,358	5,196	5,307	5,412	Saline
MB09	Project	~~5,520~~	13,758	15,130	13,909	13,566	11,582	12,117	11,989	11,933	11,909	11,845	11,735	11,506	12,064	11,403	Saline to highly saline
MB10	Project	-	5,668	4,846	4,322	4,353	4,034	4,170	4,121	4,028	3,980	3,876	3,881	3,818	3,806	3,762	Saline
MB12	Project	22,800	19,469	17,854	17,231	20,878	16,725	15,644	22,200#	22,444	22,178	22,840	22,533	21,998	21,953	21,470	Highly saline
MB13	VCM	-	-	-	-	-	-	-	-	-	-	-	4,110	4,021	4,084	3,970	Saline

Notes: * *from the classification of Mayer et al. (2005) and excluding the initial June samples for MB04 and MB09*

laboratory data substituted for field data

Table 5-10 Historical summary of field pH

Bore ID	Area	Jun 2019	Jul 2019	Aug 2019	Sep 2019	Oct 2019	Dec 2019	Mar 2020	Jun 2020	Aug 2020	Oct 2020	Dec 2020	Mar 2021	May 2021	Jul 2021	Sep 2021
MB04	VCM	~~7.92~~	5.93	5.90	5.79	5.84	5.73	5.54	5.75	5.57	5.66	5.53	6.04	6.31	6.29	5.84
MB05	VCM	8.55	7.00	7.02	6.92	6.94	6.89	6.96	7.49#	6.84	6.90	6.67	7.21	7.63	7.44	6.92
MB07	Project	8.78	7.04	7.00	6.75	6.93	6.78	-	6.74	6.72	6.91	6.86	7.08	7.23	7.42	6.94
MB09	Project	~~8.58~~	6.90	7.00	6.90	6.87	6.93	7.08	6.78	6.64	6.72	6.71	7.26	7.21	7.51	6.96
MB10	Project	-	6.78	6.94	6.88	6.97	6.81	7.03	6.89	6.86	6.91	6.89	7.20	7.29	7.43	7.07
MB12	Project	8.29	6.86	6.79	6.66	6.57	6.62	6.78	7.08#	6.38	6.37	6.57	7.08	6.96	7.01	6.61
MB13	VCM	-	-	-	-	-	-	-	-	-	-	-	7.04	6.97	6.99	6.69

The Durov diagram (Figure 5.11) is best considered as a series of joint diagrams with the right side of Figure 5.11 being a scattergraph of sodium (as a percentage of all cations) vs TDS. The bottom diagram is a scatter of chloride (as a percentage of all anions) vs pH. The innermost square is the projection of the two scatters, i.e. it shows sodium (as a percentage of all cations) vs. chloride (as a percentage of all anions). The two ternary diagrams are for anion percentages (top) and cation percentages (left).

Figure 5.11 indicates that most of the site's groundwater is strongly dominated by sodium (Na) and moderate to strongly dominated by chloride (Cl). All the site-specific groundwater would fall into the sodic waters of marine origin category of Raymond and McNeil (2011). Chloride, as a percentage of anions, varies between 40% and nearly 100%; however, some samples (MB05, MB07, MB10 and MB13) indicate the presence of moderate bicarbonate (HCO_3). There does not appear to be a simple relationship between the hydro-stratigraphic unit and groundwater quality. For example, the markers for MB05, the deepest sampled coal seam (MAT), are indicating the lowest salinity and chloride percentage, contrary to the general observations made by URS (2012) and Arrow Energy (2016) indicating increase in salinity with increasing depth. There are three bores (MB04, MB09 and MB10) targeting the DLL seam, and as Figure 5.11 indicates, the markers for these bores are widely spread.

The Piper diagram in Figure 5.12 shows the major cation percentages on the left and the anion percentages on the right, the observations from the ternary diagram are next projected to the top rhomboid. The rhomboid indicates that all groundwater is of sodium-potassium (Na_K> 50%) and sulphate-chloride (SO_4-Cl (>50%) type. The ternary diagrams provide further breakdown, i.e. that the groundwater is dominated by sodium-potassium cations combined with mostly chloride as the dominant anion; although the MB05 samples contain 30-40% bicarbonate (HCO_3).

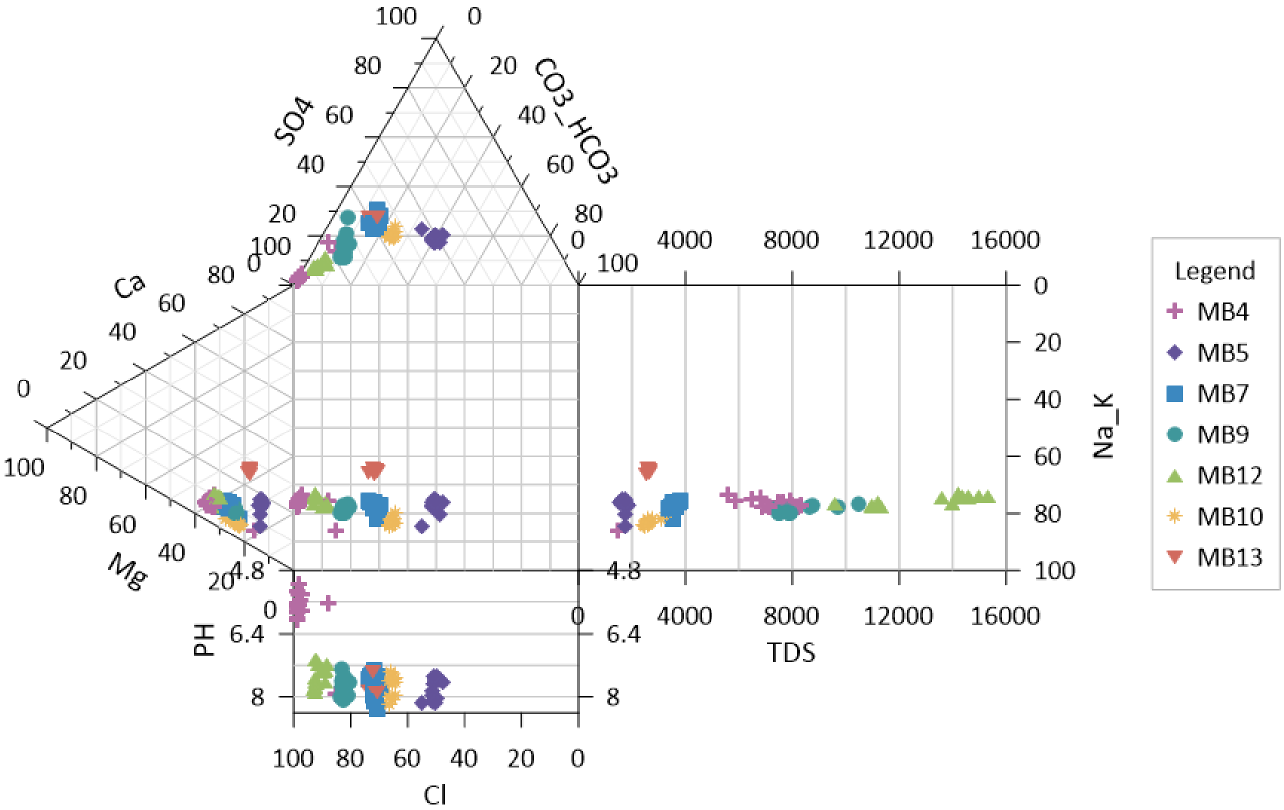


Figure 5.11 Extended Durov diagram for site specific monitoring bores

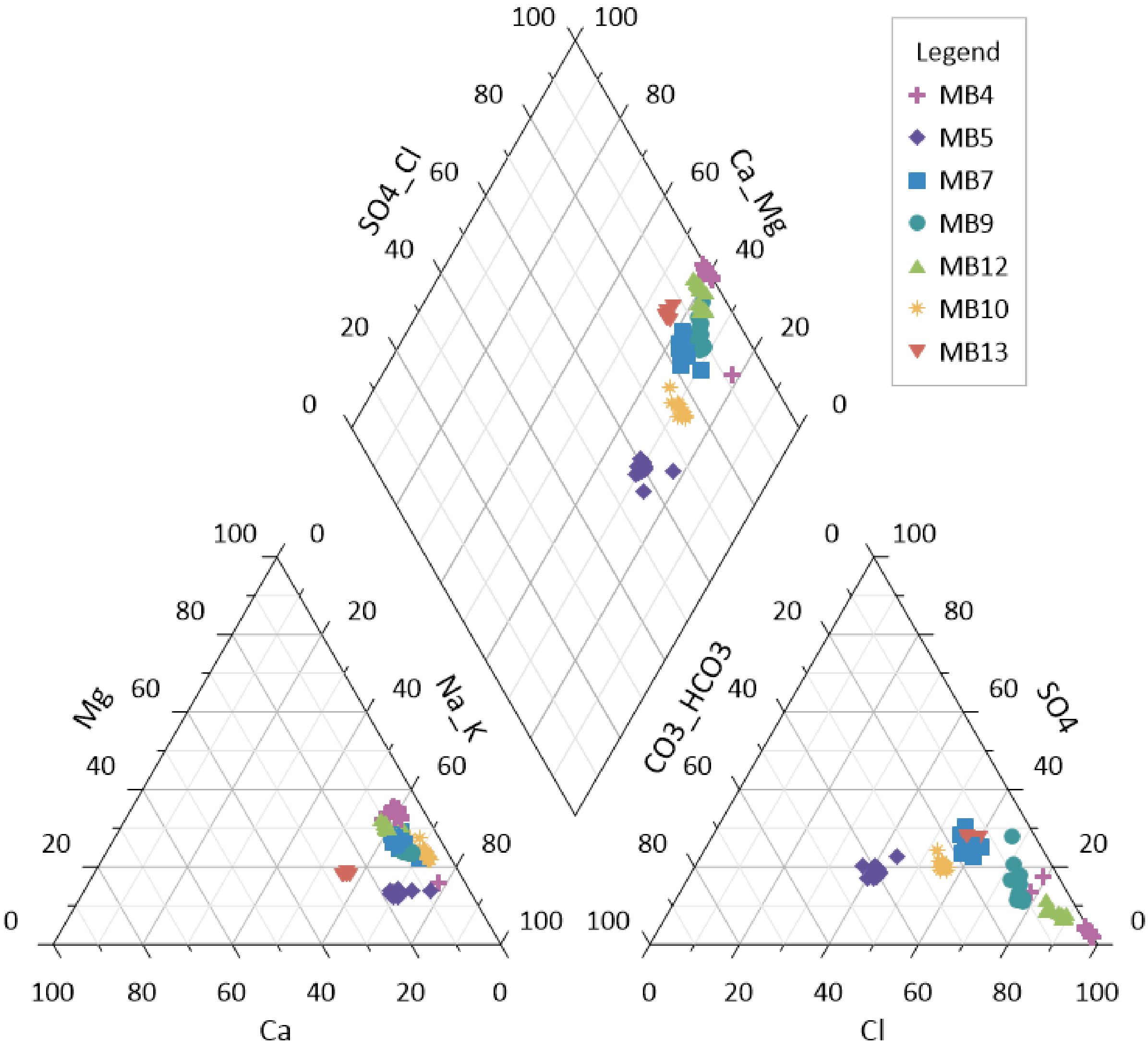


Figure 5.12 Piper diagram for site specific monitoring bores

5.8.2. Regional data

Regional data is presented here for various mining and energy projects and locations. The classification of salinity is adopted from the relevant publication and therefore may somewhat differ from that of Mayer *et al*. (2005); however, it has not significantly influenced the findings presented below.

URS, 2009 (Caval Ridge Mine)

Groundwater chemistry is typically of near-neutral pH for all formations near the Caval Ridge Mine (URS, 2009). The alluvium groundwater is fresh to brackish while the coal seam (and basalt formation) groundwater is brackish to saline. The laboratory analytical results indicate that sodium is the dominant cation in the groundwater from all monitoring bores but one in the alluvium that is calcium dominant. The dominant anion is chloride in most monitoring bores in the coal measures although the dominant anion is bicarbonate in some coal measures, basalt and alluvium bores (URS, 2009).

AECOM, 2016 (Saraji Mine)

At Saraji Mine, all groundwater analysed was sodium-chloride type with brackish water in the Quaternary, and brackish to saline water in the Tertiary and Permian coal measures. Salinity is generally the highest in the Permian and lowest in the Quaternary. None of the groundwater analysed was suitable for drinking, with the regional (Tertiary and Permian) groundwater generally not considered suitable for livestock (AECOM, 2016).

HydroSimulations, 2018 (Olive Downs Coal Project)

Alluvium groundwater is dominated by sodium-calcium (Na-Ca) or sodium-magnesium (Na-Mg) cations and is higher in bicarbonate than the other groundwater units. The proportion of chloride is higher within the regolith material, which can be classified as sodium-chloride or sulphate ($Na\text{-}Cl\text{-}SO_4$) or sodium-chloride or bicarbonate ($Na\text{-}Cl\text{-}HCO_3$) type water. The Permian coal measures generally contain sodium-chloride (Na-Cl) type water, with some also recording a high proportion of Mg but with very little sulphate compared to the other groundwater units (HydroSimulations, 2018).

Water within the Isaac River is largely fresh, while water within the alluvium is fresh to moderately saline with a range between 300 µS/cm and 5,200 µS/cm. Water within the regolith material is brackish to highly saline with a range between 2,200 µS/cm and 28,400 µS/cm. Water within the Permian coal measures can range between fresh and highly saline, but is generally saline within the coal seams, and brackish to moderately saline within the interburden units (HydroSimulations, 2018). Coal seam units of the Permian coal measures record an average EC of 11,040 µS/cm, ranging between 3,800 µS/cm and 22,000 µS/cm. The interburden units of the Permian coal measures record an average EC of 7,080 µS/cm, ranging between 630 µS/cm and 27,500 µS/cm (HydroSimulations, 2018).

In addition, salinity within the Isaac River and alluvium can be highly variable, both spatially and temporally. HydroSimulations (2018) provides examples where the river and groundwater salinity for the same sites vary in time between fresh through brackish to moderately saline waters.

URS, 2012 and Arrow Energy, 2016 (Bowen Gas project)

Arrow Energy (2016) has monitored groundwater quality since 2012 and concluded that groundwater quality:

- varies from brackish to saline in the Quaternary alluvium;
- varies from brackish to saline in the Tertiary basalt aquifer;
- is fresh to brackish in the Tertiary sediments;
- is brackish in the weathered coal measures;
- is fresh to brackish in the Fort Cooper Coal Measures; and
- is fresh to brackish in the Moranbah Coal Measures.

The description above appears to be based on URS (2012), which in turn, is based on groundwater quality studies by Pearce and Hansen (2006), Raymond and McNeil (2011) and site-specific data. Pearce and Hansen (2006) provided an overview of groundwater quality in the Isaac-Connors (and McKenzie) sub-catchments for pH and salinity.

Raymond and McNeil (2011), in URS (2012) interpreted groundwater in the Fitzroy catchment to two different types including:

- alluvial sequence with mostly rainfall related ionic composition, found near creeks and areas of relatively high rainfall; and
- sodic sequence, near marine origin and ionic composition; deep groundwater in low rainfall areas.

5.8.3. Environmental values

As described in Section 2.1.1, the Isaac River Sub-basin Environmental Values and Water Quality Objectives (Department of Environment and Heritage Protection, 2011) is made pursuant to the provisions of the EPP Water, which is subordinate legislation under the EP Act. The EPP Water provides a framework for identifying EVs for Queensland waters, and deciding the WQO to protect or enhance those EV. The Isaac River Sub-basin Environmental Values and Water Quality Objectives (Department of Environment and Heritage Protection, 2011) document contains EV (Section 2, Table 1) and WQO for waters (including groundwaters) in the Isaac River Sub-basin.

For Isaac groundwaters, the EV selected for protection are listed as follows:

- aquatic ecosystems;
- irrigation;
- farm supply/use;
- stock water;
- primary recreation;
- drinking water; and
- cultural and spiritual.

An assessment of groundwater quality is presented below, in terms of the relevant EV used in the Isaac River Sub-basin Environmental Values and Water Quality Objectives (Department of Environment and Heritage Protection, 2011). Although EV are not selected for protection of industrial use, this has also been included for completeness as mine water use is an important aspect given the number of coal mines operating in the catchment.

Aquatic ecosystems

The WQO, for aquatic ecosystems, where groundwaters interact with surface waters, is that groundwater quality should not compromise the identified EV and WQO for those waters. For example, Table 1 lists a WQO of <720 µS/cm for Upper Isaac River catchment waters. **hydrogeologist.com.au** interprets that groundwater that is identified to support the Upper Isaac River catchment surface waters should not exceed 720 µS/cm. None of the site monitoring bores reported such a low salinity; with all reporting field ECs > 2,700 µS/cm.

The deep groundwater (Section 5.3) in all bores with the exception of MB05, in addition to the brackish to highly saline groundwater quality and the absence of significant groundwater-surface water interaction in the Project area (Section 5.6) would render almost all the local groundwater unsuitable for use for GDEs because it is mostly out of reach (too deep for terrestrial flora) and its quality could not support fresh- or even marginal water ecosystems.

Farm Use / Irrigation

Table 3 of the Isaac River Sub-basin Environmental Values and Water Quality Objectives (Department of Environment and Heritage Protection, 2011) refers to the suitability for farm supply/use WQO as "*Objectives as per AWQG*". The AWQG (2018), however, bundles the guidelines, in Section 4.2, for irrigation and general water use. Hence, these EVs will be discussed together.

The objectives for pathogens and metals are provided in Tables 8 and 9 of the Isaac River Sub-basin Environmental Values and Water Quality Objectives (Department of Environment and Heritage Protection, 2011). For indicators other than pathogens and metals, the WQOs are those included in the AWQG (2018). For most pastures and loams and clays, the salinity threshold in Table 4.2.5 of the AWQG (2018) is between 1,000 μS/cm and 7,300 μS/cm.

In addition, the AWQG (2018) warns that certain combinations of salinity and sodium adsorption ratio (SAR) are likely to induce degradation of soil structure and corrective management may be required (e.g. application of lime or gypsum). Most groundwater on-site would be classified as "marginal quality" in Figure 4.2.2 of the AWQG (2018) (i.e. soil degradation may occur if the water was used for irrigation depending on soil and rainfall) and would therefore need caution if used for irrigation.

hydrogeologist.com.au interprets that the brackish to highly saline groundwater, and all the indications for low sustainable bore yields (low airlift rates, low hydraulic conductivities, and thin coal seams), preclude the potential use of the local groundwater for irrigation supply. In other words, neither the quantity nor the quality of local groundwater is suitable for irrigation.

Livestock watering

The review of DRDMW GWDB and the bore census data indicate that groundwater in the area may be used for limited livestock beef cattle watering. There are 14 records within 5 km of the numerical flow model domain that are classified as "*water supply*" (Section 5.7.1). Some of these may be used for mine supply and others for private farm supply that may or may not include livestock watering.

Information (Section 5.8.1) from local monitoring bores suggests that groundwater quality (salinity) varies from brackish to highly saline. Although some groundwater is within the guidelines for livestock watering, Section 4.3.3.5 of the AWQG (2018) states that loss of production and a decline in animal health occurs if stock is exposed to high salinity water for prolonged periods. For beef cattle, decline or loss may occur if the EC is between 7,463 μS/cm and 14,925 μS/cm.

Of the local groundwater, MB05, MB07, MB10 and MB13 have EC that is less than 7,463 μS/cm; MB04 and MB09 are between 7,463 μS/cm and 14,925 μS/cm. Groundwater at MB12 is greater than 14,925 μS/cm.

At the Saraji Mine, adjacent to the Project area, the regional (Tertiary and Permian) groundwater was generally not considered suitable for livestock (AECOM, 2016). **hydrogeologist.com.au** concurs with this interpretation but note that, although the local groundwater is generally not considered suitable for livestock, limited livestock watering may occur and therefore should be recognised as an EV because of the three monitoring bores that returned EC less than 7,463 μS/cm.

Primary recreation

This category of EV is considered not applicable to local groundwater. There are no groundwater springs in the Project area (Section 5.7.2) that could be considered for recreational use. This EV is more common for surface water features that are readily accessible for recreation.

Drinking water suitability

The site specific groundwater quality data, as presented in Section 5.8.1, indicates that groundwater is generally unsuitable for human consumption before treatment primarily due to elevated levels of salinity. The WQO in Table 4 of the Isaac River Sub-basin Environmental Values and Water Quality Objectives (2011) specifies an EC of 400 µS/cm as suitable for drinking quality and none of the site monitoring bores yield groundwater of such low EC; in fact, all reported field ECs are greater than 2,700 µS/cm and the median field EC for all local samples (Table 5-9) is 6,091 µS/cm, 15 times higher than specified by Isaac River Sub-basin Environmental Values and Water Quality Objectives (2011).

Further, Table 4 of the Isaac River Sub-basin Environmental Values and Water Quality Objectives (2011) also refers to a sodium objective of 30 mg/L and a total hardness objective of 150 mg/L as $CaCO_3$ in raw water. The local groundwater contains both sodium and total hardness well in excess of those: the minimum concentration of sodium in any of the groundwater samples to date is 389 mg/L, and the minimum concentration of total hardness is 242 mg/L.

Groundwater within the Project area is therefore not considered suitable for drinking because it would require significant treatment.

Cultural and spiritual values

There are no groundwater springs or seeps (Section 5.7.2) that supply surface water bodies in the Project area known to have significant indigenous and/or non-indigenous cultural heritage associations.

Industrial use

Table 3 of the Isaac River Sub-basin Environmental Values and Water Quality Objectives (Department of Environment and Heritage Protection, 2011) provides no defined WQOs for industrial uses:

"Water quality requirements for industry vary within and between industries. The AWQG do not provide guidelines to protect industries, and indicate that industrial water quality requirements need to be considered on a case-by-case basis. This EV is usually protected by other values, such as the aquatic ecosystem EV".

The nearest industries to the Project area are coal mines. **hydrogeologist.com.au** understands that Vitrinite may intend to use some of the groundwater inflow to the proposed pits, if available after evaporation, for industrial purposes. It is understood that the nearest mine, Saraji Mine does not utilise groundwater for its operations. No industrial users, other than mines, appear to be within close proximity of the Project area and the salinity of the groundwater would likely impede most industrial uses. The local brackish to highly saline groundwater, which may report to the proposed pits, however, can potentially be used for mining use such as dust suppression. It is the view of **hydrogeologist.com.au**, therefore, that the EV associated with industrial use should be recognised in this report.

Summary

In summary, the evaluation of groundwater EV in the Project area indicates that groundwater in the "deep" hydrogeological units, associated with the regolith and/or Permian coal measures is of no, or limited value, for most uses and may potentially have the following EVs:

- livestock beef cattle watering (limited); and
- industrial purposes, limited to dust suppression in mining.

5.8.4. Water quality objectives

The Project area is adjacent to the Isaac-Dawson groundwater quality zone (No. 34) of Raymond and McNeil (2011). Groundwater within Zone 34 is described as slightly to moderately saline ('shallow' groundwater, within 30 mbgl) or slightly to very saline ('deep' groundwater, deeper than 30 mbgl). Groundwater within Zone 34, both shallow and deep, is of sodium-chloride (Na-Cl) type; that is, sodium is the dominant cation and chloride is the dominant anion.

Using Raymond and McNeil's (2011) shallow (<30 m deep) and deep (>30 m) categories, only MB04 is shallow and all other Project monitoring bores are classified as deep. MB04 is screened in the DLL coal seam of the Moranbah Coal Measures.

While MB04, strictly speaking, is less than 30 m deep and would therefore classify as 'shallow' according to Raymond and McNeil (2011), its target, the DLL coal seam and its water quality type (sodic-marine similar to deep bores on-site) together suggest that it would be more prudent to list it among the 'deep' monitoring bores. As Figure 5.11 indicates, MB04 is a Na-Cl type water that blends well with the markers for the bores that are greater than 30 m deep, plotting close on the ternary diagrams, in particular, to MB12 representing Permian underburden.

The WQOs is to maintain or improve the quality of groundwater within the zone, i.e. maintain or reduce salinity. The percentile statistics provided in the WQOs are broad and it is expected by **hydrogeologist.com.au** that local groundwater within the Project area would naturally differ somewhat from the percentiles provided for the entire Zone 34. The statistics and percentiles presented in the WQOs provide a general indication of expected groundwater quality and are not to be used as triggers or exceedance criteria.

The WQOs for Zone 34 (Table 14 Fitzroy groundwater: water quality objectives (aquatic ecosystem) according to water chemistry zones), provides the following EC percentiles for deep groundwaters in Zone 34:

- 20^{th} percentile:3,419 µS/cm EC;
- 50^{th} percentile or median: 6,100 µS/cm EC; and
- 80^{th} percentile: 16,000 µS/cm.

Table 5-11 lists the statistics for Zone 34 (deep) for EC and other analytes. At the time of writing this report, data from fifteen monitoring rounds (each consisting of up to seven bores) was available (including duplicate samples). This is less than those recommended (minimum of 18 samples over at least 12 and preferably 24 months for each bore) for comparison with scheduled WQOs according to the guideline (Department of Environment and Science or DES, 2021) and therefore not sufficient to calculate bore-specific percentile statistics at present. However, the water quality dataset will be sufficient to derive interim guidelines (DES, 2021).

In Table 5-11, therefore, the data for Zone 34 (deep) are compared with the median of all data (maximum of 92 counts, from 15 rounds and up to seven bores in each round). Although the EC for these bores spans a wide range, the median for EC, 5,360 µS/cm, is below the 50^{th} percentile statistics provided for Zone 34 (deep), 6,100 µS/cm.

Of the major constituents and physical measures, the median of local monitoring data compares well with the Zone 34 statistics for Ca; while total hardness, observed alkalinity, Mg, SO_4 and HCO_3 are in excess of the 50^{th} percentile statistics provided for Zone 34. The observed median lab pH, Cl, Na and SAR are below those of the Zone 34 statistics.

Of the minor constituents, the median of local monitoring data is below the Zone 34 statistics for observed silicon (as SiO_2). The results for dissolved metals (Cu, Fe, and Zn) are probably unduly affected (biased towards the small values) by the large proportion of less than detectable results (for the purposes of Table 5-11, a value equivalent of less than the detectable limit was ignored).

Notwithstanding the above, more data are needed in order to provide reliable statistics and before defensible WQOs can be developed. WQOs and groundwater monitoring criteria and trigger levels, consistent with DES (2021), should be established and documented within a Water Management Plan (WMP) as soon as minimum of 18 samples over 12 to 24 months of data have been collected from the site monitoring bores. Interim guidelines will be developed using the existing water quality dataset from the groundwater monitoring network.

Table 5-11 Zone 34 deep percentiles and medians of preliminary local monitoring data

Analyte	Unit	20th	50th	80th	Median of local monitoring * data	Comments
EC	(μS/cm)	3,419	6,100	16,000	5,630	Lab EC excluding the initial results for June 2019 for MB04 and MB09
Total Hardness	(mgL^{-1}as CaCO3)	359	919	3,208	1,110	
pH		7.4	7.8	8.03	7.59	Lab pH excluding the initial results for June 2019 for MB04 and MB09
Alkalinity	(mg/L)	156	275	536	616	
Ca	(mg/L)	46	145	442	128	
Mg	(mg/L)	35	115	491	193	
Na	(mg/L)	480	1,100	2,565	867	
Cl	(mg/L)	753	1,900	5,905	1,320	
SO_4	(mg/L)	25	138	398	572	
HCO_3	(mg/L)	188	330	650	752	
NO_3	(mg/L)	0.01	2.15	14.92		Not analysed
SiO_2	(mg/L)	16	25	36	20.5	
F	(mg/L)	0.02	0.155	0.4	0.4	
Fe	(mg/L)	0	0.05	0.246	0.63	As dissolved Fe, influenced by large number of less than detectable, <0.05 results
Mn	(mg/L)	0	0.05	0.291	0.237	As dissolved Mn
Zn	(mg/L)	0.01	0.025	0.317	0.017	As dissolved Zn, influenced by large number of less than detectable,<0.005 results
Cu	(mg/L)	0.017	0.03	0.03	0.001	As dissolved Cu, influenced by large number of less than detectable,<0.001 results
SAR		10.5	15.6	24.65	12.5	
RAH	(meq/L)	0	0.24	6.25	N/A	Not analysed
Eh	(mV)	ID	ID	ID	N/A	Not analysed

Note: **From fifteen monitoring rounds*

5.9. Conceptual model

The west to east conceptual hydrogeological cross-section of **hydrogeologist.com.au** is presented in Figure 5.13, based on the review of various reports, data and information, as summarised in Sections 3 to 5.8 of this report.

There are eight hydrogeological units shown in Figure 5.13:

1. Quaternary alluvium (localised only);
2. Tertiary sediments / weathered zone (regolith, extensive, generally between 1 m to 30 m);
3. Fort Cooper Coal Measures – Permian overburden;
4. Moranbah Coal Measures – Permian overburden;
5. DL coal seam (extracted at Saraji Mine);
6. Moranbah Coal Measures – Permian interburden;
7. DLL coal seam (proposed to be extracted at the VS pits); and
8. Back Creek Group.

The west to east section in Figure 5.13 is sub-parallel to the lateral groundwater flow direction (Section 5.5.5). The groundwater table is hosted by several units, from the outcropping/sub-cropping Back Creek Group in the west through the Tertiary sediments and Moranbah Coal Measures to the Fort Cooper Coal Measures in the east. As a result of the sloping groundwater table and the easterly dip of the hydrogeological units, some of the units may be partially unsaturated, particularly in the west, as is shown in Figure 5.4.

A minor component of rainfall recharge (Section 5.5) acts on the top of the land surface. Evapotranspiration occurs from groundwater that is situated within the extinction zone, however the groundwater table is often too deep, so significant (Figure 5.10) evaporation is likely only from the proposed and existing nearby mine pits. The interaction between surface and groundwater is insignificant within the model domain. The western boundary in Figure 5.13 is a catchment and groundwater divide in the Harrow Range. The eastern conceptual model boundary adopted is the Jellinbah Fault Zone, which is a north-west trending zone with several easterly dipping thrust faults with throws in the order of 100 m to 500 m (URS, 2012).

Near the proposed Vulcan South and the Saraji Mine, the Moranbah Coal Measures, down to the DLL coal seam (VS) and DL coal seam (at Saraji Mine) are depressurised and dewatered. Because of the low hydraulic conductivity and transmissivity, and the low storage of the units within the Moranbah Coal Measures, the cones of depression surrounding the mines are expected to be deep (to pit depth) but laterally limited. Once mining, depressurisation and dewatering cease, groundwater will start to recover and eventually will reach steady state in the backfilled material within the former pit. The recovery processes will largely be driven by the boundary conditions discussed above and the hydraulic parameters discussed in Section 5.4.

As discussed in Section 5.5.5, the MAT coal seam, which is proposed to be mined as part of the Highwall Mining area, is demonstrated to be dry and the highwall mining proposed as part of the Project will not interact with groundwater. On this basis, the Highwall Mining area has not been included in the conceptual model for the Project and has not been included in the numerical model predictions.

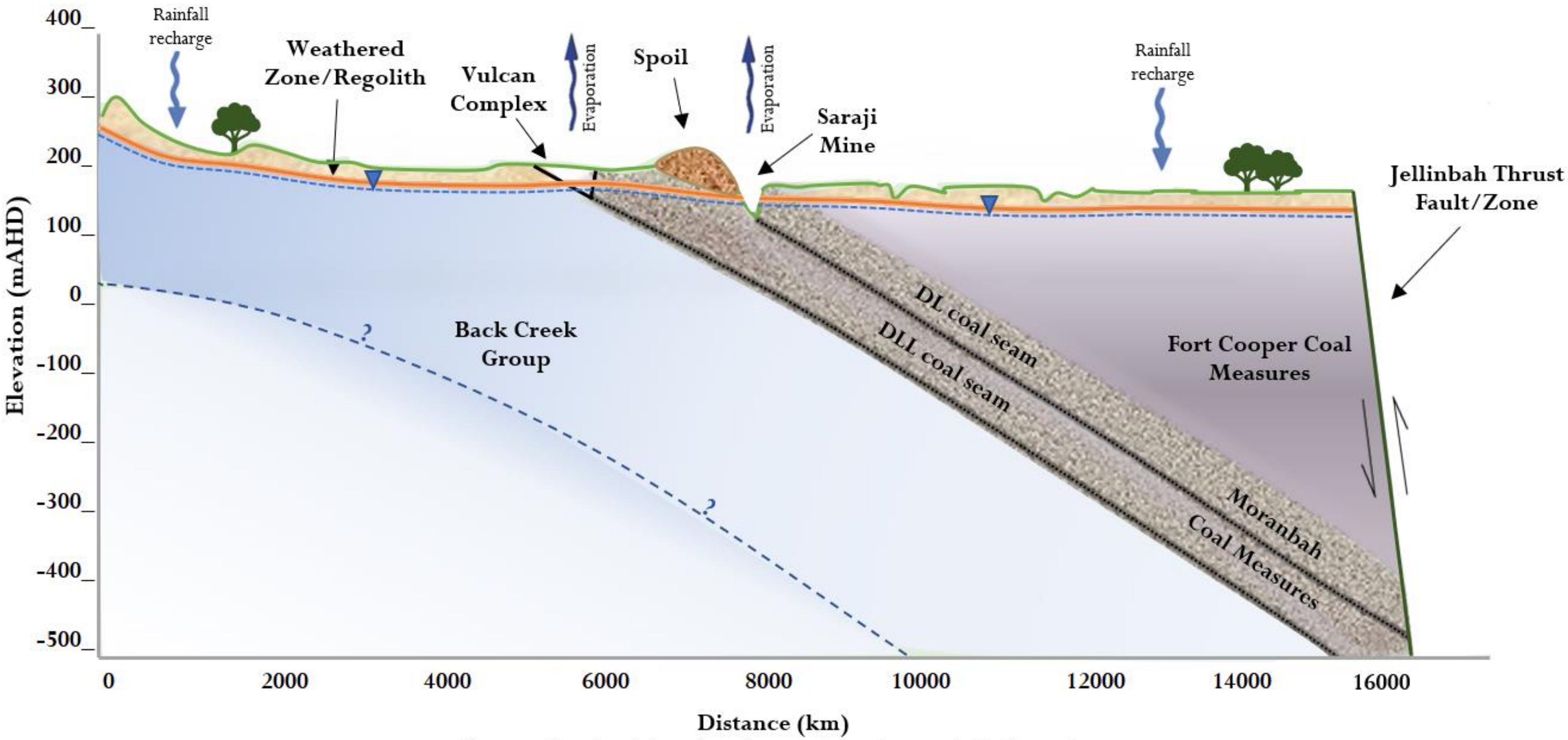


Figure 5.13 West to east conceptual hydrogeological cross-section

6. Impact assessment

6.1. Summary of numerical modelling

6.1.1. Objectives

The conceptual model presented in Section 5.9 has been used as the basis to develop a numerical groundwater flow model. This process, including model build, calibration and predictions is summarised in this section. A detailed description of the numerical model is provided in Appendix C.

The objectives of the numerical model are to assess the quantitative impacts of the Project both in terms of drawdown and groundwater fluxes. Due to the existence of numerous coal mines, especially Saraji Mine, in the close vicinity of the Project, groundwater impacts will need to be quantified both due to the Project only and cumulatively.

6.1.2. Design

The MODFLOW-USG (Panday *et al.*, 2015) code, based on the U.S. Geological Survey MODFLOW-2005 groundwater modelling code, was used. MODFLOW-USG simulates groundwater flow using a finite-difference approach and allows non-orthogonally structured grids to be used for groundwater flow simulations (Panday *et al.*, 2013). Model calibration and parameter sensitivity analysis was undertaken using Model-Independent Parameter Estimation and Uncertainty Analysis (or PEST, Doherty, 2019a and 2019b) and BEOPEST (or efficient parallel run management version of PEST, Doherty, 2012).

The model domain consists of a maximum of 22492 cells per layer extending over a total area of 650 km^2. The area of individual cells varies between 5,000 m^2 and 911,000 m^2. In general, this area is small for cells close to the proposed pits (50 m x 100 m), existing mines (150 m x 250 m) and main surface water drainages; and is large towards the outer margins of the model (Figure 6.1). This is to improve the convergence and resolution of the numerical model in places with the most potential to present changes in groundwater drawdown and flux.

The temporal discretisation adopted consists of a pre-calibration steady state model leading into 48 year-long calibration period (1972 – 2019) and a prediction (mining) period from 2020 through to 2032 (Table 6-1).

Table 6-1 Temporal discretisation – calibration and predictive models

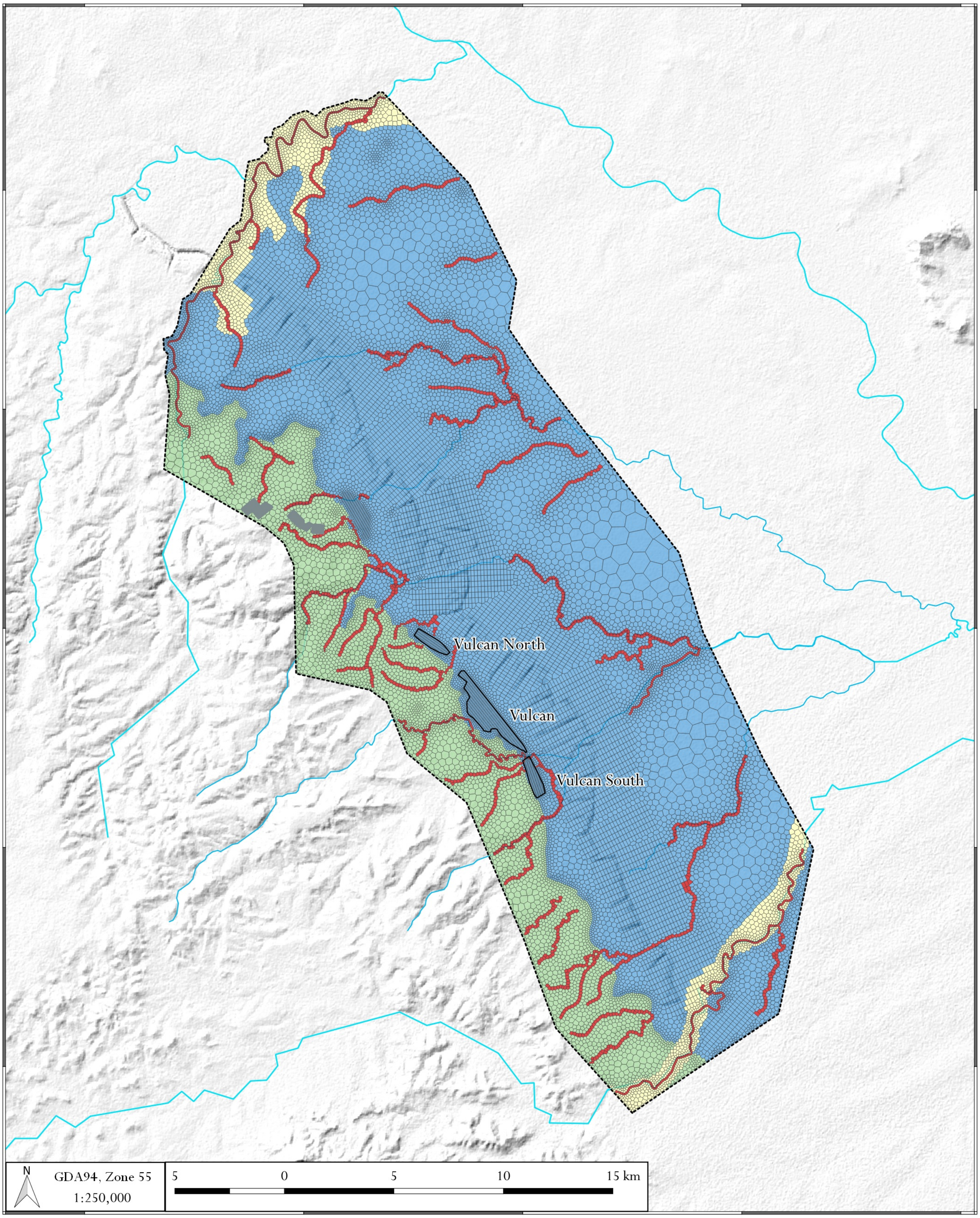
No. of stress periods	Stress period length	Dates	Modelling phase
Steady state	N/A	N/A	Pre-calibration
1 - 47	1 year	01/01/1972 – 31/12/2018	calibration
48 - 51	3 months	01/01/2019 – 31/12/2019	
52 - 55	3 months	01/01/2020 – 31/12/2020	prediction - mining
56 – 78	6 months	01/01/2021 – 30/06/2032	

The boundary conditions selected for the model are based on the description of the hydrogeology (Section 5, the numbers refer to Figure 6.2):

1. NW no-flow boundary (parallel to regional groundwater flow (Section 5.5.5) system in the north-west;
2. Jellinbah Fault Zone boundary;
3. SE no-flow boundary (parallel to regional groundwater flow (Section 5.5.5) system in the and south-east; and
4. SW no-flow boundary.

The eight hydro-stratigraphic units (Section 5.9) are represented by a total of eleven layers (Figure 6.3), from discrete and isolated zones of Quaternary alluvium through to the lowermost and extensive Permian Back Creek Group. Several hydro-stratigraphic units (Fort Cooper Coal Measures and overburden, and the Moranbah Coal Measures interburden between the DL and DLL coal seams) are represented by two (split) layers to improve model convergence.

Key model layers include layer 2 (Tertiary sediments) and layer 10 (DLL coal seam, representing mining from the Vulcan pits). Model layer 7 represents the DL coal seam which is mined at Saraji Mine.



LEGEND

Recharge zones

- 1 - Regolith
- 2 - Alluvium
- 3 - above DLL outcrop
- 4 - River cell

- Model domain
- Proposed pit
- Highwall mining area
- Watercourse

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22/02/2022

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Model mesh and recharge zones

FIGURE No.
6.1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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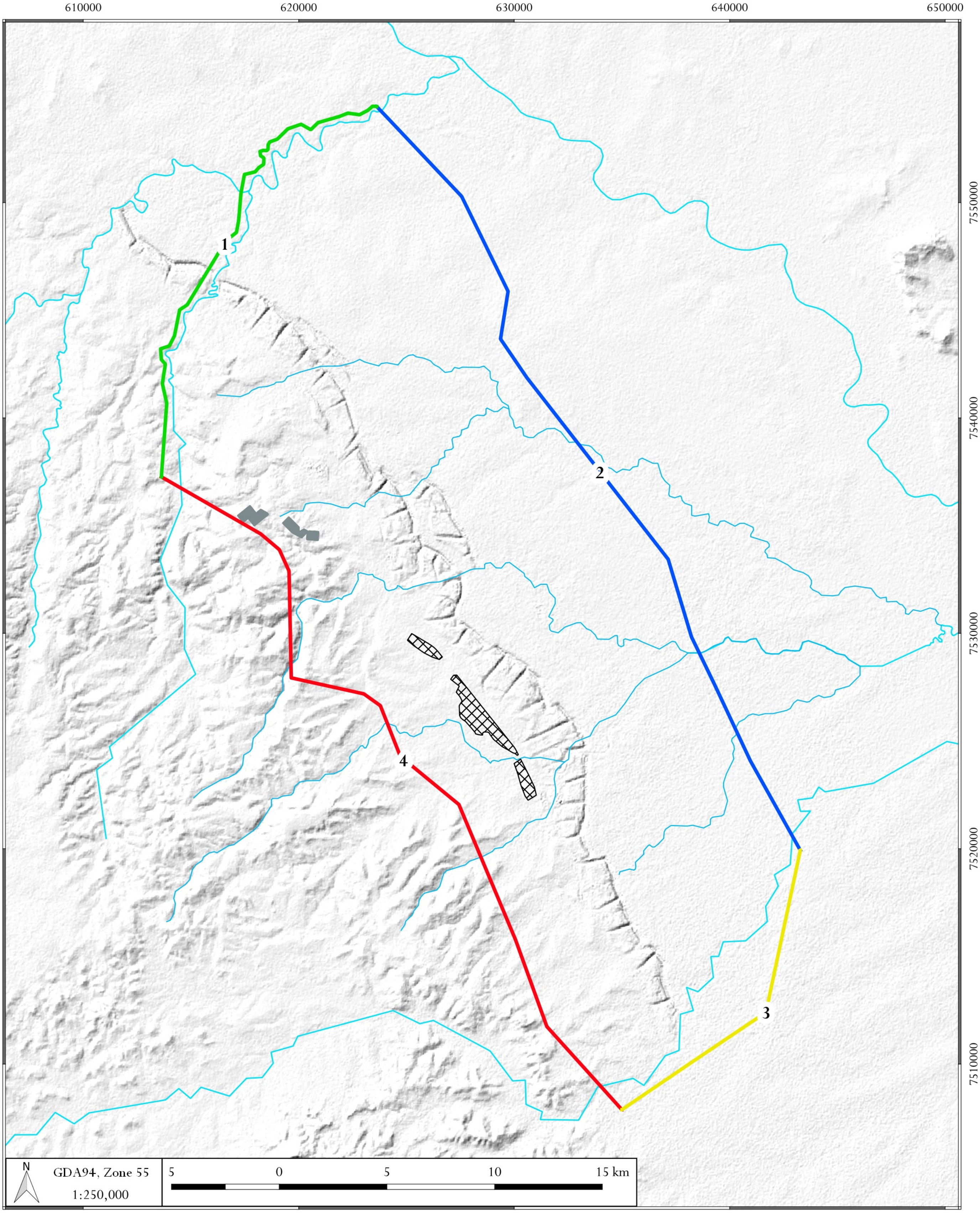

LEGEND

Model boundaries

- 1 - NW no-flow boundary
- 2 - Jellinbah Fault Zone boundary
- 3 - SE no-flow boundary
- 4 - SW no-flow boundary

- Proposed pit
- Highwall mining area
- Watercourse

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22/02/2022

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Vulcan South - Groundwater Impact Assessment (4027)

Boundaries of the model domain

FIGURE No.
6.2

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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Model layers

1 - Quaternary alluvium
2 - Tertiary sediments / weathered zone / regolith
3 / 4 - Fort Cooper Coal Measures
5 / 6 - Moranbah Coal Measures overburden
7 - DL coal seam
8 / 9 - Moranbah Coal Measures interburden
10 - DLL coal seam
11 - Back Creek Group underburden

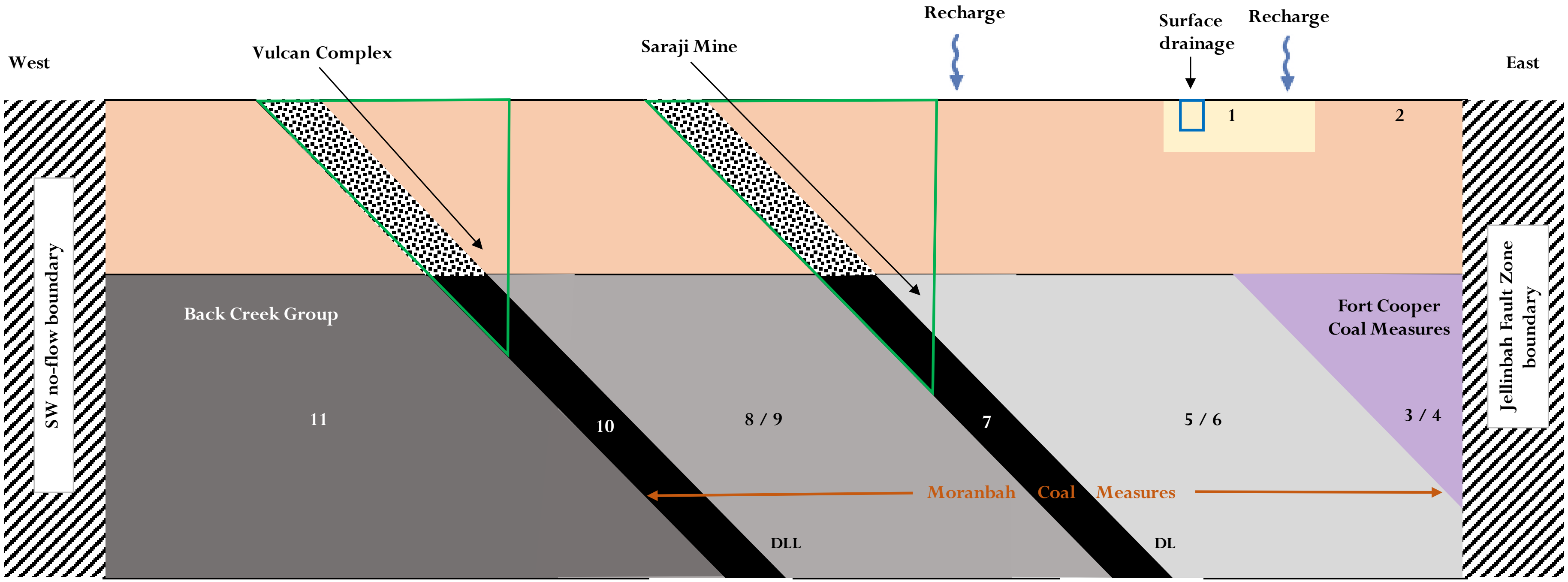


Figure 6.3 Model layers and boundary conditions

Surface water

Surface watercourses are represented by the MODFLOW-USG river (RIV) package. If the head (groundwater elevation) in the cell connected to the river drops below the bottom of the riverbed, water enters the groundwater system from the river at a constant rate. If the head is above the bottom of the river, water will either leave or enter the groundwater system depending on whether the head is above or below the head in the river. The calculated water flux is proportional to the difference between the groundwater and river heads.

Recharge/discharge

Groundwater recharge from rainfall was applied to the uppermost saturated model layer as a percentage of rainfall. Zonation was applied to the modelled recharge to represent the following key areas (Figure 6.1, numbers correspond to the recharge zones) or systems:

1. regolith (east of DLL subcrop);
2. Quaternary alluvium (associated with major creeks);
3. regolith (west of DLL subcrop); and
4. river cells.

Recharge to the steady state model was applied as a percentage of the annual average rainfall from the SILO data (Section 3.1, 582 mm/yr). Recharge for the transient calibration period of 1972-2019 (Table 6-1) was applied as a percentage of actual rainfall data (SILO data) accumulated over the stress period[1]. Recharge for the predictive model (2020-2032) was applied as a percentage based on long-term (1900-2018) averages (SILO data) for the stress period length. Evapotranspiration was not explicitly modelled as it was incorporated into the rainfall recharge applied to the model. For more information relating to the modelled recharge the reader is referred to Appendix C.

Initial hydraulic parameters

The initial hydraulic parameters (starting values, upper bound and lower bound) were based upon the values derived from existing reports, site specific data and a general knowledge and experience in the region. These values were applied on a trial and error basis initially to inform the general behaviour of the model, then applied using PEST to develop the calibrated solution.

Drains

Mining (both historical and proposed) was simulated using the drain (DRN) package. Site specific information on the Project enabled an accurate representation of mine progression in accordance with the proposed mining schedule. The drains were applied to the base of the DLL (layer 10) in the Project area.

For the representation of the Saraji Mine, historical mine development was captured in five yearly images downloaded from Landsat then digitised. The general extent of mining was then formulated into an annual sequence to approximate historical mine progression. The DRN cells were generally applied to the base of the DL coal seam (layer 7) for Saraji Mine.

[1] Stress periods are used to define time intervals during which the inputs for the model remain constant.

6.1.3. Transient calibration

The numerical model includes a steady-state and a transient calibration (1972 to 2019). The transient calibration captures historical development at Saraji Mine and Peak Downs Mine which was based upon an interpolated mine progression assessed from Landsat imagery.

In accordance with the Australian groundwater modelling guidelines (Barnett *et al.*, 2012), the objective of a model calibration is to replicate the groundwater levels measured in the site monitoring network and other bores. A set of 55 selected observation points (and a total of 176 observations) were used in the calibration process, some with single values and some with time-series observations. The observation points included historical observation data from mining investigations (AECOM, 2016), publicly available sources (AECOM, 2016; Department of Natural Resources, Mines and Energy, 2019), and on-site data collected from open drill-holes and data collected from the new monitoring bores (**hydrogeologist.com.au**, 2019).

A scatter diagram of observed vs. modelled groundwater elevations (Figure 6.4) indicates that most points are situated close to the 1:1 line (perfect fit). While outliers do exist, most of the observations are within ±5 m of the 1:1 line. It is important to note that no significant or obvious trends or systematic departures appear to occur from the 1:1 line (the various colours representing different hydrogeological units scatter around the 1:1 line in a generally random pattern).

An overall (all observations and all time steps) transient calibration was achieved with an RMS (root mean square error) of 3.6 m and an SRMS (scaled root mean square error) of 4%. The SRMS value of 4% (3.6 m / 90.5 m=0.04 or 4%) indicates a good fit between measured and modelled data. Notwithstanding that, other criteria (such as good correlation between measured and modelled hydrographs and contour maps) also apply, an SRMS that is less than 10% may be acceptable (Barnett *et al.*, 2012) while an SRMS < 5% represents generally good calibration in the experience of **hydrogeologist.com.au**.

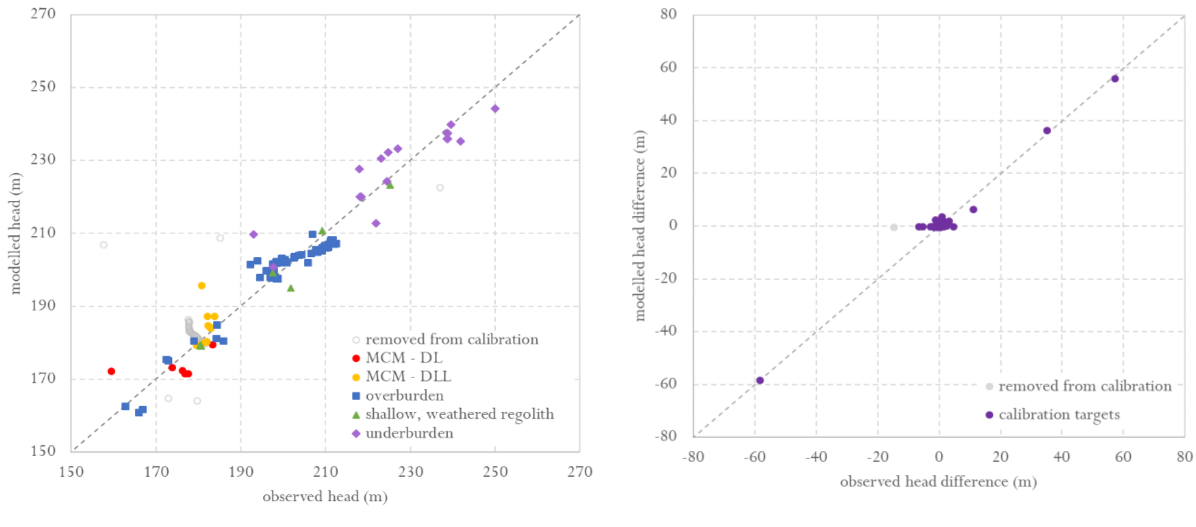


Figure 6.4 Model calibration scatter diagrams – observed and modelled heads and head differences

6.2. Predictions

The model predictions presented below are based upon 'mine' vs 'no mine' model scenarios to determine the true impact of the Project on the groundwater system. The 'mine' scenario simulates the VS, the VCM, along with Saraji Mine and Peak Downs Mine, and the 'no mine' scenario simulates the VCM, Saraji Mine and Peak Downs Mine only. The differences in drawdown and fluxes, between the 'mine' and 'no mine' scenarios, represent the impact of the Project on the groundwater system.

6.2.1. Mine inflows

Figure 6.5 shows the predicted inflow to the proposed VS Vulcan pits. The prediction shows a maximum inflow of less than 43 m^3/d occurring in Year 5 (or 2027) of mining. Vulcan North and Vulcan South pits are both predicted to have less than 5 m^3/d of groundwater inflow and will effectively be dry pits during mining. The majority of the inflow is predicted to occur during mining of the Vulcan main pit.

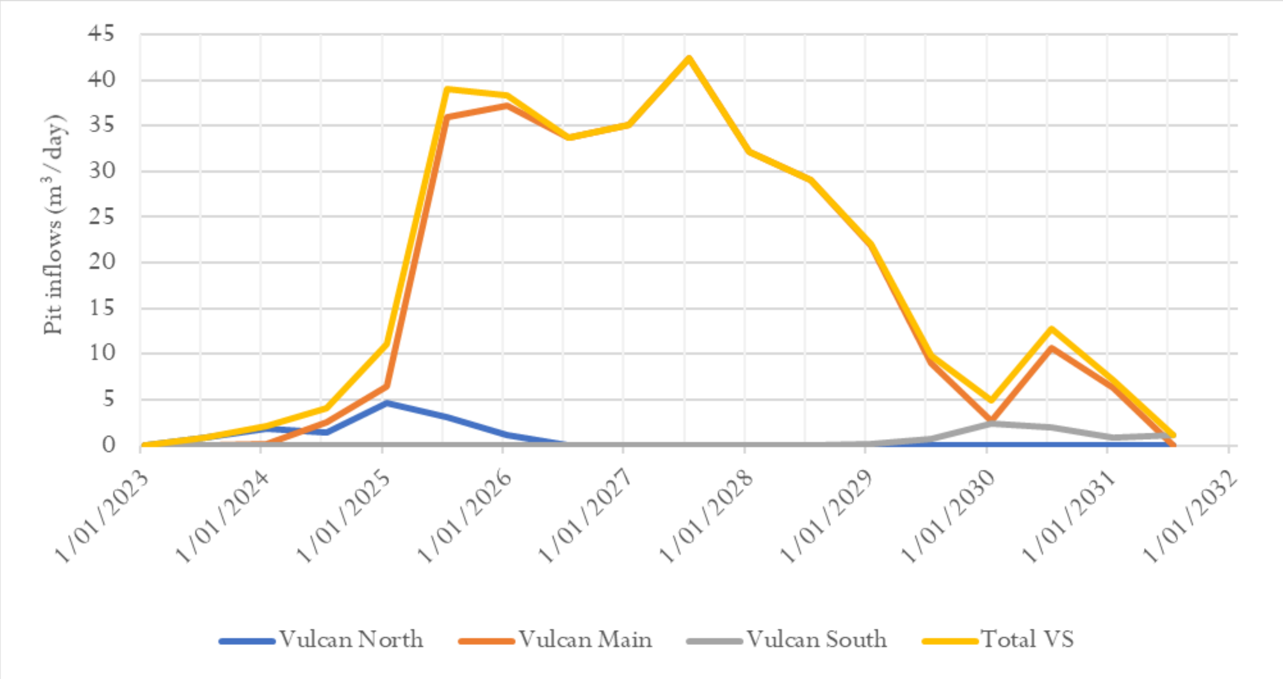


Figure 6.5 Predicted mine inflow rates

Table 6-2 summarises the predicted inflows rates and volumes for the proposed VS Vulcan pits. The rate of inflow to the Vulcan pits is consistent with Figure 6.5 and shows that the maximum inflow is less than 43 m^3/d occurring in Year 3 (or 2023) of mining. The maximum annual volume of predicted inflow to the VCM pit is less than 15 ML/yr.

Table 6-2 Numerical model – zone budget – predicted inflow rates for the Project

SP	days	SP end	DRN inflow (m^3/day)			Volume (ML)
			Vulcan North	Vulcan Main	Vulcan South	
59	184	01/01/2023	0.00	0.00	0.00	0.16
60	181	01/07/2023	0.88	0.00	0.00	
61	184	01/01/2024	1.86	0.21	0.00	1.12
62	182	01/07/2024	1.45	2.60	0.00	
63	184	01/01/2025	4.71	6.41	0.00	9.11
64	181	01/07/2025	3.09	35.93	0.00	
65	184	01/01/2026	1.15	37.14	0.00	13.15
66	181	01/07/2026	0.00	33.72	0.00	
67	184	01/01/2027	0.00	35.09	0.00	14.14
68	181	01/07/2027	0.00	42.42	0.00	
69	184	01/01/2028	0.00	32.20	0.00	11.20
70	182	01/07/2028	0.00	29.00	0.00	
71	184	01/01/2029	0.00	21.90	0.15	5.83
72	181	01/07/2029	0.00	9.05	0.77	
73	184	01/01/2030	0.00	2.62	2.34	3.23
74	181	01/07/2030	0.00	10.72	2.05	
75	184	01/01/2031	0.00	6.28	0.89	1.52
76	181	01/07/2031	0.00	0.00	1.10	

Overall, the predicted groundwater seepage to the proposed pits is low and will very likely be lost through evaporation on the pit face or as entrained moisture within the mined coal. Hence seepage to the pit is very unlikely to be observed during the Project.

6.2.2. Water fluxes (water budget)

The water budget of the model and the major components are:

- rainfall recharge (RCH boundary condition) inflow to the uppermost layer;
- groundwater outflow through the Jellinbah Fault Zone boundary;
- groundwater outflow to surface water outside the Project area (RIV cells); and
- when appropriate, groundwater outflow to mining voids.

Groundwater extraction for pastoral use is considered negligible and has not been included in the numerical model.

Table 6-3 shows the water fluxes (water budget) for the steady-state, transient calibration, and transient predictions. The outflow to the RIV cells and the balance of outflow-inflow for Jellinbah Fault Zone general head boundary (GHB) cells are largely driven by temporal changes in RCH which in turn is driven by rainfall. As Table 6-3 indicates, the predicted steady state recharge (1,360 m^3/d) is considerably less than the average for the transient calibration period (1972 to 2019). This is because at the beginning of the transient calibration, between 1973 and 1979, the annual average rainfall and therefore the predicted recharge rate is significantly higher (consistent with the CRD graph in Figure 3.2).

Table 6-3 also indicates that during the steady-state simulation (pre-1972) most of the inflow, from rainfall recharge, is balanced by outflow through the Jellinbah Fault Zone boundary and to RIV cells (surface watercourses mostly in the south and north).

Once Saraji Mine and Peak Downs Mine are simulated, groundwater outflows to mine voids (DRN) dominate the water balance and the groundwater outflow, in excess of inflows, is sourced from groundwater storage (drawdown near the pits). From 2023 the VS becomes active (transient-prediction). There is a significant increase in outflows to mine voids (DRN), however this is primarily due to the future representation of Saraji Mine and Peak Downs Mine as the VS is predicted to have very minor seepage.

Table 6-3 Numerical model water budget summary

Groundwater flow components		Steady state	Transient - calibration	Transient - prediction
		Average flow (m^3/d)		
in	recharge (RCH)	1,362	1,579	1,637
	Jellinbah Fault Zone boundary head dependant boundary (GHB)*	392	367	416
out	surface drainage (RIV)	635	801	644
	Jellinbah Fault Zone boundary head dependant boundary (GHB)*	1,119	1,007	870
	mining (DRN)	0	2,123	4,406

Notes: **Along the Jellinbah Fault Zone most of the GHB component of flow is out of the model although for technical reasons a small inflow exists, mainly in the north. For correctness, both are shown; however, for analysis the balance (for example, 1,119 m^3/d – 392 m^3/d = 727 m^3/d for steady state) can be used.*

The predicted changes in modelled flows due to the Project only (general head boundaries - GHB) and discharge to river (RIV) cells are shown in Figure 6.6. The predicted changes are calculated as the difference between the 'mine' and 'no mine' scenarios. 'RIV out' is a proxy for groundwater outflow (baseflow) that occurs from the groundwater system to surface waters. The change in flow in 'RIV out' is less than 0.10 m^3/d (or 100 L/d) over the entire model domain which is considered negligible.

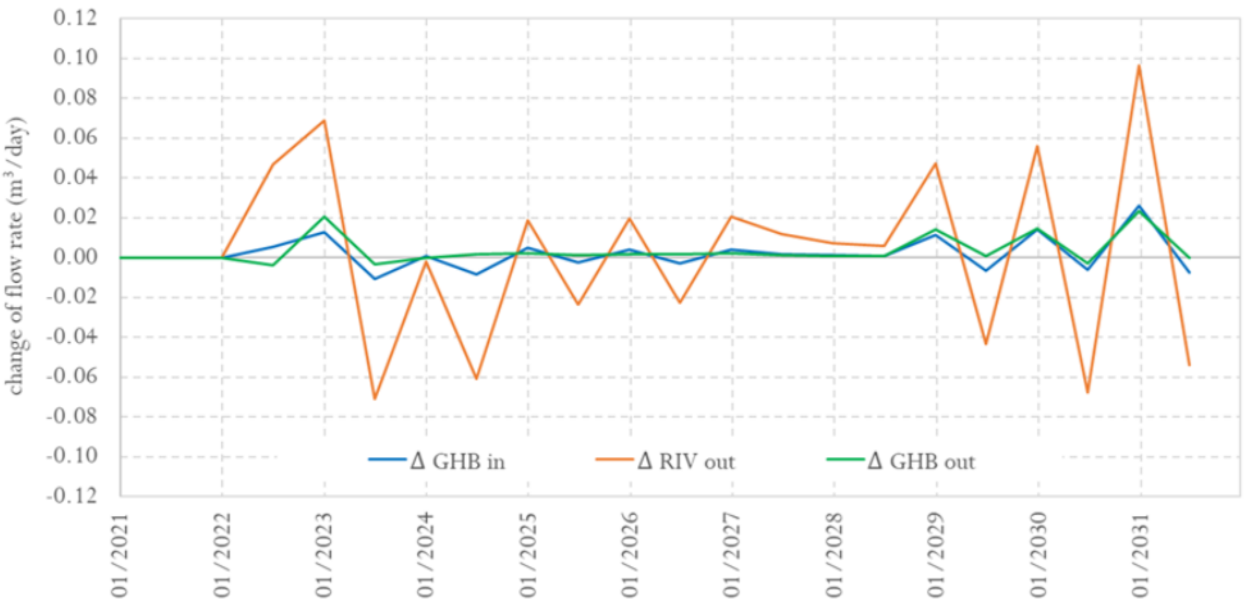


Figure 6.6 Predicted changes in flows - difference between the 'mine' vs 'no mine' scenarios

6.2.3. Drawdown

The predicted drawdown in the Tertiary / weathered zone (layer 2) and the DLL coal seam (layer 10) are shown in Figure 6.7 and Figure 6.8, respectively. The figures show the maximum predicted drawdown throughout the model simulation. The drawdowns represent the Project only drawdown and do not include the impacts of the VCM, Saraji Mine or Peak Downs Mine.

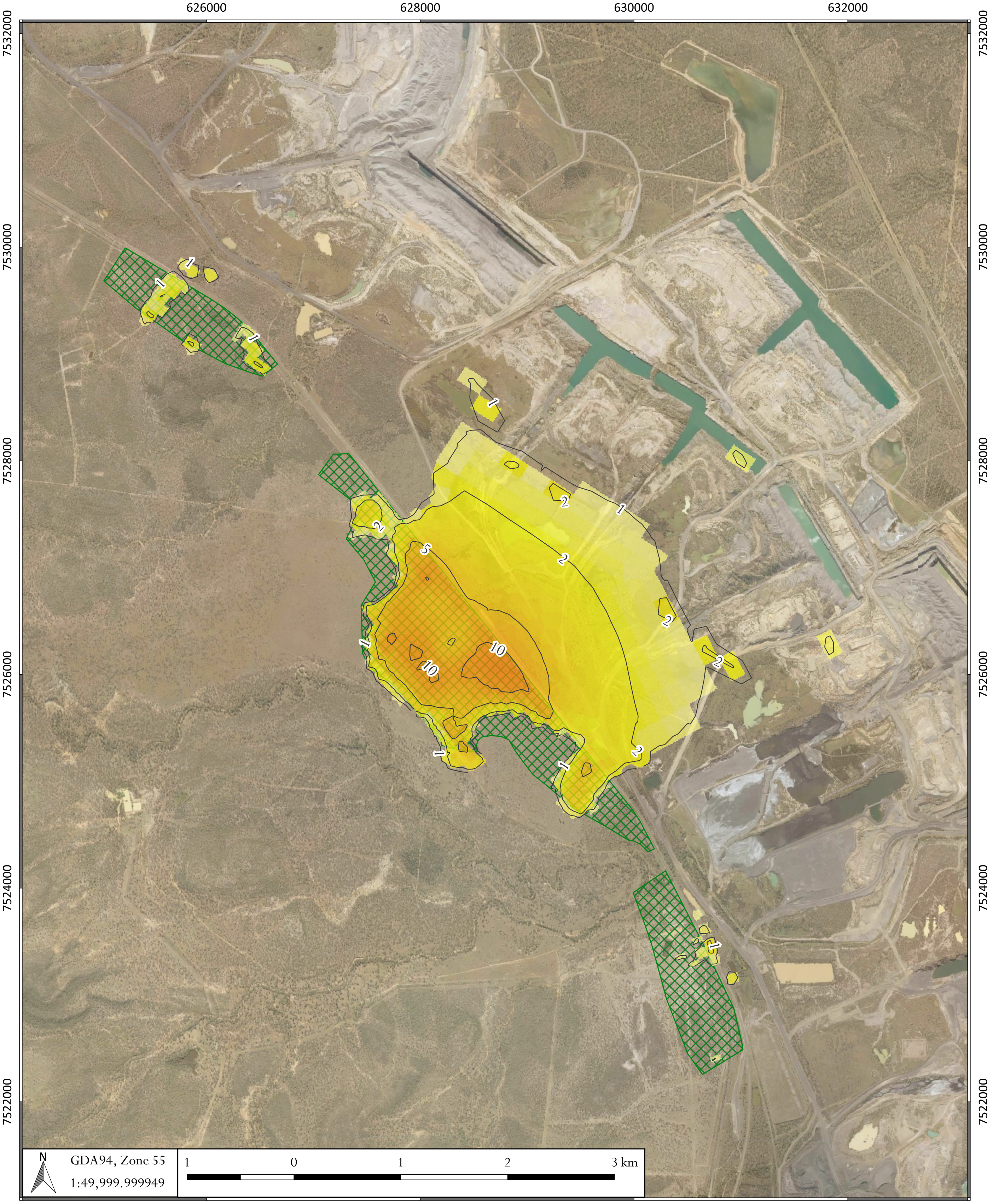
The maximum predicted drawdown in the Tertiary / weathered zone (layer 2) is approximately 10 m in the vicinity of the Vulcan Main pit. Negligible drawdown is predicted in layer 2 in the vicinity of the Vulcan North pit and Vulcan South pit. The drawdown extent occurs some 2,200 m (from the pit crest to the 1 m drawdown contour) and the predicted drawdown preferentially propagates towards the east and the existing Saraji Mine.

The proposed pits are to be backfilled following mining and therefore no residual drawdown is expected to occur post closure. There may be some minor change to the local groundwater elevations and flow directions post closure however these are expected to the negligible and will not result in impact to the groundwater regime.

The maximum drawdown in the DLL coal seam (layer 10) is predicted to be larger than, but of a similar magnitude to, that predicted for layer 2. The maximum magnitude of drawdown is approximately 10 m in the vicinity of the proposed Vulcan Main pit with negligible drawdown predicted in the vicinity of the Vulcan North pit and Vulcan South pit. The drawdown extent in layer 10 occurs some 2,400 m (from the pit crest to the 1 m drawdown contour) and the predicted drawdown preferentially propagates towards the east and existing Saraji Mine.

As per the layer 2 drawdown, the proposed pits are to be backfilled following mining and therefore no residual drawdown is expected to occur post closure in layer 10.

Predicted drawdown due to the proposed VS is limited to generally less than 2 km from the proposed pit (that is the lateral distance from the pit to the 1 m drawdown contour). This limited drawdown propagation is mainly due to the limited extent of saturation in the Project area, the low hydraulic conductivities and low storage coefficients. The predicted drawdown extends towards the east, toward Saraji Mine. The predicted maximum drawdowns in Figure 6.7 and Figure 6.8 are for any stage throughout the simulation for the weathered zone/regolith (layer 2) and the DLL coal seam (layer 10), respectively, and the actual drawdowns at any other times during the simulations will be less than those presented.



LEGEND

Maximum drawdown (m):

- 1
- 2
- 5
- 10

Proposed pit

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Predicted drawdown in Tertiary / weathered zone (L02)

FIGURE No.
6.7

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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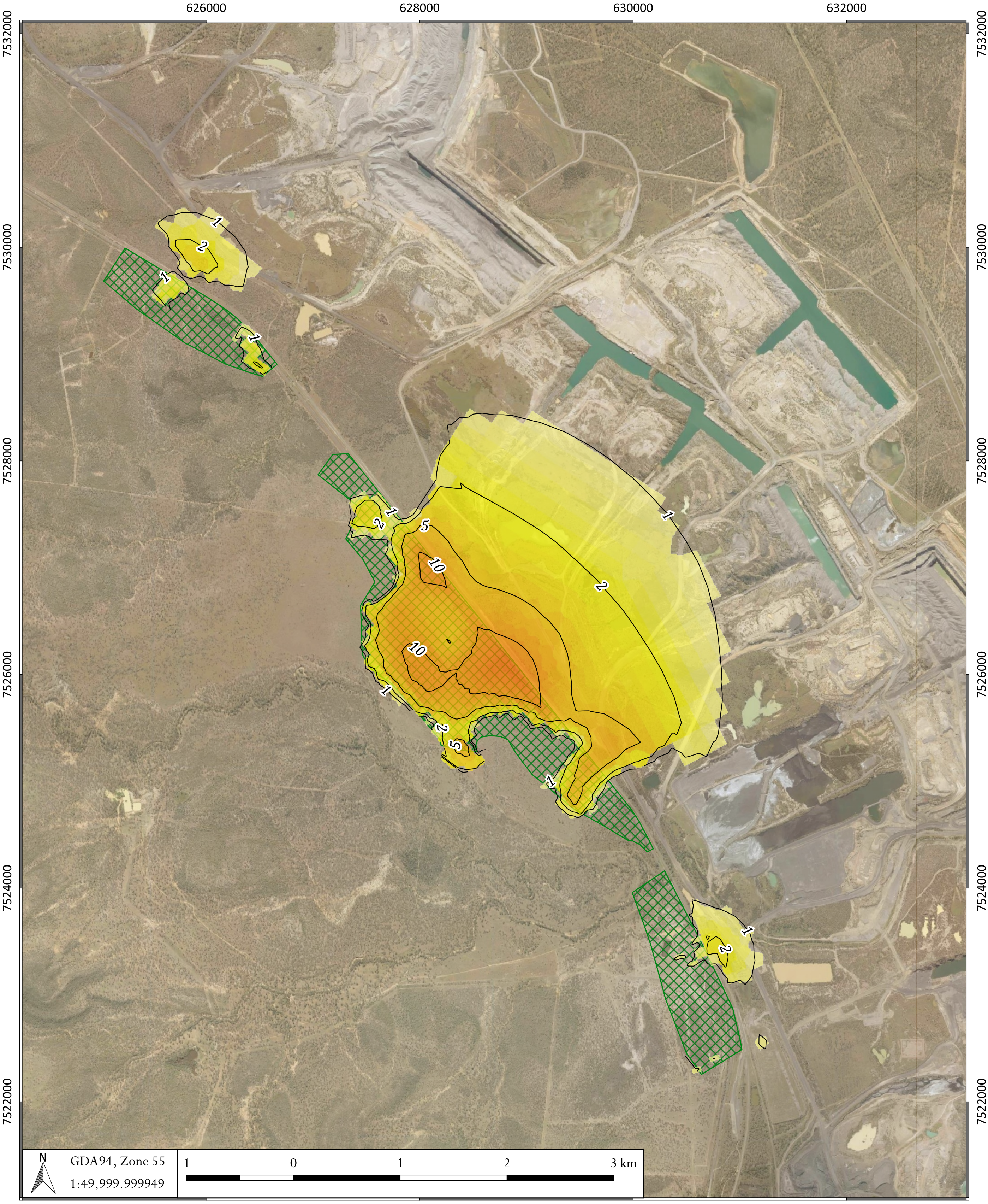

LEGEND

Maximum drawdown (m):

- 1
- 2
- 5
- 10

Proposed pit

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Vulcan South - Groundwater Impact Assessment (4027)

Predicted drawdown in DLL coal seam (L10)

FIGURE No.
6.8

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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6.2.4. Uncertainty

Uncertainty analysis was carried out to understand the ranges of possible inflows and drawdown from the model under various parameter bounds. The analysis was completed in consultation with the IESC information guidelines on uncertainty analysis and was carried out using a calibration constrained, null space Monte Carlo stochastic method. A series of model parameter sets were generated and run using the 'mine' vs 'no mine' model scenarios. These models were compared against the calibrated 'basecase' model for calibration statistics such as SRMS and the objective function within PEST (that is phi which is equivalent to the sum of square residuals) to ensure the parameter sets generated acceptable results against the calibrated model. The predicted pit inflows and drawdown were then processed to determine pre-defined percentiles in accordance with the IESC information guidelines on uncertainty analysis. The following results present the outcome of the uncertainty analysis.

Figure 6.9 shows the uncertainty analysis of groundwater inflows (DRN) to the VS. The calibrated prediction or 'basecase' model is shown by a dashed black line and is consistent with the results presented in Figure 6.5 and Table 6-2. The coloured zones represent probability ranges, i.e. the dark green zone reflects the bottom 10th percentile of scenarios with DRN inflows generally < 25 m^3/d. The uncertainty analysis shows that there is a small probability (> 90th percentile) that the maximum inflow (in year 3 or 2025) would be between 60 m^3/d and 115 m^3/d, but would most likely be within the range of 30 m^3/d to 50 m^3/d for year 3. As discussed in Section 6.2.1, the predicted groundwater seepage to the VS is low and is highly likely to be lost through evaporation on the pit face or as entrained moisture within the mined coal. Hence seepage is unlikely to be observed during mining.

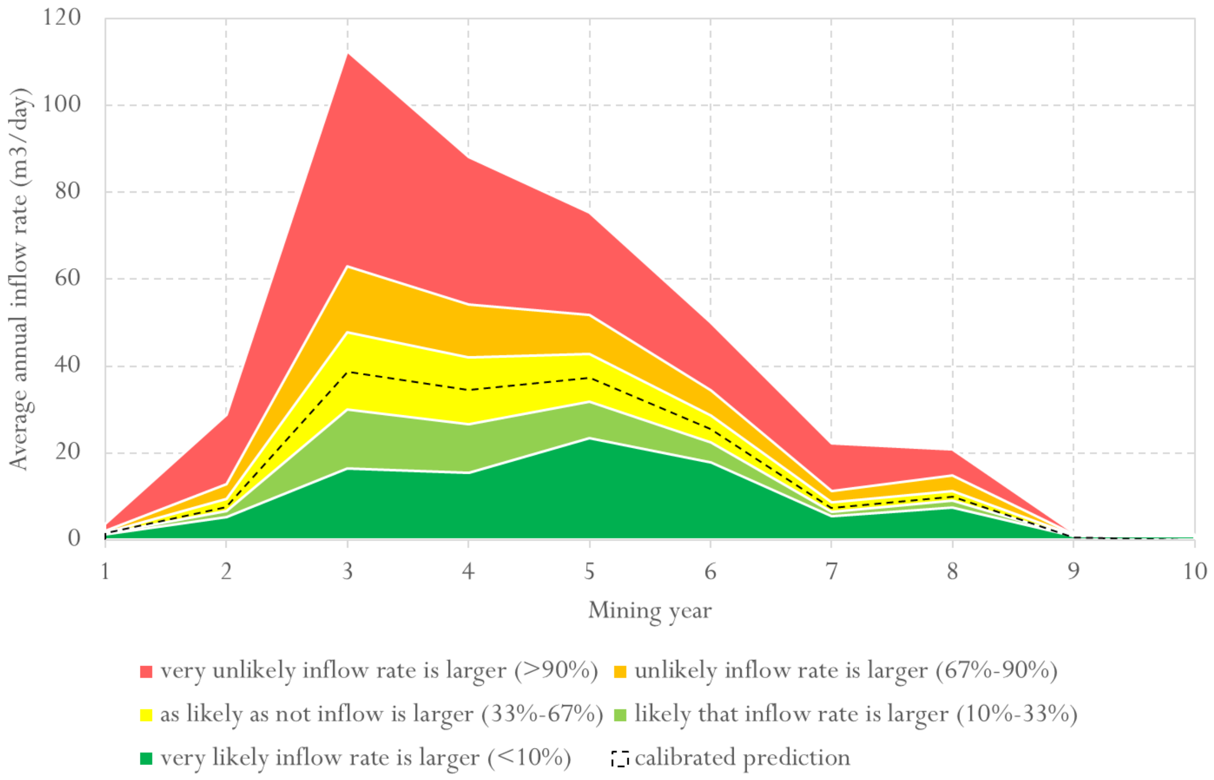
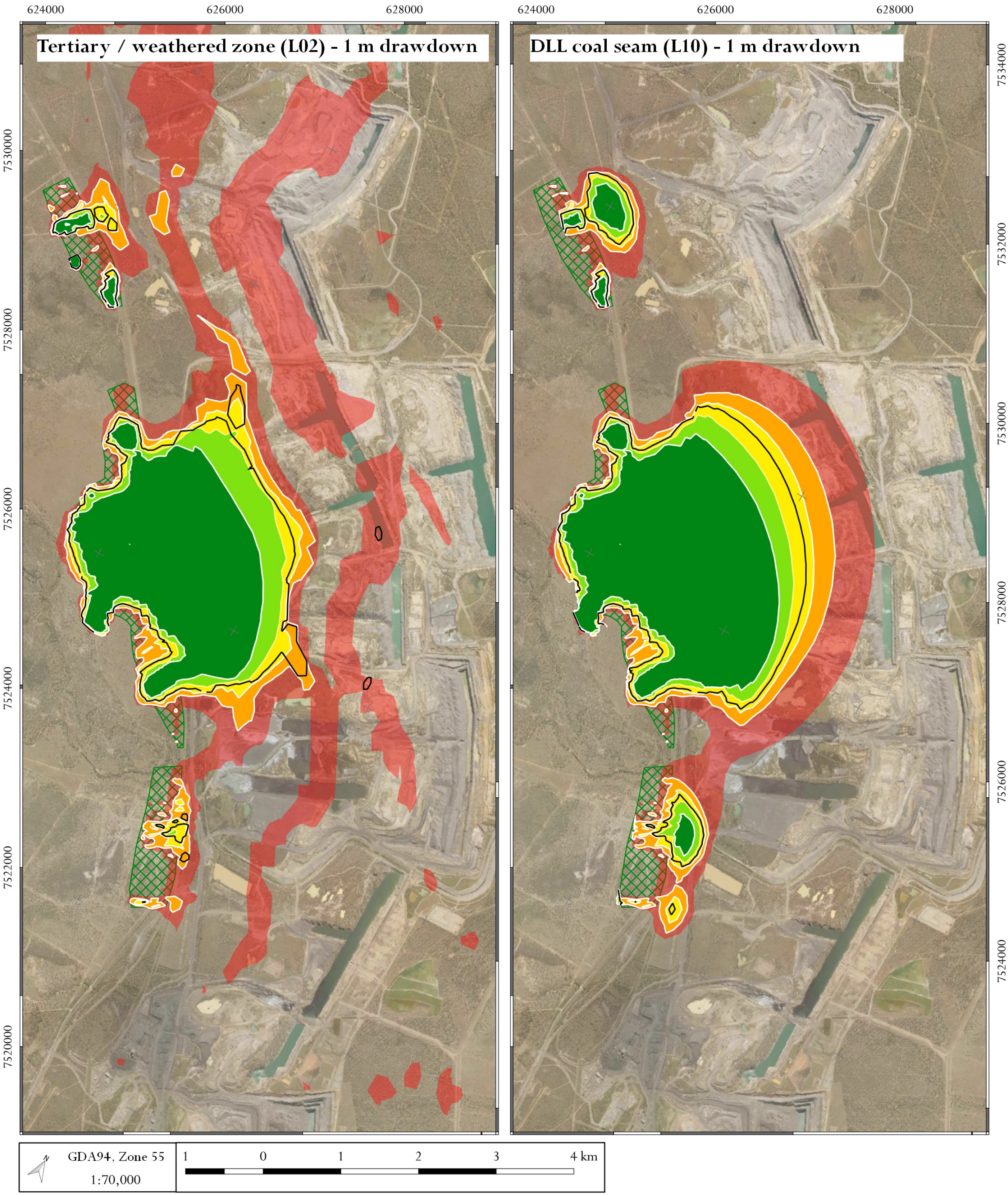


Figure 6.9 Uncertainty analysis – pit inflows

The maximum drawdowns (representing 1 m) generated from the uncertainty analysis for the Tertiary / weathered zone (layer 2) and the DLL coal seam (layer 10) are shown in Figure 6.10 along with the 'basecase' model predictions (solid line within the yellow envelope). The 'basecase' model predicted drawdowns are also shown in Figure 6.7 and Figure 6.8 for layers 2 and 10 respectively.

The coloured zones indicate the maximum extent for the 1 m drawdown within the probability envelopes, i.e. the light green coloured zone contains the 10th to 33rd percentiles of scenario results (the position of the 1 m drawdown contour), whereas the 67th percentile results indicate that the 1 m contour will be situated further to the east from the proposed pits.



LEGEND

- Proposed pit
- <10% - it is very likely that the outcome is larger than this value
- 10% - 33% - it is likely that the outcome is larger than this value
- 33% - 67% - it is as likely as not that the outcome is larger than this value
- 67% - 90% - it is unlikely that the outcome is larger than this value
- >90% - it is very unlikely that the outcome is larger than this value
- Maximum drawdown - basecase

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Uncertainty analysis - maximum drawdown

FIGURE No.
6.10

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
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6.3. Impacts on users

As Figure 6.7, Figure 6.8 and Figure 6.10 indicate, the predicted extent of maximum drawdown in the Tertiary / weathered zone (layer 2) and the DLL coal seam (layer 10) are limited. There are no third-party groundwater users within the predicted extent of drawdown and hence impacts on existing users are considered very unlikely. The nearest third party bores (to any of the VS pits) comprise a network of monitoring bores drilled at Saraji Mine by BMA. These are approximately 400 m from the 1 m predicted drawdown contour line.

The uncertainty analysis shows that the maximum probable drawdown extent (Figure 6.10) includes this BMA monitoring bore network. Whilst predicted drawdown at these monitoring bores is possible, the bores are not relied upon for water supply and they have been designed to monitor for mine related impact to the groundwater regime. On this basis impacts to third party groundwater users is unlikely and the proposed monitoring program (Section 7) will ensure that third-party bores are not put at undue risk by the Project.

6.4. Impacts on surface drainage

In Section 5.5.1 (Figure 5.3) the mechanism of recharge from surface water systems in the Project area was presented. Further discussion of the surface – groundwater interaction followed in Section 5.6 and it was concluded that there was no significant surface-groundwater interaction in the Project area.

Further, surface watercourses in the model were represented by RIV cells that are a more flexible option than DRN cells. This is because RIV cells allow groundwater inflow or outflow (depending on the relationship between surface water and groundwater heads) whereas DRN cells only allow groundwater outflow.

The predicted changes in modelled groundwater in- or out-flow from/to river (RIV) cells due to the Project only were shown in Figure 6.6. These changes, calculated as the difference between the 'mine' and 'no mine' scenarios, are due to the Project only and are generally less than 0.1 m^3/d (or 100 L/d) over the entire model domain and are therefore considered negligible. For these reasons impacts on surface waters are considered extremely unlikely.

6.5. Impacts on GDEs

Figure 6.11 shows the maximum predicted drawdowns anytime during the modelling and the location of mapped aquatic GDEs (same as Figure 5.8). The modelled drawdown in layer 2 would be considered representative of impact to the groundwater table and the shallowest aquifer.

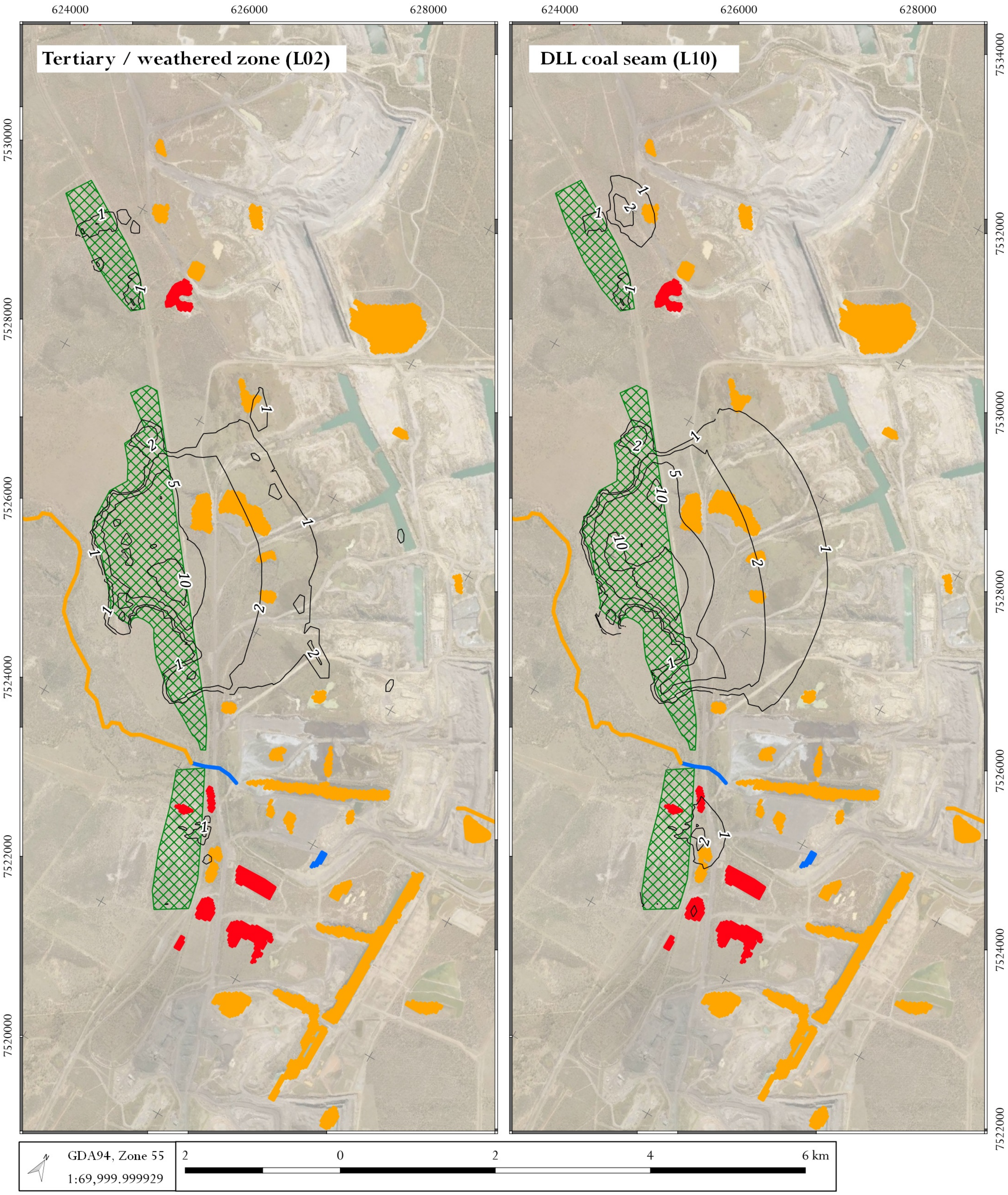
While there are small pockets of high- and moderate potential aquatic GDEs shown within the maximum drawdown associated with the Vulcan Main pit, in Section 5.7.2 it was the interpretation of **hydrogeologist.com.au** that it is highly unlikely for aquatic GDEs to be present within 1 km of the proposed pits. This is because aquatic GDEs with high or moderate potential for groundwater interaction are most likely to occur in areas where the seasonally high groundwater potentiometric heads are above or close to the corresponding surface water heads. This is necessary to maintain a hydraulic gradient from the groundwater to surface water, or at least have a hydraulically 'connected' system. Within or adjacent to the Project area, the surface water systems are above the groundwater table (see Section 5.6) and the surface water system is hydraulically disconnected from the groundwater system.

In addition, groundwater in the Project area is brackish to saline and therefore unsuitable for the maintenance of freshwater GDEs (see Section 5.8 for further information on groundwater quality). Further, with the exception of Hughes Creek, aquatic GDEs associated with a number of separate wetlands along the Moranbah – Dysart Road, between Phillips Creek and Boomerang Creek, all appear to be manmade impoundments associated with Saraji Mine or pastoral properties.

Figure 6.12 shows maximum predicted drawdowns anytime during the modelling and the position of mapped terrestrial GDEs (same as Figure 5.9). Figure 6.12 indicates very small and insignificant overlaps between the drawdown affected areas and mapped terrestrial GDEs adjacent to the proposed pits.

As stated in Section 5.7.2, it is the experience of **hydrogeologist.com.au** that terrestrial GDEs with high or moderate potential for groundwater interaction are most likely to occur in areas where depth to groundwater is less than 10 m. Analysis of the depth to groundwater data surrounding the Project area identified that groundwater was typically recorded at levels deeper than 10 m (Figure 5.10) and likely to be outside of the accessible reach of Eucalypt vegetation. There is an area of mapped terrestrial GDEs associated with Hughes Creek which is located within an area where the depth to groundwater is less than 10 m. However, the predicted drawdown does not extend into this mapped area and as a result impacts to terrestrial GDEs are highly unlikely.

For the reasons stated above, **hydrogeologist.com.au** interprets that there are no valid aquatic or terrestrial GDEs within the maximum drawdown zones and impacts on GDEs are considered highly unlikely. The reader is directed to the Vulcan South – Ecological Impact Assessment report for further information regarding the presence of aquatic or terrestrial GDEs.



LEGEND

Proposed pit

Aquatic GDEs

- High potential GDE - from national assessment
- Low potential GDE - from national assessment
- Moderate potential GDE - from national assessment

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Maximum drawdown and aquatic GDEs

FIGURE No.
6.11

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
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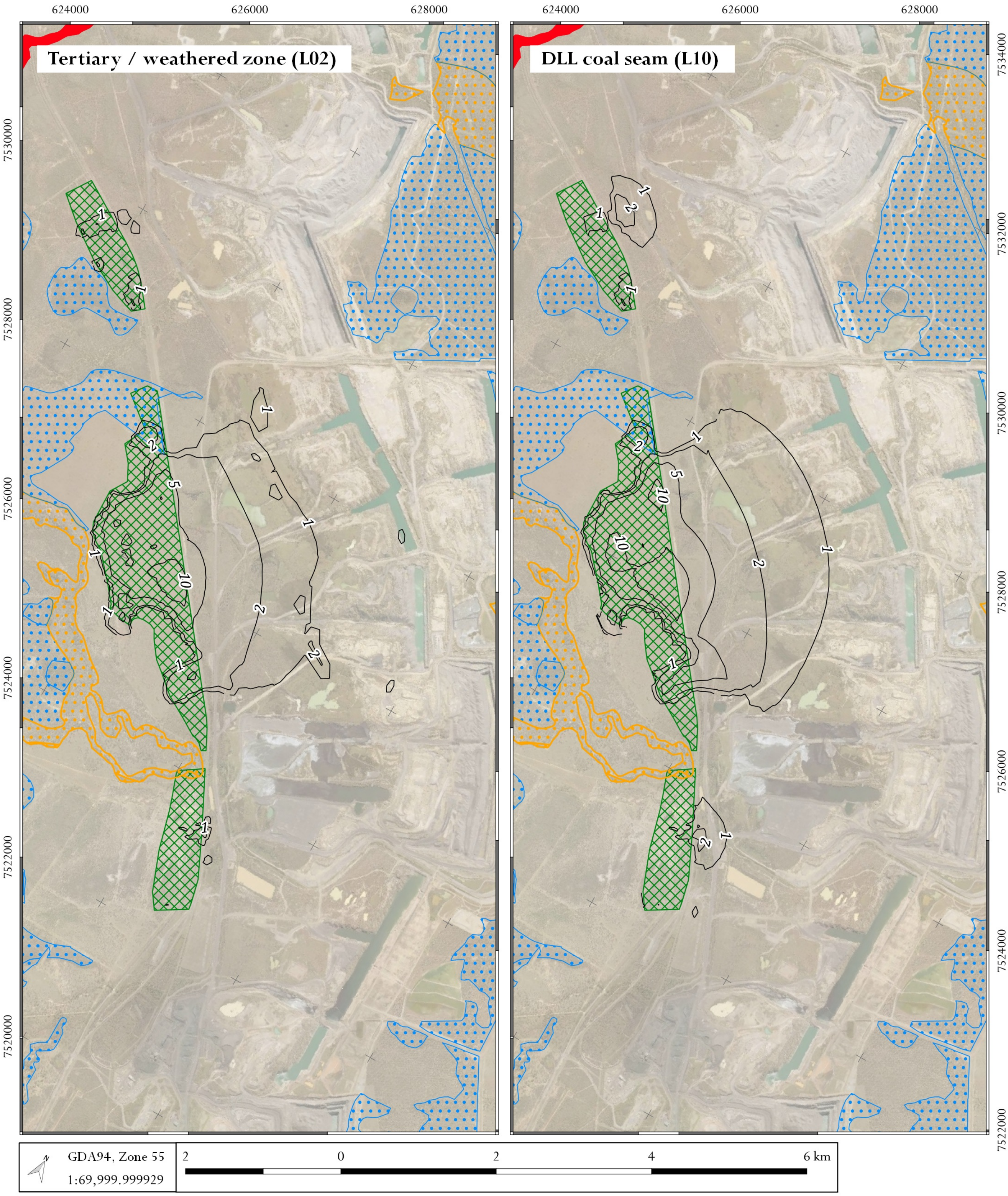

LEGEND

Proposed pit

Terrestrial GDEs

- High potential GDE - from national assessment
- Moderate potential GDE - from national assessment
- Low potential GDE - from national assessment

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22/02/2022

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Vulcan South - Groundwater Impact Assessment (4027)

Maximum drawdown and terrestrial GDEs

FIGURE No.
6.12

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\06_12_4027_Vulcan South_Max drawdown against terrestrial GDEs.qgz

6.6. Impacts on groundwater quality

During mining, the proposed pits and the Saraji Mine pits will act as sinks for surrounding groundwater. Any local contamination of the groundwater regime will report to the mine pit and will be contained during operations. The ex-pit and in-pit waste rock emplacement areas will be progressively rehabilitated during mine development and therefore no final voids or evaporative sinks will remain in the Project area. Groundwater is predicted to recover towards the pre-mining groundwater levels, subject to mining plans that include the adjacent Saraji and Peak Downs Mines. It is assumed that the pit voids at Saraji Mine and Peak Downs Mine will likely remain into perpetuity and will behave as regional evaporative sinks on the groundwater system hence minimising any eastward migration of potential contaminants.

The evaluation of groundwater EV in the Project area (Section 5.8.3) indicated that groundwater is of no, or limited value for most uses because of the high salinity. Local groundwater was found to be brackish to highly saline and even an unprecedented 50% increase in salinity would not impact on the beneficial uses identified (livestock beef cattle watering (limited); and industrial purposes, limited to dust suppression in mining). This is because the salinity of local groundwater is well in excess of the WQOs for aquatic ecosystems and drinking water suitability.

Therefore, the risk of groundwaters within the backfilled pit impacting on surrounding groundwater quality is highly unlikely.

All new mine infrastructure areas including workshops, fuel and chemical storage areas will include spill containment measures, for example bunding and / or spill kits. These structural and administrative controls will assist in preventing groundwater contamination. Impacts on groundwater quality, associated with local contamination from mine activities are considered highly unlikely.

6.7. Cumulative impacts

Cumulative impacts have been assessed by representing historical and proposed mining for the VCM, Saraji Mine and Peak Downs Mine, the latter have been active since the 1970s. The impacts of these approved mines have been predicted in isolation of the Project and in a cumulative sense through the development of the 'mine' vs 'no mine' model scenarios. For the purposes of this assessment, the cumulative impact on groundwater is represented in Figure 6.13. The graph shows the long-term model predicted inflows to the Saraji Mine and Peak Downs Mine with recent and proposed average annual inflow rates in the order of 3,000 m^3/day to 5,000 m^3/day. The proposed mining inflow rates correlate with AECOM (2016). The minimal inflow rates predicted for the Project (maximum inflow rate of 43 m^3/d) represent less than a 1% increase in groundwater seepage within the model domain.

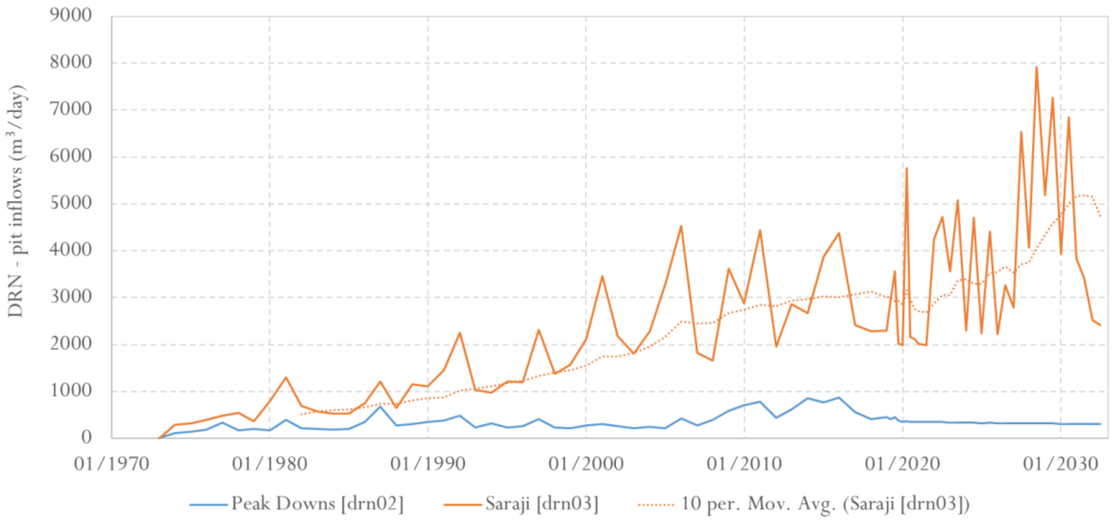

Figure 6.13 Predicted inflow rates – Saraji Mine and Peak Downs Mine

7. Management and mitigation

7.1. Licensing

The proposed pits will intercept groundwater from Groundwater Unit 2 (sub-artesian aquifers) under the Water Plan (Fitzroy Basin) 2011. The predicted take of groundwater, based on the numerical model (Section 6.2.1) and the life of the Project, will involve allocation of up to 14.1 ML/year from Groundwater Unit 2. This annual inflow rate was calculated as the product of the maximum daily inflow, 43 m^3/d (Figure 6.5) over the modelled stress periods.

Post mining there will be no requirement for a perpetual water licence as the pit will be progressively backfilled. No final void will remain in the Project area and therefore no evaporative sink will act on the groundwater regime. Groundwater is predicted to recover towards the pre-mining groundwater levels, subject to on-going mining that may occur at Saraji Mine and Peak Downs Mine.

7.1. Adaptive management strategy

The following section summarises the proposed framework for the on-going Groundwater Management Strategy to be developed to assist with the management and mitigation of drawdown and potential water quality impacts.

7.1.1. Drawdown

The predicted drawdown resulting from the Project is shown in Figure 6.7, Figure 6.8 and Figure 6.10. Section 6.2.3 discusses and summarises the extent and magnitude of drawdown, and Section 6.3 through to Section 6.7 discuss the resulting impacts of this predicted drawdown on the surrounding environment.

The groundwater monitoring network (Section 5.3 and Appendix A) established by **hydrogeologist.com.au** (2019) is considered fit for purpose for this assessment, and will form the basis for ongoing drawdown monitoring and management through the life of the Project. A number of the Project area monitoring bores will be disturbed by mining operations and replacement monitoring bores will be established to enable long term monitoring. Any replacement monitoring bore will also need to be representative and consider the potential contaminant sources. The groundwater monitoring network may be regularly amended to ensure it remains representative of groundwater conditions and fit for purpose.

Monitoring of groundwater levels from the groundwater monitoring network will enable natural groundwater level fluctuations (such as responses to rainfall recharge) to be distinguished from potential groundwater level impacts (drawdown) due to dewatering/depressurisation resulting from proposed mining activities. Automatic data loggers are currently installed in the groundwater monitoring network and they will continue to be used to enable daily measurements. These data loggers should be downloaded quarterly to coincide with groundwater quality sampling.

Queensland government monitoring bore RN13040283 is located adjacent to the Project area. Pending access to the bore, quarterly groundwater level monitoring of this bore would also provide benefit in understanding the regional behaviour of the groundwater regime in relation to mining.

A number of the site-specific monitoring bores are situated within (or adjacent to) the predicted drawdown zone. Other site-specific monitoring bores are distant from the proposed VS Vulcan pits, however groundwater level data from all monitoring bores within the groundwater monitoring network will be assessed in an annual comparison between actual and modelled drawdowns. This annual comparison and assessment will be completed in consideration of the DES (2021) guidelines for *using monitoring data to assess groundwater quality and potential environmental impacts*. This assessment will allow for verification of the numerical model predictions.

Private water supply bore RN 162506 is the nearest third party bore to the Vulcan pits. The bore is located in excess of 10 km from the predicted impact of drawdown. Pending agreement to access the bore, quarterly groundwater level monitoring of this bore would provide benefit in understanding the regional behaviour of the groundwater regime in relation to mining. Any Project related impacts at RN 162506 would be mitigated through Make Good Provisions under the Water Act (see Section 2.1.1).

There is merit in a groundwater data sharing arrangement between Vitrinite and BMA. Routine groundwater level and quality monitoring from Saraji Mine and Peak Downs Mine would provide Vitrinite with a greater understanding of the hydrogeological system responses during mining.

Given the low pit inflow predictions, limited extent of drawdown and unlikely impacts on the groundwater regime, regular updates to the numerical model are not likely to be required. However, it will be important to compare and assess on an annual basis the groundwater level observations against the modelled predictions to verify that observations are consistent with model outputs.

Every three years, consideration will be given for the redevelopment and or recalibration of the numerical groundwater model. Any such redevelopment or recalibration of the numerical groundwater model may require an iterative review of the conceptual hydrogeological model. This may result from measuring hydraulic responses that are inconsistent with the conceptual understanding or model predictions, changes to the mine plan, or modification of potential contamination sources.

The reporting obligations proposed as part of on-going Groundwater Management Strategy will be defined as conditions in the EA.

7.1.2. Groundwater quality

Quarterly groundwater quality monitoring and sampling of the groundwater monitoring network will continue in order to provide longer term baseline data for the formulation of site-specific triggers. The groundwater quality parameters to be monitored will be consistent with those provided in Appendix A, which have been developed in consideration of the DES (2017) Guideline: Model mining conditions. The monitoring and sampling will be carried out in consideration of DES (2018a).

Interim guidelines can be developed using the existing water quality dataset from the groundwater monitoring network and defined in the EA. The definition of compliance and reference sites in respect to target formations will be provided during the development of the interim guidelines which will be carried out in consideration of DES (2021).

Once interim triggers are established, groundwater quality data during operations will be compared to these interim trigger values, and potential exceedances will be investigated and reported. Once 12 to 24 months of groundwater quality data is available from the groundwater monitoring network the interim guidelines will be replaced with a series of groundwater trigger levels and contaminant limits. These groundwater trigger levels, and contaminant limits will be developed in consideration of DES (2021). The regulatory reporting obligations and conditions will be defined in the EA.

7.1.3. Summary

In summary, an adaptive management strategy is proposed to assist with the management and mitigation of drawdown and potential water quality impacts. The framework of the adaptive management strategy includes the following iterative components which will be defined in the EA:

- Acceptance of the groundwater monitoring network to include the site-specific monitoring bores, Queensland government monitoring bore RN 13040283 and private water supply bore RN 162506.
- Development of interim groundwater quality guidelines (in consideration of DES [2021]). These guidelines will be derived from the current dataset and would be included as conditions in the EA.
- Quarterly groundwater sample collection, level measurement and datalogger download.

- Development of groundwater trigger levels and contaminant limits once 12 to 24 months of groundwater quality data is available, to be included as amended conditions in the EA.
- Develop a suitable WMP for the Project that includes consideration of groundwater.
- Annual assessment of the suitability of the groundwater monitoring network for the Project to provide a representative and spatially adequate understanding of the groundwater regime.
- Annual assessment of groundwater level and quality data in consideration of DES (2021).
- Every three years consider the requirement to redevelop, and or recalibrate the numerical groundwater model.

7.2. Mitigation measures

No mitigation measures are currently proposed or required as part of the Project. There are no impacts predicted for third party groundwater users and surface water systems. Impacts to GDEs are considered highly unlikely as are impacts on groundwater quality and EV. Should monitoring and subsequent assessment determine potential impacts, mitigation strategies would be considered commensurate with the level and risk of environmental impact.

8. Conclusions

hydrogeologist.com.au has prepared a groundwater impact assessment to support the EA application for the Project. The Project is to the immediate west of the BMA Saraji Mine and Peak Downs Mine. The Project involves the open cut mining of coal from the DLL coal seam of the Permian Moranbah Coal Measures from three individual pits, and mining of the MAT coal seam in the Highwall Mining Area.

The main hydro-stratigraphic units occurring at the Project area include the Tertiary sediments or weathered zone (regolith) and the Permian coal measures. There is no Quaternary alluvium present within the Project area; however, it remains an important regional hydro-stratigraphic unit. The Permian DLL coal seam is partially / variably saturated over the Project area and the pit will intersect the regional groundwater table which has been historically depressurised by mining at Saraji Mine and Peak Downs Mine. A portion of mining will occur above the regional groundwater table. The highwall mining is not expected to intersect groundwater and is in an area of coal that is unsaturated.

Groundwater quality within the mined coal seam (and within other hydro-stratigraphic units) is generally brackish to saline and this is consistent with other mine sites in the region. The groundwater quality within the Project area has limited or no environmental value and potentially may be used for livestock beef cattle watering and / or industrial purposes (such as dust suppression in mining).

The groundwater quality is considered too saline to support aquatic GDEs and the depth to groundwater is generally considered too deep to support terrestrial GDEs. There are limited third party groundwater users in the region and Vitrinite has developed a clear understanding of where these third-party groundwater bores are located.

A numerical groundwater flow model has been developed to support the groundwater impact assessment and has been undertaken in accordance with relevant Australian guidelines. The model is assessed to be a reliable and acceptable simulator of historical mining activities and of groundwater level behaviour in and surrounding the Project area. Future predictions have been made by representing proposed mining at Saraji Mine and Peak Downs Mine, and the proposed mining schedule for the Project.

The model predictions show limited pit inflows (less than 43 m^3/day) to the pit and it is likely that most of the predicted inflows would be lost through evaporation on the pit face or as entrained moisture within the mined coal. Hence seepage to the pit is unlikely to be observed during the Project's life. The drawdown predicted from the Project is limited in extent (maximum up to 2,000 m to the east toward existing mining) and magnitude (up to 10 m in the deepest part of the Vulcan Main pit. The model demonstrates that given the variable saturation of the mined coal seam, some of the proposed pits will not be affected by drawdown as the coal seam is known to be unsaturated. Calibration constrained, null space Monte Carlo stochastic method uncertainty analysis has been carried out for the groundwater impact assessment. This uncertainty analysis has been completed in consideration of the IESC guidelines and confirms minimal inflows reporting to the pit, and limited drawdown extent and magnitude.

The extent of predicted drawdown does not encroach on any of the third-party groundwater users in the region and therefore impacts in this regard are considered very unlikely. The model predicts negligible change in the water balance components that represent surface water discharge and as a result impacts on surface waters are considered very unlikely. It is the assessment of hydrogeologist.com.au that there are no valid aquatic or terrestrial GDEs within the maximum drawdown zones and impacts on GDEs are considered very unlikely. Furthermore, impacts on groundwater quality are assessed to be very unlikely and there would need to be an unprecedented change in salinity to affect the current beneficial use and environmental values of the groundwater regime.

An adaptive management strategy is proposed for the Project to assist with the management and mitigation of drawdown and potential water quality impacts. The framework of the strategy includes iterative components which will be defined as conditions in the EA.

9. References

AECOM (2016). Groundwater Technical Report, Saraji Open Cut Extension Project prepared for BM Alliance Coal Operations Pty Ltd.

Arrow Energy (2012). 2012 Bowen Basin 2D Seismic Survey Report ATP1103 & ATP1031.

Arrow Energy (2016). Underground Water Impact Report for PL 191, 196, 223, 224 and Authority to Prospect 1103, 742, 831 and 1031. August 2016.

Arrow Energy (2019). Underground Water Impact Report for PL 191, 196, 223, 224 and Authority to Prospect 742, 1031 and 1103. 4 April 2019.

Australasian Groundwater and Environmental Consultants Pty Ltd, (2007). Report on Hydrogeological Regime and Impact Assessment Saraji Mine, Project No. G1387, December 2007

Australasian Groundwater and Environmental Consultants Pty Ltd, (2011). Report on Saraji East Project Groundwater Impact Assessment, Project No. G1549, December 2011

Australasian Groundwater and Environmental Consultants Pty Ltd, (2012a). Australian Groundwater & Environmental Consultants Memorandum – Predicted Inflows and Drawdown Extents – Saraji East Underground Mine, ref. G1549, dated 24 February 2012

Australian and New Zealand Guidelines for Fresh and Marine Water Quality (AWQG, October 2000), prepared by the Australian and New Zealand Environment and Conservation Council (ANZECC) and the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ).

Australian and New Zealand Guidelines for Fresh and Marine Water Quality (AWQG, 2018), prepared by the Australian and New Zealand Environment and Conservation Council (ANZECC) and the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ). https://www.waterquality.gov.au/guidelines/anz-fresh-marine

Barnett B, Townley LR, Post V, Evans RE, Hunt RJ, Peeters L, Richardson S, Werner AD, Knapton A and Boronkay A. (2012). Australian groundwater modelling guidelines, Waterlines report, National Water Commission, Canberra.

Bureau of Meteorology. (2016). "Australian Climate Averages - Climate Classifications." November 2016. http://www.bom.gov.au/jsp/ncc/climate_averages/climate-classifications/index.jsp.

CDM Smith (2013). Westside Corporation, Underground Water Impact Report ATP688. https://environment.des.qld.gov.au/management/non-mining/documents/westside-report

CSIRO (2002). Acarp Project C9021. Exploration and Mining Report 976c. Bowen Basin Supermodel 2000. Open report, August 2002, CSIRO Exploration and Mining Report.

Department of Environment and Heritage Protection (2009). Queensland Water Quality Guidelines, Version 3, ISBN 978-0-9806986-0-2.

Department of Environment and Heritage Protection (2011). Environmental Protection (Water) Policy 2009 Isaac River Sub-basin Environmental Values and Water Quality Objectives Basin No. 130 (part), including all waters of the Isaac River Sub-basin (including Connors River). September 2011.

Department of Environment and Science, (2016). "Guideline – Environmental protection Act 1994 – Requirement for site specific and amendment applications – underground water rights", ESR/2016/3275, Version 1.00, Effective: 06 Dec 2016.

Department of Environment and Science (2017). Guideline. Environmental Protection (Water) Policy 2009. Model mining conditions, March 2017, version 6.02.

Department of Environment and Science (2018a). Environmental Protection (Water) Policy 2009. Monitoring and Sampling Manual, June 2018, version 2.

Department of Environment and Science (2018b). Guideline. Environmental Protection (Water) Policy 2009. Deciding aquatic ecosystem indicators and local water quality guidelines, December 2018, draft.

Department of Environment and Science (2021). Using monitoring data to assess groundwater quality and potential environmental impacts. Version 2. February 2021.

Doherty, J., (2012). Windows BEOPEST.

Doherty, J., (2019a). Groundwater Data Utilities; Part C: Programs Written for Unstructured Grid Models.

Doherty, J., (2019b). PEST - Model-Independent Parameter Estimation; user manual Part I: PEST, SENSAN and Global Optimisers.

Doherty, J., (2019c). PEST - Model-Independent Parameter Estimation; User manual Part II: PEST Utility Support Software.

Geoscience Australia (2019). Bowen Basin https://www.ga.gov.au/scientific-topics/energy/province-sedimentary-basin-geology/petroleum/onshore-australia/bowen-basin visited on 1 August 2019.

Hvorslev, M.J., (1951). Time lag and soil permeability in ground water observations, U.S. Army Corps of Engineers Waterway Experimentation Station, Bulletin 36.

hydrogeologist.com.au (2019). Hydrogeological Drilling Report – Vulcan Complex Project. Prepared for Vitrinite Coal Pty Ltd.

HydroSimulations (2018). Olive Downs Coking Coal Project Groundwater Assessment for Pembroke Olive Downs Pty Ltd

Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Information Guidelines for Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. http://www.iesc.environment.gov.au/system/files/pages/a55d4199-0218-4f91-a012-8613f62f9056/files/iesc-information-guidelines-consultation-draft.pdf

Jeffrey, Stephen J., John O. Carter, Keith B. Moodie, and Alan R. Beswick. (2001). "Using Spatial Interpolation to Construct a Comprehensive Archive of Australian Climate Data." Environmental Modelling & Software 16 (4): 309–30. https://doi.org/10.1016/S1364-8152(01)00008-1.

Mayer, XM, Ruprecht, JK & Bari, MA (2005). Stream salinity status and trends in south-west Western Australia, Department of Environment, Salinity and land use impacts series, Report No. SLUI 38.

Mining and Energy Technical Services Pty. Ltd. (METServe), (2022). Vulcan South - Ecological Impact Assessment, Prepared for Vitrinite Pty. ltd.

Office of Groundwater Impact Assessment (OGIA), (2016). Groundwater modelling report for the Surat Cumulative Management Area. State of Queensland. September 2016.

Panday, S., Langevin, C.D., Niswonger, R.G., Ibaraki, M., Hughes, J.D., (2015). MODFLOW-USG. U.S. Geological Survey. https://doi.org/10.5066/f7r20zfj

Panday, S., Langevin, C.D., Niswonger, R.G., Ibaraki, M., Hughes, J.D., (2013). MODFLOW–USG version 1: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation (No. Chapter 45 of Section A, Groundwater Book 6, Modeling Techniques), Techniques and Methods 6-A45. U.S. Geological Survey, Reston, Virginia, USA.

Pearce, Bruce R, and Hansen, James W. L. & Action Salinity & Water Australia & Queensland. Department of Natural Resources, Mines and Water. (2006). Hydrogeological investigation of the Fitzroy River sub-catchment, Central Queensland, Australia, Dept. of Natural Resources, Mines and Water, Brisbane.

Queensland Government (2014). Water Plan (Fitzroy Basin) 2011 (https://www.legislation.qld.gov.au/view/pdf/2017-09-02/sl-2011-0283).

Queensland Government (2019). LongPaddock - SILO Point Datadrill; Queensland Government 2019. https://longpaddock.qld.gov.au/silo/point-data/.

Raymond, M. A. A. and V. H. McNeil. (2011). Regional Chemistry of the Fitzroy Basin Groundwater. Brisbane: Department of Environment and Resource Management, Queensland Government.

URS (2009). Caval Ridge Groundwater Impact Assessment, prepared for BM Alliance Coal Operations Pty Ltd.

URS, (2012). Groundwater Impact Assessment, Bowen Gas Project. Prepared for Arrow Energy Pty Ltd. Available: http://www.arrowenergy.com.au/__data/assets/pdf_file/0008/3869/Appendix- L_Groundwater-and-Geology-Technical-Report.pdf

URS (2014). Dysart East Coal project. Environmental Assessment Report, Groundwater Technical Report, for Bengal Coal Pty Ltd.

WRM Water and Environment Pty. Ltd. (WRM), (2022). Vulcan South - Surface Water Assessment, prepared for Vitrinite Pty. Ltd.

Xu, Y, and Gj Van Tonder. (2001). "Estimation of Recharge Using a Revised CRD Method." Water SA 27 (3): 341–43. https://doi.org/10.4314/wsa.v27i3.4977.

Zolfaghar, S, Villalobos-Vega, R, Cleverly, J, Zeppel, M, Rumman, R & Eamus, D (2014). 'The influence of depth-to-groundwater on structure and productivity of Eucalyptus woodlands', Australian Journal of Botany, vol. 62, no. 5, pp. 428-437.

Appendix A Hydrogeological Drilling Report – Vulcan Complex Project

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Hydrogeological Drilling Report – Vulcan Complex Project

Prepared for

Vitrinite Coal Pty Ltd

1. Introduction

This report describes the hydrogeological drilling program for the Vulcan Complex Project (the project). Vitrinite Coal Pty Ltd (Vitrinite Coal) propose to develop the project comprising two open cut coal pits (Vulcan and Jupiter) located in the northern part of the Bowen Basin, Central Queensland.

The project is located approximately 15 km to the south of the township of Moranbah, within Exploration Permit Coal (EPC) 1233 and EPC 1234. The project involves the open cut mining of coal from two main areas (Vulcan and Jupiter) and transport of coal to a modular coal handling and preparation plant (CHPP) and central mine infrastructure area (MIA). The open cut mining footprint including in-pit and out of pit spoil dumps will cover an area of approximately 2500 ha (Vulcan extent) and 750 ha (Jupiter extent).

A hydrogeological monitoring program is required to characterise and understand the groundwater resource in response to the mine development, a requirement of the environmental approvals process. This report documents the establishment of the hydrogeological monitoring network to support the project. This follows on from the proposed hydrogeological monitoring program developed by **hydrogeologist.com.au** which outlined the requirements and specifications of the drilling and bore installation program.

2. Monitoring bore drilling

Twelve (12) monitoring bores were drilled between the 29th of May and 7th of June 2019. The drilling of four monitoring bores (MB13 to MB16) in the Tay Glen area (to the south) was postponed due to changes in the project description and may be drilled at a later date. A Mayhew 1000 drilling rig from Wizard Drilling Pty Ltd was used to drill and install the monitoring bores under the supervision of licenced driller Andrew Holmes (Lic. No. 3383). Table 2.1 below summarises the monitoring bore construction details.

Table 2.1 Vulcan Complex monitoring bores – construction details

ID	Area	Easting	Northing	Target unit	Casing height (maGL)	Hole depth (mbGL)	Screen interval (mbGL)	Airlift yield (L/min)
MB1	Vulcan	625608	7529692	DLL coal seam	0.70	24.9	21.9 – 24.9	Dry
MB2	Jupiter	622515	7534485	DLL coal seam	0.71	12.0	9.0 – 12.0	Dry
MB3	Jupiter	622665	7535021	DLL coal seam	0.70	33.8	30.8 – 33.8	<0.1
MB4	Jupiter	622016	7536148	DLL coal seam	0.71	21.5	18.5 – 21.5	1
MB5	Jupiter	621965	7534904	MAT coal seam	0.77	40.9	37.9 – 40.9	0.5
MB6	Vulcan	628121	7526477	Weathered Permian	0.70	24.6	21.6 – 24.6	Dry
MB7	Vulcan	628692	7526260	Weathered Permian	0.67	43.0	40.0 – 43.0	0.1
MB8	Vulcan	628094	7527017	Weathered Permian	0.70	24.0	21.0 – 24.0	Dry
MB9	Vulcan	629511	7525225	DLL coal seam	0.65	34.4	31.4 – 34.4	0.1
MB10	Vulcan	628125	7526470	DLL coal seam	0.70	40.3	37.3 – 40.3	<0.1
MB11	Vulcan	627405	7527854	DLL coal seam	0.70	29.9	26.9 – 29.9	Dry
MB12	Vulcan	625252	7526409	Permian underburden	0.66	38.2	32.2 – 38.2	1

Notes: Easting and northing coordinates are in GDA94, Zone 55
maGL – metres above ground level
mbGL – metres below ground level

Figure 2.1 shows the locations of the Jupiter monitoring bores and Figure 2.2 shows the locations of Vulcan monitoring bores. All monitoring bores were completed with a lockable monument cover. With the exception of dry monitoring bores, all bores were developed by airlifting after completion. The bore logs for each monitoring bores are included in Appendix A.

LEGEND

Groundwater monitoring bore

- DLL coal seam
- MAT coal seam
- Permian underburden
- Tertiary

- Registered bore
- Mining lease (ML)
- Exploration permit coal (EPC)
- Watercourse, non-perennial

DATE
19/06/2019

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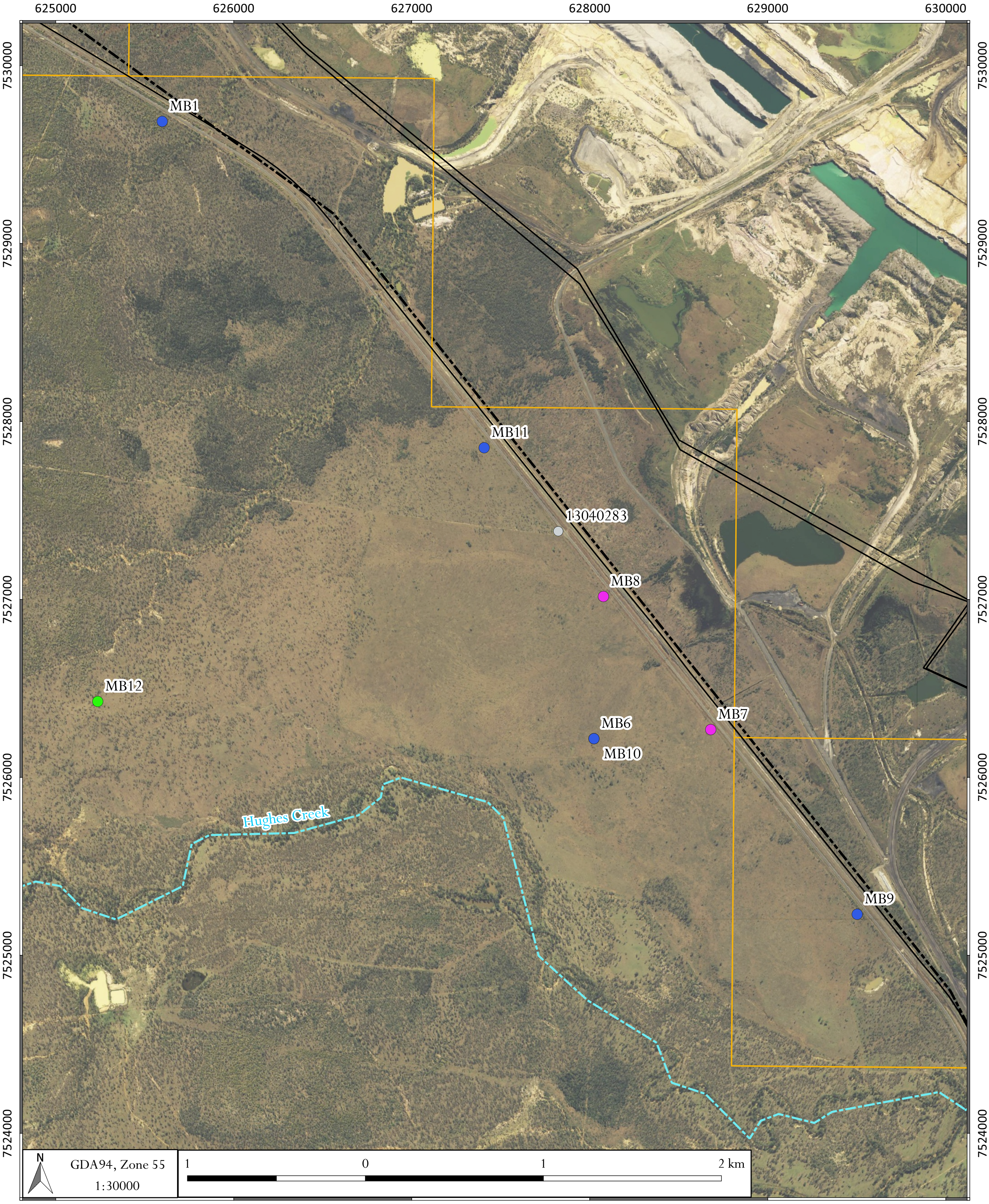
Vitrinite Coal - Hydrogeological Drilling Report – Vulcan Complex Project (4015)

Bore location plan - Jupiter

FIGURE No.
2.1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
C:\hydogeologist\4015_Saraji West\GIS\Workspaces\2_1_4015_Bore locations Jupiter_SatImage.qgz



LEGEND

Groundwater monitoring bore

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Bore location plan - Vulcan

FIGURE No.
2.2

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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3. Groundwater levels

Groundwater level measurements were recorded at each bore following construction and after airlift development. In some instances, the groundwater level measurement collected after airlift development was influenced by the development process and the low permeability of the intersected formation. The measured groundwater levels are summarised in Table 3.1.

Table 3.1 Vulcan Complex monitoring bores – groundwater levels

Bore ID	Elevation (mAHD)	Total depth (mbgl)	SWL (mbTOC)	SWL (mAHD)	Target unit
MB1	225	24.9	Dry	Dry	DLL coal seam
MB2	255	12.0	Dry	Dry	DLL coal seam
MB3	267	33.8	34.30	232.7	DLL coal seam
MB4	253	21.5	5.83	247.2	DLL coal seam
MB5	257	40.9	14.53	242.5	MAT coal seam
MB6	223	24.6	Dry	Dry	Weathered Permian
MB7	222	43.0	34.80	187.2	Weathered Permian
MB8	219	24.0	Dry	Dry	Weathered Permian
MB9	216	34.4	27.41	188.6	DLL coal seam
MB10	223	40.3	32.51	190.5	DLL coal seam
MB11	228	29.9	Dry	Dry	DLL coal seam
MB12	244	38.2	26.82	217.2	Permian underburden

Notes: mAHD – metres above Australian Height Datum
mbGL – metres below ground level
mbTOC – metres below top of casing

A total of five monitoring bores were dry following drilling and construction. It is expected that these bores will eventually recharge to provide a groundwater level however this will be confirmed during on-going monitoring.

The monitoring bores have not been surveyed at this stage. However, as the bores were constructed only 5 m to 10 m away from an exploration hole, the collar elevations for the nearby exploration hole were adopted for the monitoring bores.

The groundwater levels are generally between 185 mAHD and 220 mAHD for Vulcan, and 230 mAHD and 250 mAHD for Jupiter. The groundwater levels shown in Table 3.1 should be recognised as initial measurements only and on-going regular monitoring will define the baseline groundwater levels at the site.

In-situ dataloggers (LevelTROLL 400 with 60 psi range) have been installed in all monitoring bores and a barometric logger installed also in MB6. The dataloggers have been set to record every four hours.

Groundwater level data has been captured by Vitrinite from exploration drill holes at the project site. Figure 3.1 shows the groundwater flow contours (in mAHD) generated from this data and the general groundwater flow direction is from the north to the south and south-east. The groundwater level data captured from the exploration drill holes is generally consistent with the levels measured in the monitoring bores and demonstrates that groundwater flow generally follows topography.

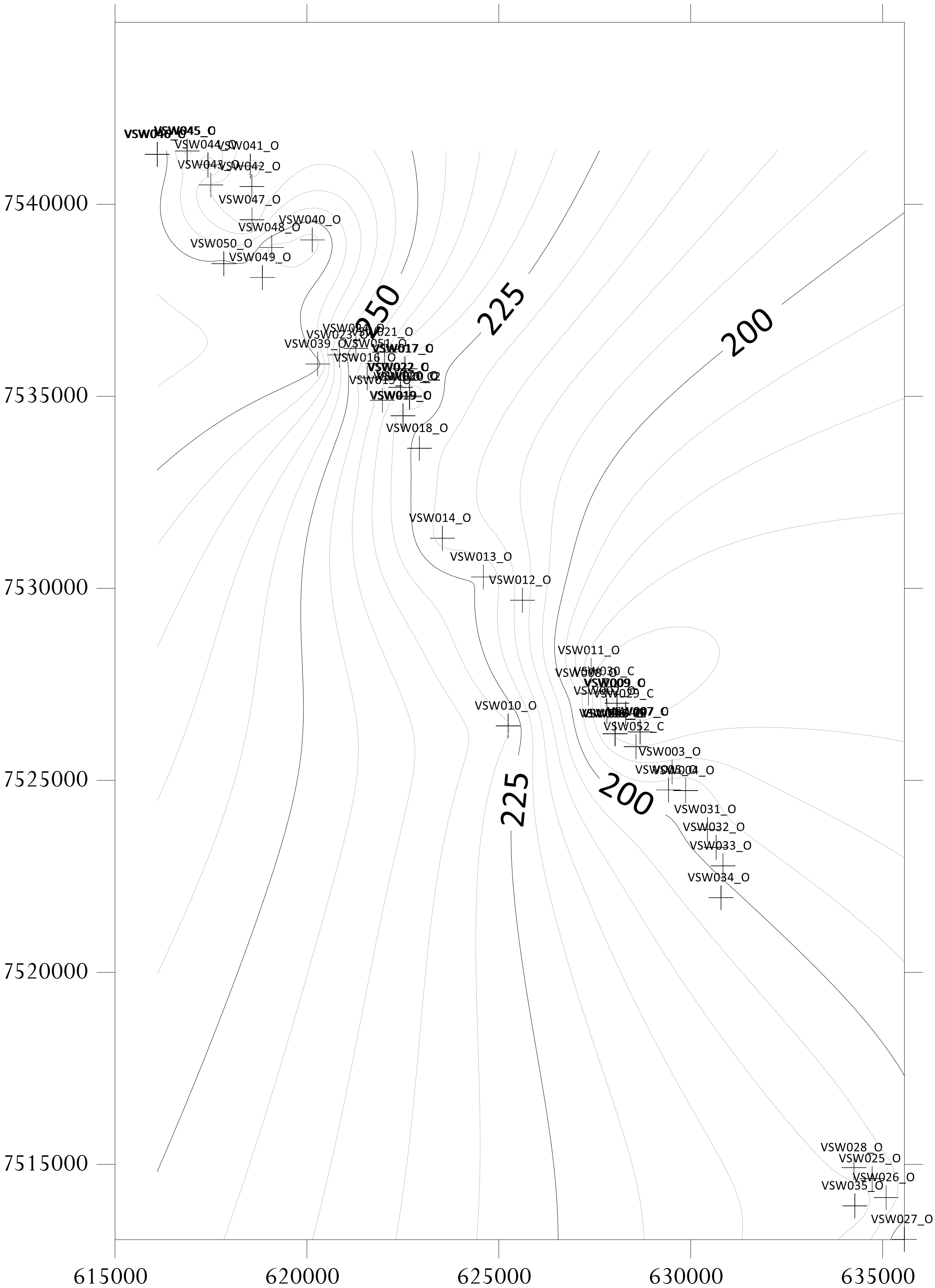

Figure 3.1 Groundwater flow contours (mAHD) from exploration drill hole data

4. Groundwater quality

The monitoring bores were airlifted by Wizard Drilling Pty Ltd following drilling and completion. A groundwater sample was taken at the end of the airlifting process. Most monitoring bores were airlifted and sampled on the 6th and 7th June after completion of the drilling program, however five monitoring bores remained dry and two monitoring bores did not yield sufficient groundwater during the airlifting process to recover a sample to surface. Table 4.1 summarises the field groundwater quality from the Vulcan Complex monitoring bores.

Table 4.1 Vulcan Complex monitoring bores – groundwater quality

Bore ID	EC - field (µS/cm)	EC - lab (µS/cm)	pH - field	pH - lab	Temp – field (°C)	Target unit	Comments
MB1	-	-	-	-	-	DLL coal seam	Dry
MB2	-	-	-	-	-	DLL coal seam	Dry
MB3	-	-	-	-	-	DLL coal seam	Insufficient water to develop, no sample taken
MB4	2520	2280	7.92	7.94	18.2	DLL coal seam	Clear, slightly yellow
MB5	2960	2680	8.55	8.17	19.0	MAT coal seam	Clear
MB6	-	-	-	-	-	Weathered Permian	Dry
MB7	5680	5430	8.78	8.31	18.9	Weathered Permian	Muddy, yellow brown
MB8	-	-	-	-	-	Weathered Permian	Dry
MB9	5520	16200	8.58	7.95	19.4	DLL coal seam	Very cloudy, yellow brown
MB10	-	-	-	-	-	DLL coal seam	Insufficient water to develop, no sample taken
MB11	-	-	-	-	-	DLL coal seam	Dry
MB12	22800	21600	8.29	7.81	19.0	Permian underburden	Slightly cloudy, olive grey

Notes: *EC – electrical conductivity*

The laboratory results for electrical conductivity (EC) and pH generally confirm the field measurements. Field EC of the groundwaters ranges from about 2500 µS/cm to 23000 µS/cm, and as such the groundwater is classified as moderately saline to saline. The field EC measurement for MB9 did not compare well with the laboratory measurement and this is considered due to the very small volumes of groundwater being discharged from the bore during airlifting. On-going monitoring and sampling will confirm the groundwater salinity. The field pH ranges from 7.9 to 8.8 and is slightly alkaline.

Groundwater salinity is important to understanding for water management and use. Salinity can be generally categorised by total dissolved solids (TDS) concentrations and the following salinity ranges are commonly used:

- Fresh 0 to 500 mg/L (0 to 750 µS/cm)
- Brackish 500 to 1500 mg/L (750-2500 µS/cm)
- Moderately saline 1500 to 7000 mg/L (2500-10000 µS/cm)
- Saline 7000 to 15000 mg/L (10000-25000 µS/cm)

Typically, groundwater quality will change as water migrates through the groundwater system. Salinity and EC can be used to infer both residence time in the aquifer and also proximity to the recharge source. For example, groundwater with an EC of less than 500 µS/cm will be closer to the recharge source and will have a shorter residence time in the aquifer, whereas groundwater of 5000 µS/cm will be further from the recharge source and will have a greater residence time.

Samples were collected in the field using laboratory supplied containers. The samples were field filtered where required using either disposable syringes and 45 micron disc filters, or steri-cups and vacuum pump for the more turbid samples. The samples were immediately stored on ice and refrigerated were possible. All samples were freighted on ice under a chain of custody (CoC) with TNT in laboratory supplied eskies. The samples were delivered directly to ALS (Mackay) and analysed at ALS (Brisbane), a NATA certified laboratory.

Laboratory certificates for all groundwaters are included in Appendix B. The laboratory water quality results of all groundwaters are summarised in Table 4.2 for major ions, Table 4.3 for dissolved metals; and Table 4.4 for total metals.

A piper diagram is presented in Figure 4.1 and extended Durov diagram presented in Figure 4.2 which shows the distribution of water types in the project area. The groundwaters are Sodium (Na) dominant with dominant Chloride (Cl) and minor bicarbonate (HCO_3) and sulphate (SO_4) anions.

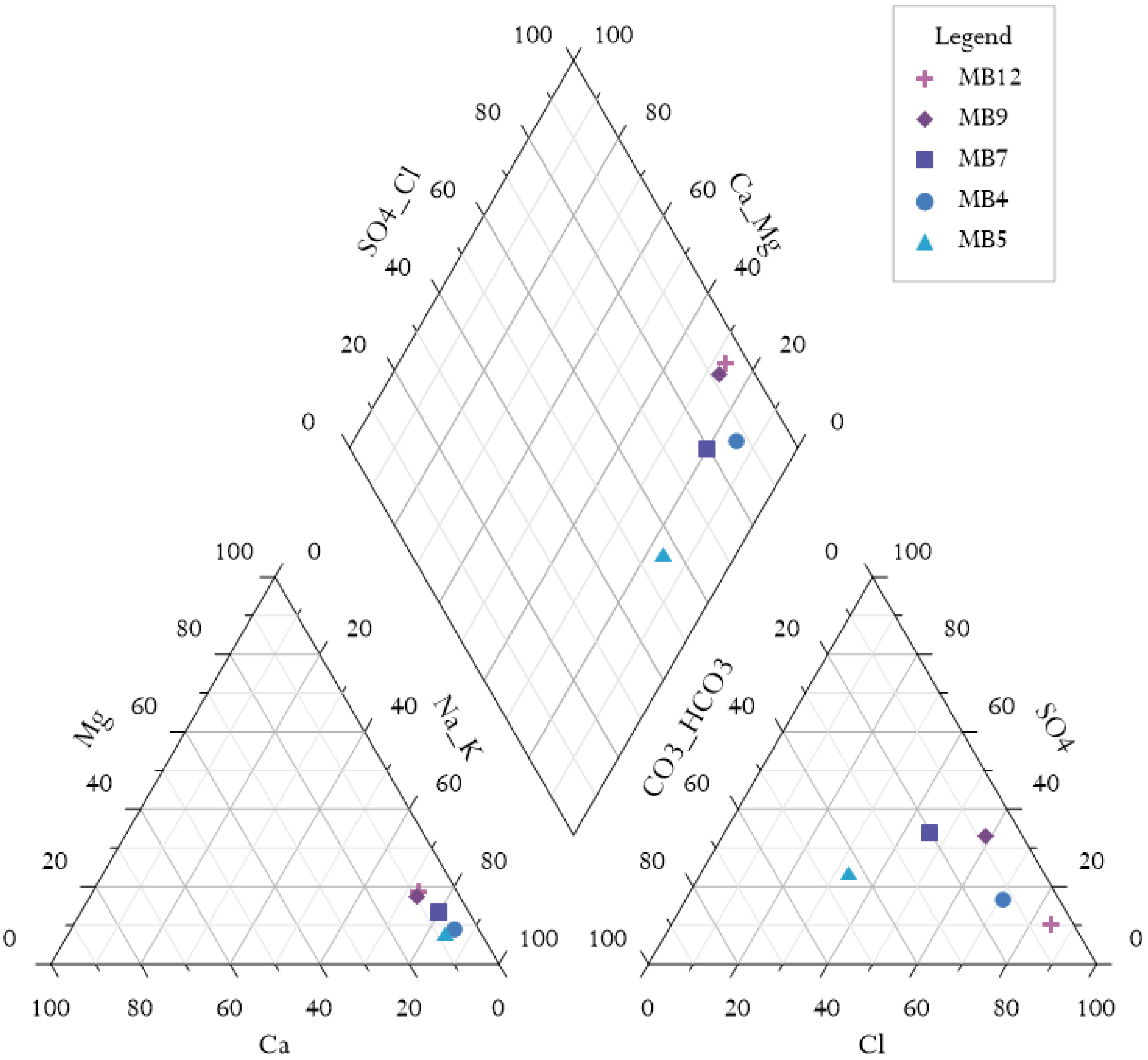

Figure 4.1 Piper diagram

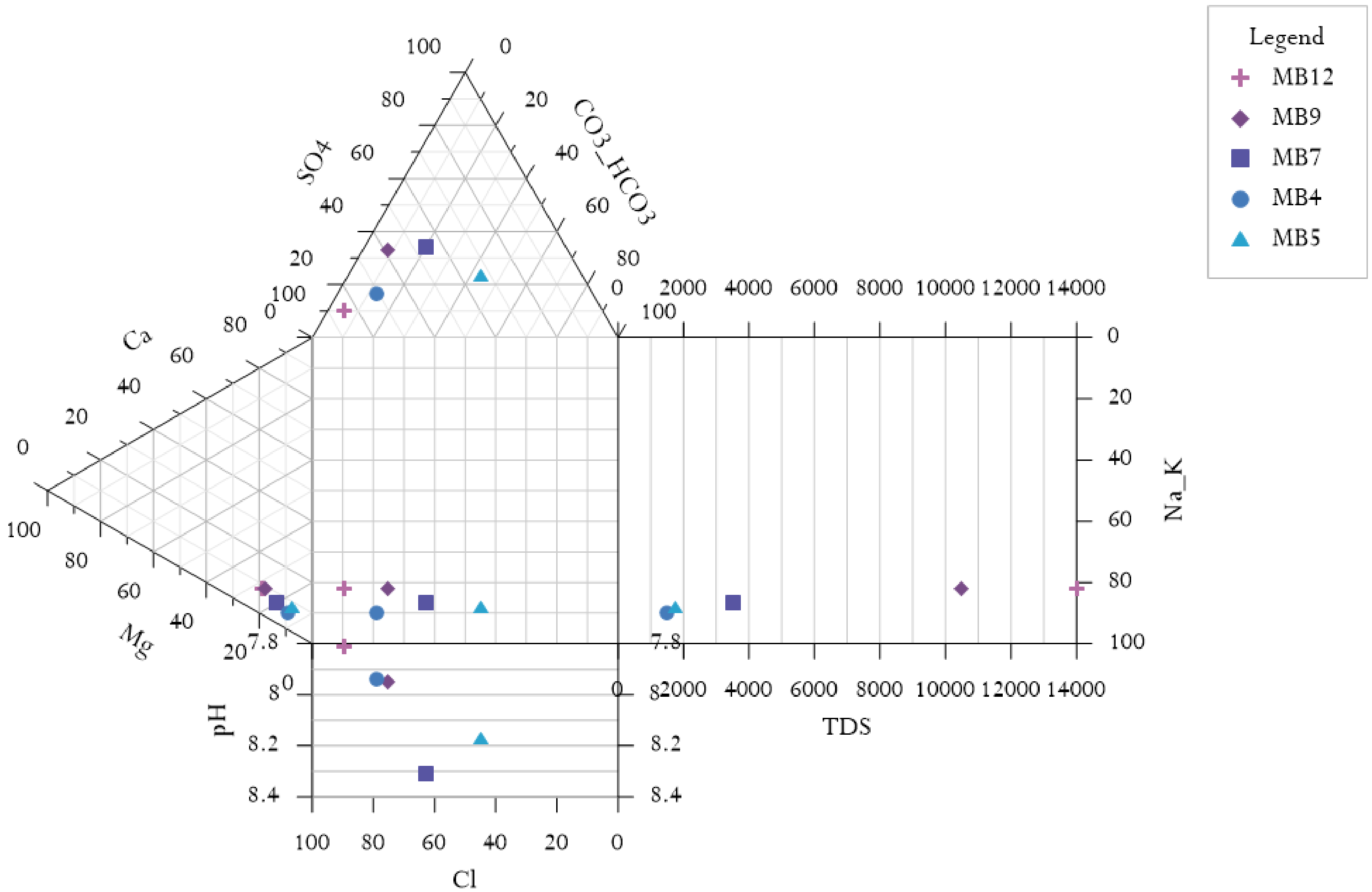

Figure 4.2 Extended Durov diagram

Table 4.2 Laboratory water quality data – major ions

Analyte grouping/Analyte	CAS Number	Unit	Limit of reporting	EB1915096001	EB1915096002	EB1915096003	EB1915096004	EB1915096005
			Sample Date:	06/06/2019	06/06/2019	06/06/2019	07/06/2019	07/06/2019
			Client sample ID (1st):	MB12	MB9	MB7	MB4	MB5
EA005P: pH by PC Titrator								
pH Value		pH Unit	0.01	7.81	7.95	8.31	7.94	8.17
EA006: Sodium Adsorption Ratio (SAR)								
Sodium Adsorption Ratio			0.01	22.1	20.0	14.4	10.9	12.5
EA010P: Conductivity by PC Titrator								
Electrical Conductivity @ 25°C		µS/cm	1	21600	16200	5430	2280	2680
EA016: Calculated TDS (from Electrical Conductivity)								
Total Dissolved Solids (Calc.)		mg/L	1	14000	10500	3530	1480	1740
EA065: Total Hardness as CaCO3								
Total Hardness as CaCO3		mg/L	1	4710	3780	905	242	345
ED037P: Alkalinity by PC Titrator								
Hydroxide Alkalinity as CaCO3	DMO-210-001	mg/L	1	<1	<1	<1	<1	<1
Carbonate Alkalinity as CaCO3	3812-32-6	mg/L	1	<1	<1	4	<1	<1
Bicarbonate Alkalinity as CaCO3	71-52-3	mg/L	1	468	632	486	108	550
Total Alkalinity as CaCO3		mg/L	1	468	632	490	108	550
ED041G: Sulfate (Turbidimetric) as SO4 2- by DA								
Sulfate as SO4 - Turbidimetric	14808-79-8	mg/L	1	908	2580	819	140	293
ED045G: Chloride by Discrete Analyser								
Chloride	16887-00-6	mg/L	1	7650	4590	1100	603	416
ED093F: Dissolved Major Cations								
Calcium	7440-70-2	mg/L	1	408	369	87	26	54
Magnesium	7439-95-4	mg/L	1	897	694	167	43	51
Sodium	7440-23-5	mg/L	1	3490	2820	997	389	534
Potassium	7440-09-7	mg/L	1	19	73	8	16	17
EG052F: Dissolved Silica by ICPAES								
Silicon as SiO2	14464-46-1	mg/L	0.1	22.5	27.8	24.2	12.7	21.8
EK040P: Fluoride by PC Titrator								
Fluoride	16984-48-8	mg/L	0.1	0.3	0.7	0.8	1.0	0.3
ED009: Anions								
Bromide	24959-67-9	mg/L	0.010	14.8	10.1	2.60	1.09	0.980
EN055: Ionic Balance								
Total Anions		meq/L	0.01	244	196	57.9	22.1	28.8
Total Cations		meq/L	0.01	246	200	61.6	22.2	30.6
Ionic Balance		%	0.01	0.49	1.07	3.17	0.19	2.91

Table 4.3 Laboratory water quality data – dissolved metals

			ALS Sample Number:	EB1915096001	EB1915096002	EB1915096003	EB1915096004	EB1915096005
			Sample Date:	06/06/2019	06/06/2019	06/06/2019	07/06/2019	07/06/2019
			Client sample ID (1st):	MB12	MB9	MB7	MB4	MB5
Analyte grouping/Analyte	**CAS Number**	**Unit**	**Limit of reporting**					
Aluminium	7429-90-5	mg/L	0.01	0.04	0.01	0.02	<0.01	0.02
Antimony	7440-36-0	mg/L	0.001	0.002	<0.001	<0.001	<0.001	<0.001
Arsenic	7440-38-2	mg/L	0.001	0.002	0.001	0.001	<0.001	<0.001
Beryllium	7440-41-7	mg/L	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Barium	7440-39-3	mg/L	0.001	0.143	0.100	0.070	0.094	0.028
Cadmium	7440-43-9	mg/L	0.0001	<0.0001	0.0005	<0.0001	<0.0001	<0.0001
Chromium	7440-47-3	mg/L	0.001	<0.001	0.001	<0.001	<0.001	<0.001
Cobalt	7440-48-4	mg/L	0.001	0.008	0.004	0.004	0.004	<0.001
Copper	7440-50-8	mg/L	0.001	0.001	0.022	<0.001	<0.001	<0.001
Lead	7439-92-1	mg/L	0.001	0.001	<0.001	<0.001	<0.001	<0.001
Manganese	7439-96-5	mg/L	0.001	0.173	0.264	0.384	0.820	0.019
Molybdenum	7439-98-7	mg/L	0.001	0.003	0.003	0.007	<0.001	<0.001
Nickel	7440-02-0	mg/L	0.001	0.012	0.010	0.003	0.006	0.002
Selenium	7782-49-2	mg/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Silver	7440-22-4	mg/L	0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Strontium	7440-24-6	mg/L	0.001	6.27	8.28	1.69	0.171	0.392
Uranium	7440-61-1	mg/L	0.001	0.008	0.030	0.016	0.001	0.001
Vanadium	7440-62-2	mg/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	7440-66-6	mg/L	0.005	1.17	0.116	<0.005	<0.005	0.056
Boron	7440-42-8	mg/L	0.05	0.63	1.08	0.66	0.13	0.21
Iron	7439-89-6	mg/L	0.05	<0.05	<0.05	<0.05	0.36	<0.05
Mercury	7439-97-6	mg/L	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 4.4 Laboratory water quality data – total metals

			ALS Sample Number:	EB1915096001	EB1915096002	EB1915096003	EB1915096004	EB1915096005
			Sample Date:	06/06/2019	06/06/2019	06/06/2019	07/06/2019	07/06/2019
			Client sample ID (1st):	MB12	MB9	MB7	MB4	MB5
Analyte grouping/Analyte	**CAS Number**	**Unit**	**Limit of reporting**					
Aluminium	7429-90-5	mg/L	0.01	1.61	8.38	16.5	0.12	0.65
Antimony	7440-36-0	mg/L	0.001	0.002	<0.001	<0.001	<0.001	<0.001
Arsenic	7440-38-2	mg/L	0.001	0.004	0.004	0.022	<0.001	<0.001
Beryllium	7440-41-7	mg/L	0.001	<0.001	0.001	0.004	<0.001	<0.001
Barium	7440-39-3	mg/L	0.001	0.168	0.125	0.664	0.108	0.036
Cadmium	7440-43-9	mg/L	0.0001	<0.0001	0.0006	<0.0001	<0.0001	<0.0001
Chromium	7440-47-3	mg/L	0.001	0.004	0.034	0.032	<0.001	<0.001
Cobalt	7440-48-4	mg/L	0.001	0.011	0.010	0.042	0.005	0.002
Copper	7440-50-8	mg/L	0.001	0.006	0.047	0.085	0.002	0.002
Lead	7439-92-1	mg/L	0.001	0.006	0.010	0.059	<0.001	0.002
Manganese	7439-96-5	mg/L	0.001	0.222	0.332	0.627	0.846	0.027
Molybdenum	7439-98-7	mg/L	0.001	0.004	0.003	0.004	<0.001	<0.001
Nickel	7440-02-0	mg/L	0.001	0.018	0.032	0.045	0.007	0.004
Selenium	7782-49-2	mg/L	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Silver	7440-22-4	mg/L	0.001	0.001	<0.001	0.001	<0.001	<0.001
Strontium	7440-24-6	mg/L	0.001	7.09	9.36	1.94	0.167	0.411
Uranium	7440-61-1	mg/L	0.001	0.009	0.031	0.017	0.001	0.002
Vanadium	7440-62-2	mg/L	0.01	<0.01	0.04	0.05	<0.01	<0.01
Zinc	7440-66-6	mg/L	0.005	1.51	0.613	0.253	0.012	0.103
Boron	7440-42-8	mg/L	0.05	0.64	1.09	0.66	0.13	0.20
Iron	7439-89-6	mg/L	0.05	3.50	10.1	20.1	3.38	0.78
Mercury	7439-97-6	mg/L	0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001

5. Further work

The following activities and data collection are still to be carried out to complete the groundwater monitoring network and to understand the groundwater occurrence within the project area.

- Hydraulic testing of each monitoring bore is to be carried out to understand the hydraulic conductivity of the screened interval. Ideally this should occur following stabilisation of a groundwater level in each monitoring bore.
- Regular groundwater level and quality monitoring is required to establish baseline groundwater conditions for the project approval.
- Stygofauna sampling should be completed on the monitoring bore network after six months (December 2019).

Appendix A Monitoring bore logs

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Project No.: 4015

Project Name: Vulcan Complex Project

MONITORING BORE

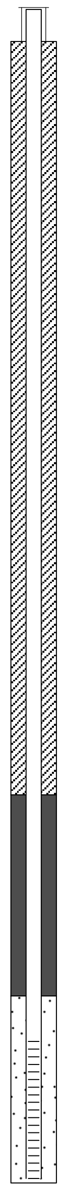
MB1

Geological Units	Material Description	Graphic Log	R.L. (mAHD)	Depth (mbGL)
Permian Coal Measures	Sand, orange brown, very fine to medium grained		231–229	0–2
	Siltstone, white, pink grey		229–228	2–3
	Siltstone, pink grey		228–223	3–8
	Siltstone, red brown		223–221	8–10
	Siltstone, orange brown		221–215.5	10–15.5
	Carbonaceous mudstone		215.5–214	15.5–17
	Siltstone, grey to dark grey		214–208	17–23
	Coal		208–206	23–25

R.L. (mAHD): 233, 232, 231, 230, 229, 228, 227, 226, 225, 224, 223, 222, 221, 220, 219, 218, 217, 216, 215, 214, 213, 212, 211, 210, 209, 208, 207, 206, 205

Depth (mbGL): 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26

Bore Construction



Bore Description

Protective lockable steel collar: +0.75 m

Stick up: +0.7 m

125 mm diameter bit: 0 m to 25 m (Air rotary)

Bore dry

Bentonite grout 0 m to 16.5 m

50 mm PN18 uPVC blank casing: +0 m to 21.9 m

Bentonite seal: 16.5 m to 20.9 m

washed, rounded gravel pack: 20.9 m to 25 m

50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 21.9 m to 24.9 m

End of hole: 25 m BGL

End cap

Date Drilled: 07.06.2019	Drilling Company: Wizard Drilling	Easting: 625608	RL: 231.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7529692	TD: 24.9
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55	

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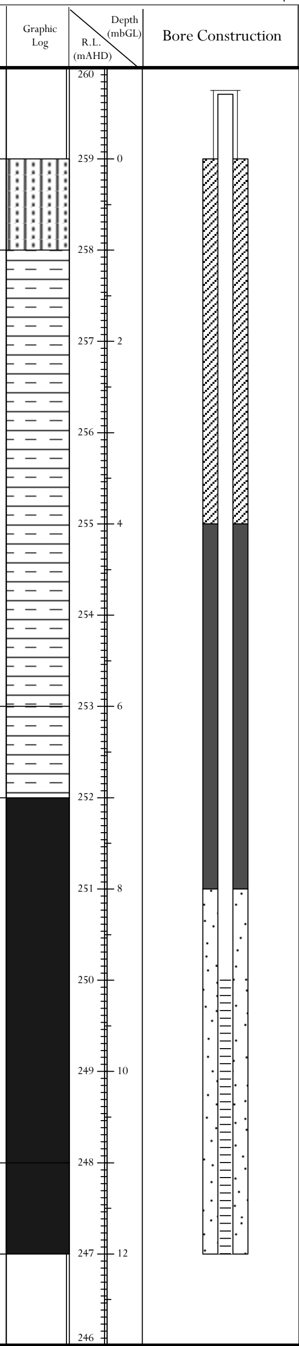
Project No.: 4015

Project Name: Vulcan Complex Project

MONITORING BORE MB2

Geological Units	Material Description
Permian Coal Measures	Silty soil, orange brown
	Carbonaceous mudstone, dark brown to black
	Carbonaceous mudstone
	Coal
	Coal and carbonaceous mudstone



Bore Description

Protective lockable steel collar: +0.75 m

Stick up: +0.71 m

Bentonite grout 0 m to 4 m

50 mm PN18 uPVC blank casing: +0 m to 9 m

Bore dry

125 mm diameter bit: 0 m to 12 m (Air rotary)

Bentonite seal: 4 m to 8 m

washed, rounded gravel pack: 8 m to 12 m

50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 9 m to 12 m

End of hole: 12 m BGL

Date Drilled: 07.06.2019	Drilling Company: Wizard Drilling	Easting: 622515	RL: 259.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7534485	TD: 12.0
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55	

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Project No.: 4015

Project Name: Vulcan Complex Project

MONITORING BORE

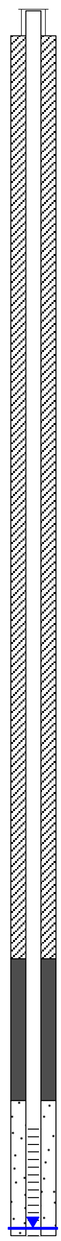
MB3

Geological Units	Material Description	Graphic Log	R.L. (mAHD) / Depth (mbGL)
Permian Coal Measures	Sandstone, light grey, orange brown, very fine to medium grained		
Permian Coal Measures	Sandstone, light grey to white, very fine to coarse grained		
Permian Coal Measures	Sandstone, light grey to red brown, very fine to fine grained		
Permian Coal Measures	Carbonaceous mudstone		
Permian Coal Measures	Carbonaceous mudstone and grey siltstone		
Permian Coal Measures	Coal		
Permian Coal Measures	Carbonaceous mudstone and grey siltstone		
Permian Coal Measures	Siltstone, grey		
Permian Coal Measures	Siltstone, dark grey with carbonaceous mudstone		
Permian Coal Measures	Siltstone, dark grey with carbonaceous mudstone		
Permian Coal Measures	Coal		

R.L. (mAHD): 265, 264, 263, 262, 261, 260, 259, 258, 257, 256, 255, 254, 253, 252, 251, 250, 249, 248, 247, 246, 245, 244, 243, 242, 241, 240, 239, 238, 237, 236, 235, 234, 233, 232, 231, 230, 229

Depth (mbGL): 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34

Bore Construction



Bore Description

- Protective lockable steel collar: +0.9 m
- Stick up: +0.7 m
- 125 mm diameter bit: 0 m to 34m (Air rotary)
- Bentonite grout 0 m to 26 m
- Bore development: No water produced during airlift
- 50 mm PN18 uPVC blank casing: +0 m to 30.8 m
- Bentonite seal: 26 m to 30 m
- washed, rounded gravel pack: 30 m to 34 m
- 50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 30.8 m to 33.8 m
- SWL: 34.3 mbtoc on the 07.06.2019
- End of hole: 34 m BGL
- End cap

Date Drilled: 07.06.2019	Drilling Company: Wizard Drilling	Easting: 622665	RL: 263.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7535021	TD: 33.8
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55	

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Project No.: 4015

Project Name: Vulcan Complex Project

MONITORING BORE

MB4

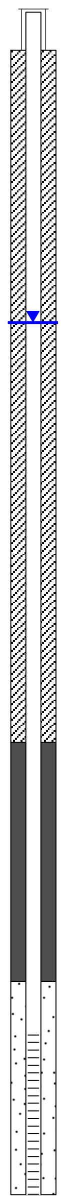
Geological Units	Material Description
Permian Coal Measures	Sand, yellow to brown, fine to coarse grained
	Sand, grey, very fine to coarse grained
	Sand, orange brown to white, quartzose, very fine to coarse grained
	Sandstone, white, very fine to coarse grained, quartzose
	Coal
	Carbonaceous mudstone
	Dark grey siltstone and carbonaceous mudstone
	Carbonaceous mudstone
	Siltstone, dark grey with carbonaceous mudstone
	Carbonaceous mudstone, dark grey
	Coal
	Carbonaceous mudstone, dark grey and coal

Graphic Log

R.L. (mAHD): 251, 250, 249, 248, 247, 246, 245, 244, 243, 242, 241, 240, 239, 238, 237, 236, 235, 234, 233, 232, 231, 230, 229, 228, 227

Depth (mbGL): 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22

Bore Construction



Bore Description

Protective lockable steel collar: +0.77 m

Stick up: +0.71 m

125 mm diameter bit: 0 m to 21.5m (Air rotary)

SWL: 5.83 mbtoc on the 07.06.2019

Bentonite grout 0 m to 13 m

Bentonite seal: 13 m to 17.5 m

50 mm PN18 uPVC blank casing: +0 m to 18.5 m

Airlift flow rate: 0.1 L/min

Bore development: 1.5 hrs; EC: 2520 uS/cm; pH: 7.92

washed, rounded gravel pack: 17.5 m to 21.5 m

50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 18.5 m to 21.5 m

End of hole: 22.1 m BGL

Date Drilled: 07.06.2019	Drilling Company: Wizard Drilling	Easting: 622016	RL: 249.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7536148	TD: 21.5
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55	

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Project No.: 4015

Project Name: Vulcan Complex Project

MONITORING BORE

MB5

Geological Units	Material Description
Permian Coal Measures	Sandstone, light red to brown, very fine to fine grained
	Sandstone, light grey, very fine grained, minor siltstone
	Sandstone, grey silty, very fine grained
	Mudstone, dark grey and siltstone
	Mudstone, grey and siltstone
	Siltstone, grey
	Carbonaceous mudstone
	Siltstone, grey to very fine sandstone
	Sandstone, grey, very fine to medium grained
	Carbonaceous mudstone, dark grey
	Sandstone, grey, very fine grained
	Mudstone, dark grey with siltstone
	Siltstone, dark grey
	Sandstone, grey, very fine to fine grained
	Sandstone, grey, very fine grained
	Carbonaceous mudstone, dark grey
	Siltstone, dark grey
	Carbonaceous mudstone with grey silstone
	Coal
	Siltstone, grey

Graphic Log | R.L. (mAHD) | Depth (mbGL) | Bore Construction

Bore Description

Protective lockable steel collar: +0.81 m
Stick up: +0.77 m

SWL: 14.53 mbtoc on the 07.06.2019

50 mm PN18 uPVC blank casing: +0 m to 37.9 m

Bore development: 1 hr; EC: 2960 uS/cm; pH: 8.55

Airlift flow rate: 0.2 L/min

125 mm diameter bit: 0 m to 41 m (Air rotary)

Bentonite grout 0 m to 32 m

Bentonite seal: 32 m to 36.8 m

washed, rounded gravel pack: 36.8 m to 41 m

50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 37.9 m to 40.9 m
End of hole: 41 m BGL

End cap

Date Drilled: 07.06.2019	Drilling Company: Wizard Drilling	Easting: 621965 / RL: 257.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7534904 / TD: 40.9
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55

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Project No.: 4015

Project Name: Vulcan Complex Project

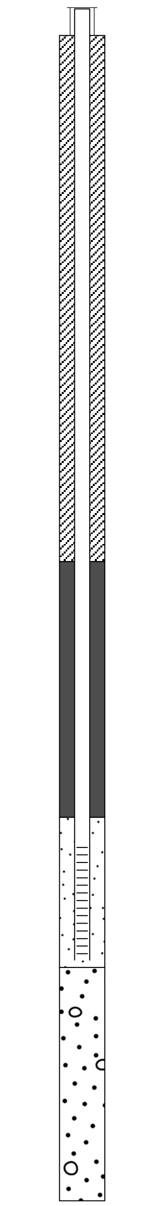
MONITORING BORE

MB6

Geological Units	Material Description	Graphic Log	R.L. (mAHD) / Depth (mbGL)	Bore Construction	Bore Description
Permian Coal Measures	Clay, dark brown				Protective lockable steel collar: +0.74 m
	Sand, brown to grey, silty				Stick up: +0.7 m
	Clay, brown, silty				Bore dry
	Silt, brown, sandy				50 mm PN18 uPVC blank casing: +0 m to 21.6 m
	Mudstone, brown				Bentonite grout 0 m to 16.8 m
	Mudstone, brown				125 mm diameter bit: 0 m to 31 m (Air rotary)
	Mudstone, brown				Bentonite seal: 16.8m to 20.8 m
	Mudstone, brown to grey				washed, rounded gravel pack: 20.8 m to 31 m
					50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 21.6 m to 24.6 m
					End cap
					Backfill
					End of hole: 31 m BGL

R.L. (mAHD): 217, 216, 215, 214, 213, 212, 211, 210, 209, 208, 207, 206, 205, 204, 203, 202, 201, 200, 199, 198, 197, 196, 195, 194, 193, 192, 191, 190, 189, 188, 187, 186, 185, 184, 183

Depth (mbGL): 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32



Date Drilled: 06.06.2019

Driller: Andrew Holmes

Drill Rig: Mayhew 1000

Drilling Company: Wizard Drilling

Drilling Method: Rotary open hole

Logged By: DFB

Easting: 628121

Northing: 7526477

Datum: MGA94 Zone55

RL: 215.0

TD: 24.6

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Project No.: 4015

Project Name: Vulcan Complex Project

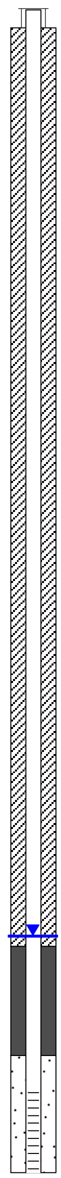
MONITORING BORE

MB7

Geological Units	Material Description
Permian Coal Measures	Clay, dark grey
	Clay, dark brown, silty
	Clay, brown, silty with silcrete bands
	Clay, light brown, silty, weathered siltstone
	Gravel, 1 mm to 30 mm subrounded lithic clasts
	Sand, silty, light brown, very fine to fine grained
	Sand, silty, brown
	Sand, silty, very fine to fine grained
	Sand, gravelly, 1 mm to 15 mm quartz with lithic clasts
	Silt, orange brown
	Sandstone, light grey to orange brown, quartzose, very fine to medium grained
	Sandstone, light grey to orange brown, quartzose, very fine to medium grained
	Sandstone, orange brown, silty
	Sandstone, light grey to light brown, very fine to coarse grained quartzose, minor gravel at base
	Siltstone, brown with dark brown siltstone at base

Graphic Log | R.L. (mAHD) 221–173 | Depth (mbGL) 0–44

Bore Construction



Bore Description

Protective lockable steel collar: +0.71 m
Stick up: +0.67 m

50 mm PN18 uPVC blank casing: +0 m to 40.0 m

Bore development: 0.5 hr; EC: 5680 uS/cm; pH: 8.78

Airlift flow rate: 0.5 L/min

125 mm diameter bit: 0 m to 43 m (Air rotary)

Bentonite grout 0 m to 34.5 m

SWL: 34.80 mbtoc on the 06.06.2019

Bentonite seal: 34.5 m to 38.6 m

washed, rounded gravel pack: 38.6 m to 43 m

50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 40.0 m to 43.0 m

End of hole: 43 m BGL

Date Drilled: 06.06.2019	Drilling Company: Wizard Drilling	Easting: 628692 · RL: 217.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7526260 · TD: 43.0
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55

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Project No.: 4015

Project Name: Vulcan Complex Project

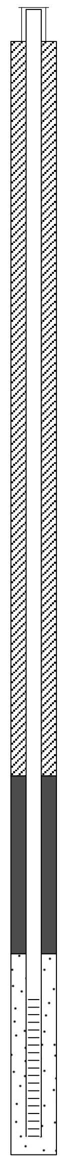
MONITORING BORE

MB8

Geological Units	Material Description
Permian Coal Measures	Clay, dark brown to black, stiff
	Clay, brown to orange brown
	Clay, light grey to grey
	Clay, light grey, silty, sandy
	Sand, white to light grey, silty, very fine to medium grained
	Sand, white, silty, very fine grained
	Sand, white, very fine grained to medium grained
	Sand, white to light grey, silty, quartzose, very fine to medium grained
	Siltstone, light orange brown, very minor sandstone, very fine to fine grained lenses

Graphic Log | R.L. (mAHD) 216–188 | Depth (mbGL) 0–26

Bore Construction



Bore Description

Protective lockable steel collar: +0.75 m

Stick up: +0.7 m

125 mm diameter bit: 0 m to 24.4 m (Air rotary)

Bentonite grout 0 m to 16.1 m

50 mm PN18 uPVC blank casing: +0 m to 21 m

Bore dry

Bentonite seal: 16.1 m to 20 m

washed, rounded gravel pack: 20 m to 24.4 m

50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 21 m to 24 m

End of hole: 24.4 m BGL

End cap

Date Drilled: 06.06.2019

Driller: Andrew Holmes

Drill Rig: Mayhew 1000

Drilling Company: Wizard Drilling

Drilling Method: Rotary open hole

Logged By: DFB

Easting: 628094

Northing: 7527017

Datum: MGA94 Zone55

RL: 214.0

TD: 24.0

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Project No.: 4015

Project Name: Vulcan Complex Project

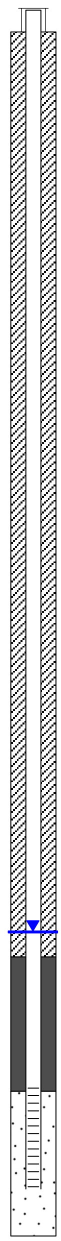
MONITORING BORE

MB9

Geological Units	Material Description
Permian Coal Measures	Clay, brown grey, silty
	Sand, orange to brown, silty, very fine to medium grained
	Sand, orange to brown, silty, very fine to medium grained
	Clay, brown to grey, silty
	Clay, grey to brown, silty
	Gravel, orange to brown, clayey, subrounded 10 mm to 25 mm
	Sandstone, grey to brown, silty, very fine to fine grained
	Clay, brown to grey, mottled
	Sandstone, light grey, very fine to fine grained with brown mudstone
	Mudstone, grey to brown
	Mudstone, brown and grey sandstone, very fine grained
	Sandstone, brown, silty with brown mudstone
	Sandstone, brown to grey, very fine grained
	Sandstone, brown, very fine to medium grained
	Mudstone, brown to grey
	Siltstone, light brown and very fine grained sandstone
	Carbonaceous mudstone
	Coal and mudstone

Graphic Log | R.L. (mAHD) 215 to 177 | Depth (mbGL) 0 to 36

Bore Construction



Bore Description

Protective lockable steel collar: +0.7 m

Stick up: +0.65 m

125 mm diameter bit: 0 m to 35.8 m (Air rotary)

50 mm PN18 uPVC blank casing: +0 m to 31.4 m

Bentonite grout 0 m to 27.5 m

Bore development: 0.5 hrs; EC: 5520 uS/cm; pH: 8.58

Airlift flow rate: spray and dripping

SWL: 27.41 mbtoc on the 06.06.2019

Bentonite seal: 27.5 m to 31.0 m

washed, rounded gravel pack: 31.0 m to 35.8 m

50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 31.4 m to 34.4 m

End of hole: 35.8 m BGL

Date Drilled: 06.06.2019	Drilling Company: Wizard Drilling	Easting: 629511 RL: 213.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7525225 TD: 34.4
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55

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Project No.: 4015

Project Name: Vulcan Complex Project

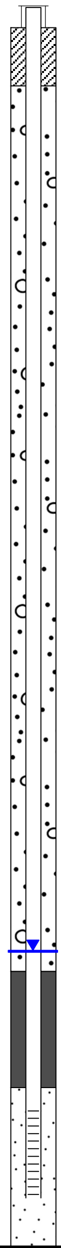
MONITORING BORE

MB10

Geological Units	Material Description	Graphic Log	R.L. (mAHD) / Depth (mbGL)	Bore Construction	Bore Description
Permian Coal Measures	Clay, dark brown				Protective lockable steel collar: +0.75 m Stick up: +0.70 m
	Sand, brown to grey, silty				Bentonite grout 0 m to 2 m
	Clay, brown, silty				125 mm diameter bit: 0 m to 42 m (Air rotary) Backfill 2 m to 32.5 m 50 mm PN18 uPVC blank casing: +0 m to 37.3 m
	Silt, brown, sandy				Airlift flow rate: spray and dripping
	Mudstone, brown				
	Mudstone, brown				
	Mudstone, brown				
	Mudstone, brown to grey				SWL: 32.51 mbtoc on the 06.06.2019
	Mudstone, grey				Bentonite seal: 32.5 m to 36.5 m
	Carbonaceous mudstone				washed, rounded gravel pack: 36.5 m to 42 m
	Coal				50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 37.3 m to 40.3 m
	Carbonaceous mudstone				
	Carbonaceous mudstone and siltstone				End of hole: 42 m BGL

R.L. (mAHD): 217, 216, 215, 214, 213, 212, 211, 210, 209, 208, 207, 206, 205, 204, 203, 202, 201, 200, 199, 198, 197, 196, 195, 194, 193, 192, 191, 190, 189, 188, 187, 186, 185, 184, 183, 182, 181, 180, 179, 178, 177, 176, 175, 174, 173

Depth (mbGL): 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42



Date Drilled: 06.06.2019	Drilling Company: Wizard Drilling	Easting: 628125	RL: 215.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7526470	TD: 40.3
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55	

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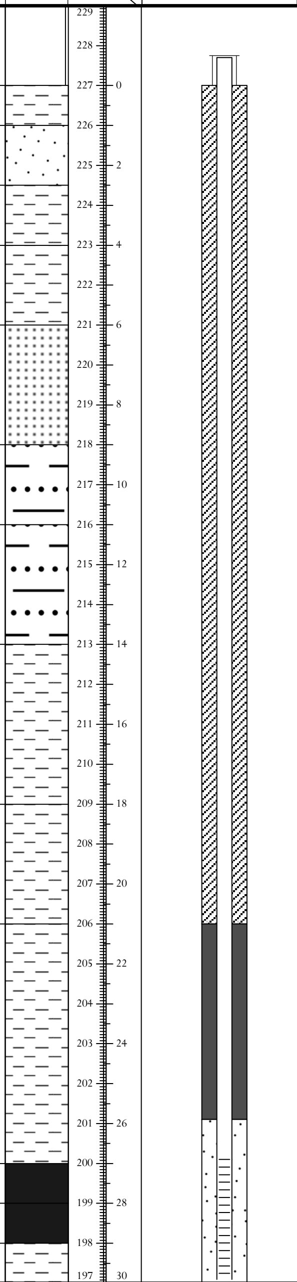
Project No.: 4015

Project Name: Vulcan Complex Project

MONITORING BORE MB11

Geological Units	Material Description
Permian Coal Measures	Clay, grey to brown, with minor gravel
	Sand, gravel, quartzose and basalt, 1 mm to 30 mm clasts
	Clay, white, kaolinitic
	Siltstone, white to yellow, kaolinitic
	Sandstone, white to yellow brown, very fine to medium grained
	Siltstone, white, very fine grained sandstone
	Siltstone, white to light brown, with very fine grained sandstone
	Siltstone, light grey to brown
	Siltstone, red to brown
	Siltsotne, light grey to brown
	Coal with brown siltstone
	Coal with dark grey siltstone
	Grey siltstone

Graphic Log / R.L. (mAHD) / Depth (mbGL) / Bore Construction



Bore Description

- Protective lockable steel collar: +0.75 m
- Stick up: +0.7 m
- 50 mm PN18 uPVC blank casing: +0 m to 26.9 m
- 125 mm diameter bit: 0 m to 30 m (Air rotary)
- Bentonite grout 0 m to 21 m
- Bore dry
- Bentonite seal: 21 m to 25.9 m
- washed, rounded gravel pack: 25.9 m to 30 m
- 50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 26.9 m to 29.9 m
- End of hole: 30 m BGL

Date Drilled: 06.06.2019	Drilling Company: Wizard Drilling	Easting: 627405	RL: 227.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7527854	TD: 29.9
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55	

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Project No.: 4015

Project Name: Vulcan Complex Project

MONITORING BORE

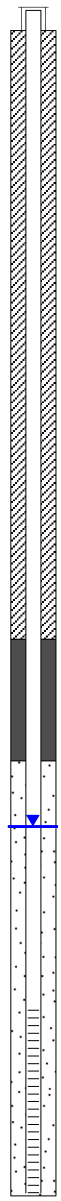
MB12

Geological Units	Material Description
Permian Coal Measures	Silt, brown, clayey
	Sandstone, orange brown, very fine grained
	Siltstone, light grey
	Sandstone, light grey, very fine to coarse grained
	Sandstone, light grey brown, fine to coarse grained
	Sandstone, light grey, very fine to medium grained
	Sandstone, light grey brown, silty, very fine grained
	Carbonaceous mudstone
	Siltstone, dark grey, with very fine grained sandstone
	Siltstone, dark grey
	Sandstone, light orange brown, very fine grained
	Sandstone, light grey, very fine grained
	Siltstone, grey
	Siltstone, dark grey

Graphic Log

R.L. (mAHD)	Depth (mbGL)
249	
248	
247	0
246	
245	2
244	
243	4
242	
241	6
240	
239	8
238	
237	10
236	
235	12
234	
233	14
232	
231	16
230	
229	18
228	
227	20
226	
225	22
224	
223	24
222	
221	26
220	
219	28
218	
217	30
216	
215	32
214	
213	34
212	
211	36
210	
209	38
208	
207	40

Bore Construction



Bore Description

Protective lockable steel collar: +0.77 m

Stick up: +0.66 m

125 mm diameter bit: 0 m to 38.3 m (Air rotary)

Bentonite grout 0 m to 20 m

Bore development: 1 hr; EC: 2280 uS/cm; pH: 8.29

Airlift flow rate: 0.1 L/min

50 mm PN18 uPVC blank casing: +0 m to 32.2 m

Bentonite seal: 20 m to 24 m

SWL: 26.82 mbtoc on the 07.06.2019

washed, rounded gravel pack: 24 m to 38.3 m

50 mm PN18 uPVC machine slotted casing, slot aperture: 1 mm, 32.2 m to 38.2 m

End of hole: 38.3 m BGL

End cap

Date Drilled: 06.06.2019	Drilling Company: Wizard Drilling	Easting: 625252	RL: 247.0
Driller: Andrew Holmes	Drilling Method: Rotary open hole	Northing: 7526409	TD: 38.2
Drill Rig: Mayhew 1000	Logged By: DFB	Datum: MGA94 Zone55	

Appendix B ALS Certificate of analysis

ALS Environmental

CERTIFICATE OF ANALYSIS

Work Order	: **EB1915096**	Page	: 1 of 5
Client	: **VITRINITE PTY LTD**	Laboratory	: Environmental Division Brisbane
Contact	: Mike Cavanagh	Contact	: Customer Services EB
Address	: Level 6 Suite 2 12 Creek Street Brisbane 4000	Address	: 2 Byth Street Stafford QLD Australia 4053
Telephone	: ----	Telephone	: +61-7-3243 7222
Project	: 4015 Vulcan	Date Samples Received	: 13-Jun-2019 09:30
Order number	:	Date Analysis Commenced	: 14-Jun-2019
C-O-C number	: ----	Issue Date	: 21-Jun-2019 11:36
Sampler	: Thomas Muehe		
Site	: ----		
Quote number	: TV/029/19 v2		
No. of samples received	: 5		
No. of samples analysed	: 5		

ilac-MRA NATA

Accreditation No. 825
Accredited for compliance with
ISO/IEC 17025 - Testing

This report supersedes any previous report(s) with this reference. Results apply to the sample(s) as submitted. This document shall not be reproduced, except in full.

This Certificate of Analysis contains the following information:

- General Comments
- Analytical Results

Additional information pertinent to this report will be found in the following separate attachments: Quality Control Report, QA/QC Compliance Assessment to assist with Quality Review and Sample Receipt Notification.

Signatories

This document has been electronically signed by the authorized signatories below. Electronic signing is carried out in compliance with procedures specified in 21 CFR Part 11.

Signatories	*Position*	*Accreditation Category*
Kim McCabe	Senior Inorganic Chemist	Brisbane Inorganics, Stafford, QLD
Mark Hallas	Senior Inorganic Chemist	Brisbane Inorganics, Stafford, QLD
Tom Maloney	Senior Inorganic Chemist	Brisbane Inorganics, Stafford, QLD
Tom Maloney	Senior Inorganic Chemist	WB Water Lab Brisbane, Stafford, QLD

General Comments

The analytical procedures used by the Environmental Division have been developed from established internationally recognized procedures such as those published by the USEPA, APHA, AS and NEPM. In house developed procedures are employed in the absence of documented standards or by client request.

Where moisture determination has been performed, results are reported on a dry weight basis.

Where a reported less than (<) result is higher than the LOR, this may be due to primary sample extract/digestate dilution and/or insufficient sample for analysis.

Where the LOR of a reported result differs from standard LOR, this may be due to high moisture content, insufficient sample (reduced weight employed) or matrix interference.

When sampling time information is not provided by the client, sampling dates are shown without a time component. In these instances, the time component has been assumed by the laboratory for processing purposes.

Where a result is required to meet compliance limits the associated uncertainty must be considered. Refer to the ALS Contact for details.

Key : CAS Number = CAS registry number from database maintained by Chemical Abstracts Services. The Chemical Abstracts Service is a division of the American Chemical Society.
LOR = Limit of reporting
^ = This result is computed from individual analyte detections at or above the level of reporting
ø = ALS is not NATA accredited for these tests.
~ = Indicates an estimated value.

- EG035T (Total Mercury): Positive mercury results have been confirmed by re-extraction and re-analysis.
- It is recognised that EG020T (Total Metals) is less than EG020F (Dissolved Metals) for some samples. However, the difference is within experimental variation of the methods.
- EA016: Calculated TDS is determined from Electrical conductivity using a conversion factor of 0.65.
- Sodium Adsorption Ratio (where reported): Where results for Na, Ca or Mg are <LOR, a concentration at half the reported LOR is incorporated into the SAR calculation. This represents a conservative approach for Na relative to the assumption that <LOR = zero concentration and a conservative approach for Ca & Mg relative to the assumption that <LOR is equivalent to the LOR concentration.

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	MB12	MB9	MB7	MB4	MB5
			Client sampling date / time	06-Jun-2019 12:50	06-Jun-2019 15:10	06-Jun-2019 16:15	07-Jun-2019 09:30	07-Jun-2019 11:40
Compound	CAS Number	LOR	Unit	EB1915096-001	EB1915096-002	EB1915096-003	EB1915096-004	EB1915096-005
				Result	Result	Result	Result	Result
EA005P: pH by PC Titrator								
pH Value	----	0.01	pH Unit	**7.81**	**7.95**	**8.31**	**7.94**	**8.17**
EA006: Sodium Adsorption Ratio (SAR)								
^ Sodium Adsorption Ratio	----	0.01	-	**22.1**	**20.0**	**14.4**	**10.9**	**12.5**
EA010P: Conductivity by PC Titrator								
Electrical Conductivity @ 25°C	----	1	µS/cm	**21600**	**16200**	**5430**	**2280**	**2680**
EA016: Calculated TDS (from Electrical Conductivity)								
Total Dissolved Solids (Calc.)	----	1	mg/L	**14000**	**10500**	**3530**	**1480**	**1740**
EA065: Total Hardness as CaCO3								
Total Hardness as CaCO3	----	1	mg/L	**4710**	**3780**	**905**	**242**	**345**
ED037P: Alkalinity by PC Titrator								
Hydroxide Alkalinity as CaCO3	DMO-210-001	1	mg/L	<1	<1	<1	<1	<1
Carbonate Alkalinity as CaCO3	3812-32-6	1	mg/L	<1	<1	**4**	<1	<1
Bicarbonate Alkalinity as CaCO3	71-52-3	1	mg/L	**468**	**632**	**486**	**108**	**550**
Total Alkalinity as CaCO3	----	1	mg/L	**468**	**632**	**490**	**108**	**550**
ED041G: Sulfate (Turbidimetric) as SO4 2- by DA								
Sulfate as SO4 - Turbidimetric	14808-79-8	1	mg/L	**908**	**2580**	**819**	**140**	**293**
ED045G: Chloride by Discrete Analyser								
Chloride	16887-00-6	1	mg/L	**7650**	**4590**	**1100**	**603**	**416**
ED093F: Dissolved Major Cations								
Calcium	7440-70-2	1	mg/L	**408**	**369**	**87**	**26**	**54**
Magnesium	7439-95-4	1	mg/L	**897**	**694**	**167**	**43**	**51**
Sodium	7440-23-5	1	mg/L	**3490**	**2820**	**997**	**389**	**534**
Potassium	7440-09-7	1	mg/L	**19**	**73**	**8**	**16**	**17**
EG020F: Dissolved Metals by ICP-MS								
Aluminium	7429-90-5	0.01	mg/L	**0.04**	**0.01**	**0.02**	<0.01	**0.02**
Antimony	7440-36-0	0.001	mg/L	**0.002**	<0.001	<0.001	<0.001	<0.001
Arsenic	7440-38-2	0.001	mg/L	**0.002**	**0.001**	**0.001**	<0.001	<0.001
Beryllium	7440-41-7	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Barium	7440-39-3	0.001	mg/L	**0.143**	**0.100**	**0.070**	**0.094**	**0.028**
Cadmium	7440-43-9	0.0001	mg/L	<0.0001	**0.0005**	<0.0001	<0.0001	<0.0001
Chromium	7440-47-3	0.001	mg/L	<0.001	**0.001**	<0.001	<0.001	<0.001
Cobalt	7440-48-4	0.001	mg/L	**0.008**	**0.004**	**0.004**	**0.004**	<0.001
Copper	7440-50-8	0.001	mg/L	**0.001**	**0.022**	<0.001	<0.001	<0.001
Lead	7439-92-1	0.001	mg/L	**0.001**	<0.001	<0.001	<0.001	<0.001

Analytical Results

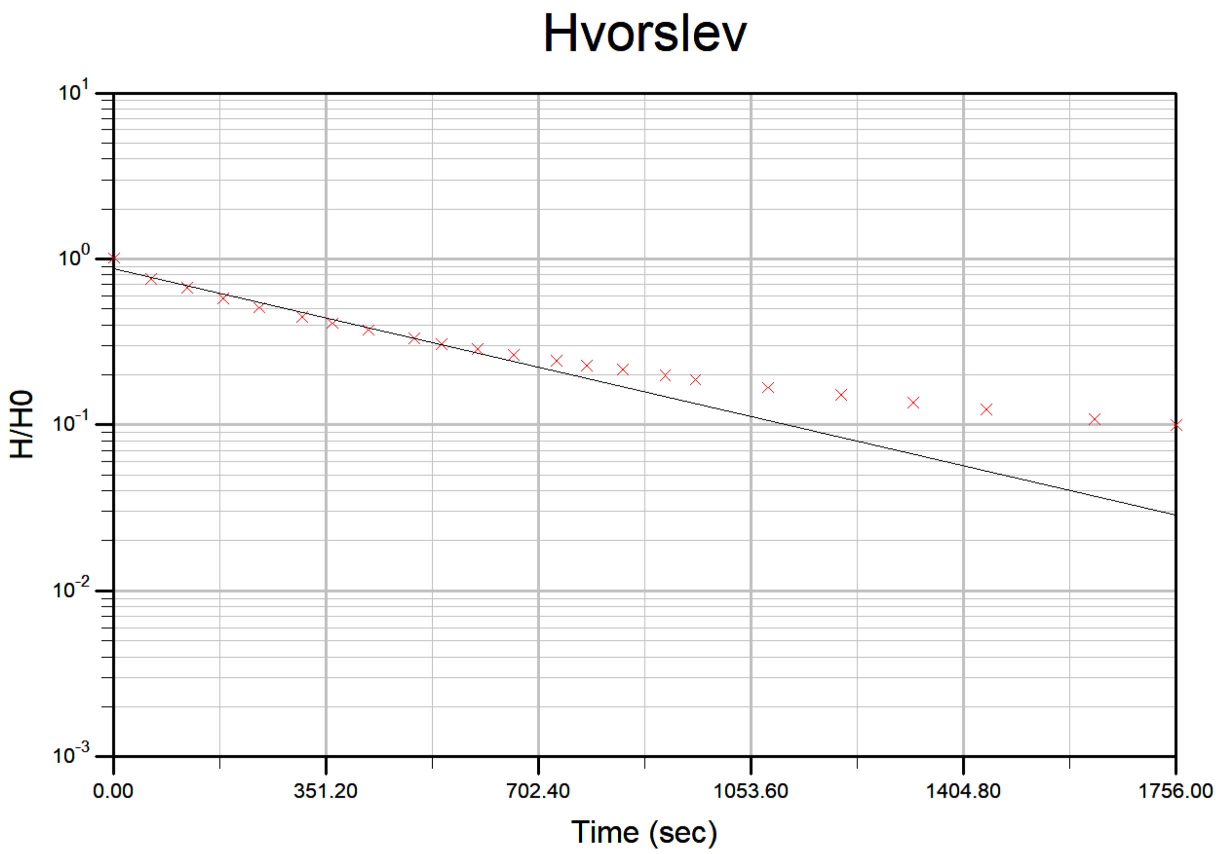
Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	MB12	MB9	MB7	MB4	MB5
			Client sampling date / time	06-Jun-2019 12:50	06-Jun-2019 15:10	06-Jun-2019 16:15	07-Jun-2019 09:30	07-Jun-2019 11:40
Compound	CAS Number	LOR	Unit	EB1915096-001	EB1915096-002	EB1915096-003	EB1915096-004	EB1915096-005
				Result	Result	Result	Result	Result
EG020F: Dissolved Metals by ICP-MS - Continued								
Manganese	7439-96-5	0.001	mg/L	**0.173**	**0.264**	**0.384**	**0.820**	**0.019**
Molybdenum	7439-98-7	0.001	mg/L	**0.003**	**0.003**	**0.007**	<0.001	<0.001
Nickel	7440-02-0	0.001	mg/L	**0.012**	**0.010**	**0.003**	**0.006**	**0.002**
Selenium	7782-49-2	0.01	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Silver	7440-22-4	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Strontium	7440-24-6	0.001	mg/L	**6.27**	**8.28**	**1.69**	**0.171**	**0.392**
Uranium	7440-61-1	0.001	mg/L	**0.008**	**0.030**	**0.016**	**0.001**	**0.001**
Vanadium	7440-62-2	0.01	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc	7440-66-6	0.005	mg/L	**1.17**	**0.116**	<0.005	<0.005	**0.056**
Boron	7440-42-8	0.05	mg/L	**0.63**	**1.08**	**0.66**	**0.13**	**0.21**
Iron	7439-89-6	0.05	mg/L	<0.05	<0.05	<0.05	**0.36**	<0.05
EG020T: Total Metals by ICP-MS								
Aluminium	7429-90-5	0.01	mg/L	**1.61**	**8.38**	**16.5**	**0.12**	**0.65**
Antimony	7440-36-0	0.001	mg/L	**0.002**	<0.001	<0.001	<0.001	<0.001
Arsenic	7440-38-2	0.001	mg/L	**0.004**	**0.004**	**0.022**	<0.001	<0.001
Beryllium	7440-41-7	0.001	mg/L	<0.001	**0.001**	**0.004**	<0.001	<0.001
Barium	7440-39-3	0.001	mg/L	**0.168**	**0.125**	**0.664**	**0.108**	**0.036**
Cadmium	7440-43-9	0.0001	mg/L	<0.0001	**0.0006**	<0.0001	<0.0001	<0.0001
Chromium	7440-47-3	0.001	mg/L	**0.004**	**0.034**	**0.032**	<0.001	<0.001
Cobalt	7440-48-4	0.001	mg/L	**0.011**	**0.010**	**0.042**	**0.005**	**0.002**
Copper	7440-50-8	0.001	mg/L	**0.006**	**0.047**	**0.085**	**0.002**	**0.002**
Lead	7439-92-1	0.001	mg/L	**0.006**	**0.010**	**0.059**	<0.001	**0.002**
Manganese	7439-96-5	0.001	mg/L	**0.222**	**0.332**	**0.627**	**0.846**	**0.027**
Molybdenum	7439-98-7	0.001	mg/L	**0.004**	**0.003**	**0.004**	<0.001	<0.001
Nickel	7440-02-0	0.001	mg/L	**0.018**	**0.032**	**0.045**	**0.007**	**0.004**
Selenium	7782-49-2	0.01	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Silver	7440-22-4	0.001	mg/L	**0.001**	<0.001	**0.001**	<0.001	<0.001
Strontium	7440-24-6	0.001	mg/L	**7.09**	**9.36**	**1.94**	**0.167**	**0.411**
Uranium	7440-61-1	0.001	mg/L	**0.009**	**0.031**	**0.017**	**0.001**	**0.002**
Vanadium	7440-62-2	0.01	mg/L	<0.01	**0.04**	**0.05**	<0.01	<0.01
Zinc	7440-66-6	0.005	mg/L	**1.51**	**0.613**	**0.253**	**0.012**	**0.103**
Boron	7440-42-8	0.05	mg/L	**0.64**	**1.09**	**0.66**	**0.13**	**0.20**
Iron	7439-89-6	0.05	mg/L	**3.50**	**10.1**	**20.1**	**3.38**	**0.78**
EG035F: Dissolved Mercury by FIMS								

Analytical Results

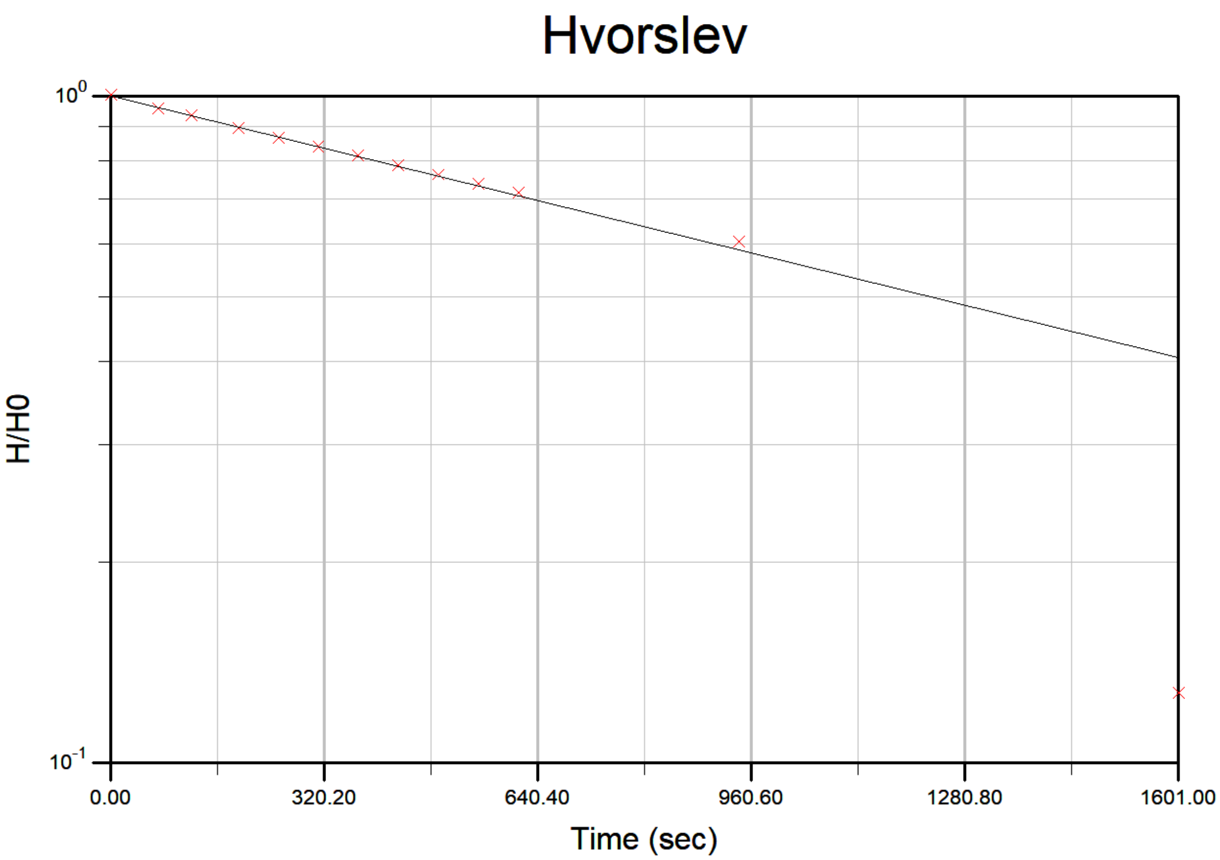
Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	MB12	MB9	MB7	MB4	MB5
			Client sampling date / time	06-Jun-2019 12:50	06-Jun-2019 15:10	06-Jun-2019 16:15	07-Jun-2019 09:30	07-Jun-2019 11:40
Compound	CAS Number	LOR	Unit	EB1915096-001	EB1915096-002	EB1915096-003	EB1915096-004	EB1915096-005
				Result	Result	Result	Result	Result
EG035F: Dissolved Mercury by FIMS - Continued								
Mercury	7439-97-6	0.0001	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
EG035T: Total Recoverable Mercury by FIMS								
Mercury	7439-97-6	0.0001	mg/L	<0.0001	<0.0001	**0.0001**	<0.0001	<0.0001
EG052F: Dissolved Silica by ICPAES								
Silicon as SiO2	14464-46-1	0.1	mg/L	**22.5**	**27.8**	**24.2**	**12.7**	**21.8**
EK040P: Fluoride by PC Titrator								
Fluoride	16984-48-8	0.1	mg/L	**0.3**	**0.7**	**0.8**	**1.0**	**0.3**
EN055: Ionic Balance								
ø **Total Anions**	----	0.01	meq/L	**244**	**196**	**57.9**	**22.1**	**28.8**
ø **Total Cations**	----	0.01	meq/L	**246**	**200**	**61.6**	**22.2**	**30.6**
ø **Ionic Balance**	----	0.01	%	**0.49**	**1.07**	**3.17**	**0.19**	**2.91**
ED009: Anions								
Bromide	24959-67-9	0.010	mg/L	**14.8**	**10.1**	**2.60**	**1.09**	**0.980**

Appendix B Hydraulic testing results

MB4

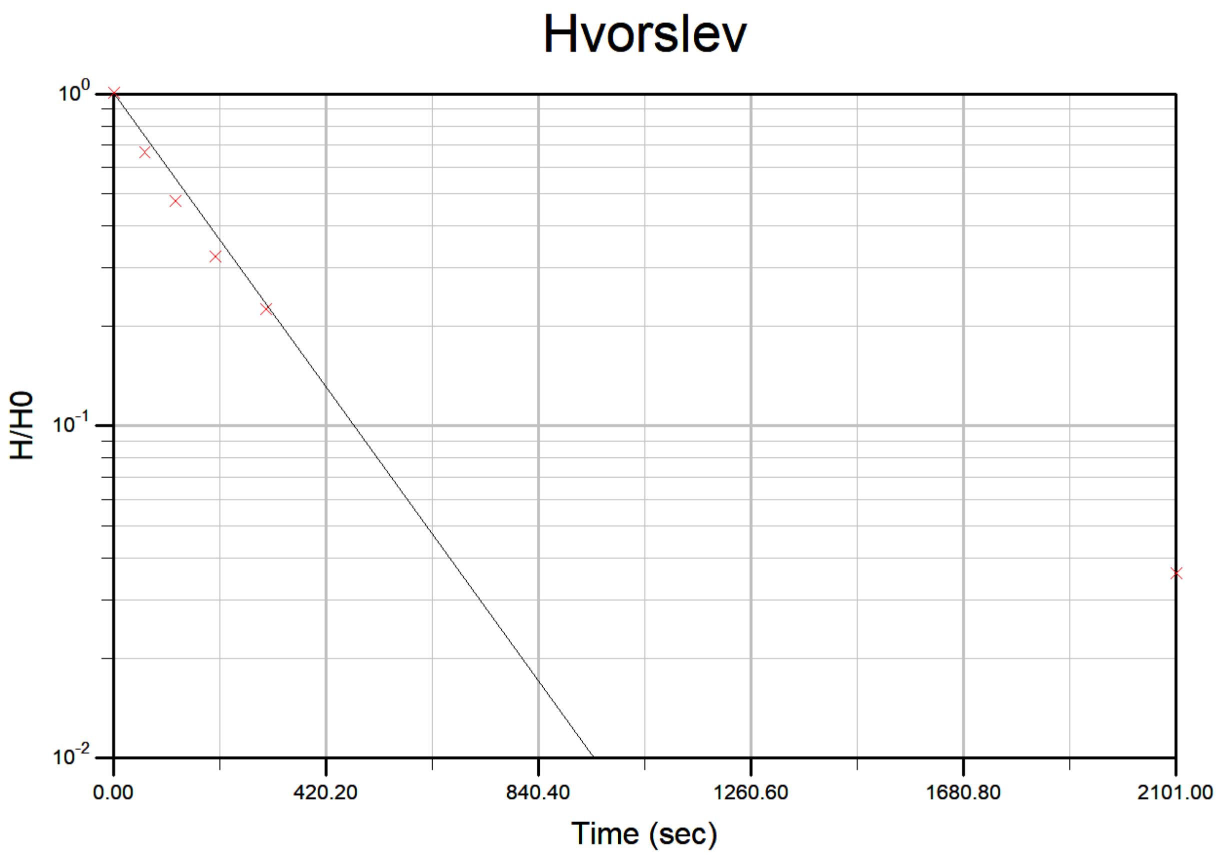

Hvorslev
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
H/H0
0.00
351.20
702.40
1053.60
1404.80
1756.00
Time (sec)

MB5

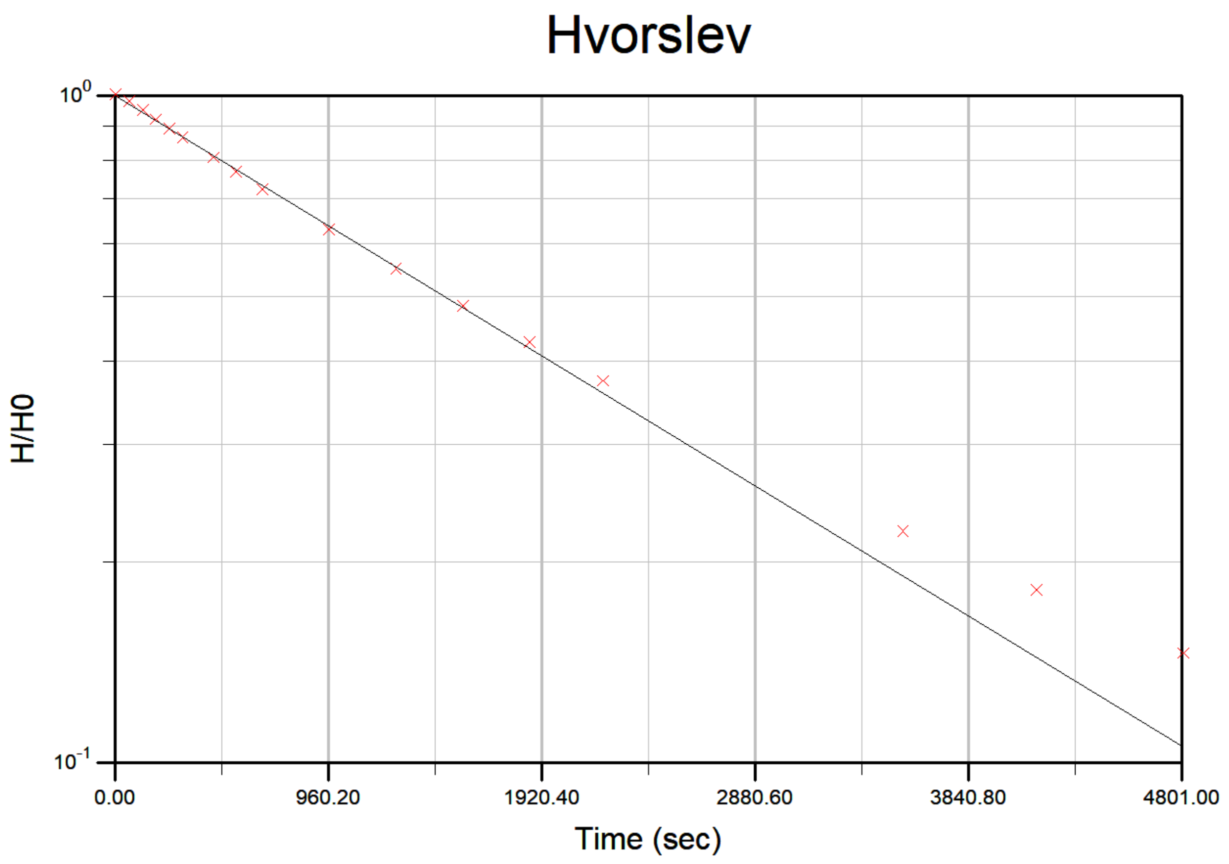


Hvorslev
10^0
10^{-1}
H/H0
0.00
320.20
640.40
960.60
1280.80
1601.00
Time (sec)

MB7

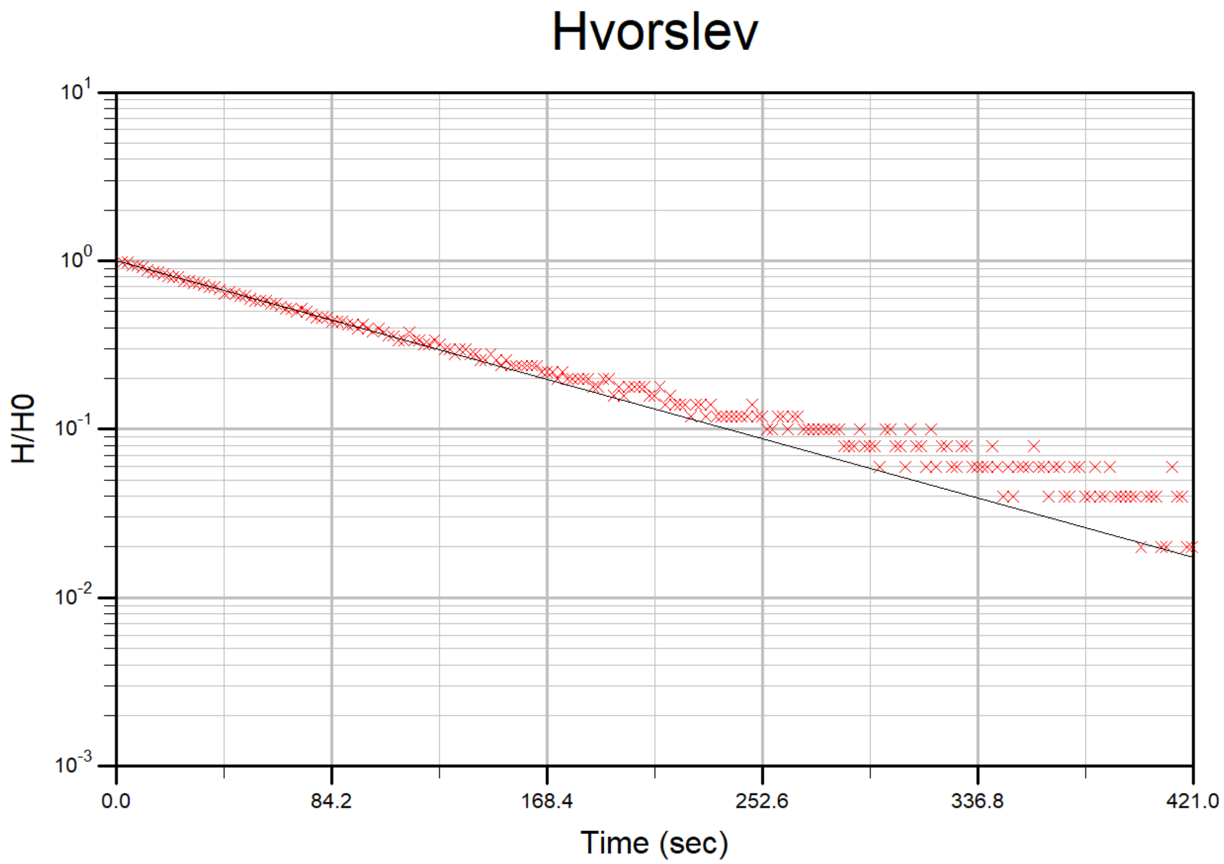

Hvorslev
H/H0
10^0
10^-1
10^-2
0.00
420.20
840.40
1260.60
1680.80
2101.00
Time (sec)

MB9



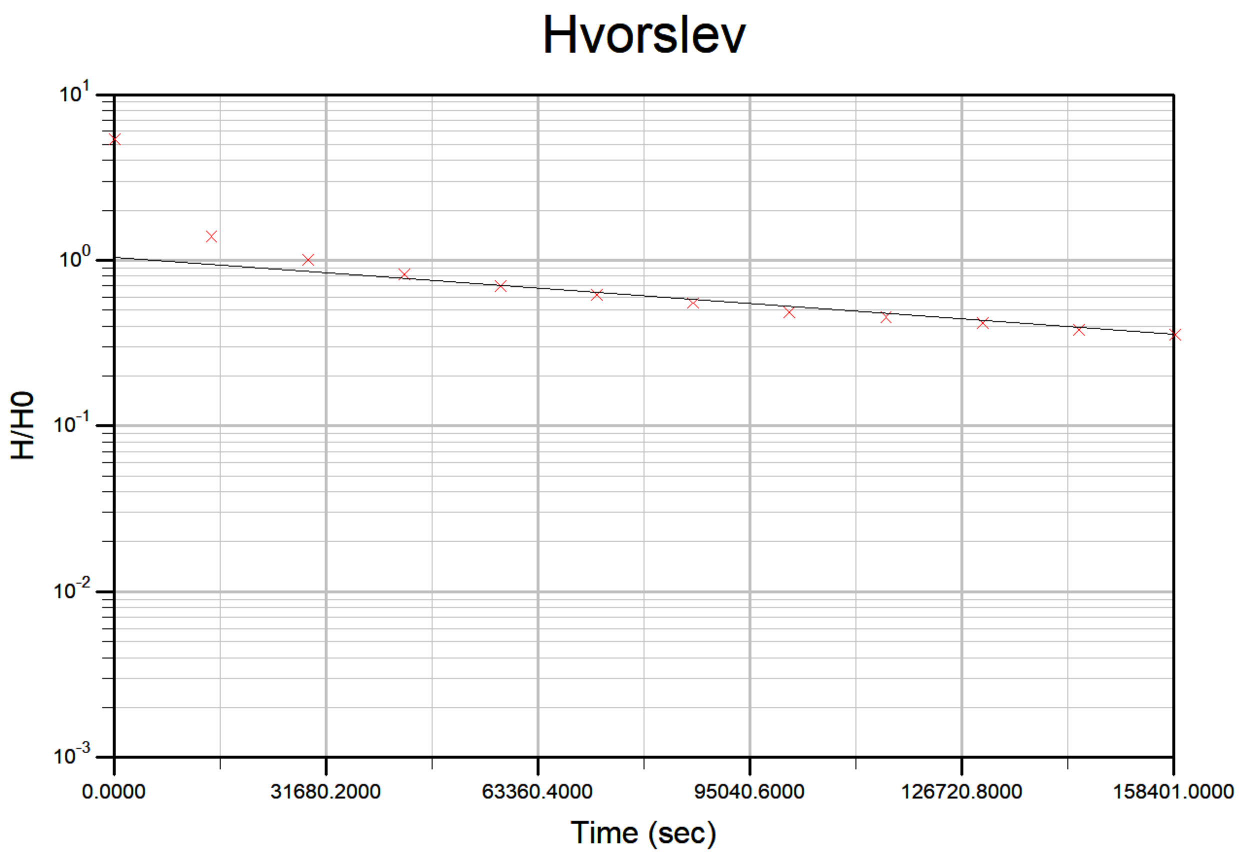
Hvorslev
10^0
10^{-1}
H/H0
0.00
960.20
1920.40
2880.60
3840.80
4801.00
Time (sec)

MB10



Hvorslev
10^1
10^0
10^-1
10^-2
10^-3
H/H0
0.0
84.2
168.4
252.6
336.8
421.0
Time (sec)

MB12


Hvorslev
H/H0
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0.0000
31680.2000
63360.4000
95040.6000
126720.8000
158401.0000
Time (sec)

Appendix C Groundwater modelling

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Vulcan South – Groundwater Impact Assessment

Groundwater Modelling Appendix

Prepared for

Vitrinite Pty Ltd

1. Introduction

Numerical groundwater flow modelling requires an understanding of the hydrogeological conceptualisation, the modelling process and the requirements of the key stakeholders. The numerical groundwater model is often reviewed and assessed to determine whether the model outputs that are created (e.g. calibration and predictions) are fit for purpose (Barnett *et al.*, 2012).

The groundwater modelling appendix presents the modelling objectives, design and construction, calibration and predictions for the Vulcan South (the Project) and is designed to provide a standalone technical document for the key stakeholders to assess and review the project impact assessment numerical groundwater flow model (the numerical model).

1.1. Stakeholders

METServe has been engaged by Vitrinite to manage the environmental approval process for the Project. Vitrinite has commissioned environmental assessment work for the purposes of preparing a mining lease application (MLA) and EA application. The groundwater impact assessment will also support the likely referral of the Project to the Commonwealth Department of the Environment and Energy (DoEE) under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

Stakeholders actively involved in the project are:

- Vitrinite – Project owner;
- MET Serve – manager of the project environmental approval; and
- **hydrogeologist.com.au** – groundwater impact assessment including groundwater monitoring (groundwater levels and groundwater quality), hydrogeological conceptualisation, and prediction of groundwater impacts using the numerical model.

Other stakeholders not directly involved with the Project include:

- Queensland and Commonwealth Governments and their respective agencies including:
    - Queensland Department of Natural Resources Mines and Energy (DNRME);
    - Queensland Department of Environment and Science (DES);
    - Commonwealth Department of the Environment and Energy (DoEE); and
    - Independent Expert Scientific Committee (IESC).
- local landholders, water users (agricultural activity, recreation) – assessment of change to availability of groundwater or changes in groundwater quality; and
- other industrial groundwater users in the region (e.g. BMA and Arrow Energy) – assessment of change to availability of groundwater or changes in groundwater quality.

1.2. Modelling objectives

The objective of the assessment is to identify the impacts of the Project on groundwater in a robust manner that meets the expectations of multiple stakeholders. To achieve this objective, the numerical model has been developed to support the impact assessment and the environmental approvals process. The numerical model needs to quantify the response of groundwater levels and flows to the proposed future stresses on the groundwater system, that is groundwater extraction due to coal mining activities. The quantification of impacts will be provided in the form of:

- Drawdown - providing spatial and temporal information about the extent and magnitude of impacts on the groundwater resource and third-party users (e.g. landholders or groundwater dependant ecosystems [GDE]).
- Groundwater balance of individual hydro-stratigraphic units. This will provide an insight into changes in flow within the groundwater system and will allow for the quantification of pit inflows (or seepage). Understanding the predicted changes in flow rates between individual hydro-stratigraphic units may also provide an indication of changes in groundwater quality.

Given the existence of historical coal mining in the close vicinity to the project (that is BMA Saraji Mine), the analysis of groundwater impacts will be shown in a cumulative sense, as well as groundwater impacts solely due to the project.

1.3. Confidence level classification

The degree of confidence with which model predictions can be used are described using a 'confidence classification' scale which is presented as part of the Australian Groundwater Modelling Guidelines (Barnett *et al.*, 2012). The classification scale conveys understanding about the model complexity, level of calibration and potential for the predictions to be incorrect. The model can fall into three classes:

- *Class 1* – the simplest model, often not calibrated, used as starting points for more complex models, used for prediction of low-value aquifers, least amount of confidence in the modelling results;
- *Class 2* – more complex models, prediction capability could vary depending on the location within the model domain, calibration and prediction runs can vary in terms of magnitude of model stresses and time discretisation, used for prediction in medium- or high-value aquifers; and
- *Class 3* – detailed and complex models, high trust in validity of modelling predictions, used to simulate detailed, small scale processes, used for predictions in high-value aquifers, the highest amount of confidence in the results of the modelling.

Barnett *et al.* (2012) state that every model should be evaluated using multiple criteria, that is:

- *Available data*, accuracy of the data, spatial and temporal distribution of the data. Is the dataset sufficiently representing the described system (in place and in time)? Is the dataset giving us sufficient insight into the system behaviour?
- *Quality of calibration* process undertaken during model development. What type of data was used to calibrate the model? To what level does the model replicate past behaviour given the properties of the model and model inputs (boundary conditions)? Is the higher level of calibration localized in specific area or is it evenly distributed throughout the whole model domain?
- *Consistency between the calibration and predictive analysis*. Are the calibration run and prediction run consistent with respect to length of the model run, temporal discretisation, model stresses?

1.3.1. Data quality indicators

Table 1 below summarises the classification indicators suggested by groundwater modelling guidelines (Barnett *et al.*, 2012) for the available data. A self-assessment has been completed by **hydrogeologist.com.au** and the resultant classification for each indicator is presented.

Table 1 Model classification – available data indicators

Classification indicator	Classification
Climate data	*Class 2*
• Long term rainfall and evaporation data is available in the form of long-term synthetic/interpolated dataset only. (Class 2)	
Landuse information	*Class 3*
• Ecological field survey/mapping undertaken to complement generalised state-wide datasets. (Class 3)	
Surface drainage (streams) and SW/GW interaction	*Class 2*
• Streamflow data and baseflow estimates available at a few points. (Class 2)	
Groundwater flow system – hydraulic properties	*Class 3*
• Key aquifer parameters were defined by in-situ (or laboratory) aquifer tests. The tests spatially cover either the whole model domain or at least the area of interest and adjacent aquifer (hydro-stratigraphic) units (Class 3)	
Groundwater flow system – structure, aquifer geometry	*Class 3*
• Good quality and adequate spatial coverage of digital elevation model to define ground surface elevation. (Class 3) • Spatial distribution of bore logs and associated stratigraphic interpretations clearly define aquifer geometry. (Class 3)	
Observations of water levels	*Class 2*
• Groundwater head observations and bore logs are available but may not provide adequate coverage throughout the model domain. • Transient observation data are available for only few bores with temporal extent not covering the whole calibration period.	
Groundwater and surface water use (recharge and discharge)	*Class 1*
• No available records of metered groundwater extraction or injection. • Little useful data on river flows and/or stage elevations.	

1.3.2. Level of calibration

Table 2 below summarises the classification indicators presented by (Barnett *et al.*, 2012) for the calibration. A self-assessment has been completed by **hydrogeologist.com.au** and the resultant classification for each indicator is presented.

Table 2 Model classification – calibration indicators

Classification indicator	Classification
Calibration statistics	*Class 3*
• Calibration statistics are acceptable. (Class 3) • Mass balance closure error is less than 0.5% of total. (Class 3)	
Long term trends replication, temporal discretization	*Class 2 – Class 3*
• Long-term trends are adequately replicated where these are important. (Class 3) • Seasonal fluctuations are adequately replicated where these are important. (Class 3) • Validation either not undertaken or is not demonstrated for the full model domain. (Class 2) • Transient calibration to historic data but not extending to the present day. (Class 2)	
Types of calibration targets, spatial distribution of calibration targets	*Class 2 – Class 3*
• Transient calibration is current, i.e. uses recent data. (Class 3) • Observations of the key modelling outcomes (water levels in Project observation bores) is used in calibration. (Class 3) • Calibration only to water level dataset, predicting both water levels (water levels change) and flows (pit inflows). (Class 2)	

1.3.3. Consistency between calibration and prediction

Table 3 below summarises the classification indicators presented by (Barnett *et al.*, 2012) for the consistency between model calibration and model predictions. A self-assessment has been completed by **hydrogeologist.com.au** and the resultant classification for each indicator is presented.

Table 3 Model classification – consistency between calibration and prediction

Classification indicator	Classification
Model run length and temporal discretization	*Class 2 – Class 3*
• Length of predictive model is not excessive compared to length of calibration period. (Class 3) • Model predictive time frame is less than 3 times the duration of transient calibration. (*Class 3*) • Temporal discretization used in the prediction is different that used in transient calibration (Class 2)	
Boundary conditions and stresses	*Class 3*
• Level and type of stresses included in the predictive model are within the range of those used in the transient calibration. (Class 3)	
Steady state vs. transient	*Class 3*
• Both calibration and prediction are based on transient model. Steady state model is used to establish initial conditions for the transient predictive model. (Class 3)	

Based upon the results summarised and presented above (Table 1, Table 2 and Table 3) the model has been self-assessed by **hydrogeologist.com.au** and has been classified as a Class 2 model under the Australian Groundwater Modelling Guidelines (Barnett *et al.*, 2012).

2. Conceptual model development

2.1. Time

Temporal discretisation is one of the drivers impacting numerical solution of groundwater flow equation. It influences speed of the numerical solution and impacts outcomes (precision) of the numerical solution – calculation of both heads and flows within modelled groundwater flow domain. As such, the proposed temporal discretisation is usually constrained by requested level of detail of model prediction (for example 'actual daily inflow rates' versus 'annual average inflow rates') which in turn depend on the detail of the modelled stresses (such as extraction rates, recharge) and observation data (frequency of historical water levels measurements, rates of water flow observations).

The timing for the Project with respect to system stresses and frequency of observations is outlined in Table 4.

Table 4 Modelling timeframe, frequency of stresses and observations

Interval		Length	Stress or observation	Stress frequency	Observation frequency	Comment
A	1/01/1972 to 31/12/2018	47 years	in - RCH	continuous	daily	daily interpolated rainfall data available from SILO
			in - recharge from stream to aquifer	continuous	hourly/daily	hourly stream flow data available, however frequency of surface stream flow events could be in months to years - stream flow is intermittent
			out - EVT	continuous	daily	daily EVT estimates available from SILO
			out - discharge from aquifer to stream	continuous	hourly/daily	see above
			out - GW extraction / mining	continuous	1-5 years	the mining progression at Saraji from historical satellite snapshots, interpolated between individual years to refine
			GW levels	-	monthly	monthly measurements only from 4 bores, otherwise one-off - standing water level data
B	1/1/2019 to 31/12/2020	2 years	in – RCH	continuous	daily	see above
			in - recharge from stream to aquifer	continuous	hourly/daily	see above
			out – EVT	continuous	daily	see above
			out - discharge from aquifer to stream	continuous	hourly/daily	see above
			out - GW extraction / mining	continuous	yearly	the mining progression at Saraji from UWIR report
			GW levels	-	4 hours - monthly	Project observation bores installed, pressure transducer data available; existing GW monitoring bores being dipped in approximately monthly schedule
C	1/1/2021 to 30/06/2032	11 years, 6 months	in – RCH	continuous	-	use average value based on historical data
			in - recharge from stream to aquifer	continuous	-	use average value based on historical data
			out - EVT	continuous	-	use average value based on historical data

Interval	Length	Stress or observation	Stress frequency	Observation frequency	Comment
		out - discharge from aquifer to stream	continuous	-	use average value based on historical data
		out - GW extraction / mining	continuous	yearly	the mining progression at Saraji from UWIR report, mining at Project site as planned - annual snapshots for Project mining progression available
		GW levels	-	-	assumed continuation of future observations as part of future GMMP

2.2. Hydrogeological domain

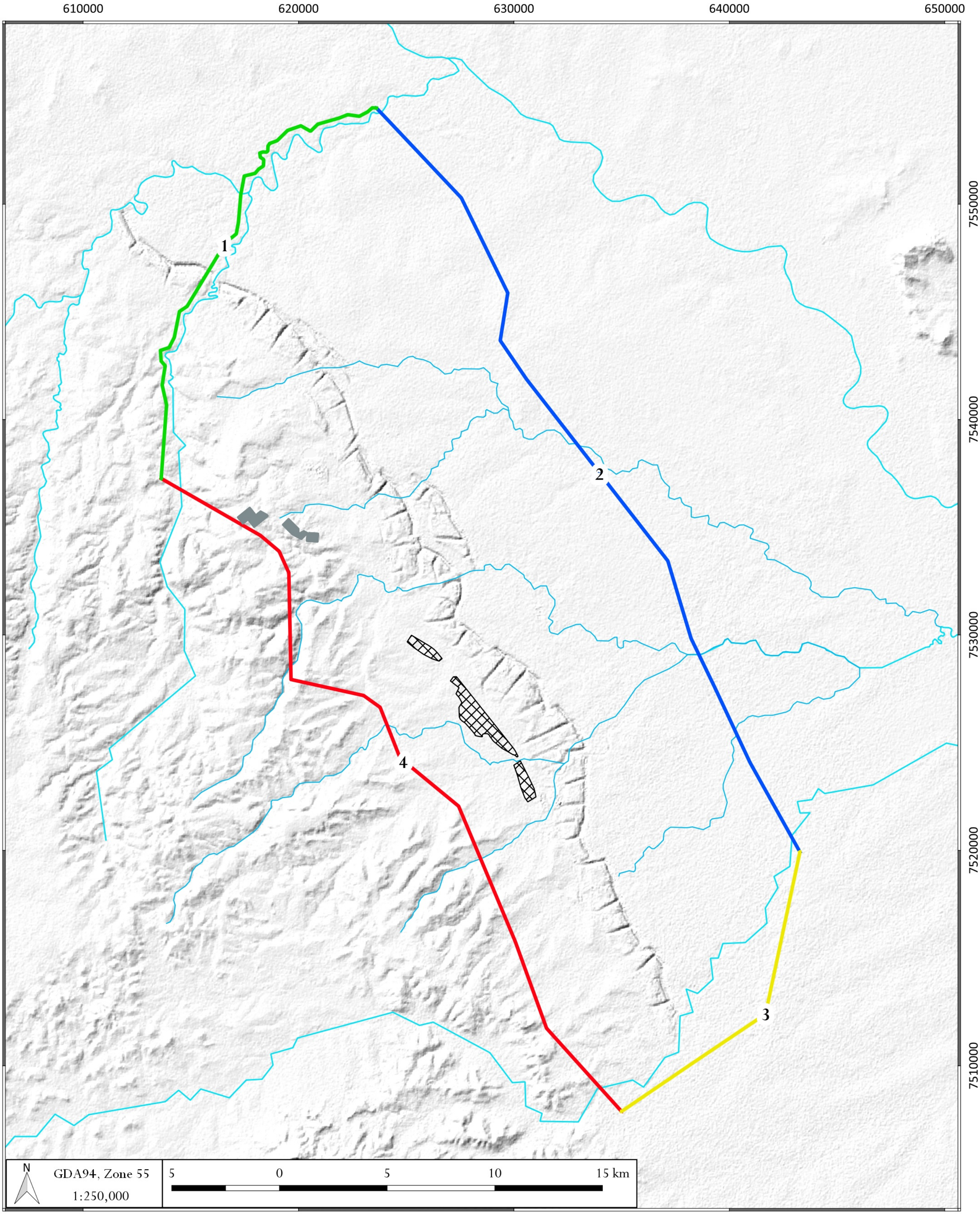
The hydrogeological domain relevant to the Project is defined as the part of the groundwater system potentially impacted by project related activities (mining). Given presence of a large open-cut mine(s) in the close vicinity of the Project, we assume that the historical and current mining of Dysart Lower seam at Saraji Mine had impacted (and will continue to impact) the groundwater system of the Project site as proposed by AECOM (2016, chaps. 10, 11). In order to capture the impact of historical mining on the groundwater flow system within the Project area, the majority of the Saraji Mine has been included in the groundwater flow model.

In terms of depth (vertical) extent, the Project targets the lowermost coal seams of the Moranbah Coal Measures, that is the Dysart Lower Lower (DLL) and ALEX coal seams.

Given the current groundwater conditions observed at the Project area (that is the partial saturation of the Tertiary sediments and weathered profile including upper parts of the target Permian coal seams), the impact of the Project is expected to be relatively minor and localised. Any drawdown will likely develop along the subcrop of the target Permian coal seams (DLL) in a north-south direction (along geological strike); drawdown expansion across the subcrop zone (in west-east direction) is expected to be minimal.

The boundaries of the model domain (Figure 1) were delineated as follows:

- Boundaries parallel to regional groundwater flow system (or perpendicular to regional system groundwater flow contours - north-western [1] and south-eastern [3] boundaries). These boundaries are by default ‘no-flow’.
- South-western inflow boundary [4] runs through the higher elevations of the Harrow Range. This boundary does not follow any physical feature, it was located parallel to the DLL subcrop, approximately 3 km from the subcrop line. The cross-boundary flow will be simulated using general head boundary condition (GHB) or will be compensated by higher recharge in the hilly areas.
- North-eastern outflow boundary [2] was located into the Jellinbah Thrust Fault zone. The zone is expected to act as a barrier to flow, however the groundwater will still move within the overlying weathered regolith zone. The cross-boundary outflow will again be simulated using general head boundary condition, however only in the semi-consolidated or unconsolidated weathered regolith zone; the fault zone itself will be considered ‘no-flow’.



LEGEND

Model boundaries

- 1 - No flow
- 2 - Cross-boundary outflow
- 3 - No flow
- 4 - Cross-boundary inflow

Proposed pit

Watercourse

Highwall mining area

DATE 22/02/2022

Vulcan South - Groundwater Modelling Appendix (4027)

Boundaries of the model domain

FIGURE No. 1

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\01_4027_Vulcan South_App_Model boundaries.qgz

2.3. Hydro-stratigraphy and layering

As defined by Maxey (1964) and updated by Seaber (1988), a hydro-stratigraphic unit can be defined as a part of a body of rock with distinct hydrologic properties (hydraulic conductivity, porosity and transmissivity), regardless of other types of classification (such as unit age or lithology). Definition of individual hydrostratigraphic units divides the hydrogeologic system into its relatively more permeable parts (aquifers) or less permeable parts (aquitards).

2.3.1. Quaternary alluvium

Within the model area, Quaternary alluvium was mapped adjacent to Cherwell Creek in the north. This unit is described as poorly consolidated sand, silt, clay, minor gravel (Department of Natural Resources, Mines and Energy, 2018). In the south, Quaternary alluvium was mapped and described around Phillips Creek. The flood plain unconsolidated deposits were classified as clays, silts, sands and gravels (Department of Natural Resources, Mines and Energy, 2018) 10 m to 25 m deep (AECOM, 2016; Department of Natural Resources, Mines and Energy, 2019a).

Given the ephemeral nature of the surface streams in the area, the alluvial deposits are not considered permanent sources of groundwater with most of the shallow monitoring bores within the alluvium being dry (AECOM, 2016). The stratigraphic logs also indicate that the coarser alluvial sediments are discontinuous along the creek, presenting a limited storage environment (AECOM, 2016). This observation is also supported by lack of government classification of the creek alluvial zones under the Fitzroy Basin Water Resource Plan (Queensland government, 2014) where the mapped alluvial zones of Cherwell and Phillips Creeks are not included within the "Isaac Connors Alluvium Groundwater Sub-area".

2.3.1. Tertiary sediments / Weathered zone / Regolith

Tertiary sediments comprise unconsolidated to semi-consolidated heterogeneously distributed colluvial and fluvial sediments which include clay, silty clay, sandy clay, clayey sand, sand and gravel in clay-rich matrix (AECOM, 2016). Thickness of Tertiary sediments varies from 15 m to approximately 60 m. The lower Tertiary is defined by up to 3 m thick, locally discontinuous basal sand and gravel sand layer considered to be a remnant of paleo-channel system related to current Phillips Creek (AECOM, 2016). The transition zone between Tertiary units and consolidated, unweathered Permian bedrock material is frequently delineated by spatially discontinuous clayey layer (AECOM, 2016) that is likely to be a product of in-situ weathering of Permian material (hydrogeologist.com.au, 2019).

The Tertiary sediments are recharged by either rainfall or surface water runoff with a possibility of interaction (both recharge from and discharge to) with underlying Permian coal measures. Groundwater within Tertiary sediments most frequently occurs within the basal gravel layer under unconfined or semi-confined conditions (AECOM, 2016). Direction of groundwater flow within the Tertiary sediments is expected to reflect topography, from topographically elevated areas in the west towards the east (AECOM, 2016).

Thickness of the Tertiary sediments (including weathered zone / regolith) was estimated using two data sources: stratigraphic records from Queensland Groundwater Database (Department of Natural Resources, Mines and Energy, 2019a) and average depth of regolith dataset from CSIRO Soil and Landscape Grid of Australia (Wilford *et al.*, 2018). The boundary between the Tertiary sediments / weathered zone / regolith and fresh bedrock was manually identified from 353 stratigraphic logs from bores within and outside of the Project area and then compared to the estimated depth of regolith dataset. The analysis of the data (Figure 2) showed the bias of the estimated regolith thickness dataset – the thicker the weathered zone estimate was, the larger difference there was between the estimate and thickness derived from stratigraphic logs. In general, the CSIRO estimated the weathered zone to be thicker than the lithology logs showed.

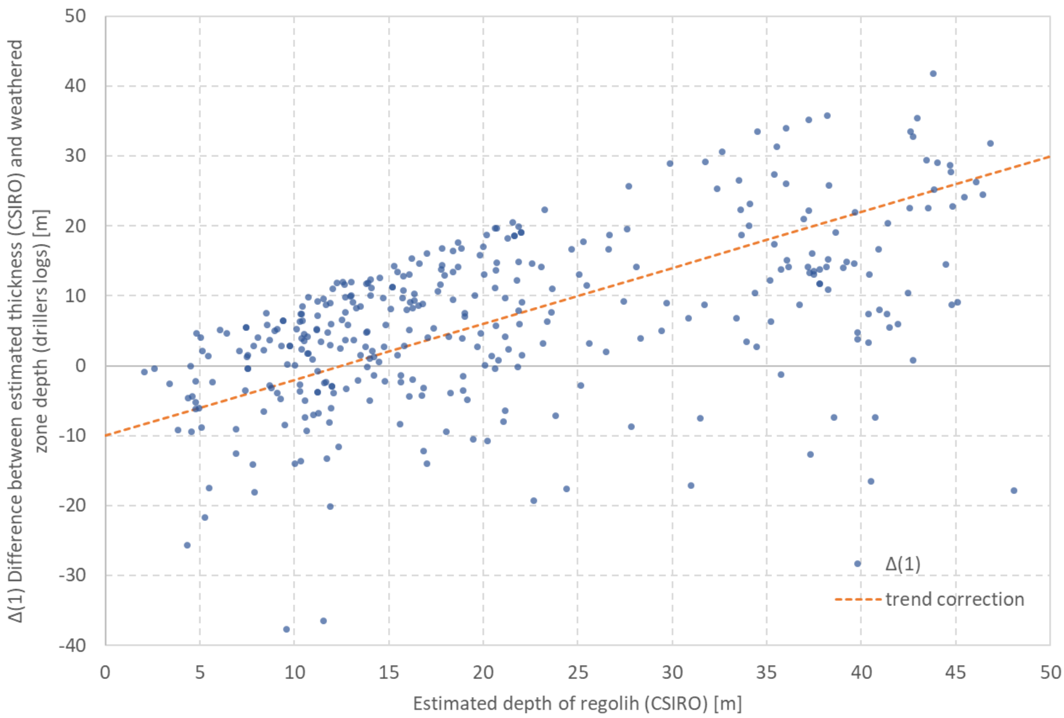


Figure 2 Estimated error of regolith thickness as a function of the thickness

The thickness of weathered zone was then adjusted in two steps; first using the general trend correction (Figure 2) to make the weathered zone thinner in thick (deep) areas and thicker in thin (shallow) areas; and second rectifying the dataset based on spatial distribution of actual localised differences between the stratigraphic logs and CSIRO thickness estimate. The resulting adjusted weathered regolith thickness dataset (corrected depth) was then compared to the depth of regolith information obtained from stratigraphic logs (measured depth) the verify the validity of the adjustment process (Figure 3). Although the general trend shows good fit between the adjusted CSIRO dataset and the stratigraphic logs data, the outliers indicate misidentification of the weathered zone boundary on some of the stratigraphic logs.

The spatial distribution of the Tertiary sediments / weathered zone / regolith (Layer 2) is extensive over the entire model domain.

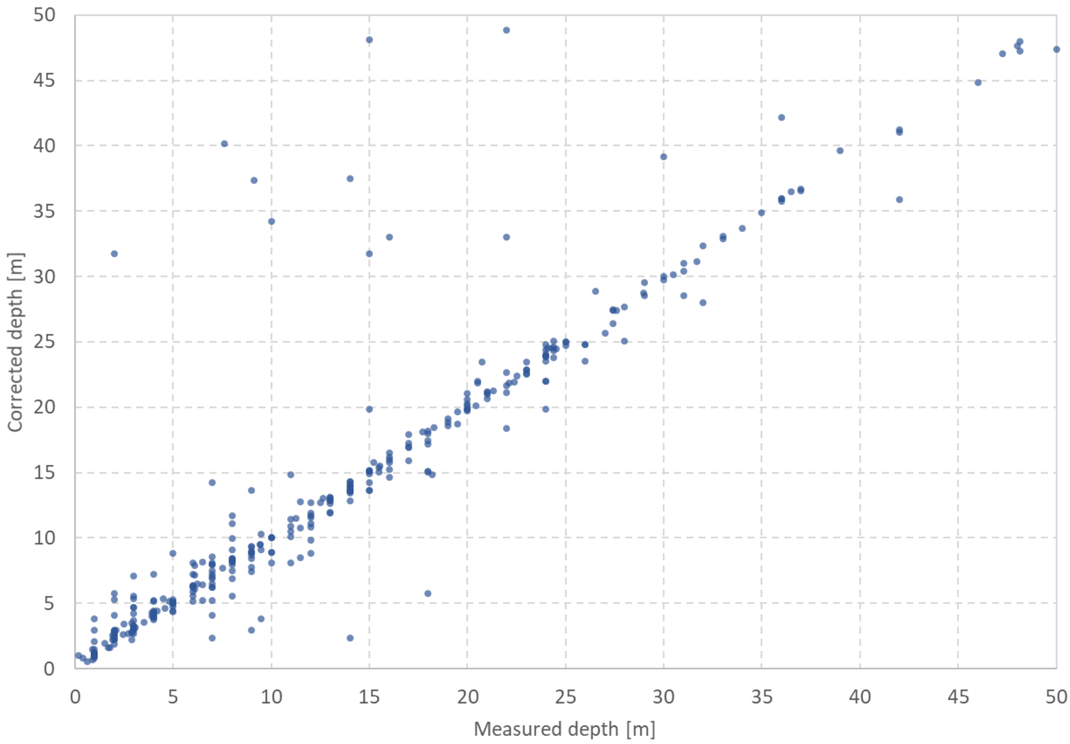


Figure 3 Validation of adjusted regolith thickness data (corrected depth) against the thickness data obtained from stratigraphic logs (measured depth)

2.3.2. Permian coal measures

Permian coal measures comprising sandstones, mudstones and coal seams generally dip in eastern or north-eastern direction, subcropping under the weathered regolith and alluvium layers. The Permian coal measures were observed to be at least partially unsaturated in the Project area. In the areas where the subcrops are shallow, groundwater recharge to the Permian coal measures is likely combination of rainfall and overland flow infiltration. Recharge may also occur through overlying Cainozoic sediments under downward vertical hydraulic gradient and along faults and other structural features (AECOM, 2016).

Within the Permian coal measures, the interburden material (sandstone and mudstone) will act as aquitard with lower hydraulic conductivity then the coal seams, in which the groundwater can move along the bedding planes (or open cleats) of the coal (HydroSimulations, 2018).

2.4. Hydraulic properties

Estimates of hydraulic properties were based on both historical information from work undertaken in the general vicinity of the Project area (AECOM, 2016; Arris, 2017; Arrow Energy, 2016; HydroSimulations, 2018; URS, 2014, 2012, 2009) as well as on-site hydraulic testing (Table 5). The on-site tests targeted the weathered regolith zone (three tests), interburden (one test) and DLL and MAT coal seams (eight tests).

Table 5 Summary of horizontal K values (m/day) – regional studies, on-site tests, adopted values

HSU	K_h (m/day) regional studies		K_h (m/day) on-site tests		K_h (m/day) adopted values	
	avg min	avg max	min	max	min	max
alluvium	4.13×10^{-1}	$7.22\times10^{+1}$	n/a		1.00×10^{-1}	$1.00\times10^{+0}$
weathered regolith	7.53×10^{-2}	$2.90\times10^{+0}$	1.00×10^{-1}	2.10×10^{-1}	1.00×10^{-2}	$1.00\times10^{+0}$
interburden / overburden	4.01×10^{-2}	2.33×10^{-1}	2.80×10^{-4}		1.00×10^{-4}	1.00×10^{-2}
coal seams	8.75×10^{-4}	$1.32\times10^{+0}$	2.00×10^{-2}	4.10×10^{-1}	1.00×10^{-3}	$1.00\times10^{+0}$

Vertical hydraulic conductivity (K_v) value was specified as a fraction of horizontal conductivity value, with the ratio (K_h:K_v) between 10:1 for unconsolidated sediments (alluvium, weathered regolith zone) and 1000:1 for consolidated sediments (sandstone, mudstone or shale of interburden and coal).

As the type of hydraulic test undertaken on-site was not suitable to ascertain storage parameter values (S_y - specific yield and S_s - specific storage), the initial range of values was based on values obtained from studies focusing on the same hydrostratigraphic units surrounding the Project area.

2.5. Boundary conditions and system stresses

2.5.1. Rainfall and evapotranspiration

Climate plays major role in defining two of the characteristics of the groundwater system; recharge and evapotranspiration. Based on the Australian Bureau of Meteorology (Bureau of Meteorology, 2016) classification criteria, the Project area can be characterised as subtropical, with mostly hot dry summer and mild winter. In terms of rainfall, the Project area is "summer rainfall dominant" with annual rainfall between 350 mm and 650 mm and majority of the rain falling between November and March.

To characterise the rainfall trend, the precipitation information from five monitoring stations (Table 6, Figure 4) surrounding the project area were used.

Table 6 Average monthly rainfall (2010-2019) for monitoring stations surrounding Project area

Station	SILO interpolated	Moranbah WTP	Wentworth	Mount Lebanon	Seloh Nolem	Booroondarra
Station number	-	34038	34015	34055	34086	35109
Lat (decimal degrees)	-22.35	-21.9947	-22.0656	-22.2211	-22.3069	-22.8181
Long (decimal degrees)	148.20	148.0308	147.7219	147.9703	148.4822	148.4900
Elevation (m)	258.0	260.0	225.0	294.0	170.0	200.0
Month	*Average monthly rainfall 2010-2019 (mm)*					
January	117.6	101.7	73.6	101.8	119.4	130.2
February	107.7	113.4	62.8	105.1	98.1	84.2

Station	SILO interpolated	Moranbah WTP	Wentworth	Mount Lebanon	Seloh Nolem	Booroondarra
March	102.1	96.2	62.5	88.9	116.9	121.8
April	28.3	24.2	24.1	27.5	25.2	35.2
May	25.1	21.1	21.7	22.8	21.8	16.9
June	21.0	17.0	15.0	19.3	19.9	20.1
July	26.6	24.4	26.1	25.8	25.0	25.7
August	25.3	24.6	20.4	23.1	25.1	25.0
September	20.1	13.0	12.6	19.2	18.1	30.6
October	28.6	25.2	14.6	22.3	29.8	32.3
November	58.5	60.8	59.0	58.6	60.9	63.9
December	98.5	106.2	76.5	95.6	97.9	119.2

The average precipitation data for all sites displays the same short-term trend (Figure 4): most of the rain (60 mm to 130 mm) falls over summer months (December to March) while autumn and winter months show lower precipitation between 10 mm and 30 mm. The SILO interpolated dataset is consistent with the data from all BOM stations except Wentworth which appears to be relatively dryer, receiving 30% less of rainfall on annual basis.

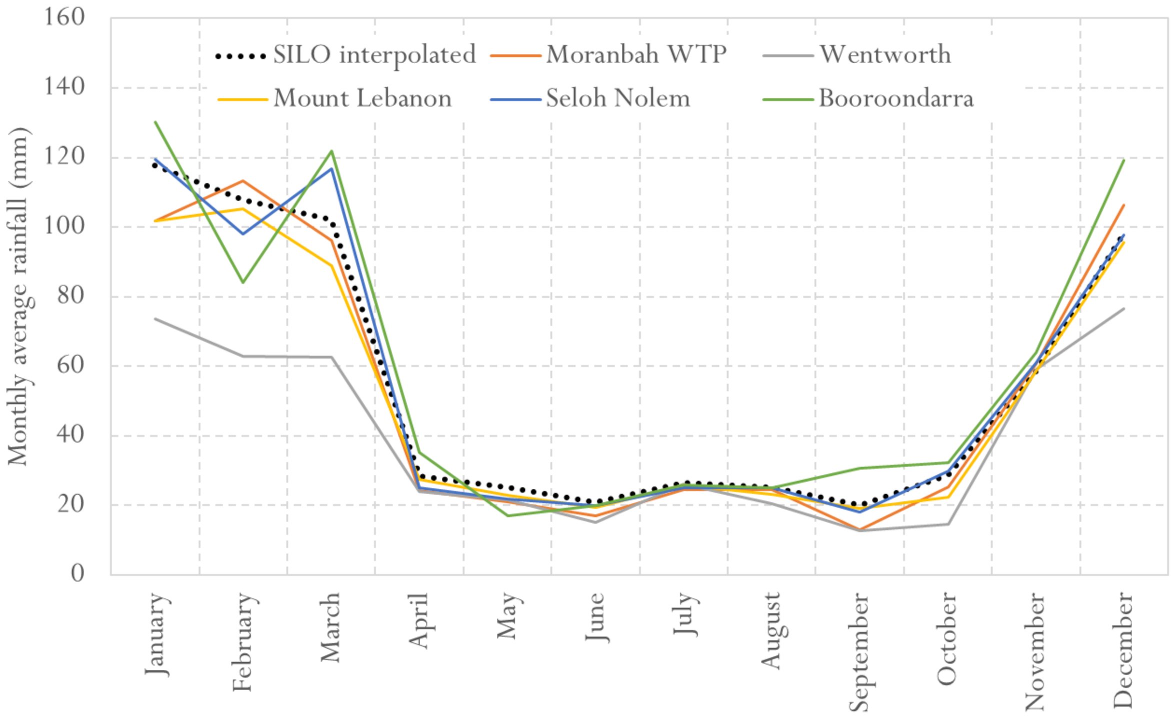


Figure 4 Average monthly rainfall (2010-2019) for monitoring stations surrounding Project area

As the long term data is not available from either of the stations, in order to establish long term rainfall and evapotranspiration trend, synthetic (interpolated) SILO data (Jeffrey *et al.*, 2001) was used. Analysis of long term evapotranspiration data (Table 7 and Figure 5) shows evapotranspiration consistently higher than rainfall. The higher EVT can potentially limit localised recharge of the groundwater system from precipitation; the rain either evaporates or is used by plants before it reaches the groundwater table.

Table 7 Comparison of mean monthly rainfall and mean monthly EVT

Month	Data interval	Mean rainfall (mm)	Mean EVT [Mact] (mm)
January	1900 - 2019	105.0	136.6
February	1900 - 2019	98.8	120.8
March	1900 - 2019	63.6	117.6
April	1900 - 2019	30.2	85.7
May	1900 - 2019	28.0	56.7
June	1900 - 2019	29.6	38.9
July	1900 - 2019	22.0	43.4
August	1900 - 2018	18.9	64.5
September	1900 - 2018	15.4	85.1
October	1900 - 2018	31.7	108.4
November	1900 - 2018	52.0	120.4
December	1900 - 2018	86.5	136.0
Annual	1900 - 2018	581.4	1115.1

Note: Mact – Morton actual EVT value

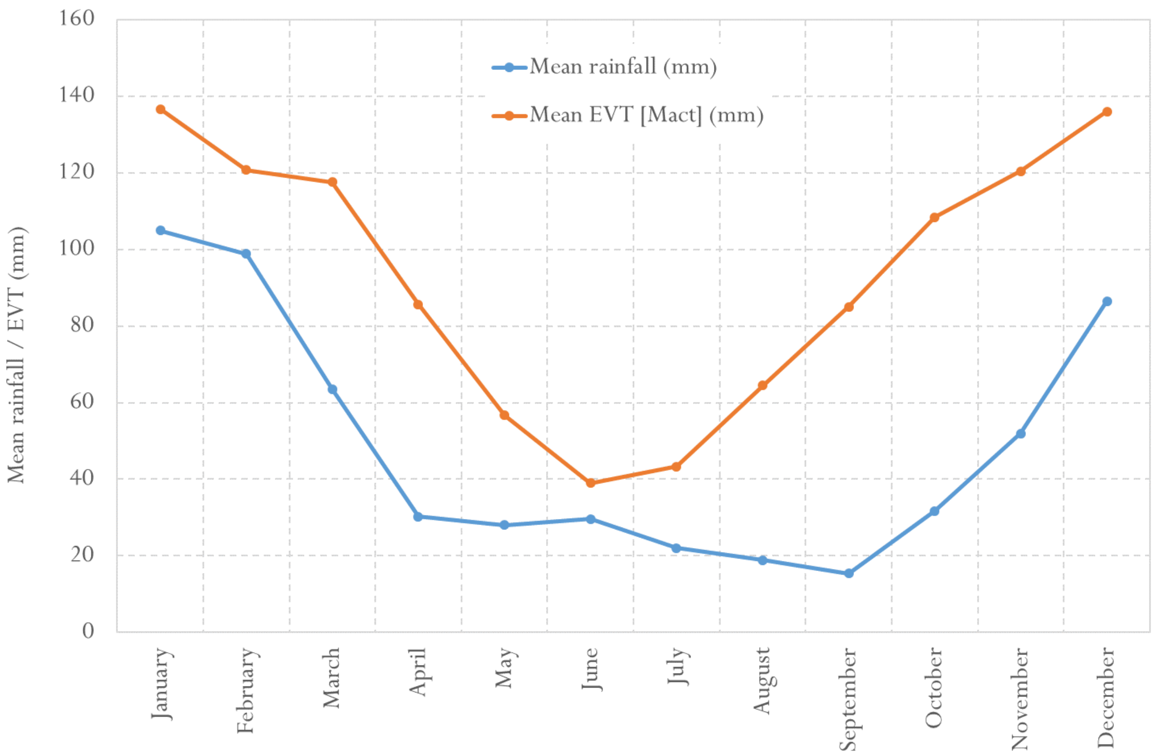


Figure 5 Comparison of mean monthly rainfall and mean monthly EVT

2.5.2. Surface stream discharge and recharge

The groundwater / surface water interaction assessment was based on data from a single stream gauging station (Philips Creek @ Tayglen – station 130409A). There is no other known monitoring data related to the surface drainage network near the Project area and given the similarity between Phillips Creek and other 'major' drainage (Boomerang Creek, Harrow Creek, Cherwell Creek) we consider it to be representative drainage feature.

Out of 7441 days when the gauge was monitored, sensors recorded 1527 days (~20% of time) of intermittent creek flow. The gauging station was active between May 1968 and September 1988, just over 20 years. The flow of the Phillips Creek was recorded only after rainfall; if the monthly rainfall was higher than monthly average rainfall (Figure 6 – time interval A), the frequency of the creek flows increases (on average 13 days of creek flow per month over period between October 1973 and July 1979), if the rainfall is lower than average (Figure 6 – time interval B) or average (Figure 6 – time interval C), the creek flow frequency decreases (on average 3 days of creek flow per month over period between November 1980 and September 1988). Unfortunately, the stream flow data from the time period of sustained drought 1991-1998 and 2000-2007 (Millennium Drought) is not available.

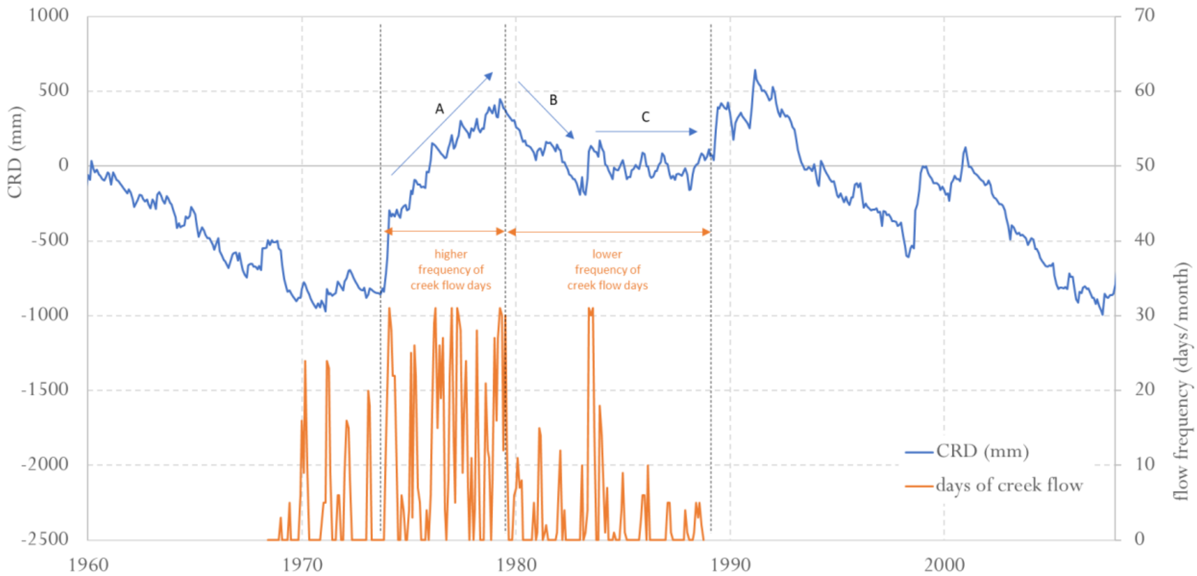


Figure 6 Frequency of creek flow compared to cumulative rainfall departure

Based on the available data, the flow of the Phillips Creek (and by proxy, flow of the other 'major' creeks in the area) appear to be supported purely by localised runoff, and there is no indication of flow supported by discharge from shallow aquifer. This assumption is also supported by the observation of lack of groundwater in shallow weathered regolith profile.

Given the perceived low impact of surface water flow on overall recharge to the groundwater system, the creek network was conceptualised as 'drainage-only'. It removes surface runoff water from the model domain, and it has potential for removing the groundwater under the condition that the groundwater table in the vicinity of the creek is above the bottom of the creek.

2.5.3. Water extraction due to mining

Saraji Mine is the closest mine to the Project and may potentially impact the groundwater system adjacent to the proposed open pit. Saraji Mine has been in operation since 1974 with the estimated overall mine inflow between 1.6 GL/year and 2.1 GL/year (~4.4 ML/day to ~5.8 ML/day) (AECOM, 2016). This water is extracted from the groundwater system as moisture locked in coal or minor seepage in the highwall, removed by evaporation. The transient observation data from BMA monitoring bores (alluvium bore MB2, Tertiary bores PZ02A and PZ04A and Permian bores MB31, MB33 to MB37) indicate that the impact of mining at Saraji Mine appears to be contained in the area adjacent to the pits, likely due to low permeability of the mined strata and Permian overburden (AECOM, 2016).

Given the hydraulic properties of the Permian strata combined with only partially saturated shallow weathered / Tertiary aquifer, the water extraction rates for the Project are expected to be low.

2.6. Observations

A set of 55 selected observation points were used in the calibration process. These observation points, as outlined in Table 8 below, include historical observation data from publicly available sources (AECOM, 2016; Department of Natural Resources, Mines and Energy, 2019a), on-site one-off data collected from open drill-holes and data collected from new monitoring bores (hydrogeologist.com.au, 2019).

Table 8 Observation points – target stratigraphy and data sources

Bore ID / RN	Easting	Northing	Target stratigraphic unit	Data source
32924	638285.0	7514125.0	Moranbah coal measures - overburden	2
42182	637746.0	7514257.0	Moranbah coal measures - overburden	2
43639	638938.6	7511033.0	Moranbah coal measures - DLL coal seam	1
44336	634974.7	7509309.7	Back Creek group	1
46899	636931.8	7515269.0	Moranbah coal measures - DL coal seam	2
49995	637834.7	7514392.0	Moranbah coal measures - DL coal seam	2
49997	637879.3	7514635.0	Moranbah coal measures - DL coal seam	2
84538	641353.3	7516737.0	Moranbah coal measures - DL coal seam	1
100291	626431.5	7542882.6	Fort Cooper coal measures	1
136092	633415.8	7512196.5	Tertiary sediments, weathered zone, regolith	1
136689	635867.8	7528233.7	Back Creek group	1
141382	628490.0	7542693.0	Fort Cooper coal measures	1
141384	623784.0	7549391.0	Moranbah coal measures - overburden	1
141386	626507.0	7544152.0	Fort Cooper coal measures	1
158010	642528.4	7519938.8	Fort Cooper coal measures	1
158011	640035.0	7514094.9	Moranbah coal measures - overburden	1
158012	632270.5	7515394.7	Back Creek group	1
158013	637781.5	7518065.5	Moranbah coal measures - overburden	1
158014	636495.7	7519991.1	Moranbah coal measures - overburden	1
162138	620083.8	7547612.9	Moranbah coal measures - overburden	1
162177	616863.0	7547756.0	Moranbah coal measures - overburden	1
162506	621630.0	7534800.0	Back Creek group	1

Bore ID / RN	Easting	Northing	Target stratigraphic unit	Data source
162816	618975.0	7552309.0	Tertiary sediments, weathered zone, regolith	1
162829	623671.0	7549482.0	Tertiary sediments, weathered zone, regolith	1
13040283	627823.3	7527382.7	Moranbah coal measures - DLL coal seam	1
MB04	622014.3	7536148.2	Back Creek group	4
MB05	621964.5	7534905.0	Back Creek group	4
MB07	628691.1	7526258.1	Tertiary sediments, weathered zone, regolith	4
MB09	629511.2	7525222.7	Moranbah coal measures - DLL coal seam	4
MB10	628123.6	7526469.3	Moranbah coal measures - DLL coal seam	4
MB12	625251.5	7526409.2	Back Creek group	4
MB30	642503.0	7519162.0	Fort Cooper coal measures	2
MB32	637481.0	7510535.0	Back Creek group	2
MB4	635928.0	7527934.0	Moranbah coal measures - overburden	2
PC056	640288.3	7516655.0	Moranbah coal measures - DL coal seam	2
PC058XC	640054.7	7516179.0	Moranbah coal measures - DL coal seam	2
PC066XC	639328.9	7517206.0	Moranbah coal measures - DL coal seam	2
PZ06A	639272.0	7513326.0	Moranbah coal measures - overburden	2
PZ06C	639272.0	7513326.0	Moranbah coal measures - DL coal seam	2
PZ08A	634647.0	7523069.0	Moranbah coal measures - DL coal seam	2
TG1	635215.0	7508903.0	Tertiary sediments, weathered zone, regolith	2
VSW002	627811.8	7526808.7	Moranbah coal measures - DLL coal seam	3
VSW006	628024.8	7526217.7	Moranbah coal measures - DLL coal seam	3
VSW007	628679.8	7526268.7	Moranbah coal measures - DLL coal seam	3
VSW008	627335.8	7527263.7	Back Creek group	3
VSW009	628076.8	7527016.7	Moranbah coal measures - DLL coal seam	3
VSW011	627406.8	7527852.8	Moranbah coal measures - DLL coal seam	3
VSW013	624599.8	7530294.8	Back Creek group	3
VSW014	623534.8	7531296.8	Back Creek group	3
VSW016	621573.8	7535486.8	Back Creek group	3
VSW017	622555.8	7535727.8	Back Creek group	3
VSW018	622937.8	7533623.8	Back Creek group	3
VSW019	622513.8	7534503.8	Back Creek group	3
VSW020	622672.8	7535009.8	Moranbah coal measures - DLL coal seam	3
VSW021	622024.8	7536169.8	Back Creek group	3

Data sources:

1 - Groundwater database – Queensland (Department of Natural Resources, Mines and Energy, 2019a)
2 - Saraji Open Cut Extension Project, Underground Water Impact Report (AECOM, 2016)
3 - on-site core drillholes, one-off measurement (November-December 2018, pers. comm.)
4 - Hydrogeological drilling report, Vulcan complex project (hydrogeologist.com.au, 2019)

3. Numerical model development

3.1. Software used

MODFLOW-USG (Panday *et al.*, 2015), based on the U.S. Geological Survey MODFLOW-2005 groundwater modelling code, was used as modelling code of choice. MODFLOW-USG simulates groundwater flow using a generalised control volume finite-difference approach, which allows non-orthogonally structured grids to be used for groundwater flow simulations (Panday *et al.*, 2013).

The model mesh was constructed using AlgoMesh (Merrick, 2016). The spatial discretisation of the model domain is discussed in more detail in Section 3.3.

Post processing of the model outputs was using combination of Groundwater utilities (Doherty, 2019a), in-house Fortran and Python code and QGIS (QGIS Development Team, 2019); QGIS was also used to manage all the spatial data and produce map outputs.

Model calibration and parameter sensitivity analysis was undertaken using PEST (Doherty, 2019b, 2019c) and BeoPEST (Doherty, 2012).

3.2. Temporal discretisation and Output control (OC)

Based on the understanding of temporal discretisation of stresses and observation combined with required model output timing (Section 2.1), the timing of the model run was defined as described in Table 9 below:

Table 9 Temporal discretisation – calibration and prediction runs

Stress period	Stress period length	Dates	Modelling phase
1 - 47	1 year	01/01/1972 – 31/12/2018	calibration
48 - 51	3 months	01/01/2019 – 31/12/2019	
52 - 55	3 months	01/01/2020 – 31/12/2020	prediction - mining
56 - 76	6 months	01/01/2021 – 30/06/2032	

The length of each stress period in MODFLOW-USG is defined in the discretisation (DISU) file, while discretisation of time within each individual stress period is defined in Output Control (OC) package. Every stress period has variable-length time-stepping with minimum timestep length of 0.1 of a day and maximum timestep length of ½ of stress period length.

3.3. Spatial discretisation – mesh definition

A mostly non-orthogonally structured polygonal mesh was designed to cover the model domain. The mesh combines rectangular cells blocks in the area of mining ('no-refine' regular cell size imposed on mining areas - Table 10) and Voronoi polygonal cells in the remaining areas. The non-mining areas of the mesh were refined around surface streams, geological boundaries (alluvium boundary, DLL subcrop boundary) and observation points. The mesh consists of 22492 polygons. Area of the cells varies between 1000 m^2 to 911000 m^2. The extent of the full model mesh (including spatial definition features) is presented in Figure 7 below.

Table 10 Model mesh definition – 'no-refine' polygons representing mining areas

Pit	Rotation	Cell size (m)
Vulcan Coal Mine	120°	50×100
VS Vulcan north pit	145°	50×100
VS Vulcan main pit	128°	50×100
VS Vulcan south pit	109°	50×100
Peak Downs	50°	150×250
Saraji – Yura Nth	43°	150×250
Saraji – Yura Sth	15°	150×250
Saraji – Boomerang Nth	2°	150×250
Saraji – Boomerang Sth	52°	150×250
Saraji – Acacia	57°	150×250
Saraji - Bauhinia	28°	150×250
Saraji – Coolibah	-1.5°	150×250
Saraji – Dogwood	27°	150×250
Saraji – Ebony	24°	150×250
Saraji – Grevillia	25°	150×250
Saraji – Hakea	50°	150×250

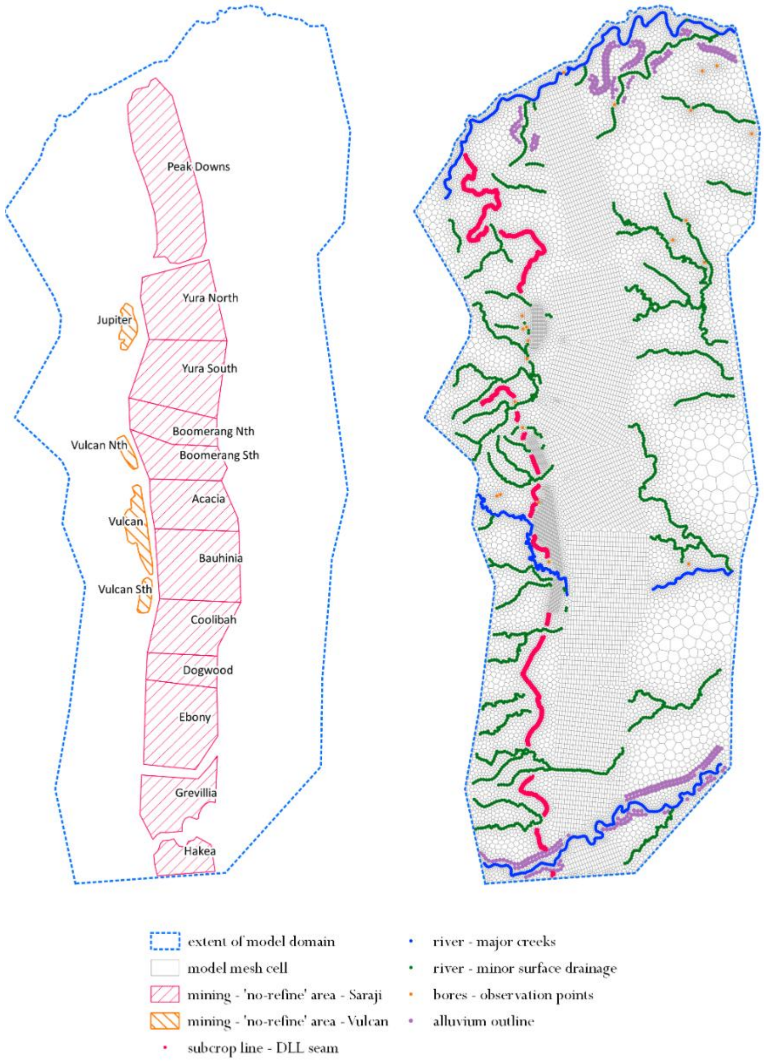


Figure 7 Mesh definition features for mining ('no-refine' zones) and non-mining areas

3.4. Spatial discretisation – model layers

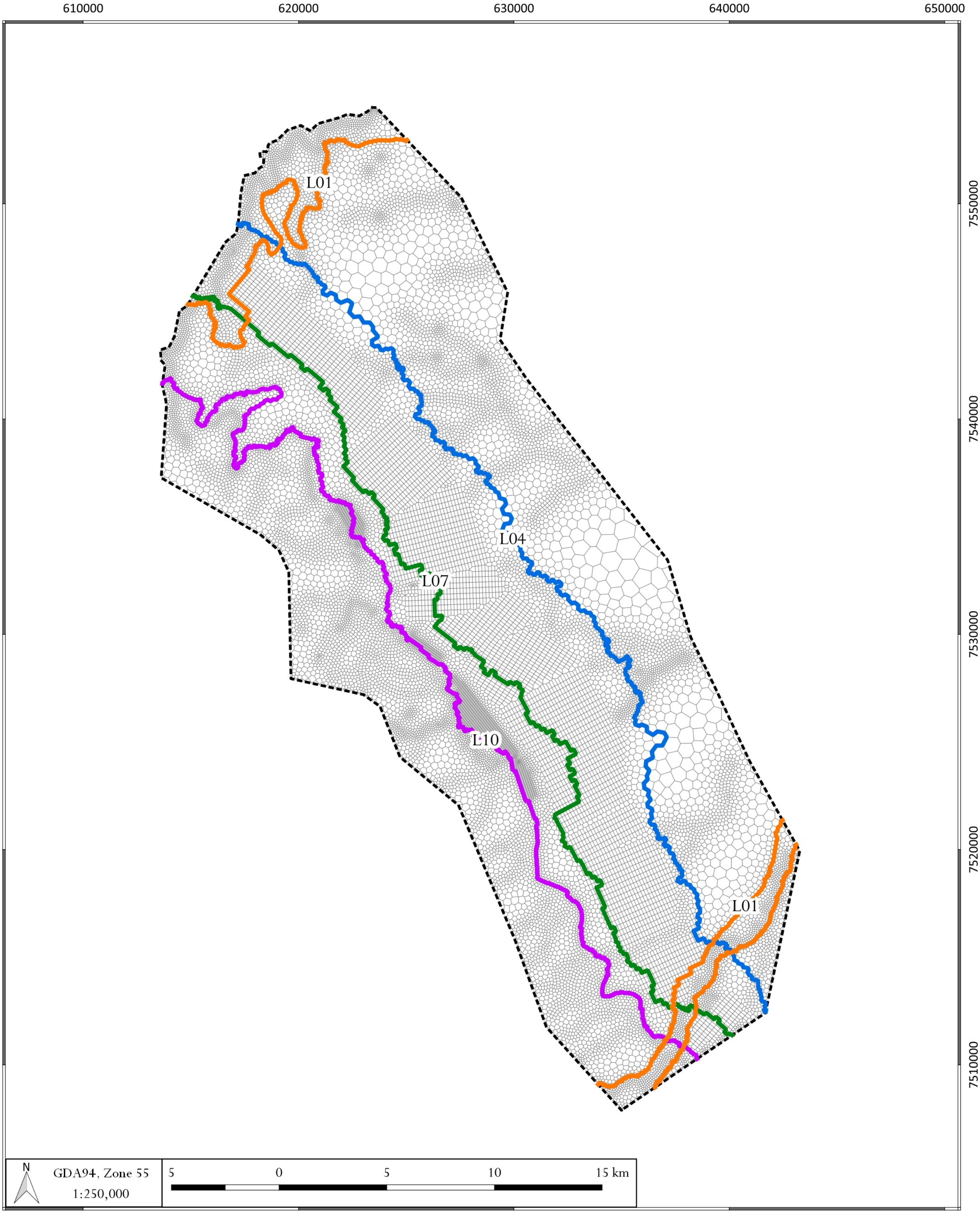
The vertical discretisation of the model domain is based on analysis of the hydrostratigraphic units (Section 2.3). The unconsolidated layers (alluvium and weathered regolith) and coal seams are expected to be the more permeable aquifers while the overburden and underlying material are expected to act as less permeable aquitard. Although individual hydrostratigraphic units could be used directly as model layers, in order to facilitate numerical convergence of the model as well as the calibration process, the overburden Permian (aquitard) layers were split in two; mainly to decrease the layer thickness. The definition of model layers, compared to previously defined hydrostratigraphic units, is summarised in Table 11.

Table 11 Model layer definition

Hydro-stratigraphic unit	Unit function	Model layer	Cells per layer
Quaternary alluvium	*aquifer*	1	2649
Tertiary sediments / weathered Zone / regolith	*aquifer*	2	22492
Fort Cooper Coal Measures	aquitard	3	3214
	aquitard	4	5784
Moranbah Coal Measures overburden	aquitard	5	8375
	aquitard	6	11037
DL coal seam	*aquifer*	7	11108
Moranbah Coal Measures interburden	aquitard	8	12380
	aquitard	9	15278
DLL coal seam	*aquifer*	10	15582
Back Creek Group	aquitard	11	22492

The elevation of layer floors were established using a combination of regional structural data such as mapped and extrapolated floors of stratigraphic units (Esterle and Sliwa, 2002), location (and elevation) of outcrops using local and regional mapping (Department of Natural Resources, Mines and Energy, 2018), drilling logs (Department of Natural Resources, Mines and Energy, 2019b). Within the footprint of the proposed pit, the elevation of the DLL seam floor was derived from detailed exploration drilling data.

The extent of the major hydrostratigraphic units (layer floors subcrop lines) within the model grid is shown on Figure 8, elevation contours and isopachs representing the floors of weathered regolith layer (L02), Fort Cooper coal measures (L04), and floors of Dysart Lower seam (DL – L07) and Dysart Lower Lower (DLL – L10) are shown on Figure 9, Figure 10, Figure 11 and Figure 12.



LEGEND

Extent of unit

- L01 extent - alluvium
- L04 subcrop line - Fort Cooper Coal Measures floor
- L07 subcrop line - MCM DL floor
- L10 subcrop line - MCM DLL floor

Model domain

Model mesh

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Extent of alluvium and major stratigraphic units

FIGURE No.
8

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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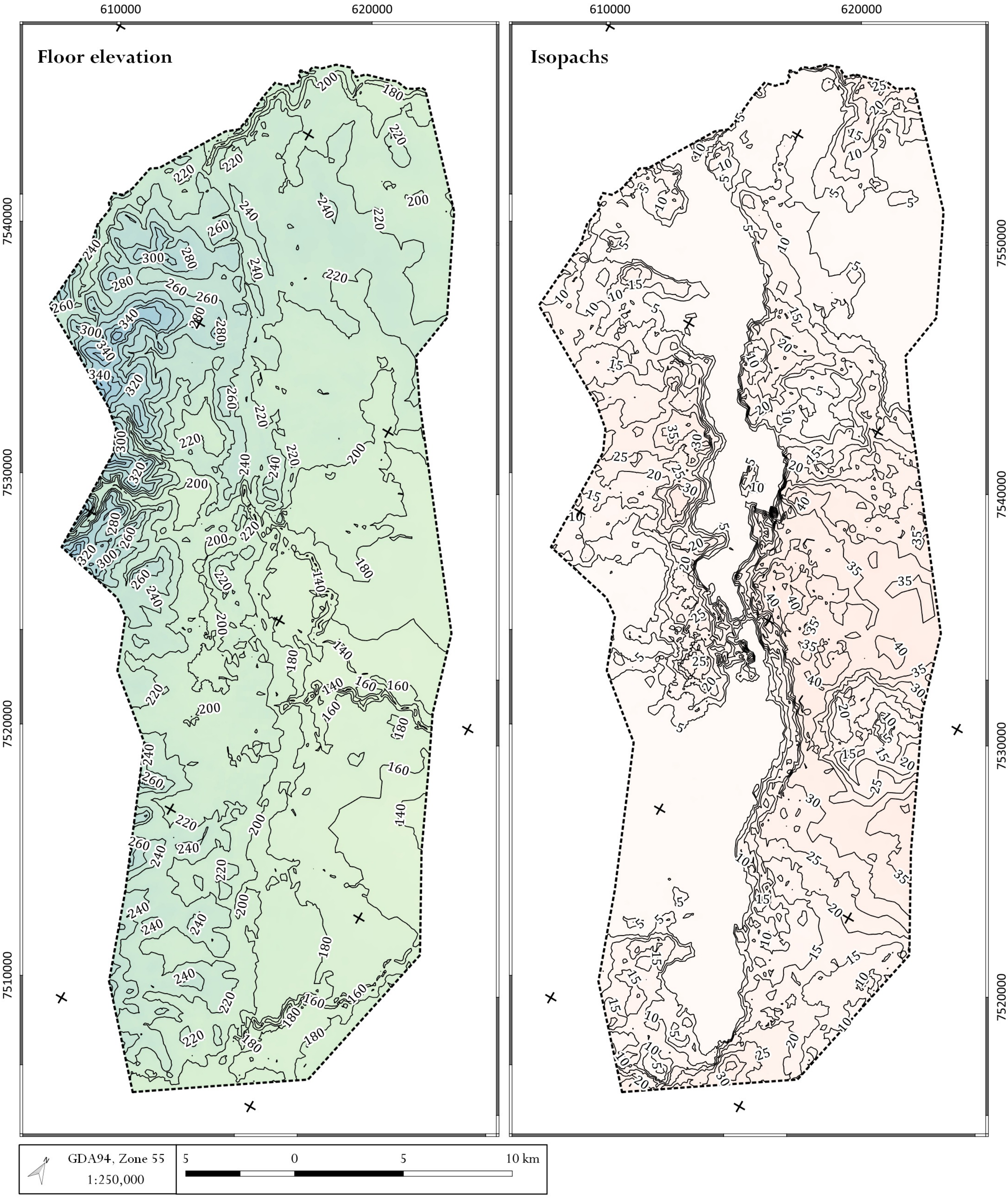

LEGEND

Floor elevation (mRL)

- -400
- -300
- -200
- -100
- 0
- 100
- 200
- 300
- 400

Isopach (m)

- 0
- 50
- 100
- 200
- 300
- 400
- 500

Model domain

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Layer floor elevations and isopachs (L02)

FIGURE No.
9

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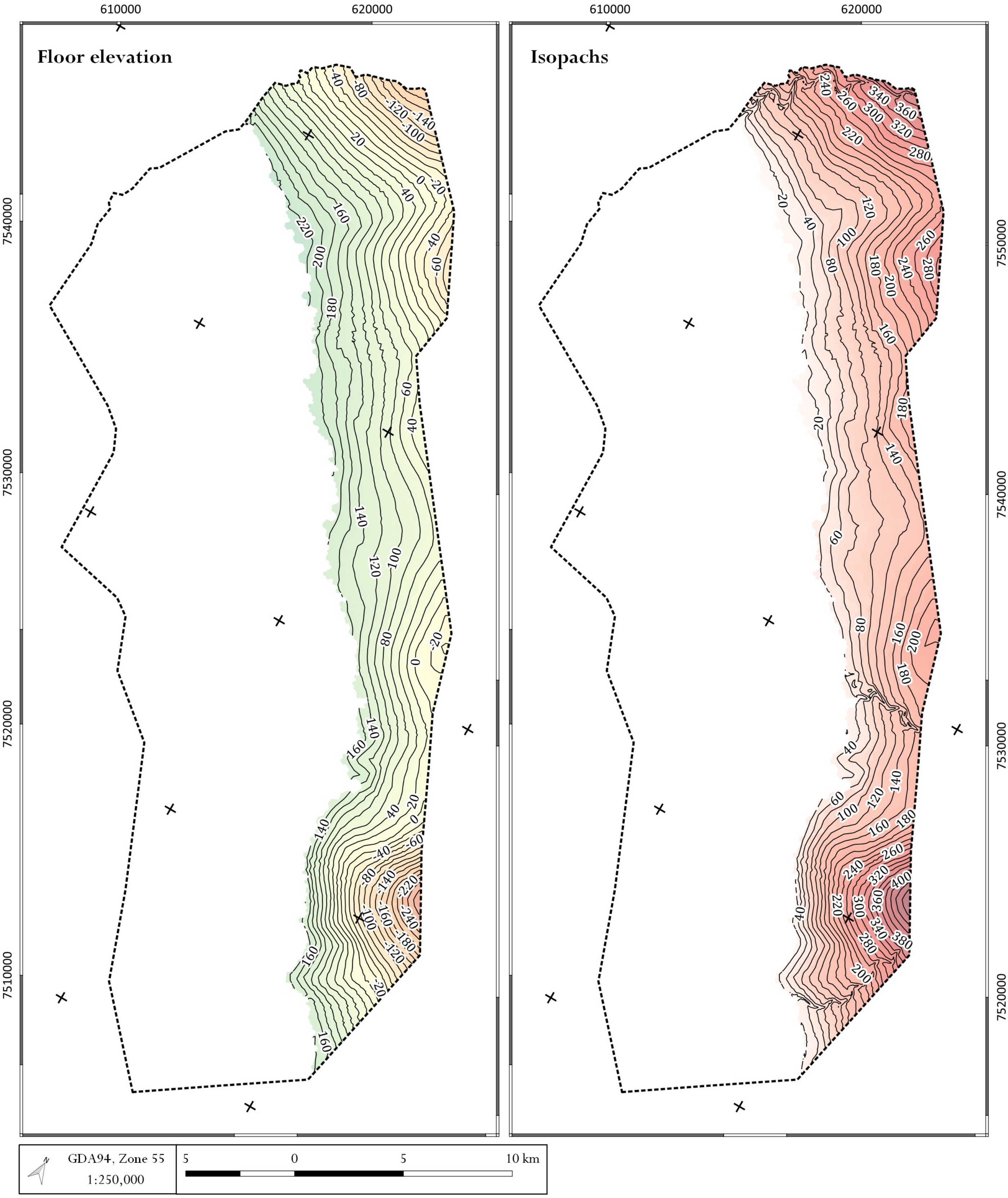

LEGEND

Floor elevation (mRL)

- -400
- -300
- -200
- -100
- 0
- 100
- 200
- 300
- 400

Isopach (m)

- 0
- 50
- 100
- 200
- 300
- 400
- 500

Model domain

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Layer floor elevations and isopachs (L04)

FIGURE No.
10

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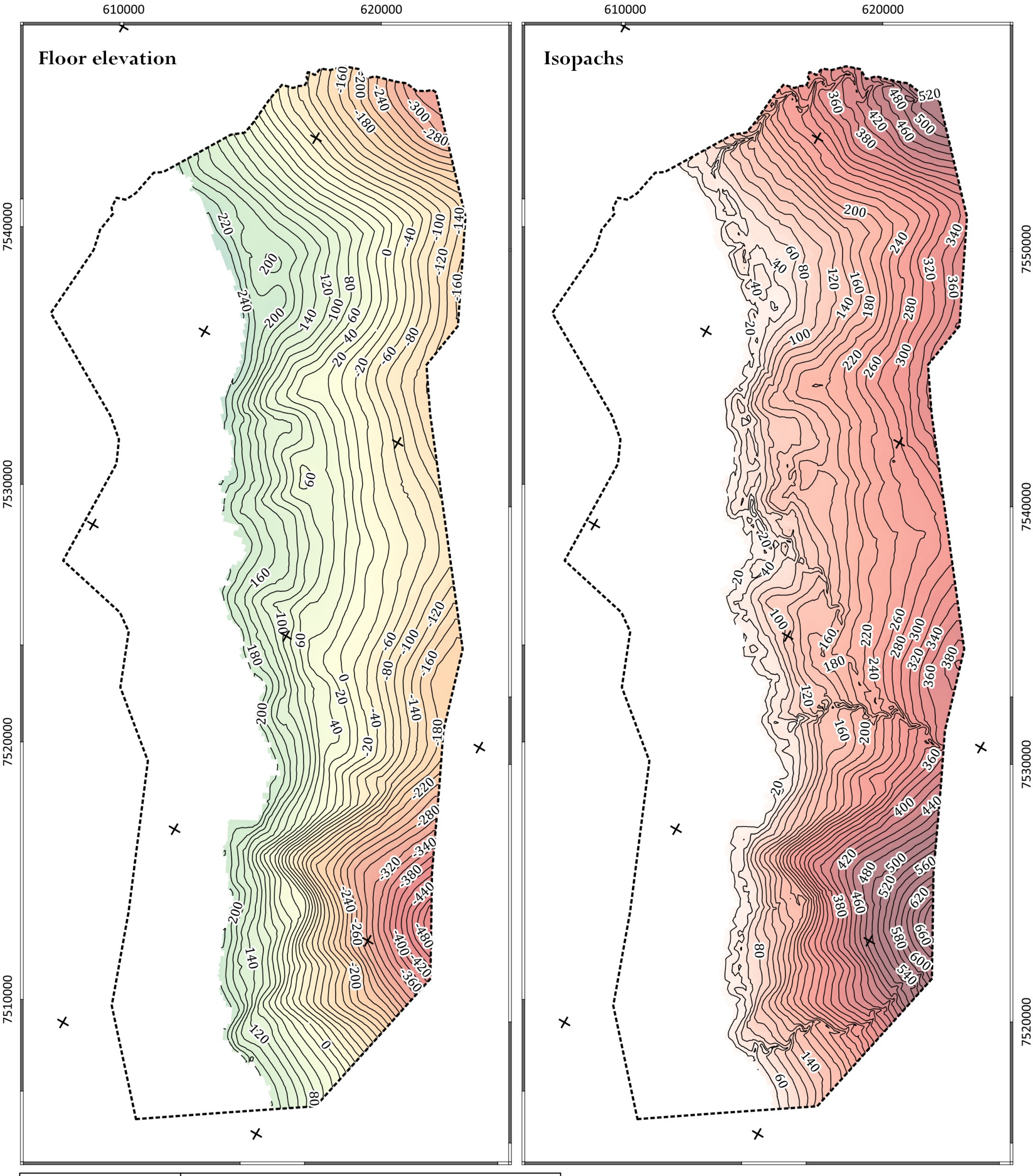

GDA94, Zone 55
1:250,000

5 0 5 10 km

LEGEND

Floor elevation (mRL)

- -400
- -300
- -200
- -100
- 0
- 100
- 200
- 300
- 400

Isopach (m)

- 0
- 50
- 100
- 200
- 300
- 400
- 500

Model domain

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Vulcan South - Groundwater Modelling Appendix (4027)

Layer floor elevations and isopachs (L07)

FIGURE No.
11

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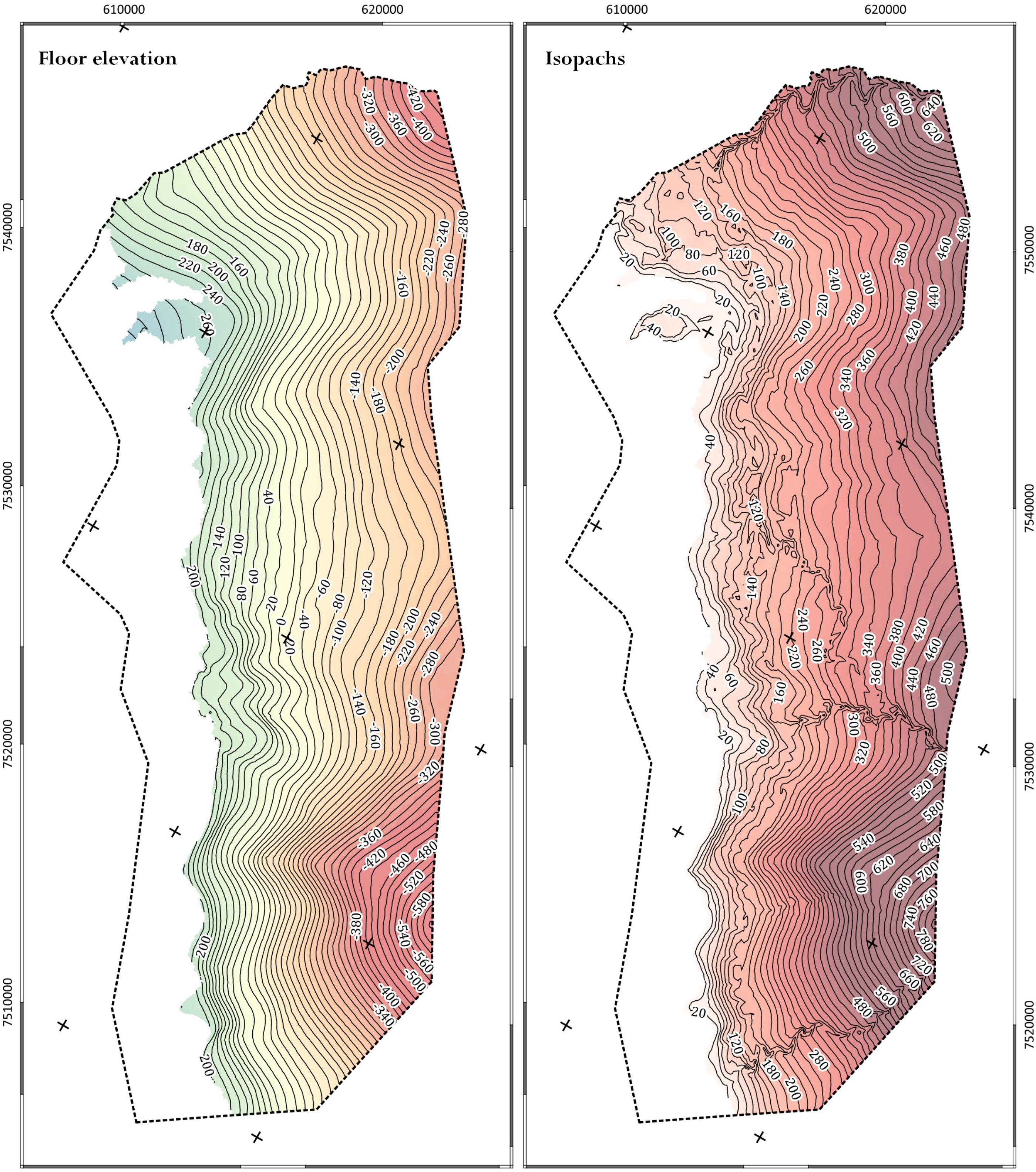

GDA94, Zone 55
1:250,000

5 0 5 10 km

LEGEND

Floor elevation (mRL)

-400	100
-300	200
-200	300
-100	400
0	

Isopach (m)

0	300
50	400
100	500
200	

Model domain

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Layer floor elevations and isopachs (L10)

FIGURE No.
12

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3.5. Aquifer properties (LPF)

The Layer-Property Flow module (Harbaugh *et al.*, 2000) is used to control flow between individual model cells. The module reads arrays of horizontal and vertical hydraulic conductivities and, for transient models, storage parameters (specific yield and specific storage) and calculates conductance for cell-cell connections using the hydraulic properties and cell geometry information. Other flow control definitions include type of layer (confined, unconfined, convertible), isotropy/anisotropy and re-wetting parameters.

The hydraulic properties can be assigned to individual grid cells either on layer basis or zone basis. The Project numerical model assigns a 'single value per layer'.

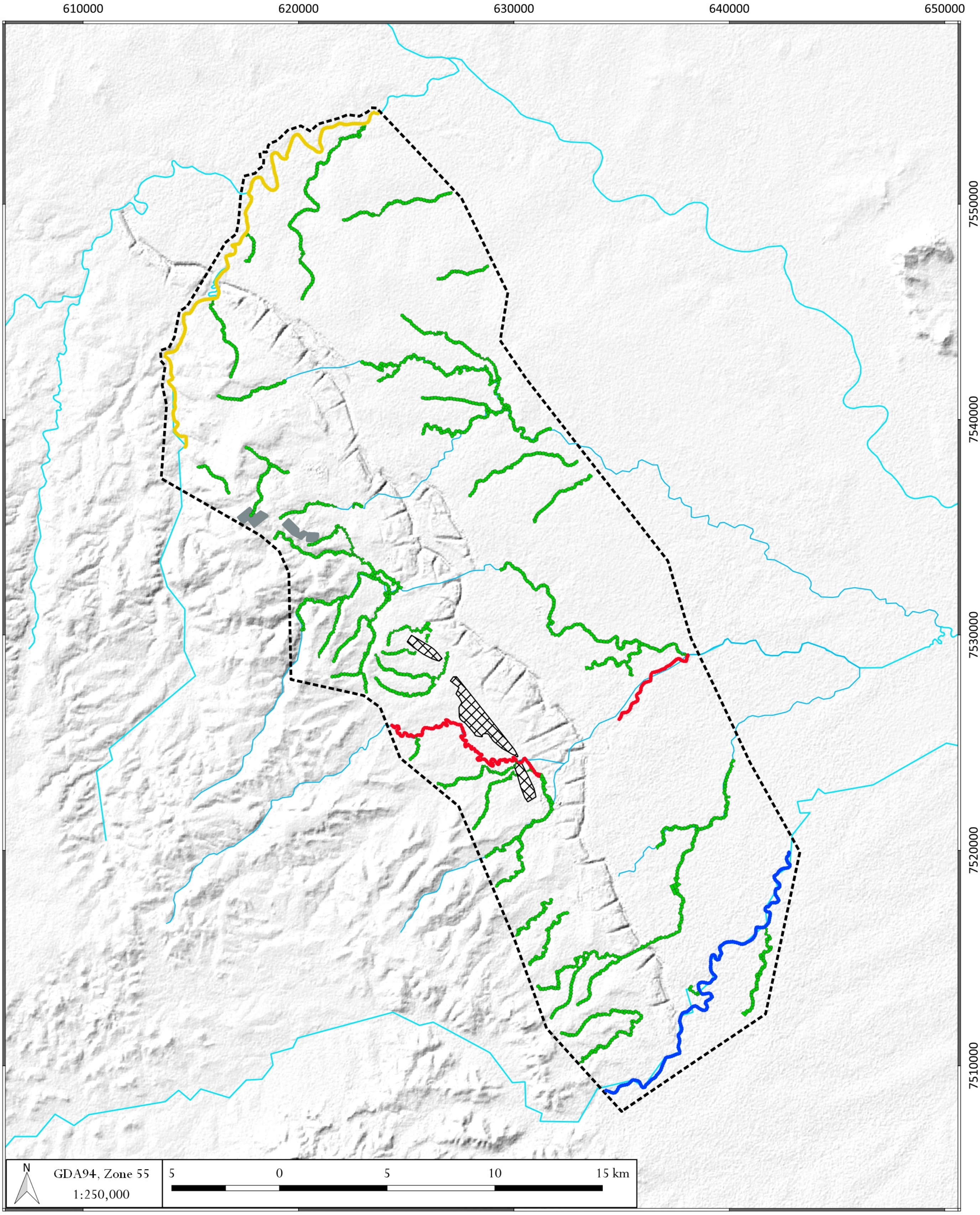
3.6. Surface drainage (RIV)

Groundwater / surface water interaction was modelled using the MODFLOW river (RIV) module. The river module simulates a head-dependent flux boundary (Harbaugh *et al.*, 2000); if the head in the cell falls below a certain threshold, the flux from the river to the model cell is set to a specified lower bound. In our numerical representation, all the surface streams were set as *dry* with no head in the streams which means the streams act only as drains. If a groundwater gradient towards the river cell exists, it will remove the water out of the system. In the opposite scenario, there will be no flux from the river to the aquifer. Hydraulic conductance for each of the river cells is calculated individually based on cell geometry (length of the stream within the cell) and dimensions of the stream itself (width, depth, thickness and vertical K of the stream bed - Table 12).

Table 12 Definition of RIV zones

Zone	Creek name	Vertical K (m/day)	Stream width (m)	Stream depth (m)	Bed thickness (m)
1	Phillips Ck.	1.00	5.00	0.50	1.00
2	Boomerang Ck.	1.00	5.00	0.50	1.00
3	Harrow, Cherwell Ck.	1.00	5.00	0.50	1.00
4	minor surface drainage	1.00	2.00	0.50	1.00

The river cells were placed into the highest active layer in the model, which was mostly layer 1 (alluvium) or layer 2 (weathered regolith/tertiary). Spatial distribution of modelled surface drainage is presented on Figure 13.



LEGEND

River zones

- 1 - Phillips Creek
- 2 - Boomerang Creek
- 3 - Harrow Creek, Cherwell Creek
- 4 - Minor drainage

- Model domain
- Proposed pit
- Highwall mining area
- Watercourse

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River zones

FIGURE No.
13

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

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3.7. Recharge (RCH)

Diffuse rainfall recharge was modelled using the MODFLOW Recharge (RCH) module, a representation of specified flux boundary condition spread over the upper most active model layer. Diffuse recharge is calculated from rainfall by applying a multiplication factor that depends on the recharge zone.

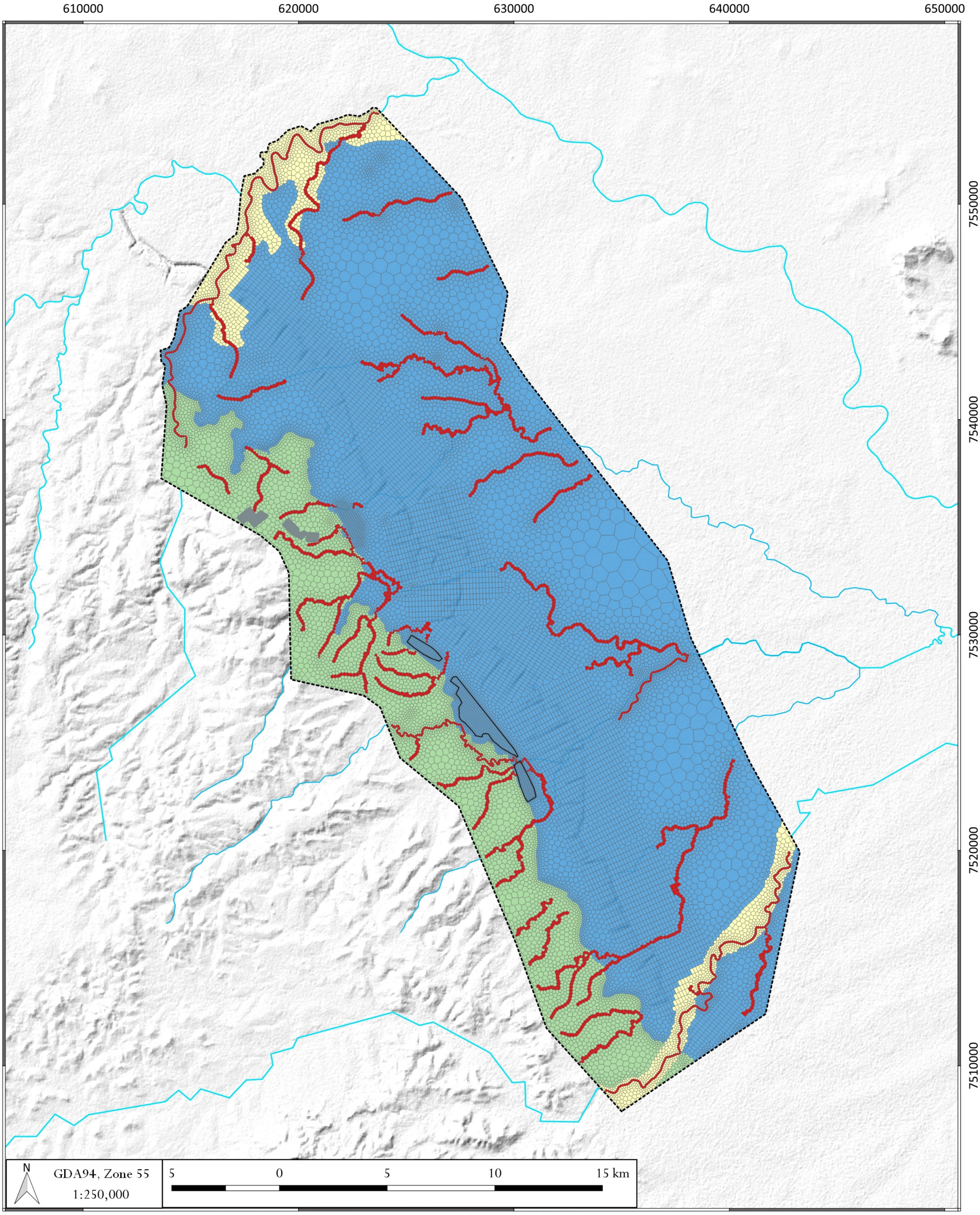
For the steady state run, the recharge factors were applied on the average annual rainfall (582.13 mm/year) where the average was calculated using the time interval between 1900 and 1972. The transient run uses interpolated SILO rainfall between 1973 and 2019 and synthetic data (based on quarterly or six-monthly average calculated from the historical rainfall data). The rainfall values for each stress period are listed in Table 13. Recharge factors were estimated as part of calibration process and are listed in Table 18 (Section 4.6). The spatial extent of recharge zones is shown in Figure 14.

Table 13 Historical (calibration) and synthetic (prediction) rainfall

SP	Start date	End date	SP length (days)	Annual rainfall (mm/SP)
1	1/01/1972	31/12/1972	366	474.6
2	1/01/1973	31/12/1973	365	846.5
3	1/01/1974	31/12/1974	365	910.7
4	1/01/1975	31/12/1975	365	908.1
5	1/01/1976	31/12/1976	366	749.8
6	1/01/1977	31/12/1977	365	608.2
7	1/01/1978	31/12/1978	365	751.8
8	1/01/1979	31/12/1979	365	430.7
9	1/01/1980	31/12/1980	366	423.8
10	1/01/1981	31/12/1981	365	596.6
11	1/01/1982	31/12/1982	365	275.5
12	1/01/1983	31/12/1983	365	895.2
13	1/01/1984	31/12/1984	366	500.2
14	1/01/1985	31/12/1985	365	624.4
15	1/01/1986	31/12/1986	365	522.4
16	1/01/1987	31/12/1987	365	505.6
17	1/01/1988	31/12/1988	366	749.3
18	1/01/1989	31/12/1989	365	818.8
19	1/01/1990	31/12/1990	365	617.4
20	1/01/1991	31/12/1991	365	725.0
21	1/01/1992	31/12/1992	366	296.8
22	1/01/1993	31/12/1993	365	298.9
23	1/01/1994	31/12/1994	365	424.8
24	1/01/1995	31/12/1995	365	633.3
25	1/01/1996	31/12/1996	366	418.8

SP	Start date	End date	SP length (days)	Annual rainfall (mm/SP)
26	1/01/1997	31/12/1997	365	509.6
27	1/01/1998	31/12/1998	365	956.3
28	1/01/1999	31/12/1999	365	419.0
29	1/01/2000	31/12/2000	366	871.5
30	1/01/2001	31/12/2001	365	338.0
31	1/01/2002	31/12/2002	365	300.5
32	1/01/2003	31/12/2003	365	482.1
33	1/01/2004	31/12/2004	366	415.3
34	1/01/2005	31/12/2005	365	506.3
35	1/01/2006	31/12/2006	365	443.0
36	1/01/2007	31/12/2007	365	672.5
37	1/01/2008	31/12/2008	366	788.6
38	1/01/2009	31/12/2009	365	412.3
39	1/01/2010	31/12/2010	365	1152.7
40	1/01/2011	31/12/2011	365	689.8
41	1/01/2012	31/12/2012	366	696.9
42	1/01/2013	31/12/2013	365	652.4
43	1/01/2014	31/12/2014	365	589.4
44	1/01/2015	31/12/2015	365	397.6
45	1/01/2016	31/12/2016	366	774.4
46	1/01/2017	31/12/2017	365	605.8
47	1/01/2018	31/12/2018	365	402.1
48	1/01/2019	31/03/2019	90	330.0
49	1/04/2019	30/06/2019	91	56.8
50	1/07/2019	30/09/2019	92	56.29
51	1/10/2019	31/12/2019	92	170.14
52	1/01/2020	31/03/2020	91	330
53	1/04/2020	30/06/2020	91	56.8
54	1/07/2020	30/09/2020	92	56.29
55	1/10/2020	31/12/2020	92	170.14
56	1/01/2021	30/06/2021	181	386.8
57	1/07/2021	31/12/2021	184	226.43
58	1/01/2022	30/06/2022	181	386.8
59	1/07/2022	31/12/2022	184	226.43

SP	Start date	End date	SP length (days)	Annual rainfall (mm/SP)
60	1/01/2023	30/06/2023	181	386.8
61	1/07/2023	31/12/2023	184	226.43
62	1/01/2024	30/06/2024	182	386.8
63	1/07/2024	31/12/2024	184	226.43
64	1/01/2025	30/06/2025	181	386.8
65	1/07/2025	31/12/2025	184	226.43
66	1/01/2026	30/06/2026	181	386.8
67	1/07/2026	31/12/2026	184	226.43
68	1/01/2027	30/06/2027	181	386.8
69	1/07/2027	31/12/2027	184	226.43
70	1/01/2028	30/06/2028	182	386.8
71	1/07/2028	31/12/2028	184	226.43
72	1/01/2029	30/06/2029	181	386.8
73	1/07/2029	31/12/2029	184	226.43
74	1/01/2030	30/06/2030	181	386.8
75	1/07/2030	31/12/2030	184	226.43
76	1/01/2031	30/06/2031	181	386.8



LEGEND

Recharge zones

- 1 - Regolith
- 2 - Alluvium
- 3 - Above DLL outcrop
- 4 - River cell

- Model domain
- Proposed pit
- Highwall mining area
- Watercourse

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Diffuse recharge zones

FIGURE No.
14

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3.8. Extraction due to mining (DRN)

The mining progression was simulated using drain (DRN) package. The schedule of placement of 'active mine' (open pit) cells within Saraji Mine and Peak Downs Mine was estimated using historical satellite photography, the schedule for the Project was provided by Vitrinite (annual intervals).

The elevation of each drain cell was based on the elevation of the target coal seam (DL in case of Saraji Mine, DLL in case of the Project) and to guarantee full desaturation of the layers above target coal seams, within the open pit footprint, drain cells were placed on the floor of each overlying layer. The conductance of the drain cells were set to 100 m^2/day, regardless of actual cell size.

4. Calibration

4.1. Methodology

Model calibration is a process of adjusting model parameters (hydraulic properties and boundary conditions such as recharge rates or cross-boundary flow rates) so that the model replicates the behaviour of the physical groundwater system. The quality of this replication can be assessed by comparing model outputs (modelled heads and flows) with calibration targets - observed behaviour of the actual groundwater flow system (observed heads and flows).

4.2. Calibration targets (observations)

Structural information (model layer, mesh node ID, global node ID) for each of the observation locations is provided in Table 14. The surveyed ground surface elevation of bores associated with the Project (MBx, VSWx) can vary from the elevation of upper-most model layer. The top elevation of every model cell is represented by elevation of the centroid of that cell. Because of the size (area) of each cell combined with potentially variable (steep) terrain, a difference between surveyed and model elevations will always occur; this difference represents a compromise in a construction of the numerical model as it is a simplification of a groundwater flow system. The difference between surveyed and modelled elevation is one of many indicators of the scale of 'structural uncertainty' of the numerical model and can have an impact on quality of calibration. The 'structural uncertainty' will be discussed in greater detail in Section 6.

Table 14 Observation points – mesh nodes and model layers

Bore ID / RN	Mesh node ID (rnode)	Model layer	Global node ID (gnode)	Topo surface elevation (model) mRL	Topo surface elevation (surveyed) mRL
32924	20435	6	53243	204.90	-
42182	20604	6	53344	210.61	-
43639	21469	10	107767	211.56	-
44336	22331	11	130230	217.08	-
46899	20662	7	64464	209.25	-
49995	20523	7	64391	211.25	-
49997	20409	7	64315	209.96	-
84538	17948	7	62743	190.70	-
100291	633	4	28816	223.11	-
136092	21671	2	24320	233.47	-

Bore ID / RN	Mesh node ID (rnode)	Model layer	Global node ID (gnode)	Topo surface elevation (model) mRL	Topo surface elevation (surveyed) mRL
136689	11475	11	119374	188.45	-
141382	1782	4	29477	212.71	-
141384	551	5	34688	213.62	-
141386	1785	4	29480	219.21	-
158010	17260	4	33205	185.91	-
158011	19890	5	42374	198.86	-
158012	20105	11	128004	237.35	-
158013	18909	5	41873	197.72	-
158014	18467	5	41662	186.29	-
162138	5157	5	37371	223.50	-
162177	11583	6	49395	186.31	-
162506	6476	11	114375	257.83	-
162816	6801	2	9450	196.30	-
162829	554	2	3203	213.01	-
13040283	7355	10	98747	218.92	-
MB04	3762	11	111661	245.31	243.28
MB05	5290	11	113189	254.35	252.70
MB07	8934	2	11583	217.48	215.99
MB09	9090	10	99947	210.53	208.98
MB10	10854	10	101110	215.88	214.60
MB12	13044	11	120943	243.14	241.43
MB30	17093	4	33117	162.33	-
MB32	21898	11	129797	206.81	-
MB4	12375	6	49645	189.47	-
PC056	18580	7	63149	193.80	-
PC058XC	18692	7	63216	194.36	-
PC066XC	19017	7	63420	196.23	-
PZ06A	20276	6	53150	202.23	-
PZ06C	20276	7	64245	202.23	-
PZ08A	16852	7	61993	203.39	-
TG1	22430	2	25079	218.63	-
VSW002	9888	10	100463	217.66	215.94
VSW006	11794	10	101721	217.96	216.82

Bore ID / RN	Mesh node ID (rnode)	Model layer	Global node ID (gnode)	Topo surface elevation (model) mRL	Topo surface elevation (surveyed) mRL
VSW007	8931	10	99790	216.99	215.76
VSW008	8908	11	116807	221.43	219.74
VSW009	8512	10	99510	213.94	212.25
VSW011	7344	10	98736	226.06	225.49
VSW013	7293	11	115192	231.05	229.49
VSW014	6900	11	114799	228.79	227.20
VSW016	5740	11	113639	257.43	255.88
VSW017	2072	11	109971	243.62	242.50
VSW018	6118	11	114017	235.32	236.23
VSW019	5285	11	113184	260.68	254.99
VSW020	3719	10	95975	259.50	257.79
VSW021	3396	11	111295	244.93	243.36

Of the 55 observation bores, 44 bores have only a single water level observation, either a standing water level value obtained when the bore was drilled, or average (composite, 'representative' value). Some of the 'representative' values obtained from the Saraji UWIR (AECOM, 2016) do not have dates associated with water level information, in these cases the publication date of the cited report was used. A summary of the groundwater level observation data used in the model calibration is provided in Table 15.

Eleven bores have transient water level measurements. Six of these are current, non-dry Project observation bores (MB04-MB12), five are long-term observation bores, sampled by QLD government organisations, usually in monthly intervals. Existing pre-mining (at Saraji) observations were incorporated into the observation dataset with a date of 31/12/2017 (end of the first annual stress period). The Project water level information (bores MB04-MB12) is recorded in 4-hourly interval, however for the purpose of the model calibration, the data was down-sampled to monthly interval.

Table 15 Observation points – dates, number of measurements and observed head

Bore ID / RN	# of observations	Observation date		Head			
		From	To	Min	Avg	Max	Δ
32924	1	01/01/2007		184.34			
42182	1	01/01/2007		184.19			
43639	1	31/12/1972		182.07			
44336	1	31/12/1972		185.15			
46899	1	01/01/2007		167.31			
49995	1	01/01/2007		172.83			
49997	1	01/01/2007		179.77			
84538	1	31/12/1972		173.80			
100291	1	09/02/2006		205.82			

Bore ID / RN	# of observations	Observation date		Head			
		From	To	Min	Avg	Max	Δ
136092	1	30/10/2002		225.23			
136689	1	18/01/2007		157.58			
141382	25	09/04/2008	07/01/2014	194.47	198.00	198.68	4.21
141384	29	19/04/2008	07/01/2014	195.97	197.28	197.89	1.92
141386	30	19/04/2008	07/01/2014	199.97	200.45	200.87	0.90
158010	1	08/07/2012		166.87			
158011	1	06/07/2012		178.97			
158012	1	08/07/2012		221.86			
158013	1	09/07/2012		172.51			
158014	1	03/07/2012		172.83			
162138	1	01/08/2012		206.94			
162177	36	01/06/2008	25/10/2017	192.28	206.62	212.50	20.22
162506	1	28/10/2015		268.49			
162816	1	08/02/2006		201.71			
162829	1	09/02/2006		197.49			
13040283	36	29/08/2004	17/04/2018	177.62	179.24	181.57	3.95
MB04	3	15/06/2019	11/08/2019	238.60	238.69	238.75	0.15
MB05	3	15/06/2019	11/08/2019	238.66	238.74	238.87	0.21
MB07	3	15/06/2019	11/08/2019	180.48	180.51	180.55	0.07
MB09	3	15/06/2019	11/08/2019	181.89	181.91	181.93	0.04
MB10	3	15/06/2019	12/08/2019	182.83	182.88	182.91	0.08
MB12	3	15/06/2019	11/08/2019	218.09	218.26	218.42	0.33
MB30	1	01/01/2015		162.71			
MB32	1	01/01/2015		197.73			
MB4	1	01/01/2015		165.91			
PC056	1	01/01/2015		176.82			
PC058XC	1	01/01/2015		176.29			
PC066XC	1	01/01/2015		159.49			
PZ06A	1	01/01/2015		185.90			
PZ06C	1	01/01/2015		183.40			
PZ08A	1	01/01/2015		177.60			
TG1	1	01/01/2015		209.16			
VSW002	1	15/11/2018		182.24			
VSW006	1	09/12/2018		183.72			

Bore ID / RN	# of observations	Observation date		Head			
		From	To	Min	Avg	Max	Δ
VSW007	1	18/11/2018		181.16			
VSW008	1	19/11/2018		192.94			
VSW009	1	19/11/2018		179.55			
VSW011	1	01/12/2018		180.79			
VSW013	1	02/12/2018		224.49			
VSW014	1	02/12/2018		218.00			
VSW016	1	04/12/2018		239.48			
VSW017	1	04/12/2018		224.80			
VSW018	1	06/12/2018		223.13			
VSW019	1	07/12/2018		226.99			
VSW020	1	11/12/2018		236.99			
VSW021	1	07/12/2018		241.76			

4.3. Initial observation sensitivities

The observation sensitivities are calculated during initial PEST iterations (Jacobian calculation). They show which observations are the most sensitive to changes in input parameters. Not surprisingly, given the magnitude of impact caused by mining, observations associated with DL seams and its overburden appear to be more sensitive than the weathered regolith observations and observations located in basement bedrock (underburden) see Figure 15.

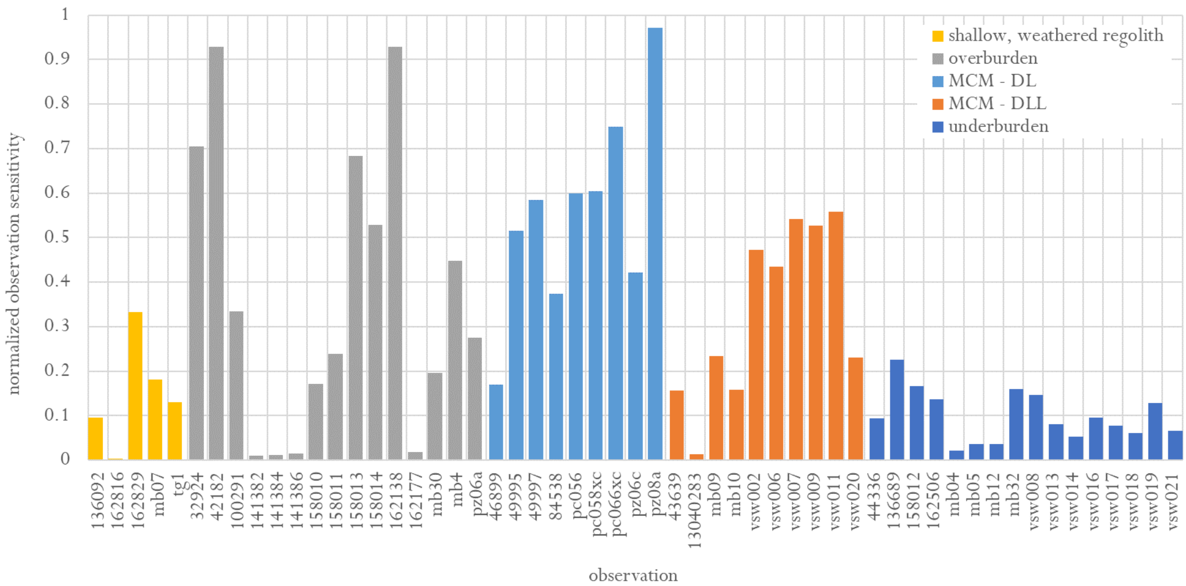


Figure 15 Normalised observation sensitivities

4.4. Initial parameter sensitivities

The calibration process appears to be the most sensitive against transient recharge into the weathered regolith profile (rch01tr), storage properties of the weathered zone (sy_z02) and horizontal hydraulic conductivity of the DLL overburden (kx_z09). The composite parameter sensitivities are presented in Figure 16.

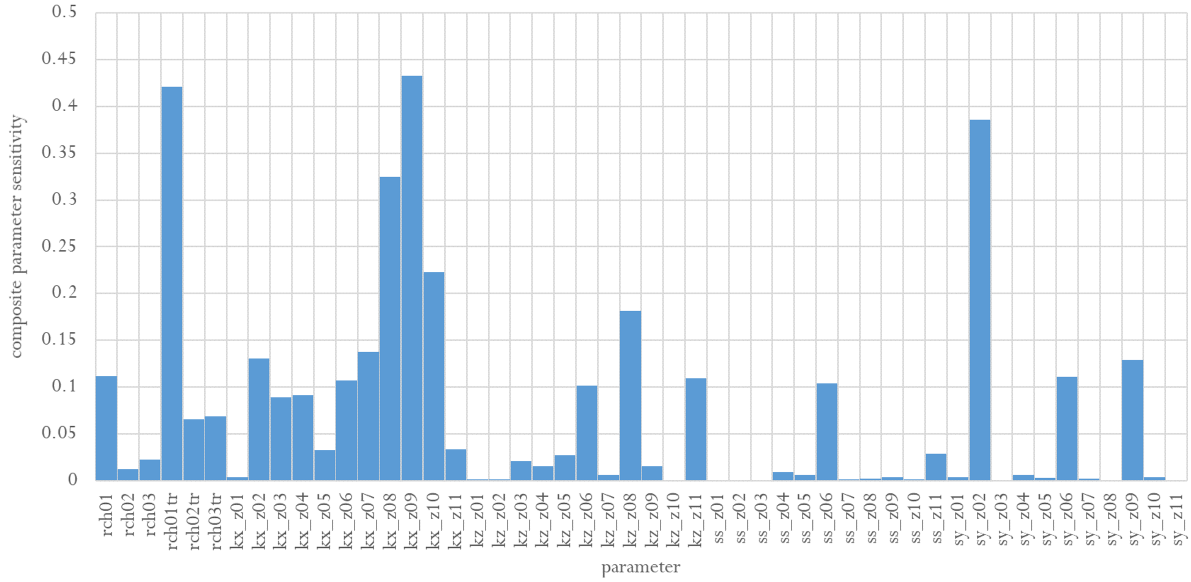


Figure 16 Composite parameter sensitivities

4.5. Calibration results – calibration statistics

The numerical model includes a steady-state and a transient calibration (1972 to 2019). The transient calibration captures historical development at Saraji Mine and Peak Downs Mine which was based upon an interpolated mine progression assessed from Landsat imagery.

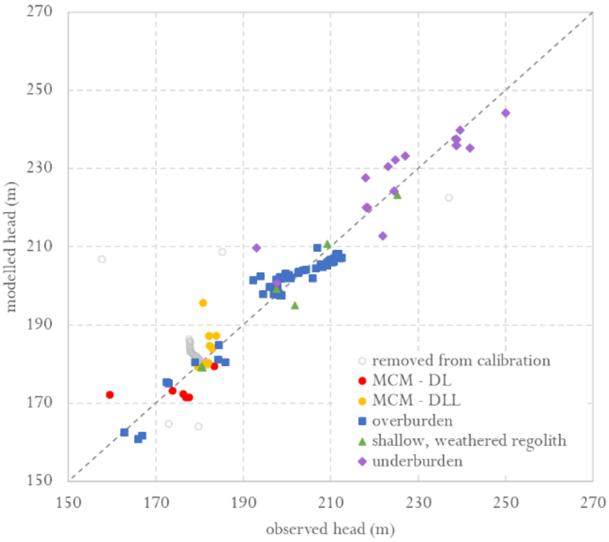
In accordance with the Australian groundwater modelling guidelines (Barnett *et al.*, 2012), the objective of a model calibration is to replicate the groundwater levels measured in the site monitoring network and other bores. A set of 55 selected observation points (and a total of 176 observations) were used in the calibration process, some with single values and some with time-series observations. The observation points included historical observation data from mining investigations (AECOM, 2016), publicly available sources (AECOM, 2016; Department of Natural Resources, Mines and Energy, 2019), and on-site data collected from open drill-holes and data collected from the new monitoring bores (**hydrogeologist.com.au**, 2019).

An overall (all observations and all time steps) transient calibration was achieved with an RMS (root mean square error) of 3.6 m and an SRMS (scaled root mean square error) of 4% (Table 16). The SRMS value of 4% (3.6 m / 90.5 m=0.04 or 4%) indicates a good fit between measured and modelled data. Notwithstanding that, other criteria (such as good correlation between measured and modelled hydrographs and contour maps) also apply, an SRMS that is less than 10% may be acceptable (Barnett *et al.*, 2012) while an SRMS < 5% represents generally good calibration in the experience of **hydrogeologist.com.au**.

Table 16 Model calibration – calibration statistics

Calibration measure		Value	Unit
number of observations	n	176	-
range of measured heads	-	90.51	m
sum of squared residuals	SSQ, Φ	2292.3	m^2
mean sum of residuals	MSR	2.7	m
scaled mean sum of residuals	SMSR	2.9	%
root mean squared error	RMS	3.6	m
scaled root mean squared error	SRMS	4.0	%

A scatter diagram of observed vs. modelled groundwater elevations (Figure 17) indicates that most points are situated close to the 1:1 line (perfect fit). While outliers do exist, most of the observations are within ±5 m of the 1:1 line. It is important to note that no significant or obvious trends or systematic departures appear to occur from the 1:1 line (the various colours representing different hydrogeological units scatter around the 1:1 line in a generally random pattern). The weighted residual of the model calibration are presented in Table 17 and shown for the various model layers in Figure 18, Figure 19 and Figure 20.



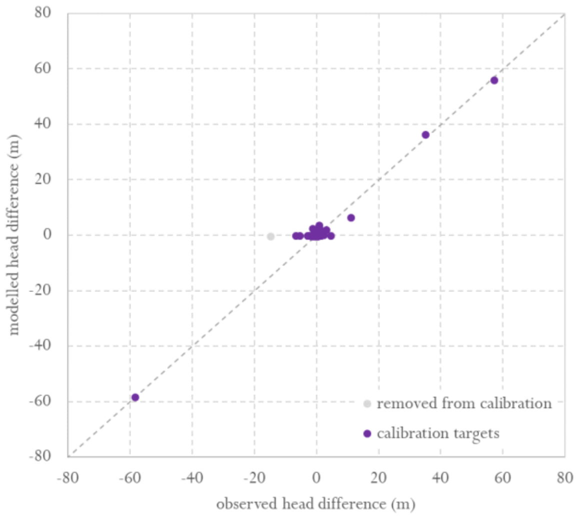


Figure 17 Model calibration scatter diagrams – observed and modelled heads and head differences

Table 17 Model calibration – weighted residuals

Bore ID	Easting	Northing	Number of observations	Observation group	Weighted sum of residuals
136092	633415.8	7512196.5	1	shallow, weathered regolith	1.94
162816	618975.0	7552309.0	1	shallow, weathered regolith	6.67
162829	623671.0	7549482.0	1	shallow, weathered regolith	-1.76
mb07	628691.1	7526258.1	3	shallow, weathered regolith	1.31
tg1	635215.0	7508903.0	1	shallow, weathered regolith	-1.54

Bore ID	Easting	Northing	Number of observations	Observation group	Weighted sum of residuals
32924	638285.0	7514125.0	1	overburden	-0.49
42182	637746.0	7514257.0	1	overburden	3.03
100291	626431.5	7542882.6	1	overburden	3.92
141382	628490.0	7542693.0	25	overburden	0.33
141384	623784.0	7549391.0	29	overburden	-2.37
141386	626507.0	7544152.0	30	overburden	-1.50
158010	642528.4	7519938.8	1	overburden	5.24
158011	640035.0	7514094.9	1	overburden	-1.45
158013	637781.5	7518065.5	1	overburden	-2.81
158014	636495.7	7519991.1	1	overburden	-2.17
162138	620083.8	7547612.9	1	overburden	-2.77
162177	616863.0	7547756.0	36	overburden	1.33
mb30	642503.0	7519162.0	1	overburden	0.14
mb4	635928.0	7527934.0	1	overburden	5.15
pz06a	639272.0	7513326.0	1	overburden	5.47
84538	641353.3	7516737.0	1	MCM - DL	0.66
pc056	640288.3	7516655.0	1	MCM - DL	5.37
pc058xc	640054.7	7516179.0	1	MCM - DL	4.02
pc066xc	639328.9	7517206.0	1	MCM - DL	-12.66
pz06c	639272.0	7513326.0	1	MCM - DL	3.95
pz08a	634647.0	7523069.0	1	MCM - DL	6.14
43639	638938.6	7511033.0	1	MCM - DLL	-5.22
mb09	629511.2	7525222.7	3	MCM - DLL	1.65
mb10	628123.6	7526469.3	3	MCM - DLL	-1.18
vsw002	627811.8	7526808.7	1	MCM - DLL	-2.42
vsw006	628024.8	7526217.7	1	MCM - DLL	-3.50
vsw007	628679.8	7526268.7	1	MCM - DLL	1.25
vsw009	628076.8	7527016.7	1	MCM - DLL	0.21
vsw011	627406.8	7527852.8	1	MCM - DLL	-14.93
158012	632270.5	7515394.7	1	underburden	9.05
162506	621630.0	7534800.0	1	underburden	5.78

Bore ID	Easting	Northing	Number of observations	Observation group	Weighted sum of residuals
mb04	622014.3	7536148.2	3	underburden	2.79
mb05	621964.5	7534905.0	3	underburden	1.36
mb12	625251.5	7526409.2	3	underburden	-1.78
mb32	637481.0	7510535.0	1	underburden	-3.01
vsw008	627335.8	7527263.7	1	underburden	-16.75
vsw013	624599.8	7530294.8	1	underburden	0.19
vsw014	623534.8	7531296.8	1	underburden	-9.60
vsw016	621573.8	7535486.8	1	underburden	-0.37
vsw017	622555.8	7535727.8	1	underburden	-7.40
vsw018	622937.8	7533623.8	1	underburden	-7.47
vsw019	622513.8	7534503.8	1	underburden	-6.31
vsw021	622024.8	7536169.8	1	underburden	6.57

LEGEND

Residuals (m)

- -15.0 - -10.0
- -10.0 - -5.0
- -5.0 - -3.0
- -3.0 - -1.0
- -1.0 - 1.0
- 1.0 - 3.0
- 3.0 - 5.0
- 5.0 - 10.0
- 10.0 - 15.0

- Model domain
- Proposed pit
- Highwall mining area
- Established mining operation

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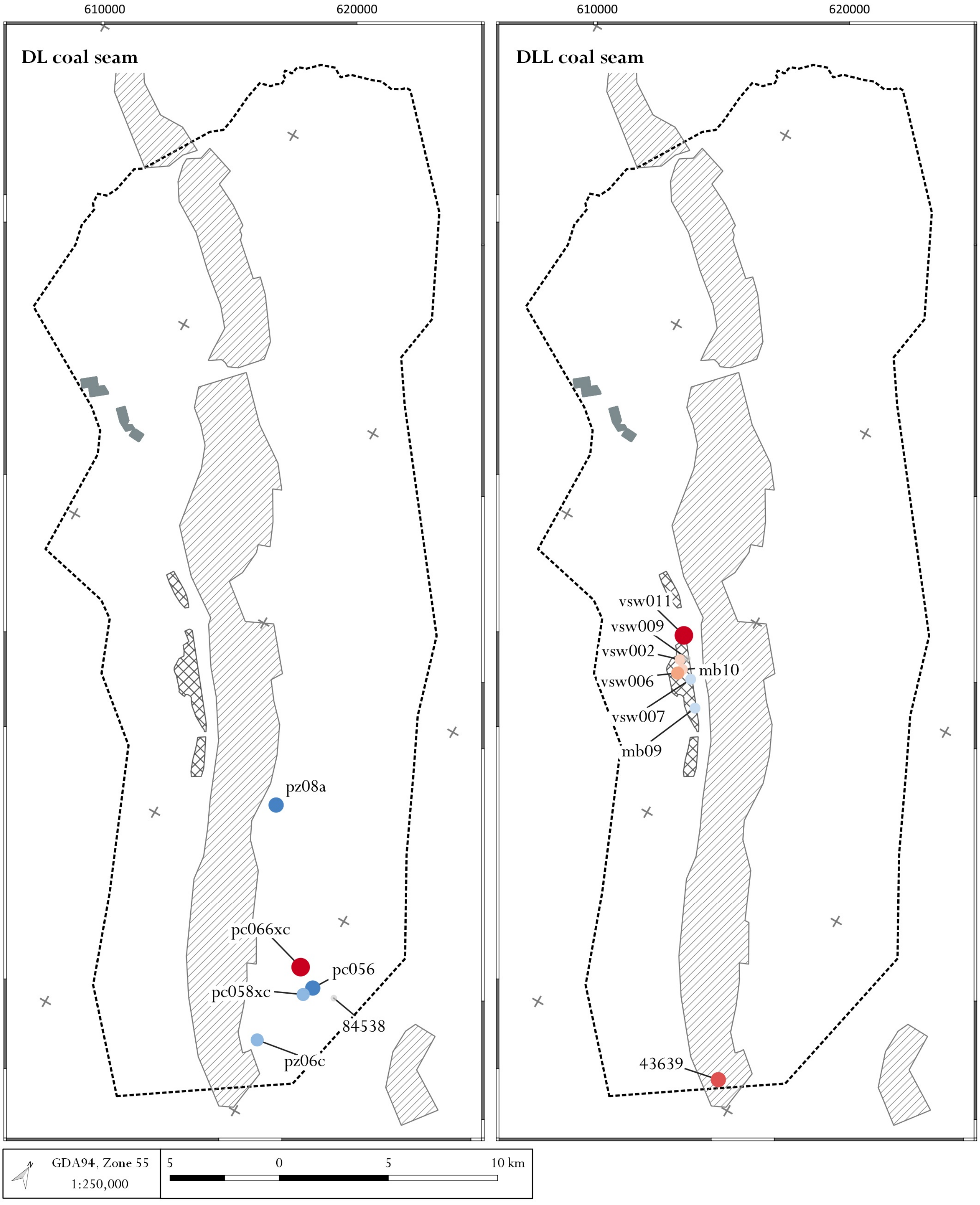
Spatial distribution of residuals – weathered zone, MCM

FIGURE No.
18

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\18_4027_Vulcan South_App_Residuals weathered zone and overburden.qgz



LEGEND

Residuals (m)

- -15.0 - -10.0
- -10.0 - -5.0
- -5.0 - -3.0
- -3.0 - -1.0
- -1.0 - 1.0
- 1.0 - 3.0
- 3.0 - 5.0
- 5.0 - 10.0
- 10.0 - 15.0

- Model domain
- Proposed pit
- Highwall mining area
- Established mining operation

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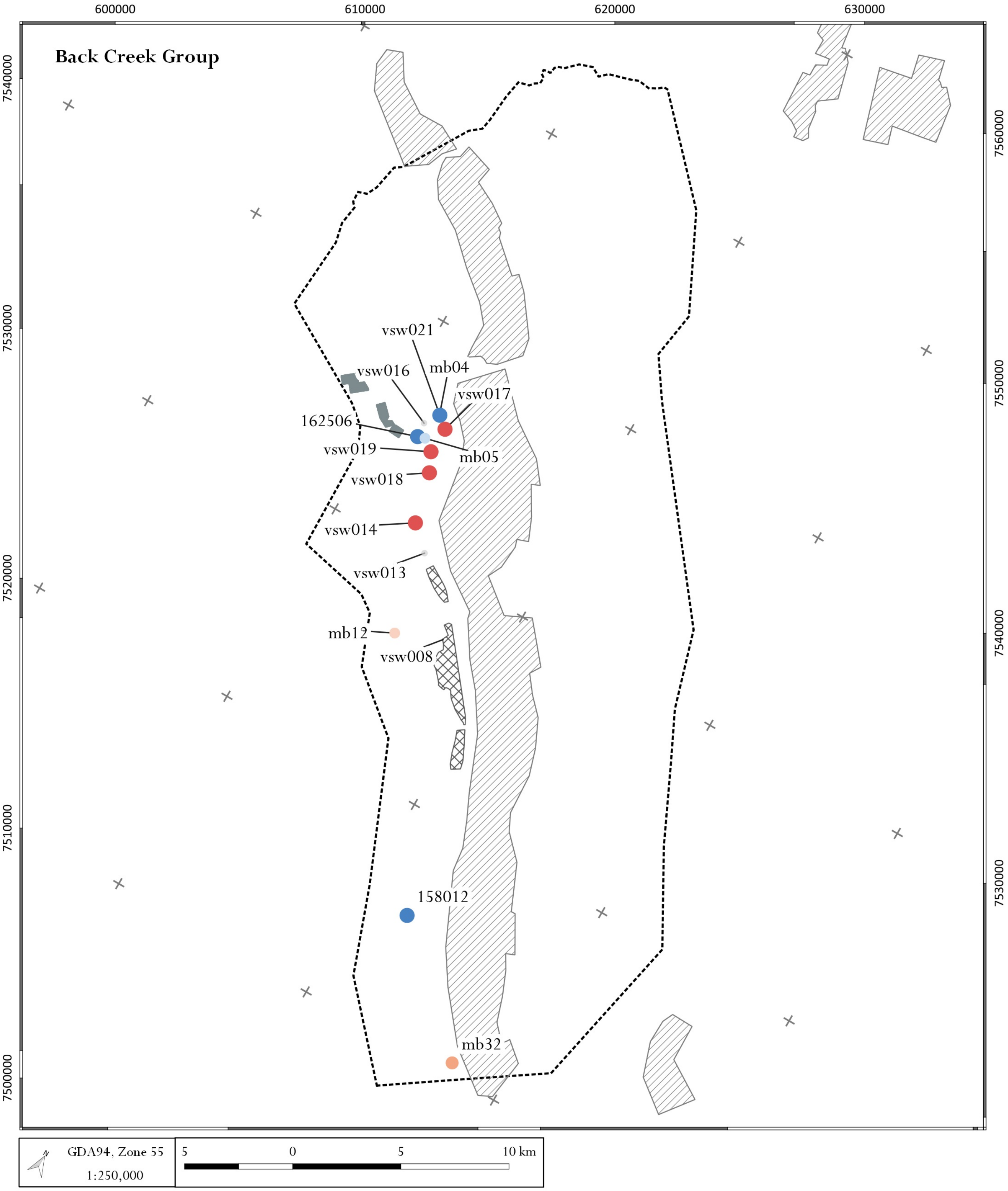
Vulcan South - Groundwater Modelling Appendix (4027)

Spatial distribution of residuals – MCM DL, MCM DLL

FIGURE No.
19

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\19_4027_Vulcan South_App_Residuals DL and DLL seams.qgz



LEGEND

Residuals (m)

- -15.0 - -10.0
- -10.0 - -5.0
- -5.0 - -3.0
- -3.0 - -1.0
- -1.0 - 1.0
- 1.0 - 3.0
- 3.0 - 5.0
- 5.0 - 10.0
- 10.0 - 15.0

- Model domain
- Proposed pit
- Highwall mining area
- Established mining operation

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Vulcan South - Groundwater Modelling Appendix (4027)

Spatial distribution of residuals – Back Creek Group

FIGURE No.
20

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\20_4027_Vulcan South_App_Residuals Back Creek Group.qgz

4.6. Calibration results – final parameter values

The final model calibrated parameter values for recharge, hydraulic conductivity and storage are summarised in Table 18, Table 19 and Table 20 respectively.

Table 18 Model calibration – parameter values – recharge

RCH zone		Zone area (km^2)	RCH rate factor (-)	
			steady state	transient
1	weathered regolith east of DLL subcrop	459.14	1.6611×10^{-3}	1.0000×10^{-3}
2	alluvium	35.36	1.0000×10^{-3}	1.0000×10^{-2}
3	weathered regolith west of DLL subcrop	114.11	5.0000×10^{-4}	1.3355×10^{-3}
4	surface drainage cells	38.97	$0.0000\times10^{+0}$	$0.0000\times10^{+0}$

Table 19 Model calibration – parameter values – hydraulic conductivity

HSU (geo zone)		model layer	K_h (m/day)	K_h factor (-)	K_v (m/day)
1	Alluvium	1	5.0000×10^{-1}	2.5000×10^{-2}	1.2500×10^{-2}
2	weathered regolith / tertiary	2	5.0000×10^{-1}	3.0000×10^{-2}	1.5000×10^{-2}
3	overburden - Fort Cooper CM	3	5.0000×10^{-2}	3.9354×10^{-2}	1.9677×10^{-3}
4	overburden - Fort Cooper CM	4	5.0000×10^{-2}	8.9302×10^{-3}	4.4651×10^{-4}
5	overburden - Moranbah CM	5	3.0515×10^{-3}	1.9493×10^{-2}	5.9485×10^{-5}
6	overburden - Moranbah CM	6	1.7230×10^{-3}	2.0546×10^{-2}	3.5400×10^{-5}
7	Dysart Lower (DL) seam - Moranbah CM	7	1.0000×10^{-2}	2.0930×10^{-2}	2.0930×10^{-4}
8	overburden - Moranbah CM	8	5.0000×10^{-4}	3.9383×10^{-2}	1.9692×10^{-5}
9	overburden - Moranbah CM	9	4.5428×10^{-2}	1.0000×10^{-3}	4.5428×10^{-5}
10	Dysart Lower Lower (DLL) seam - Moranbah CM	10	1.5511×10^{-1}	2.4871×10^{-2}	3.8577×10^{-3}
11	underburden - Back Creek Group	11	1.0000×10^{-4}	1.0000×10^{-3}	1.0000×10^{-7}

Table 20 Model calibration – parameter values – storage

HSU (geo zone)		model layer	Ss (m^{-1})	Sy (-)
1	alluvium	1	2.0000×10^{-6}	9.0000×10^{-2}
2	weathered regolith / tertiary	2	2.4900×10^{-6}	5.0000×10^{-3}
3	overburden - Fort Cooper CM	3	1.0000×10^{-6}	5.0000×10^{-3}
4	overburden - Fort Cooper CM	4	2.0000×10^{-5}	1.0000×10^{-4}
5	overburden - Moranbah CM	5	1.0000×10^{-6}	1.7598×10^{-4}
6	overburden - Moranbah CM	6	1.0000×10^{-5}	5.0000×10^{-3}
7	Dysart Lower (DL) seam - Moranbah CM	7	2.0000×10^{-5}	1.0000×10^{-3}
8	overburden - Moranbah CM	8	1.0000×10^{-5}	1.0000×10^{-4}
9	overburden - Moranbah CM	9	1.0000×10^{-5}	2.7871×10^{-3}
10	Dysart Lower Lower (DLL) seam - Moranbah CM	10	2.0000×10^{-5}	1.0000×10^{-3}
11	underburden - Back Creek Group	11	1.0000×10^{-5}	2.5000×10^{-4}

5. Predictions

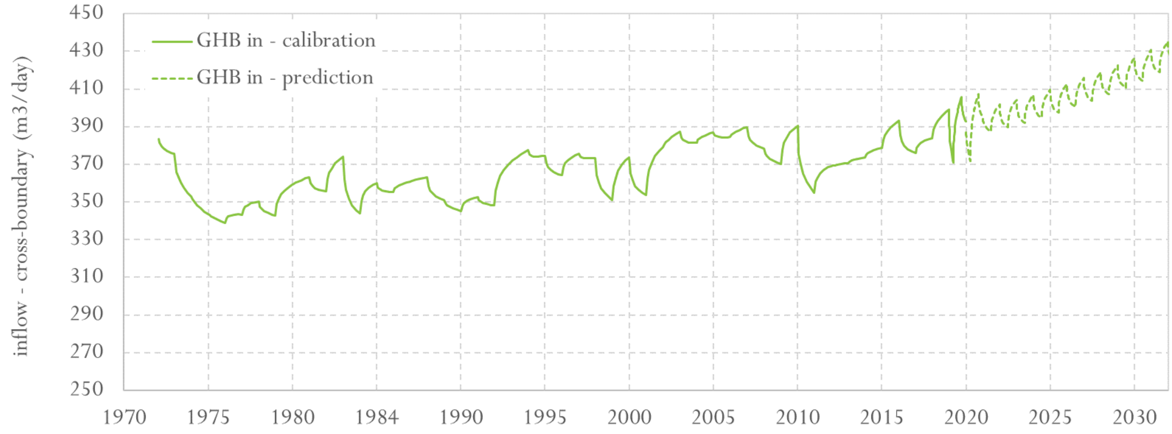
5.1. Budgets

Water budget (or water balance) of the numerical model reflects and quantifies flows entering and leaving the model domain. The inflows into the model domain are through diffuse aerial recharge (RCH boundary condition) and cross-boundary flow (GHB boundary condition). The outflows from the model domain are via surface drainage (RIV boundary condition), cross-boundary flow (GHB boundary condition) and, for transient part of the simulation, water removal through mining (DRN boundary condition)

The flow rates and volumes across individual boundaries are summarised in Table 21 and flow rate trends for individual boundaries are presented in Figure 21 (inflows) and Figure 22 (outflows). Table 22 summarises the predicted inflows rates and volumes for the Project, whereas Figure 23 and Figure 24 present the predicted inflow rates for the BMA mines and the Project respectively.

Table 21 Numerical model – water budget summary

boundary condition		steady state	transient - calibration		transient - prediction	
		flow rate (m^3/day)	cumulative volume (m^3)	average flow rate (m^3/day)	cumulative volume (m^3)	average flow rate (m^3/day)
	number of days	-	17532.0		4565.0	
in	recharge (RCH)	1362.3	27,684,805.8	1579.1	6,880,887.4	1638.7
	head dependant boundary (GHB)	391.8	6,436,659.1	367.1	1,704,982.7	406.0
out	surface drainage (RIV)	634.8	14,044,678.5	801.1	2,719,386.7	647.6
	head dependant boundary (GHB)	1119.3	17,648,669.8	1006.7	3,633,140.5	865.2
	mining (DRN)	0	37,221,053.8	2123.0	19,059,994.9	4539.2



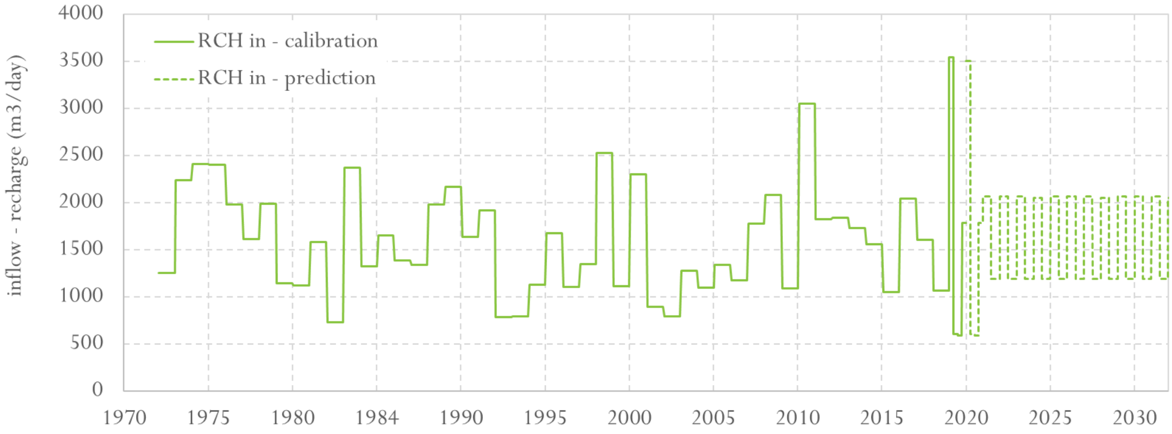


Figure 21 Numerical model budget – inflows (cross-boundary flow, rainfall related recharge)

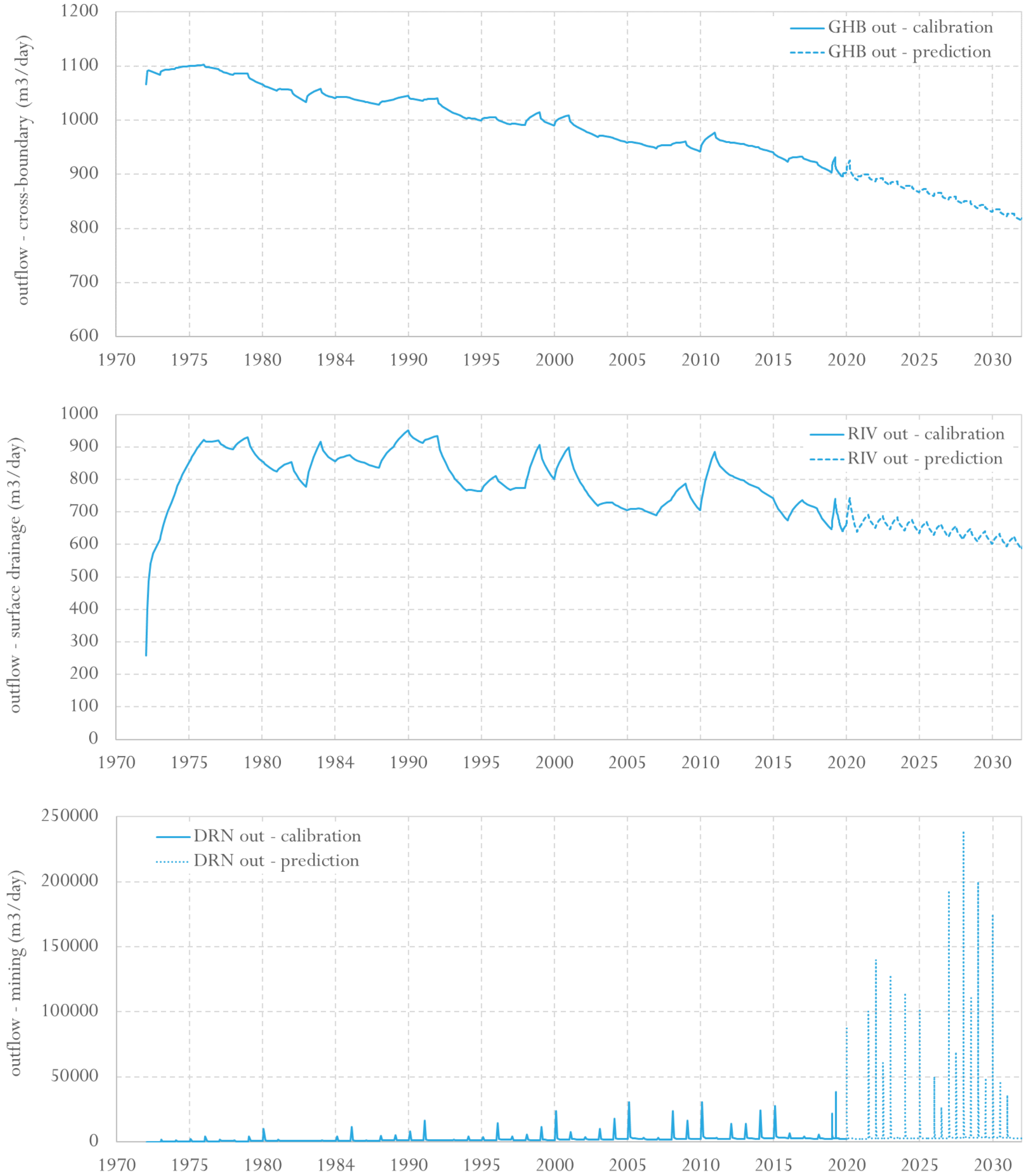


Figure 22 Numerical model budget – outflows (cross-boundary flow, surface drainage, mining)

Table 22 Numerical model – zone budget – predicted inflow rates for the Project

SP	days	SP end	DRN inflow (m^3/day)			Volume (ML)
			Vulcan North	Vulcan Main	Vulcan South	
59	184	01/01/2023	0.00	0.00	0.00	0.16
60	181	01/07/2023	0.88	0.00	0.00	
61	184	01/01/2024	1.86	0.21	0.00	1.12
62	182	01/07/2024	1.45	2.60	0.00	
63	184	01/01/2025	4.71	6.41	0.00	9.11
64	181	01/07/2025	3.09	35.93	0.00	
65	184	01/01/2026	1.15	37.14	0.00	13.15
66	181	01/07/2026	0.00	33.72	0.00	
67	184	01/01/2027	0.00	35.09	0.00	14.14
68	181	01/07/2027	0.00	42.42	0.00	
69	184	01/01/2028	0.00	32.20	0.00	11.20
70	182	01/07/2028	0.00	29.00	0.00	
71	184	01/01/2029	0.00	21.90	0.15	5.83
72	181	01/07/2029	0.00	9.05	0.77	
73	184	01/01/2030	0.00	2.62	2.34	3.23
74	181	01/07/2030	0.00	10.72	2.05	
75	184	01/01/2031	0.00	6.28	0.89	1.52
76	181	01/07/2031	0.00	0.00	1.10	

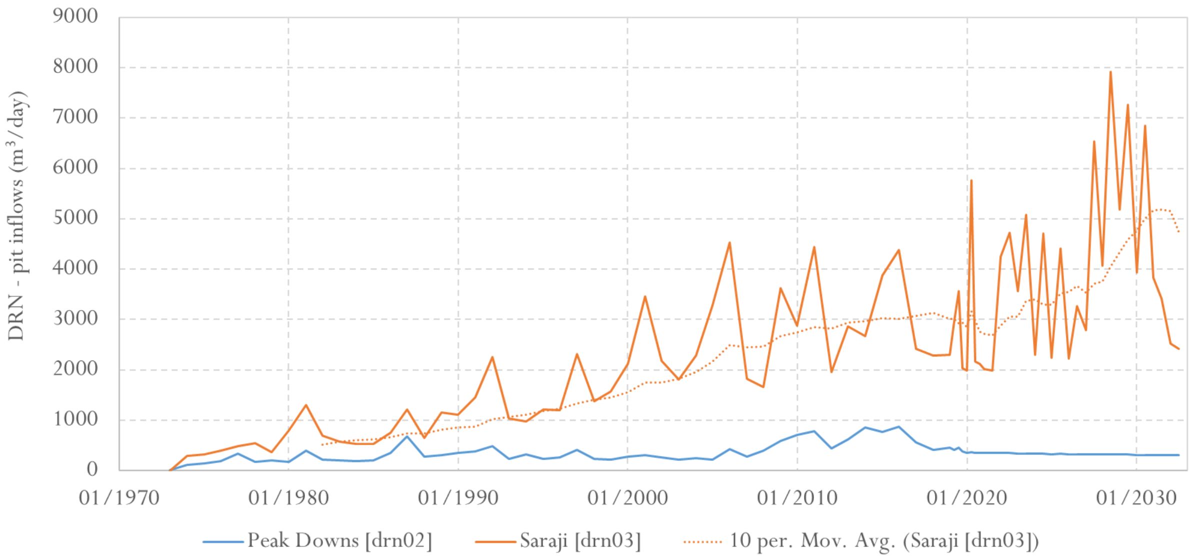


Figure 23 Numerical model zone budget – inflow rates – Peak Downs, Saraji

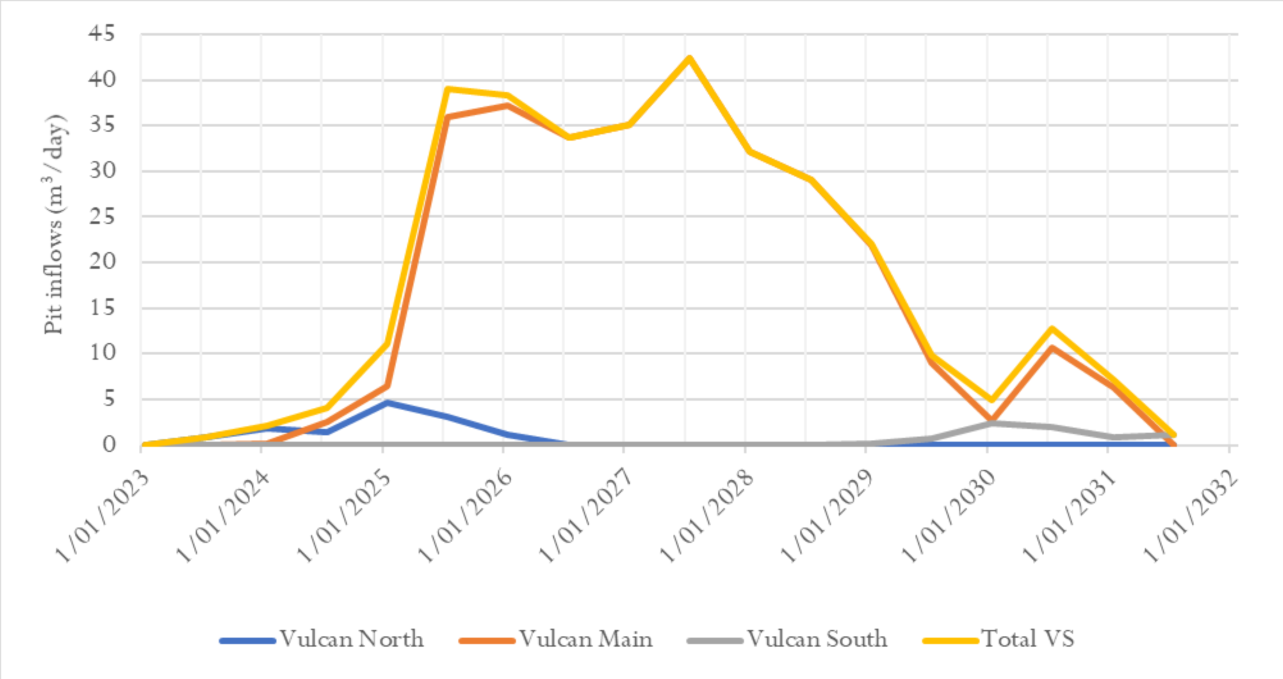
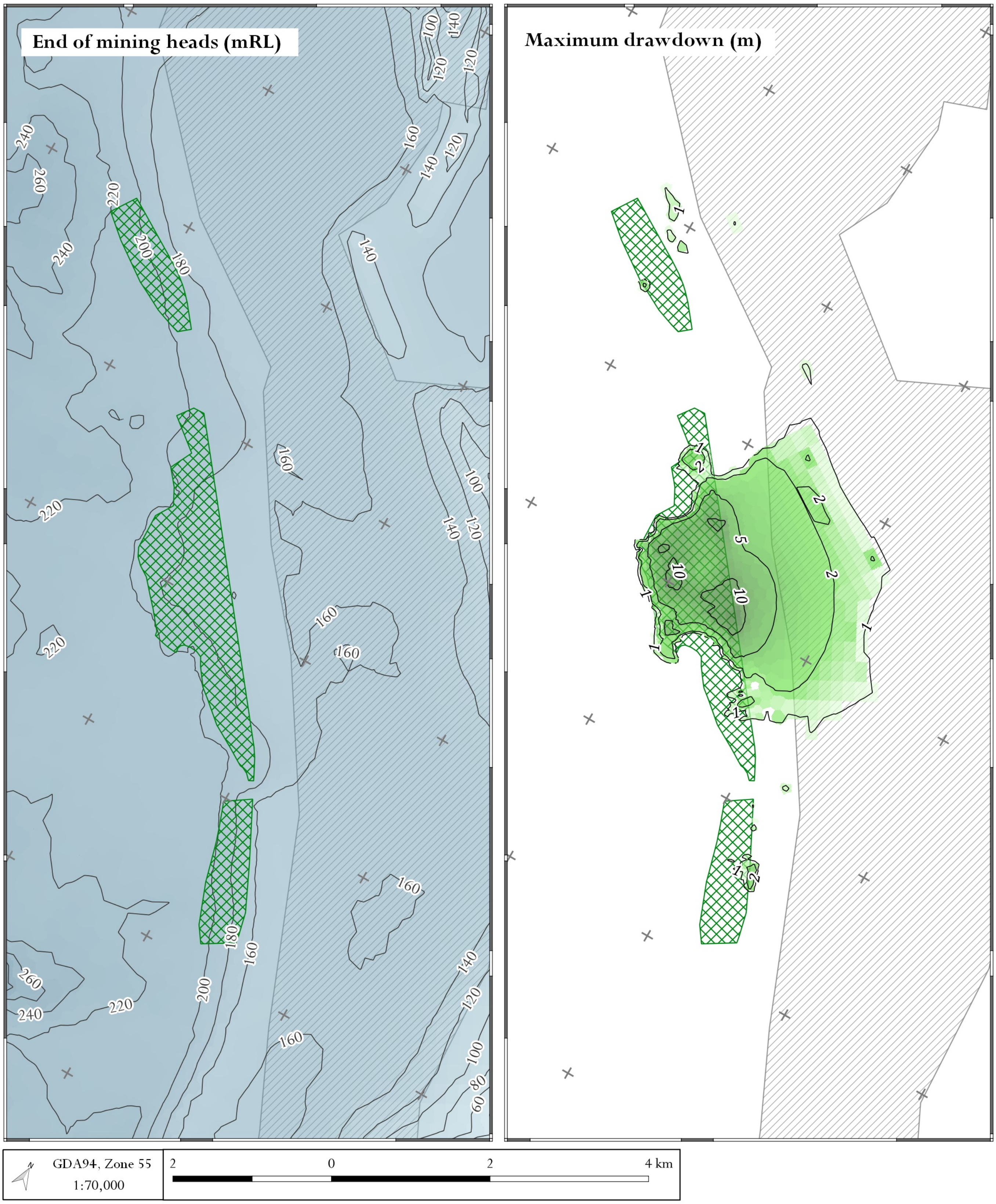


Figure 24 Numerical model zone budget – inflow rates – Project only

5.2. Heads and drawdown

The modelled end of mining heads and maximum drawdown are shown for the weathered zone and the DLL coal seam in Figure 25 and Figure 26 respectively. Figure 27 shows the model predicted heads at the start of mining for the weathered zone, whereas Figure 28 shows the model predicted heads at the start of mining for the DLL coal seam.

The impacts of the mine development on the groundwater regime are discussed in the main groundwater impact assessment report.



LEGEND

Model domain

Proposed pit

Established mining operation

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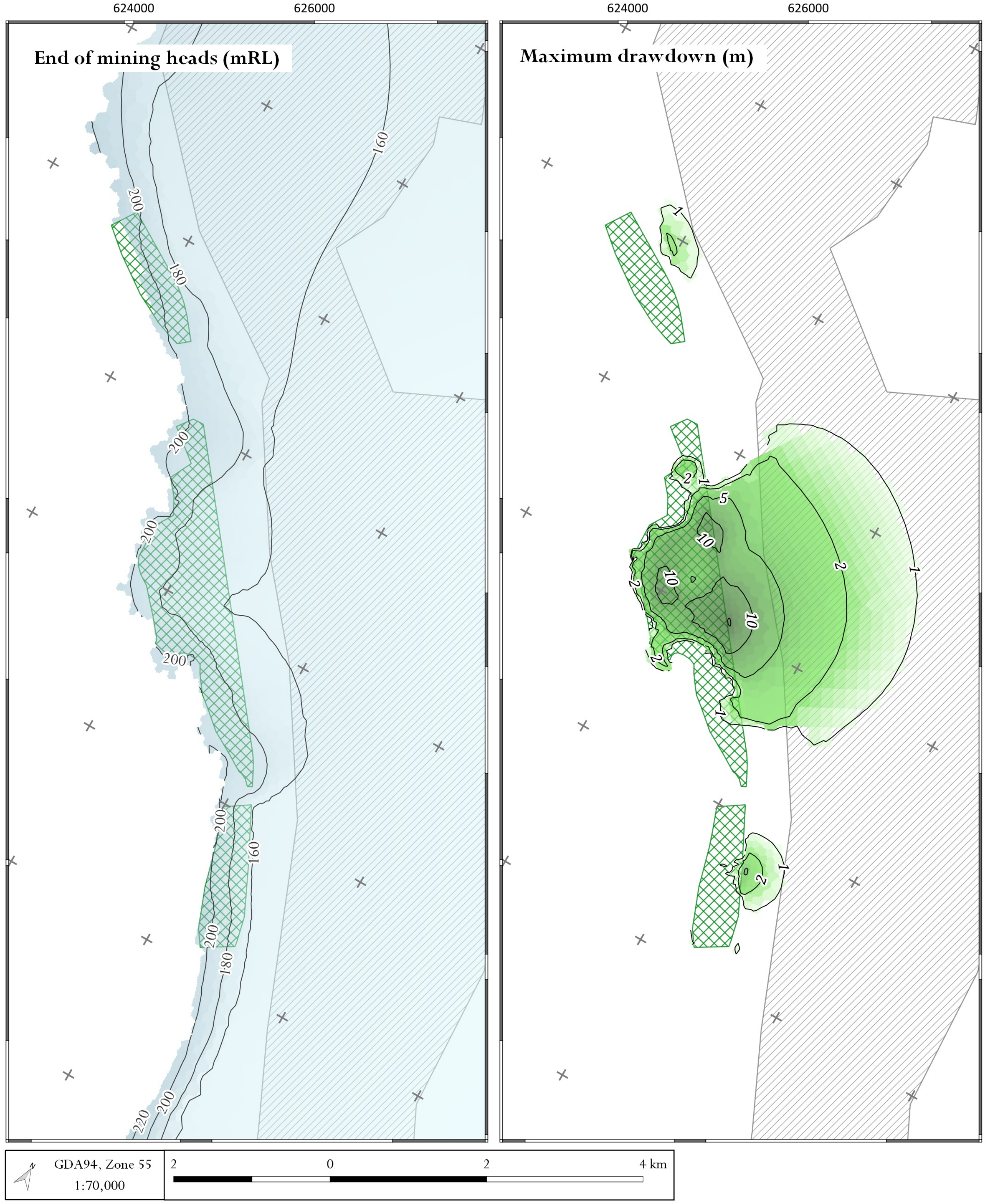
Vulcan South - Groundwater Modelling Appendix (4027)

Modelled heads and drawdown - weathered zone

FIGURE No.
25

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\25_4027_Vulcan South_App_Heads and drawdown weathered zone L02.qgz



LEGEND

Model domain

Proposed pit

Established mining operation

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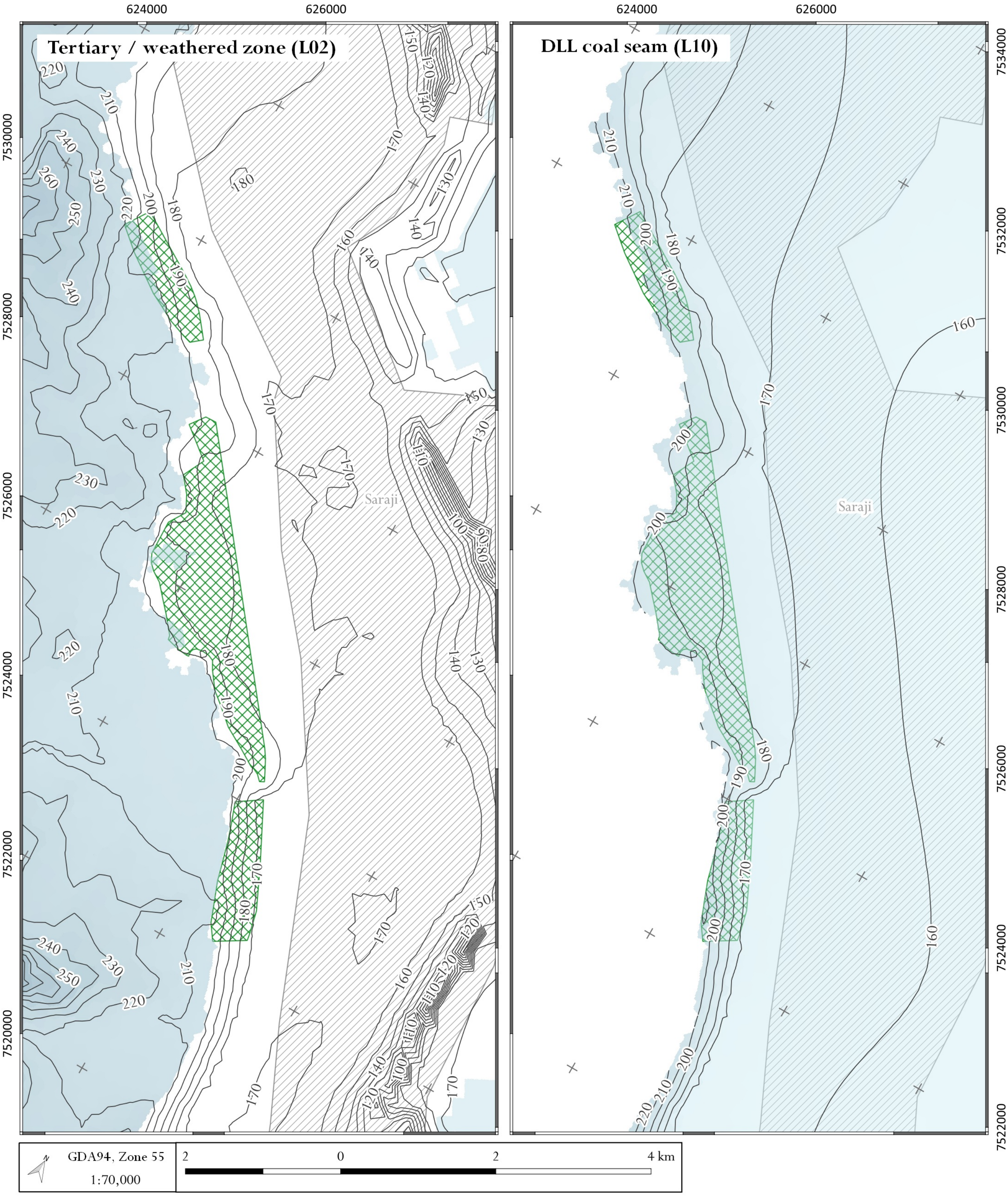
Vulcan South - Groundwater Modelling Appendix (4027)

Modelled heads and drawdown - DLL coal seam

FIGURE No.
26

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\26_4027_Vulcan South_App_Heads and drawdown DLLseam L10.qgz



LEGEND

Saturated heads (mAHD)

140	260
170	290
200	320
230	350
	380

Model domain

Proposed pit

Established mining operation

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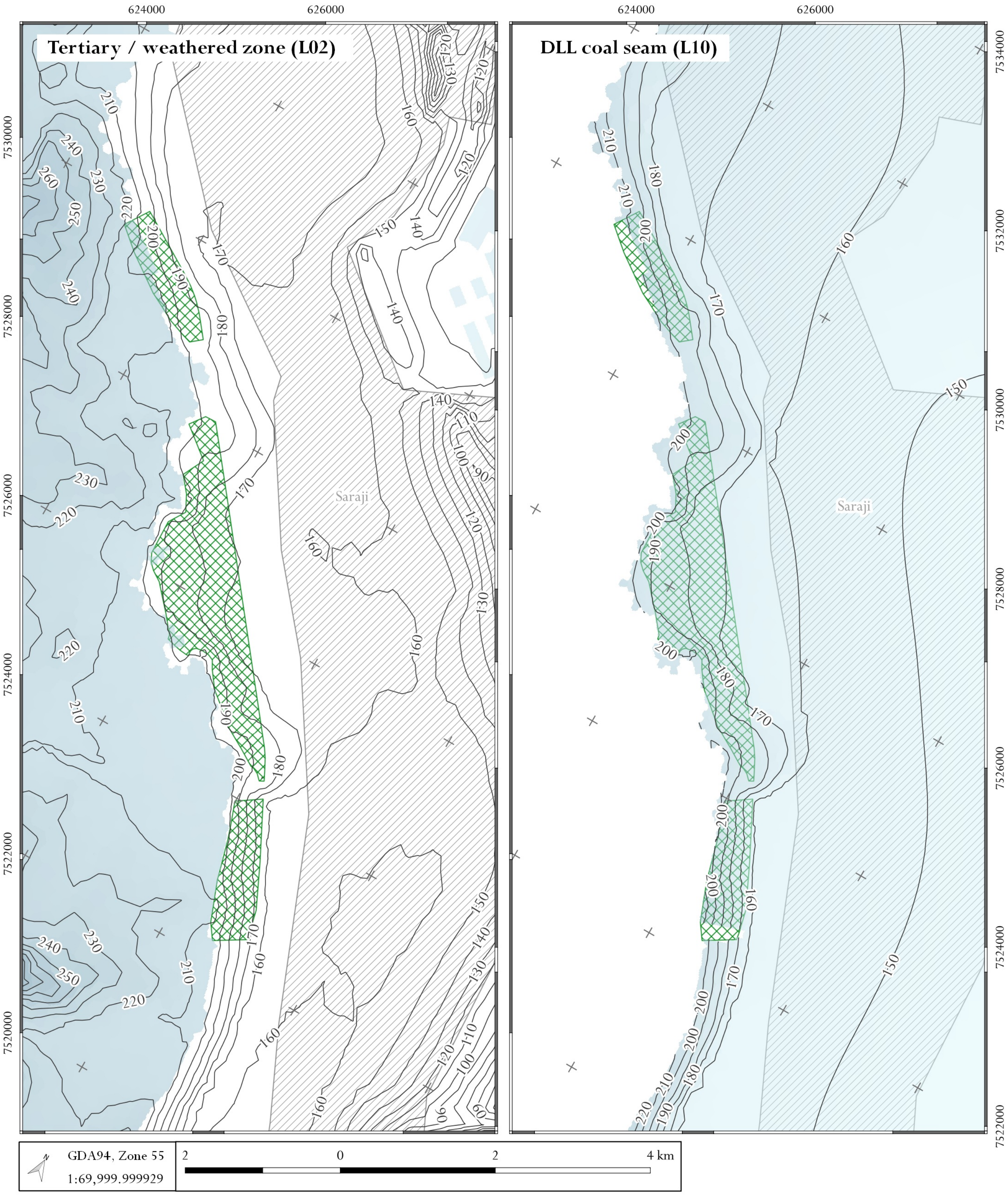
Vulcan South - Groundwater Modelling Appendix (4027)

Model predicted heads - start of mining (SP51)

FIGURE No.
27

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\27_4027_Vulcan South_App_Modelled heads SP51.qgz



LEGEND

Saturated heads (mAHD)

- 140
- 170
- 200
- 230
- 260
- 290
- 320
- 350
- 380

- Model domain
- Proposed pit
- Established mining operation

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Vulcan South - Groundwater Modelling Appendix (4027)

Model predicted heads - end of mining (SP76)

FIGURE No.
28

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.

Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\28_4027_Vulcan South_App_Modelled heads SP76.qgz

6. Uncertainty analysis

In the context of model-based decision support or risk assessment or management, uncertainty can be defined as *any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system* (Walker *et al*., 2003). Understanding where the unknowns are hidden and what their impact on modelling prediction is (or might be) is a strength of the model and a necessary tool supporting the decision-making effort (Johnson, 2010).

In more current (and Australian) context Peeters *et al.* (2018) pilot a combination of approaches to discuss impact of limitations of knowledge on modelling predictions in the context of decreasing risks associated with the environmental impact assessments. Authors further refined their recommendations in the form of guidelines (Middlemis and Peeters, 2018) where they recommend both qualitative and quantitative approach to uncertainty analysis.

6.1. Qualitative uncertainty

Qualitative uncertainties are defined by lack of knowledge with respect to either structure or processes within the groundwater flow system. They can be usually reduced by collecting more data or collecting data from areas that were not previously sampled or monitored.

The 'conceptual/knowledge' issues recognised during the evaluation of the impacts of the Project on the groundwater system are:

- precision of topographic elevation data, precision of observation elevation data;
- precision of structural elevation data – elevation/thickness of individual hydrostratigraphic units;
- existence and function of structural geological features (faults) – impact on cross-boundary flow definition;
- spatial heterogeneity of hydrostratigraphic units;
- timing of system stresses – dewatering (pumping, mining) or recharge (water storage in pits); and
- lack of relevant surface water flow information.

Precision of topographic elevation data

The information about topographic elevation was obtained from multiple sources – Lidar dataset for the Project site, SRTM dataset for the surrounding areas and elevation survey information for some of the bores on site or in the close vicinity of the site. Each of the dataset has different precision and built-in error (0.15 m for the Lidar data, ~20 m for the SRTM data, 0.01 m for the elevation survey data), however these errors can be increased by further data processing and interpolation. The uncertainty in topographic elevation data can have a flow-on effect on observations (groundwater level) or hydrologic features (elevation of surface stream bed, elevations of water storage dams).

The most precise elevation dataset covers the Project site, the less precise dataset covers area associated with Saraji. The groundwater observation sites that were suspected have incorrect elevation data were removed from the 'calibration targets' dataset.

The groundwater elevations are usually calculated using topographic surface information and depth to water. If the topography is off, the groundwater levels can be off. Any other topographic elevation errors have potential impact on surface water elevation (in case of flowing water such as stream or standing water elevation such as dam storage), potentially impacting water gradients and direction and rate of groundwater flow. As the groundwater table elevations are usually used as calibration targets and the quality of calibration is assessed by comparing the 'observed' and modelled heads, incorrect 'observed' elevation can derail the calibration process by trying to fit to wrong targets.

Given the spatial scale of the model, number of groundwater observations (calibration targets) and possibility of identification and removal of the incorrect observations from the calibration targets dataset, the impact of this issue on the modelling predictions is low.

The precision of the topographic elevation dataset can be improved by either spatially extending the Lidar dataset and/or by undertaking elevation survey in specific locations (such as selected observation bores, riverbed sections, dams). These precise elevation measurements can be then used to rectify the less-precise SRTM data.

Precision of structural elevation data

The elevation data for geological (or hydrostratigraphic units) floors is coming from multiple sources: In case of project target DLL seam, the elevation data was obtained from detailed geomodel based on on-site resource validation drill data. Precision of the elevations of the on-site geomodel dataset is ~1 m. In case of DL seam, the initial data was obtained by digitising and then re-interpolating the DL floor contours presented in the Bowen Basin Supermodel report (Esterle and Sliwa, 2002). These structure contours were originally based on CSG exploration data. Where the 'Supermodel' interpreted contours did not extend all the way to the edges of the Project model domain, the existing slope/trend was just extended to the edge with a use of existing CSG drill logs. Floor of Fort Cooper Coal Measures was based on mapped subcrop line (Department of Natural Resources, Mines and Energy, 2018) and an assumption that the dip of the structure will be similar to that of underlying DL seams. The error of these elevations could be in tens of metres, up-to 150 m.

In order to assess impact of the Project, two prediction models were run: (1) the 'null' scenario, simulating mining at Saraji only and (2) the 'baseline' scenario with mining at both Saraji and the Project. The impact of mining the Project is then expressed as difference between outputs of these two scenarios; difference in heads produces drawdown induced by the Project, difference in DRN budgets produces pit inflow estimates. As the 'uncertain' mining at Saraji is modelled identically in both scenarios, the impact of these uncertainties literally cancels itself out.

The elevation of mined coal seams (geological structures or hydrostratigraphic units in general) is important because if the elevations of the pit floors are not explicitly known, they are used to position a dewatering boundary condition (DRN boundary condition) in the numerical model. Having a groundwater flow system to be dewatered in a wrong time, wrong place or into wrong depth will create an incorrect flow gradient end will cause model to predict incorrect inflows into the mine. As this issue is directly connected with later 'timing and location of system stresses', it will be discussed in more detail there.

Given the used methodology, the impact of this issue is considered low.

Given the history of mining at Saraji and their extent of mining operations, detailed geological and stratigraphic information exists. The uncertainty of the issue could be decreased by making the existing data public, acquiring the data from secondary sources (publicly available technical reports) or obtaining the information via data sharing agreement with owners of the Saraji Mine.

Timing and location of system stresses

The most prominent system stress is dewatering associated with mining at Saraji, with the Saraji Mine boundary located 600 m to 1000 m to the east of the Project. The Saraji Mine is over 30 km long in NW-SE direction with mining pits reaching depth of ~150 m. The mining has been occurring since 1972. The mining activity would have significant drawdown impact on groundwater table in the direct vicinity of the mine and would override any other potential system stress (such as low recharge).

In the numerical model, the mining progression is simulated using drain (DRN) boundary condition, placed (in case of Saraji Mine) to the floor of Dysart Lower (DL) coal seam. The timing of the progression was estimated using satellite imagery in 5 year intervals. The location of the active mine in between the 5 year snapshots was estimated by linearly interpolating between known position of pits.

If any of the monitoring bores are impacted, the influence of the mine would be impossible to replicate in the numerical model without understanding the precise timing, location and depth of mining.

During the model calibration, monitoring bores were assessed and those assumed to be impacted by mining related drawdown were removed from the 'calibration target' dataset.

As discussed above, because the identical impact from mining at Saraji is implemented in both 'null' and 'baseline' scenarios, it effectively cancels itself out. As such, impact of this issue on the predictive capability of the numerical model with respect to the Project assessment is low.

The detailed information describing historical mining progression at Saraji Mine should be available from operators of Saraji Mine.

Existence and function of structural geological features

Small and larger scale faults were observed and mapped throughout the model domain and regional scale fault system (Jellinbah Thrust Fault zone) was used in place of model domain boundary. Based on the previous regional scale assessment of the structural features (Esterle and Sliwa, 2002), the proposed pit may be influenced to some degree by local structure mapped at the adjacent Saraji Mine and Peak Downs Mine.

Both small- and large-scale structural features can have impact the groundwater flow; in specific cases, they can obstruct, block or divert the groundwater flow, or, if behaving as conduits, creating preferential flow pathways. Given the lack of the small-scale features identified directly at the Project area, they do not present, impact of their absence on modelling prediction is low. As for structural features associated with Saraji and Peak Downs Mines, they might have impact on the flow regime within these sites, however their impact on the Project is most likely negligible.

The small-scale structural features (faults) were omitted from the numerical model. The regional-scale Jellinbah Thrust Fault zone was incorporated into the model in the form of 'no-flow' boundary condition.

Information concerning small- and large-scale geological structures is usually obtained through (core) drilling work, complemented by geophysics. Local, small-scale faults on neighbouring sites (Saraji) should be documented within their geological databases.

Spatial heterogeneity of hydrostratigraphic units

The hydraulic properties are distributed heterogeneously within each hydrostratigraphic unit. Impact of these heterogeneities depends on modelling scale – it is more important in small-scale models while in large-scale (regional) models the properties of individual hydrostratigraphic units are often modelled using 'bulk property' or 'average property' approach. Although implementation of the heterogeneous hydraulic properties within the numerical model is relatively simple, it sharply increases computational complexity of the model and without basing the heterogeneity in real world observations it can contribute towards non-uniqueness of the model calibration.

Hydraulic properties used in the numerical model have impact on predictions of both heads and flows. Combined with recharge distribution, they contribute towards a non-unique solution to the inverse-modelling (calibration) process. On local scale, the lack of spatial heterogeneity on specific, spatially limited modelling prediction can be medium to high.

The understanding of spatial variability of the hydraulic properties could be improved by hydraulic testing.

On regional scale, the lack of modelled heterogeneity was compensated by varying the bulk hydraulic properties and its impact on heads and flows prediction was quantified using stochastic analysis of the modelling impacts (see Section 6.2).

Lack of relevant surface water flow information

The information concerning surface water flow is relatively sparse in both temporal and spatial sense (see Section 3). Together with current field observation of no-flow conditions, the historical data from single stream gauge is informed the 'drain-only' conceptualisation of the surface stream network.

We adopted the 'limited-recharge' or 'drain-only' conceptualisation as plausible.

The 'drain-only' conceptualisation assumes very low or no recharge from the creeks into the groundwater system. If we underestimated the amount of surface-water related recharge into the system, it could have had impact on model calibration by adjusting rate of aerial (rainfall related) recharge or hydraulic properties to compensate for the low recharge from the streams. The impact of low resolution surface water flow data on modelling predictions under current conceptualisation is low. If more (future) data leads us to the change of the conceptualisation to 'recharge / discharge' model, the lack of historical flow data would be more important.

Longer stream gauge record would have been helpful, especially during the periods of sustained drought.

6.2. Quantitative uncertainty

Quantitative uncertainty analysis is a technique that aims to understand behaviour of the groundwater system by using mathematical and statistical approach to evaluate modelling inputs and outputs and assign a 'probability of occurrence' to selected impacts.

6.2.1. Methodology

The method quantifying the probability of impacts exceeding certain value follows these steps:

- Define sampling distributions for all model parameters.
- Generate model input dataset (model 'realisation') honouring the sampling distributions.
- Run the model for each 'realization' and extract predictions (heads, flows). Check for calibration statistics (SSQ and SRMS) to assess level of 'miscalibration'. Remove predictions from runs that would be considered not sufficiently calibrated.
- Calculate impacts (in our case pit inflows and drawdown) for each of the accepted 'realizations'.
- Calculate minimum, maximum and selected percentile values for both pit inflow rates and drawdowns.
- Use the percentile values to describe the probability of exceedance of modelled outcome (Table 23) in accordance with ISEC Uncertainty guidelines (Middlemis and Peeters, 2018).

Table 23 Combined numeric, narrative and visual description of likelihood (Middlemis and Peeters, 2018)

Percentile	Colour code	Description (in terms of likelihood of exceedance)	Alternative description or framing
<10%	(dark green)	It is **very likely** that the outcome is **larger** than this value	It is **very unlikely** that the outcome is **smaller** than this value
10–33%	(light green)	It is **likely** that the outcome is **larger** than this value	It is **unlikely** that the outcome is **smaller** than this value
33–67%	(yellow)	It is as **likely as not** that the outcome is **larger** than this value	It is as **likely as not** that the outcome is **smaller** than this value
67–90%	(orange)	It is **unlikely** that the outcome is **larger** than this value	It is **likely** that the outcome is **smaller** than this value
>90%	(red)	It is **very unlikely** that the outcome is **larger** than this value	It is **very likely** that the outcome is **smaller** than this value

6.2.2. Definition of parameter sampling distributions

The method uses 'calibrated' model and information associated with all calibrated model parameters (such as calibrated parameter value, parameter ranges, existing jacobian matrix etc.) to define a sampling distribution for each of the analysed parameters and then sample these distributions multiple times to create multiple model 'realisations' (datasets of possible inputs). The sampling (cumulative) distribution for each parameter is presented in Appendix C1 in tabular (Table C1 1) and graphical form (Figure C1 1).

6.2.3. Evaluation of model runs – calibration statistical measures

Two versions of the numerical model ('null' and 'project' scenarios) are then run with each of the generated input datasets and model predictions for each of the scenarios (heads and inflows) are extracted. For each model 'realisation', calibration statistics were calculated in order to assess the validity of that particular model prediction. In case the calibration statistics (value of SSQ and SRMS) indicated the selected dataset de-calibrated the model too much, the prediction would have been removed.

In total, 680 model pairs (680 different realisations of the input dataset) were run. None of these failed to converge, all model runs finished. Out of these, 62 (9.1%) had lower SSQ (Figure 29) which means these 'realisations' showed better calibration level than the 'calibrated' dataset (calibrated value of SSQ was 2292.3 m^2).

Value of SRMS varied between 3.9 % and 5.3 % with 72 realisations (10.6%) having better SRMS (Figure 30) than the 'calibrated' value of 4.0 %.

As the groundwater modelling guidelines suggest that SRMS of 5 % (or less) for transient observation can be considered acceptable, all 680 of the model realisations were considered as 'sufficiently calibrated' and none of the realisations were removed from further statistical evaluation of model impacts.

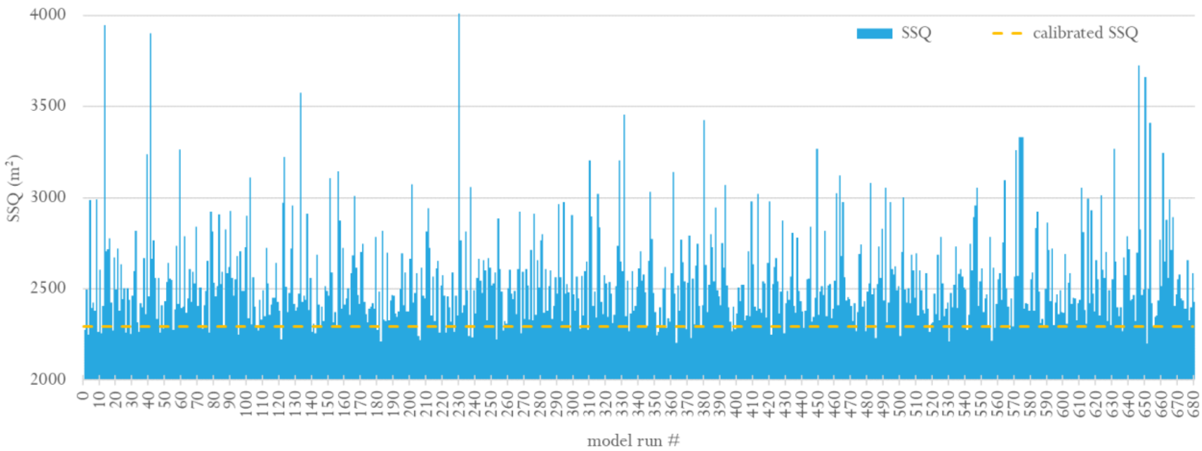


Figure 29 Evaluation of uncertainty runs – calibration statistical measures - SSQ

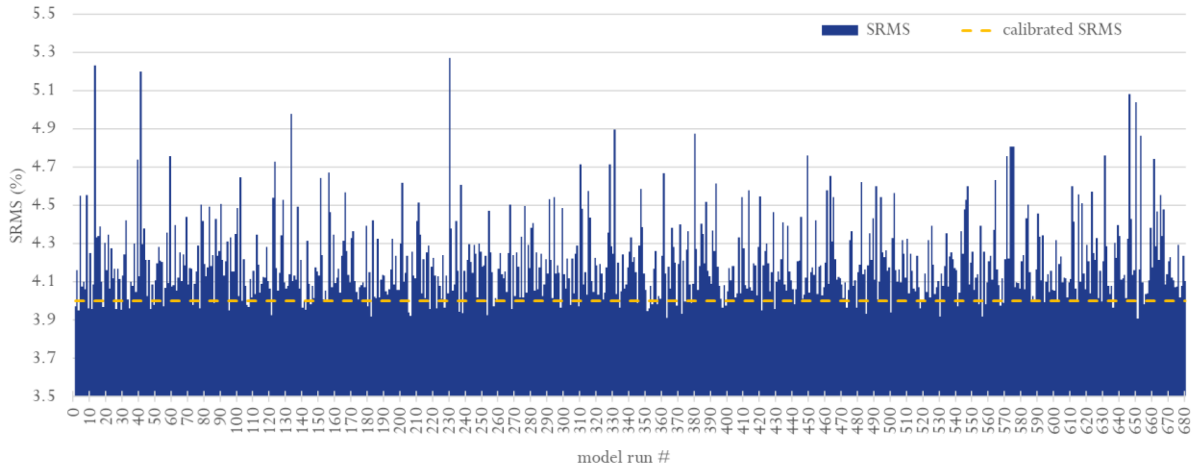


Figure 30 Uncertainty runs – SRMS

6.2.4. Uncertainty analysis of impacts

The uncertainty of exceedance of particular pit inflow rate is presented in Figure 31. The original model prediction (see Figure 24) lies within the expected 'as likely as not' exceedance probability range. This indicates that the model prediction is not 'over-calibrated' and unrealistic. The highest possible inflow rate was quantified to be 115 m³/day.

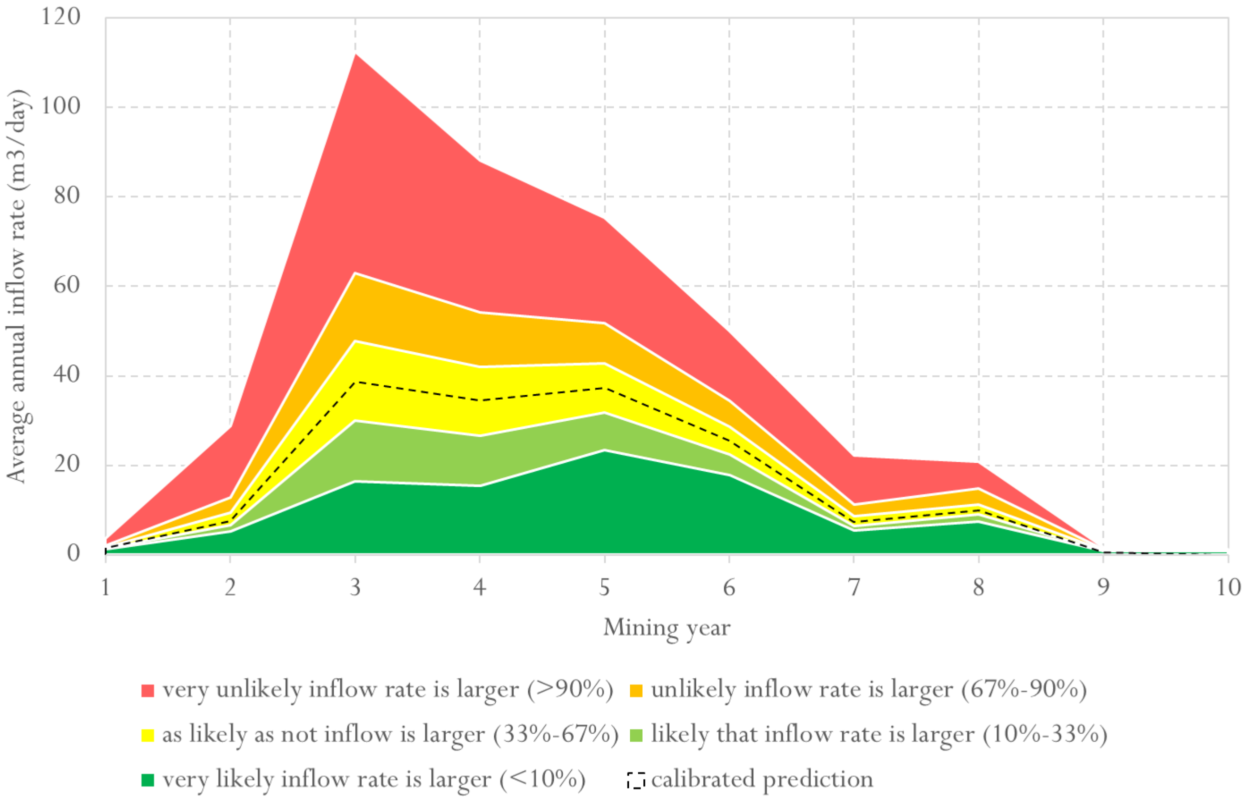
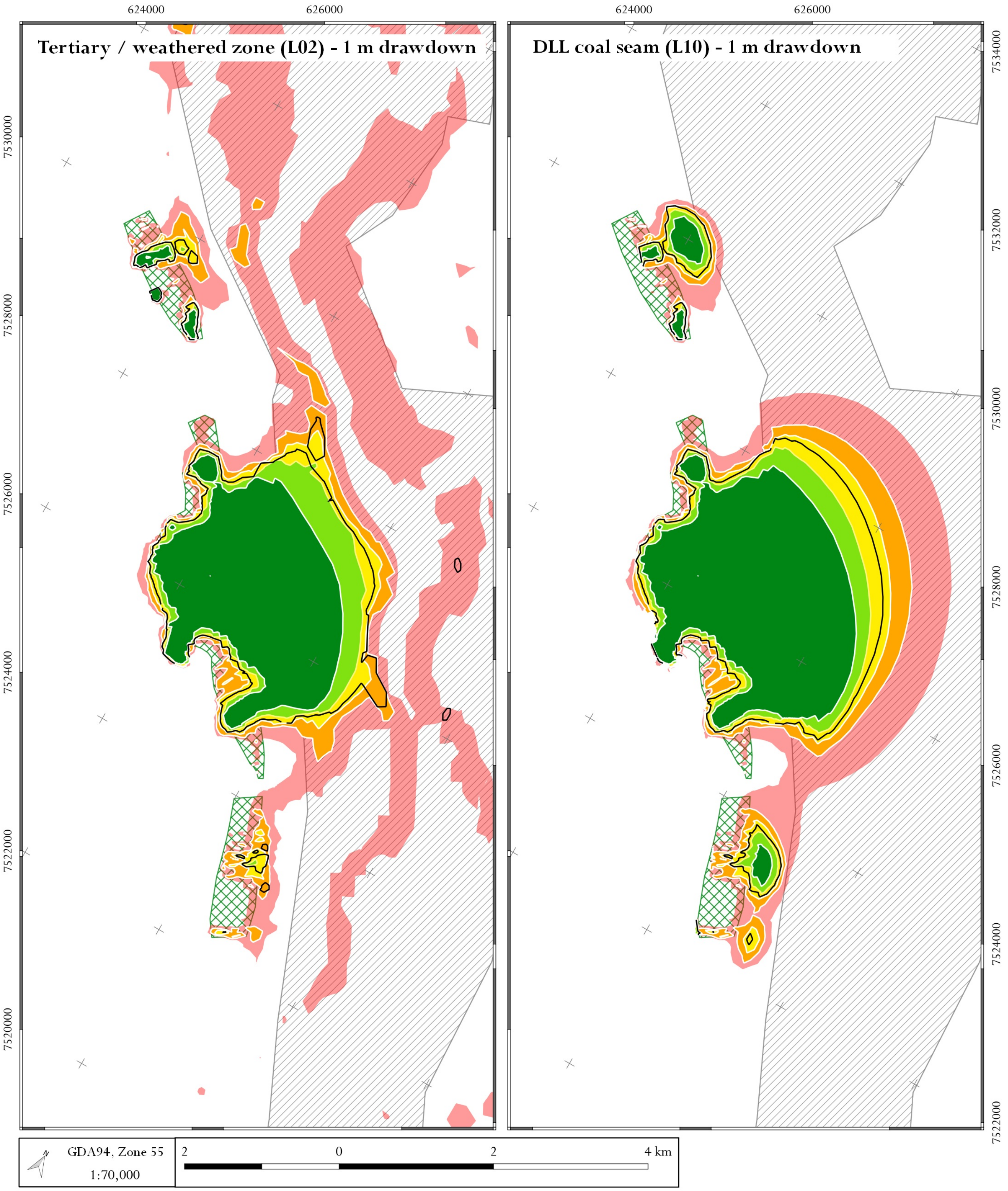


Figure 31 Uncertainty runs – Project pit inflow rates

The spatial extent of maximum drawdown (Figure 32) is represented by 1 m contour. The zones of probability of exceedance of drawdown values are again based on the ISEC Uncertainty guidelines – the green zone presents 90% probability of larger extent than presented, yellow zone means the drawdown will be larger as likely as not, the red zone shows area where the probability of exceedance of 1 m drawdown is very low – with likelihood of less than 10%. The calibrated prediction of 1 m drawdown extent (the 'basecase') is shown as black dashed line.



LEGEND

Proposed pit
Existing mining operation

<10% - it is very likely that the outcome is larger than this value
10% - 33% - it is likely that the outcome is larger than this value
33% - 67% - it is as likely as not that the outcome is larger than this value
67% - 90% - it is unlikely that the outcome is larger than this value
>90% - it is very unlikely that the outcome is larger than this value
Basecase - 'calibrated' model prediction

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Uncertainty analysis - maximum drawdown

FIGURE No.
32

Source: 1 second SRTM Derived DEM-S - © Commonwealth of Australia (Geoscience Australia) 2011.; GEODATA TOPO 250K Series 3 - © Commonwealth of Australia (Geoscience Australia) 2006.
Z:\4000_Projects\4027_Metserve_Vulcan_GIA\3_GIS\Workspaces\Vulcan South figures\Modelling appendix\32_4027_Vulcan South_App_Uncertainty drawdown in L02 and L10.qgz

7. References

AECOM, 2016. Saraji Open Cut Extension Project, Underground Water Impact Report, Rev 8.

Arris, 2017. Underground water impact report - ATP 688. prepared for Westside Corporation Ltd.

Arrow Energy, 2016. Arrow Energy Underground water impact report (UWIR) for PL 191, 196, 223, 224 and ATP 1103, 742, 831 and 1031.

Barnett, B., Hunt, R.J., Townley, L.R., Peeters, L., 2012. Australian groundwater modelling guidelines (No. Waterlines Report Series No. 82). National Water Commission, Canberra, ACT, Australia.

Bureau of Meteorology, 2019. LongPaddock - SILO point datadrill; Queensland Government [WWW Document]. URL https://longpaddock.qld.gov.au/silo/point-data/ (accessed 8.2.19).

Bureau of Meteorology, 2016. dataset | Australian Climate Averages - Climate classifications.

Department of Natural Resources, Mines and Energy, 2019a. dataset | Groundwater database - Queensland.

Department of Natural Resources, Mines and Energy, 2019b. dataset | Coal seam gas well locations - Queensland.

Department of Natural Resources, Mines and Energy, 2018. dataset | Detailed surface geology - Queensland.

Doherty, J., 2019a. Groundwater Data Utilities; Part C: Programs Written for Unstructured Grid Models.

Doherty, J., 2019b. PEST - Model-Independent Parameter Estimation; user manual Part I: PEST, SENSAN and Global Optimisers.

Doherty, J., 2019c. PEST - Model-Independent Parameter Estimation; User manual Part II: PEST Utility Support Software.

Doherty, J., 2012. Windows BEOPEST.

Esterle, J., Sliwa, R., 2002. Bowen Basin Supermodel 2000 (No. Exploration and mining report 976C). CSIRO Expoloration and Mining, ACARP, GeoGas, CSIRO Exploration & Mining, PO Box 883, Kenmore, Queensland, Australia 4069.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. MODFLOW-2000, The U.S. Geological Survey modular ground-water model - user guide to modularization concepts and the ground-water flow process (Open-File Report 00-92). USGS, Reston, VA, USA.

hydrogeologist.com.au, 2019. Hydrogeological drilling report, Vulcan complex project, Project 4015. prepared for Vitrinite Pty Ltd.

HydroSimulations, 2018. Olive Downs Coking Coal Project, Draft Environmental Impact Statement, Appendix D: Groundwater Assessment; Project No. PEM002 (No. HS2018/26).

Jeffrey, S.J., Carter, J.O., Moodie, K.B., Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software 16, 309–330. https://doi.org/10.1016/S1364-8152(01)00008-1

Johnson, J., 2010. Framework to effectively quantify and communicate groundwater model uncertainty to management and clients. U.S. Department of the Interior, Bureau of Reclamation Pacific Northwest Regional Office, River and Reservoir Operations, Boise, Idaho.

Maxey, G.B., 1964. Hydrostratigraphic units. Journal of Hydrology 2, 124–129. https://doi.org/10.1016/0022-1694(64)90023-X

Merrick, D., 2016. AlgoMesh User Guide.

Middlemis, H., Peeters, L., 2018. Uncertainty analysis - Guidance for groundwater modelling within a risk management framework. Information guidelines explanatory note (A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment and Energy). IESC, Commonwealth of Australia.

Panday, S., Langevin, C.D., Niswonger, R.G., Ibaraki, M., Hughes, J.D., 2015. MODFLOW-USG. U.S. Geological Survey. https://doi.org/10.5066/f7r20zfj

Panday, S., Langevin, C.D., Niswonger, R.G., Ibaraki, M., Hughes, J.D., 2013. MODFLOW–USG version 1: An unstructured grid version of MODFLOW for simulating groundwater flow and tightly coupled processes using a control volume finite-difference formulation (No. Chapter 45 of Section A, Groundwater Book 6, Modeling Techniques), Techniques and Methods 6-A45. U.S. Geological Survey, Reston, Virginia, USA.

Peeters, L.J.M., Pagendam, D.E., Crosbie, R.S., Rachakonda, P.K., Dawes, W.R., Gao, L., Marvanek, S.P., Zhang, Y., McVicar, T.R., 2018. Determining the initial spatial extent of an environmental impact assessment with a probabilistic screening methodology. Environmental Modelling & Software 109, 535–367.

QGIS Development Team, 2019. QGIS Geographic Information System; Open Source Geospatial Foundation Project.

Queensland government, 2014. Water Resource (Fitzroy Basin) Plan 2011.

Seaber, P.R., 1988. Hydrostratigraphic units, in: Back, W., Rosenshein, J.S., Seaber, P.R. (Eds.), Hydrogeology. Geological Society of America, U.S.A, pp. 9–14. https://doi.org/10.1130/DNAG-GNA-O2.9

URS, 2014. Dysart East Coal Project environmental assessment report; Groundwater technical report (No. 42627233/GW/04). prepared for Bengal Coal Pty Ltd.

URS, 2012. Groundwater impact assessment - Bowen Gas Project, Appendix L - groundwater and geology technical report (No. 42626960). prepared for Arrow Energy Pty Ltd.

URS, 2009. Caval Ridge Groundwater Impact Assessment - Appendix J.

Walker, W.E., Harremoës, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M.B.A., Janssen, P., Krayer von Krauss, M.P., 2003. Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. Integrated Assessment 4, 5–17. https://doi.org/10.1076/iaij.4.1.5.16466

Wilford, J., Searle, R., Thomas, M., Grundy, M., 2018. dataset | Soil and Landscape Grid National Soil Attribute Maps - Depth of Regolith (3" resolution) - Release 2. v6.

Appendix C1 Parameter sampling distributions

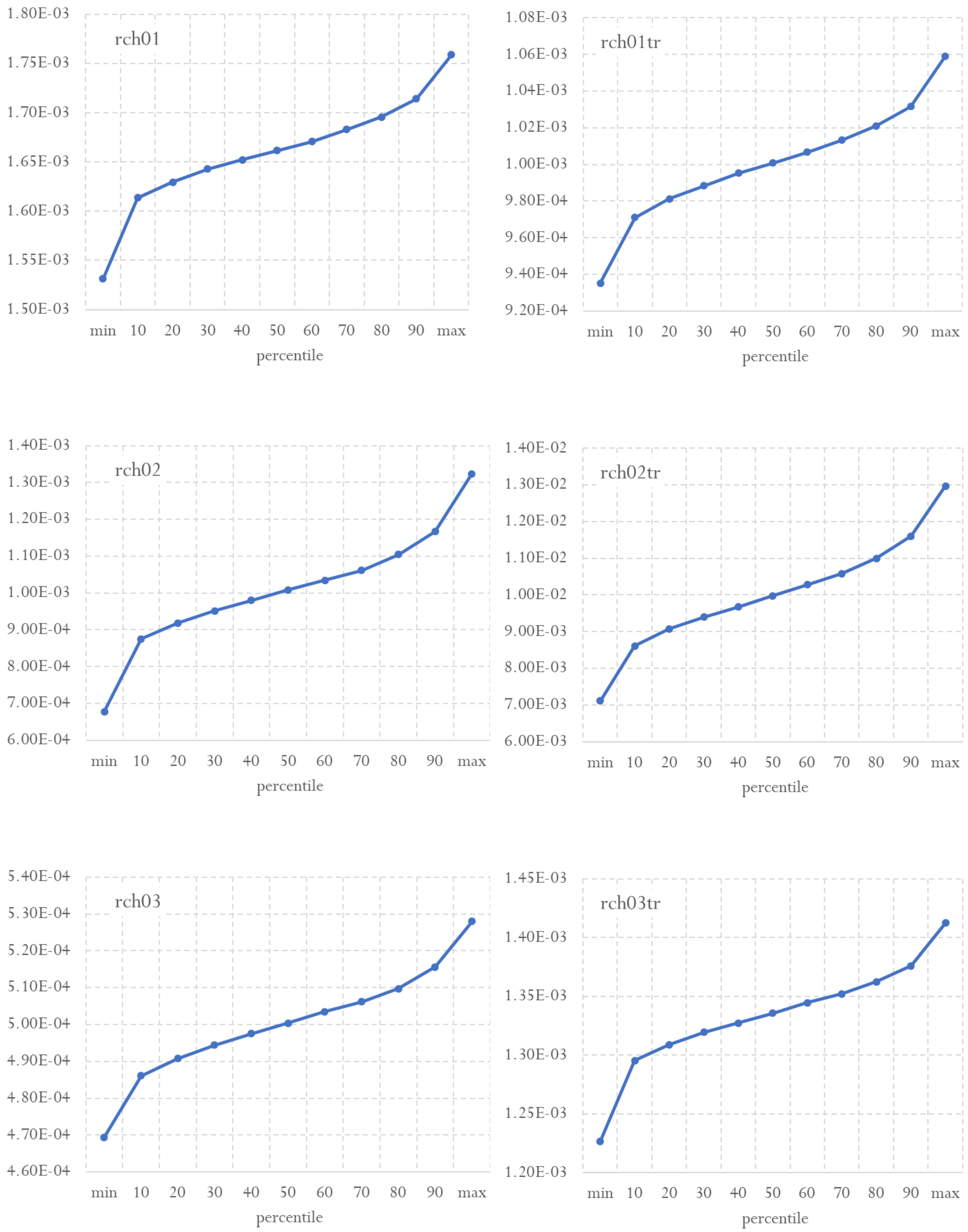
Table C1 1 Parameter distributions – cumulative percentiles

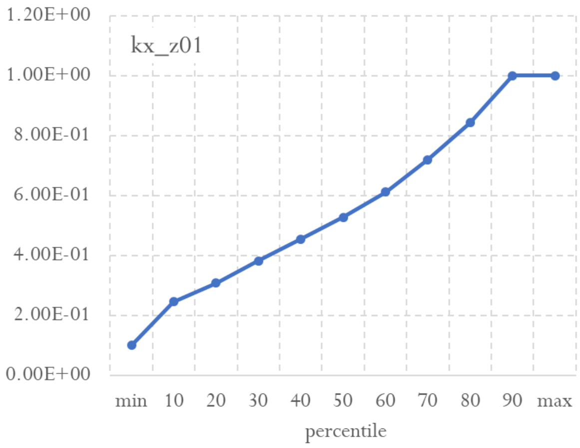
param	calibrated value	PEST definition		parameter distribution - cumulative percentiles										
		lower bound	upper bound	min	10th	20th	30th	40th	50th	60th	70th	80th	90th	max
rch01	1.661×10^{-3}	5.000×10^{-4}	2.000×10^{-2}	1.531×10^{-3}	1.614×10^{-3}	1.630×10^{-3}	1.643×10^{-3}	1.652×10^{-3}	1.662×10^{-3}	1.671×10^{-3}	1.683×10^{-3}	1.696×10^{-3}	1.714×10^{-3}	1.759×10^{-3}
rch02	1.000×10^{-3}	5.000×10^{-4}	5.000×10^{-2}	6.783×10^{-4}	8.752×10^{-4}	9.184×10^{-4}	9.515×10^{-4}	9.797×10^{-4}	1.008×10^{-3}	1.035×10^{-3}	1.062×10^{-3}	1.104×10^{-3}	1.167×10^{-3}	1.323×10^{-3}
rch03	5.000×10^{-4}	1.000×10^{-4}	2.000×10^{-2}	4.694×10^{-4}	4.861×10^{-4}	4.907×10^{-4}	4.944×10^{-4}	4.976×10^{-4}	5.004×10^{-4}	5.035×10^{-4}	5.062×10^{-4}	5.098×10^{-4}	5.156×10^{-4}	5.280×10^{-4}
rch01tr	1.000×10^{-3}	5.000×10^{-4}	2.000×10^{-2}	9.353×10^{-4}	9.712×10^{-4}	9.813×10^{-4}	9.883×10^{-4}	9.953×10^{-4}	1.001×10^{-3}	1.007×10^{-3}	1.013×10^{-3}	1.021×10^{-3}	1.032×10^{-3}	1.059×10^{-3}
rch02tr	1.000×10^{-2}	5.000×10^{-4}	5.000×10^{-2}	7.110×10^{-3}	8.612×10^{-3}	9.076×10^{-3}	9.394×10^{-3}	9.678×10^{-3}	9.973×10^{-3}	1.028×10^{-2}	1.059×10^{-2}	1.100×10^{-2}	1.160×10^{-2}	1.297×10^{-2}
rch03tr	1.335×10^{-3}	1.000×10^{-4}	2.000×10^{-2}	1.227×10^{-3}	1.295×10^{-3}	1.309×10^{-3}	1.319×10^{-3}	1.327×10^{-3}	1.336×10^{-3}	1.345×10^{-3}	1.352×10^{-3}	1.363×10^{-3}	1.376×10^{-3}	1.413×10^{-3}
kx_z01	5.000×10^{-1}	1.000×10^{-1}	$1.000\times10^{+0}$	1.000×10^{-1}	2.463×10^{-1}	3.080×10^{-1}	3.825×10^{-1}	4.547×10^{-1}	5.280×10^{-1}	6.113×10^{-1}	7.193×10^{-1}	8.435×10^{-1}	1.000×10^{0}	1.000×10^{0}
kx_z02	5.000×10^{-1}	1.000×10^{-1}	$1.000\times10^{+0}$	1.000×10^{-1}	2.402×10^{-1}	3.069×10^{-1}	3.756×10^{-1}	4.397×10^{-1}	5.061×10^{-1}	6.015×10^{-1}	6.935×10^{-1}	8.420×10^{-1}	1.000×10^{0}	1.000×10^{0}
kx_z03	5.000×10^{-2}	5.000×10^{-4}	1.000×10^{-1}	3.437×10^{-2}	4.366×10^{-2}	4.596×10^{-2}	4.737×10^{-2}	4.875×10^{-2}	5.028×10^{-2}	5.156×10^{-2}	5.312×10^{-2}	5.513×10^{-2}	5.787×10^{-2}	6.368×10^{-2}
kx_z04	5.000×10^{-2}	5.000×10^{-4}	1.000×10^{-1}	3.489×10^{-2}	4.339×10^{-2}	4.538×10^{-2}	4.718×10^{-2}	4.883×10^{-2}	5.009×10^{-2}	5.144×10^{-2}	5.302×10^{-2}	5.490×10^{-2}	5.785×10^{-2}	6.495×10^{-2}
kx_z05	3.052×10^{-3}	5.000×10^{-4}	1.000×10^{-1}	2.112×10^{-3}	2.633×10^{-3}	2.768×10^{-3}	2.866×10^{-3}	2.961×10^{-3}	3.056×10^{-3}	3.146×10^{-3}	3.236×10^{-3}	3.362×10^{-3}	3.520×10^{-3}	4.011×10^{-3}
kx_z06	1.723×10^{-3}	5.000×10^{-4}	1.000×10^{-1}	1.147×10^{-3}	1.499×10^{-3}	1.571×10^{-3}	1.628×10^{-3}	1.674×10^{-3}	1.725×10^{-3}	1.771×10^{-3}	1.826×10^{-3}	1.889×10^{-3}	1.991×10^{-3}	2.247×10^{-3}
kx_z07	1.000×10^{-2}	5.000×10^{-3}	1.000×10^{-1}	5.000×10^{-3}	5.000×10^{-3}	5.936×10^{-3}	7.091×10^{-3}	8.335×10^{-3}	9.781×10^{-3}	1.117×10^{-2}	1.324×10^{-2}	1.576×10^{-2}	2.018×10^{-2}	3.807×10^{-2}
kx_z08	5.000×10^{-4}	1.000×10^{-4}	5.000×10^{-2}	3.052×10^{-4}	4.327×10^{-4}	4.561×10^{-4}	4.712×10^{-4}	4.859×10^{-4}	5.017×10^{-4}	5.185×10^{-4}	5.320×10^{-4}	5.489×10^{-4}	5.827×10^{-4}	6.573×10^{-4}
kx_z09	4.543×10^{-2}	1.000×10^{-4}	5.000×10^{-2}	3.185×10^{-2}	3.931×10^{-2}	4.112×10^{-2}	4.254×10^{-2}	4.384×10^{-2}	4.503×10^{-2}	4.656×10^{-2}	4.824×10^{-2}	5.006×10^{-2}	5.252×10^{-2}	5.881×10^{-2}
kx_z10	1.551×10^{-1}	5.000×10^{-2}	5.000×10^{-1}	5.000×10^{-2}	7.246×10^{-2}	9.469×10^{-2}	1.152×10^{-1}	1.338×10^{-1}	1.576×10^{-1}	1.867×10^{-1}	2.149×10^{-1}	2.540×10^{-1}	3.253×10^{-1}	5.000×10^{-1}
kx_z11	1.000×10^{-4}	1.000×10^{-5}	1.000×10^{-2}	9.297×10^{-5}	9.716×10^{-5}	9.807×10^{-5}	9.877×10^{-5}	9.943×10^{-5}	1.001×10^{-4}	1.007×10^{-4}	1.012×10^{-4}	1.019×10^{-4}	1.029×10^{-4}	1.056×10^{-4}

param	calibrated value	PEST definition		parameter distribution - cumulative percentiles										
		lower bound	upper bound	min	10^{th}	20^{th}	30^{th}	40^{th}	50^{th}	60^{th}	70^{th}	80^{th}	90^{th}	max
kz_z01	2.500×10^{-2}	1.000×10^{-2}	1.000×10^{-1}	1.681×10^{-2}	2.171×10^{-2}	2.285×10^{-2}	2.359×10^{-2}	2.435×10^{-2}	2.504×10^{-2}	2.578×10^{-2}	2.660×10^{-2}	2.753×10^{-2}	2.875×10^{-2}	3.216×10^{-2}
kz_z02	3.000×10^{-2}	1.000×10^{-2}	1.000×10^{-1}	2.088×10^{-2}	2.593×10^{-2}	2.726×10^{-2}	2.814×10^{-2}	2.914×10^{-2}	3.009×10^{-2}	3.103×10^{-2}	3.200×10^{-2}	3.308×10^{-2}	3.470×10^{-2}	3.909×10^{-2}
kz_z03	3.935×10^{-2}	1.000×10^{-3}	5.000×10^{-2}	2.682×10^{-2}	3.391×10^{-2}	3.573×10^{-2}	3.695×10^{-2}	3.815×10^{-2}	3.937×10^{-2}	4.041×10^{-2}	4.176×10^{-2}	4.329×10^{-2}	4.619×10^{-2}	5.000×10^{-2}
kz_z04	8.930×10^{-3}	1.000×10^{-3}	5.000×10^{-2}	6.061×10^{-3}	7.728×10^{-3}	8.131×10^{-3}	8.414×10^{-3}	8.645×10^{-3}	8.901×10^{-3}	9.160×10^{-3}	9.452×10^{-3}	9.821×10^{-3}	1.041×10^{-2}	1.172×10^{-2}
kz_z05	1.949×10^{-2}	1.000×10^{-3}	5.000×10^{-2}	1.356×10^{-2}	1.691×10^{-2}	1.777×10^{-2}	1.839×10^{-2}	1.891×10^{-2}	1.945×10^{-2}	1.999×10^{-2}	2.058×10^{-2}	2.130×10^{-2}	2.225×10^{-2}	2.577×10^{-2}
kz_z06	2.055×10^{-2}	1.000×10^{-3}	5.000×10^{-2}	1.465×10^{-2}	1.777×10^{-2}	1.870×10^{-2}	1.931×10^{-2}	1.990×10^{-2}	2.044×10^{-2}	2.104×10^{-2}	2.170×10^{-2}	2.251×10^{-2}	2.360×10^{-2}	2.707×10^{-2}
kz_z07	2.093×10^{-2}	1.000×10^{-3}	5.000×10^{-2}	1.328×10^{-2}	1.794×10^{-2}	1.894×10^{-2}	1.961×10^{-2}	2.022×10^{-2}	2.079×10^{-2}	2.148×10^{-2}	2.216×10^{-2}	2.291×10^{-2}	2.415×10^{-2}	2.726×10^{-2}
kz_z08	3.938×10^{-2}	1.000×10^{-3}	5.000×10^{-2}	2.665×10^{-2}	3.385×10^{-2}	3.547×10^{-2}	3.686×10^{-2}	3.794×10^{-2}	3.936×10^{-2}	4.034×10^{-2}	4.150×10^{-2}	4.310×10^{-2}	4.529×10^{-2}	5.000×10^{-2}
kz_z09	1.000×10^{-3}	1.000×10^{-3}	5.000×10^{-2}	1.000×10^{-3}	1.000×10^{-3}	1.000×10^{-3}	1.000×10^{-3}	1.000×10^{-3}	1.000×10^{-3}	1.027×10^{-3}	1.062×10^{-3}	1.102×10^{-3}	1.165×10^{-3}	1.311×10^{-3}
kz_z10	2.487×10^{-2}	1.000×10^{-3}	5.000×10^{-2}	1.575×10^{-2}	2.147×10^{-2}	2.251×10^{-2}	2.334×10^{-2}	2.406×10^{-2}	2.487×10^{-2}	2.556×10^{-2}	2.638×10^{-2}	2.730×10^{-2}	2.881×10^{-2}	3.292×10^{-2}
kz_z11	1.000×10^{-3}	1.000×10^{-3}	5.000×10^{-2}	1.000×10^{-3}	1.000×10^{-3}	1.000×10^{-3}	1.000×10^{-3}	1.000×10^{-3}	1.000×10^{-3}	1.012×10^{-3}	1.024×10^{-3}	1.040×10^{-3}	1.062×10^{-3}	1.122×10^{-3}
ss_z01	2.000×10^{-6}	2.000×10^{-7}	5.000×10^{-5}	1.994×10^{-6}	1.997×10^{-6}	1.998×10^{-6}	1.999×10^{-6}	2.000×10^{-6}	2.000×10^{-6}	2.001×10^{-6}	2.001×10^{-6}	2.002×10^{-6}	2.003×10^{-6}	2.005×10^{-6}
ss_z02	2.490×10^{-6}	5.000×10^{-7}	5.000×10^{-5}	2.480×10^{-6}	2.486×10^{-6}	2.488×10^{-6}	2.488×10^{-6}	2.489×10^{-6}	2.490×10^{-6}	2.491×10^{-6}	2.491×10^{-6}	2.492×10^{-6}	2.493×10^{-6}	2.497×10^{-6}
ss_z03	1.000×10^{-6}	5.000×10^{-7}	5.000×10^{-5}	9.957×10^{-7}	9.985×10^{-7}	9.991×10^{-7}	9.995×10^{-7}	9.997×10^{-7}	1.000×10^{-6}	1.000×10^{-6}	1.001×10^{-6}	1.001×10^{-6}	1.002×10^{-6}	1.003×10^{-6}
ss_z04	2.000×10^{-5}	5.000×10^{-7}	5.000×10^{-5}	1.992×10^{-5}	1.997×10^{-5}	1.998×10^{-5}	1.999×10^{-5}	1.999×10^{-5}	2.000×10^{-5}	2.001×10^{-5}	2.001×10^{-5}	2.002×10^{-5}	2.003×10^{-5}	2.005×10^{-5}
ss_z05	1.000×10^{-6}	5.000×10^{-7}	5.000×10^{-5}	9.965×10^{-7}	9.985×10^{-7}	9.989×10^{-7}	9.993×10^{-7}	9.997×10^{-7}	1.000×10^{-6}	1.000×10^{-6}	1.001×10^{-6}	1.001×10^{-6}	1.001×10^{-6}	1.002×10^{-6}
ss_z06	1.000×10^{-5}	5.000×10^{-7}	7.500×10^{-5}	9.960×10^{-6}	9.985×10^{-6}	9.990×10^{-6}	9.995×10^{-6}	9.997×10^{-6}	1.000×10^{-5}	1.000×10^{-5}	1.001×10^{-5}	1.001×10^{-5}	1.001×10^{-5}	1.003×10^{-5}
ss_z07	2.000×10^{-5}	5.000×10^{-7}	1.000×10^{-4}	1.993×10^{-5}	1.997×10^{-5}	1.998×10^{-5}	1.999×10^{-5}	1.999×10^{-5}	2.000×10^{-5}	2.000×10^{-5}	2.001×10^{-5}	2.002×10^{-5}	2.003×10^{-5}	2.005×10^{-5}

param	calibrated value	PEST definition		parameter distribution - cumulative percentiles										
		lower bound	upper bound	min	10th	20th	30th	40th	50th	60th	70th	80th	90th	max
ss_z08	1.000×10^{-5}	5.000×10^{-7}	1.000×10^{-4}	9.961×10^{-6}	9.985×10^{-6}	9.989×10^{-6}	9.993×10^{-6}	9.996×10^{-6}	9.999×10^{-6}	1.000×10^{-5}	1.001×10^{-5}	1.001×10^{-5}	1.001×10^{-5}	1.003×10^{-5}
ss_z09	1.000×10^{-5}	5.000×10^{-7}	1.000×10^{-4}	9.966×10^{-6}	9.985×10^{-6}	9.991×10^{-6}	9.995×10^{-6}	9.998×10^{-6}	1.000×10^{-5}	1.000×10^{-5}	1.001×10^{-5}	1.001×10^{-5}	1.001×10^{-5}	1.003×10^{-5}
ss_z10	2.000×10^{-5}	5.000×10^{-7}	1.000×10^{-4}	1.992×10^{-5}	1.997×10^{-5}	1.998×10^{-5}	1.999×10^{-5}	1.999×10^{-5}	2.000×10^{-5}	2.001×10^{-5}	2.001×10^{-5}	2.002×10^{-5}	2.003×10^{-5}	2.005×10^{-5}
ss_z11	1.000×10^{-5}	5.000×10^{-7}	1.000×10^{-4}	9.965×10^{-6}	9.985×10^{-6}	9.990×10^{-6}	9.994×10^{-6}	9.997×10^{-6}	1.000×10^{-5}	1.000×10^{-5}	1.001×10^{-5}	1.001×10^{-5}	1.001×10^{-5}	1.003×10^{-5}
sy_z01	9.000×10^{-2}	1.000×10^{-3}	1.000×10^{-1}	6.194×10^{-2}	7.799×10^{-2}	8.169×10^{-2}	8.490×10^{-2}	8.753×10^{-2}	9.022×10^{-2}	9.264×10^{-2}	9.551×10^{-2}	9.918×10^{-2}	1.000×10^{-1}	1.000×10^{-1}
sy_z02	5.000×10^{-3}	1.000×10^{-3}	1.000×10^{-1}	3.484×10^{-3}	4.302×10^{-3}	4.543×10^{-3}	4.708×10^{-3}	4.881×10^{-3}	5.039×10^{-3}	5.182×10^{-3}	5.353×10^{-3}	5.567×10^{-3}	5.817×10^{-3}	6.639×10^{-3}
sy_z03	5.000×10^{-3}	5.000×10^{-4}	1.000×10^{-2}	4.652×10^{-3}	4.851×10^{-3}	4.898×10^{-3}	4.942×10^{-3}	4.975×10^{-3}	5.002×10^{-3}	5.029×10^{-3}	5.061×10^{-3}	5.102×10^{-3}	5.162×10^{-3}	5.262×10^{-3}
sy_z04	1.000×10^{-4}	5.000×10^{-5}	5.000×10^{-3}	9.041×10^{-5}	9.717×10^{-5}	9.805×10^{-5}	9.875×10^{-5}	9.943×10^{-5}	1.000×10^{-4}	1.006×10^{-4}	1.012×10^{-4}	1.020×10^{-4}	1.031×10^{-4}	1.054×10^{-4}
sy_z05	1.760×10^{-4}	5.000×10^{-5}	5.000×10^{-3}	1.647×10^{-4}	1.711×10^{-4}	1.727×10^{-4}	1.737×10^{-4}	1.750×10^{-4}	1.760×10^{-4}	1.771×10^{-4}	1.781×10^{-4}	1.794×10^{-4}	1.812×10^{-4}	1.855×10^{-4}
sy_z06	5.000×10^{-3}	5.000×10^{-5}	5.000×10^{-3}	4.641×10^{-3}	4.855×10^{-3}	4.901×10^{-3}	4.936×10^{-3}	4.971×10^{-3}	5.002×10^{-3}	5.027×10^{-3}	5.059×10^{-3}	5.094×10^{-3}	5.139×10^{-3}	5.258×10^{-3}
sy_z07	1.000×10^{-3}	5.000×10^{-5}	1.000×10^{-2}	9.324×10^{-4}	9.719×10^{-4}	9.808×10^{-4}	9.883×10^{-4}	9.954×10^{-4}	1.002×10^{-3}	1.008×10^{-3}	1.015×10^{-3}	1.022×10^{-3}	1.032×10^{-3}	1.053×10^{-3}
sy_z08	1.000×10^{-4}	5.000×10^{-5}	5.000×10^{-3}	9.287×10^{-5}	9.720×10^{-5}	9.811×10^{-5}	9.882×10^{-5}	9.944×10^{-5}	1.001×10^{-4}	1.006×10^{-4}	1.012×10^{-4}	1.019×10^{-4}	1.029×10^{-4}	1.058×10^{-4}
sy_z09	2.787×10^{-3}	5.000×10^{-5}	5.000×10^{-3}	2.627×10^{-3}	2.709×10^{-3}	2.734×10^{-3}	2.757×10^{-3}	2.775×10^{-3}	2.788×10^{-3}	2.802×10^{-3}	2.824×10^{-3}	2.844×10^{-3}	2.872×10^{-3}	2.940×10^{-3}
sy_z10	1.000×10^{-3}	1.000×10^{-4}	1.000×10^{-2}	9.207×10^{-4}	9.708×10^{-4}	9.814×10^{-4}	9.881×10^{-4}	9.947×10^{-4}	1.000×10^{-3}	1.005×10^{-3}	1.013×10^{-3}	1.020×10^{-3}	1.030×10^{-3}	1.059×10^{-3}
sy_z11	2.500×10^{-4}	1.000×10^{-5}	5.000×10^{-3}	2.344×10^{-4}	2.432×10^{-4}	2.454×10^{-4}	2.471×10^{-4}	2.486×10^{-4}	2.502×10^{-4}	2.516×10^{-4}	2.529×10^{-4}	2.547×10^{-4}	2.575×10^{-4}	2.641×10^{-4}

Figure C1 1 Parameter distributions – cumulative percentiles

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6.00E-01
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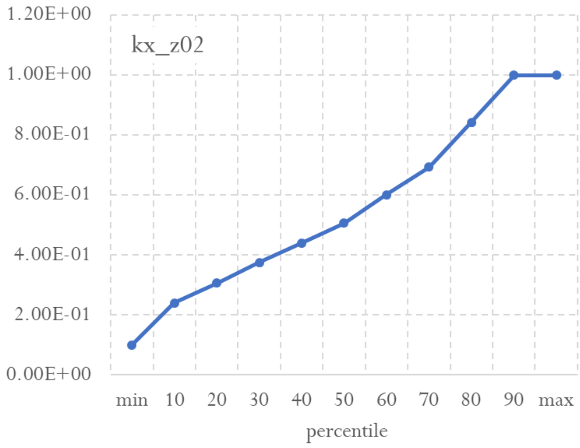
percentile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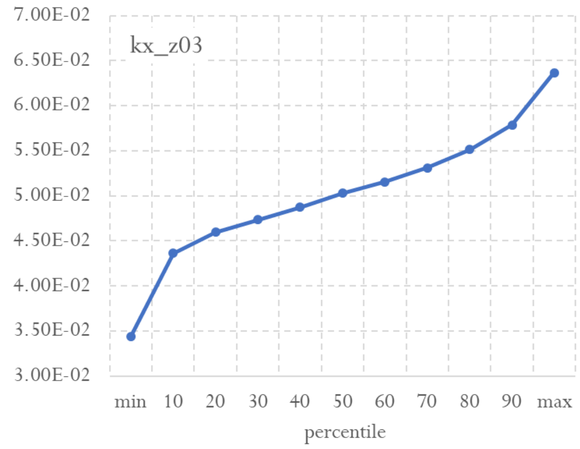
percentile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6.00E-02
5.50E-02
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4.00E-02
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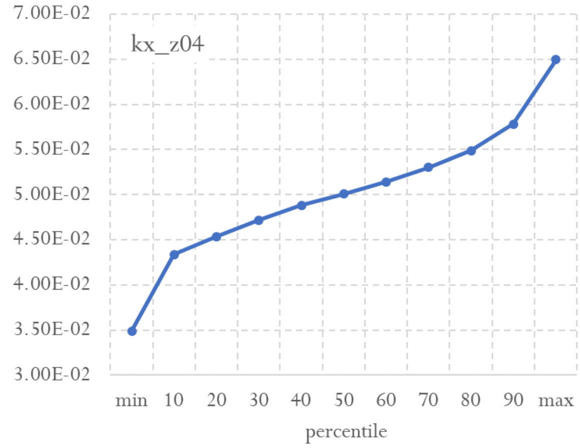
percentile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5.00E-02
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kx_z04
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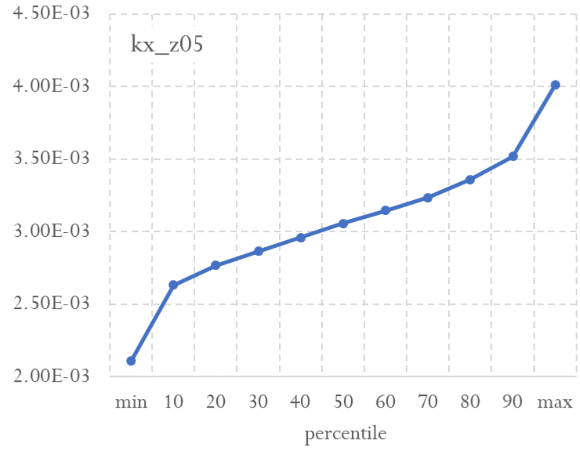
percentile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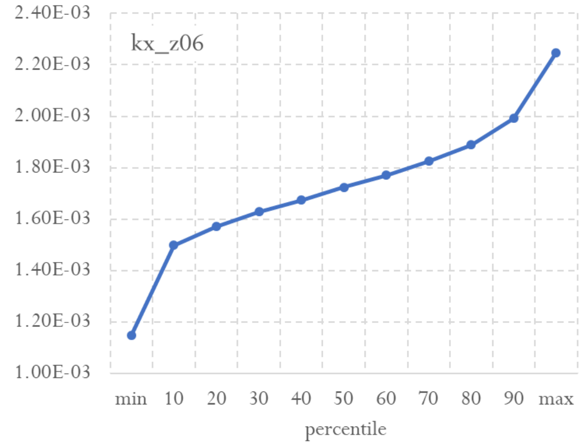
percentile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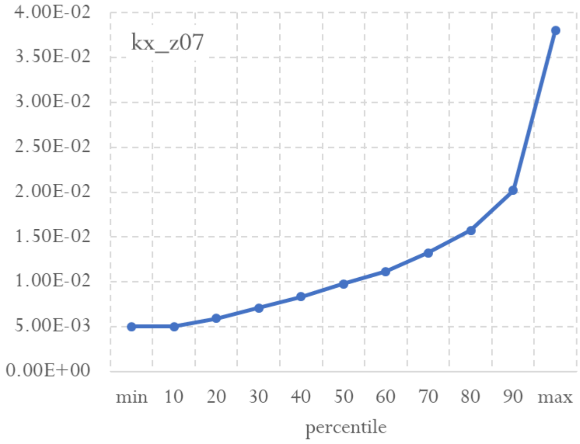
percentile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2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
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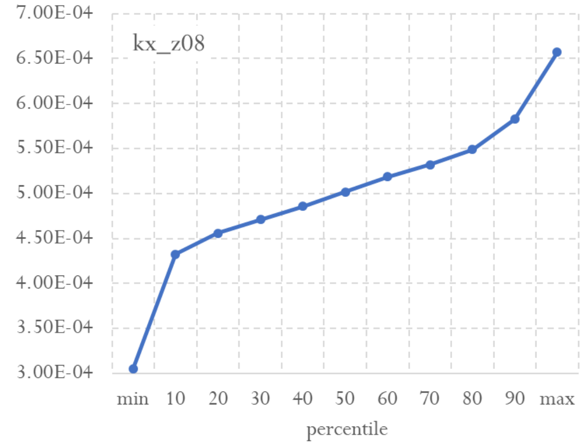
percentile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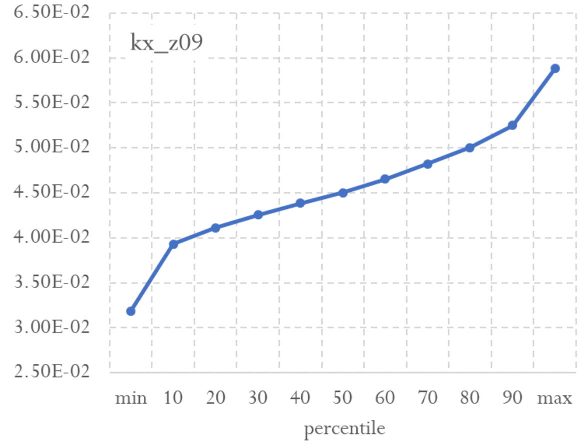
min 10 20 30 40 50 60 70 80 90 max
percentile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5.00E-02
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4.00E-02
3.50E-02
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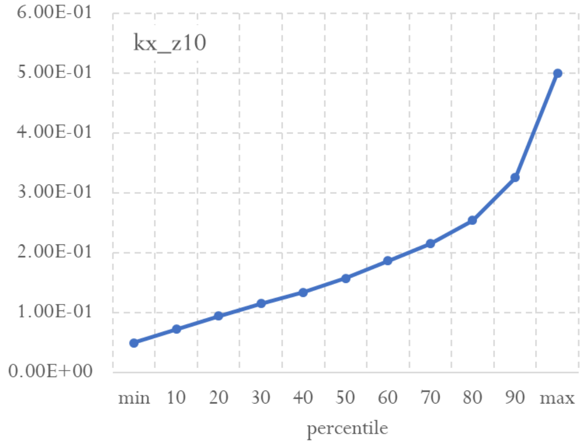
2.50E-02
min 10 20 30 40 50 60 70 80 90 max
percentile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5.00E-01
4.00E-01
3.00E-01
2.00E-01
1.00E-01
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min 10 20 30 40 50 60 70 80 90 max
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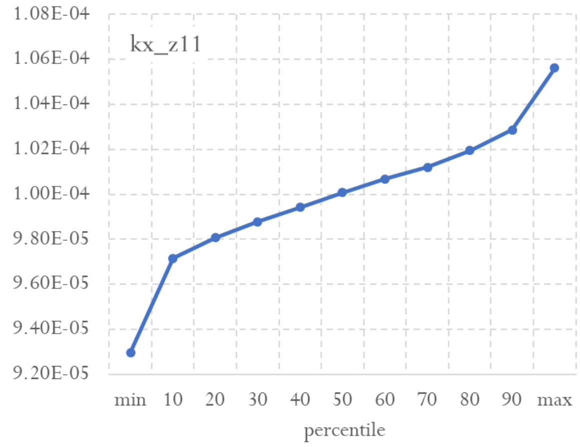
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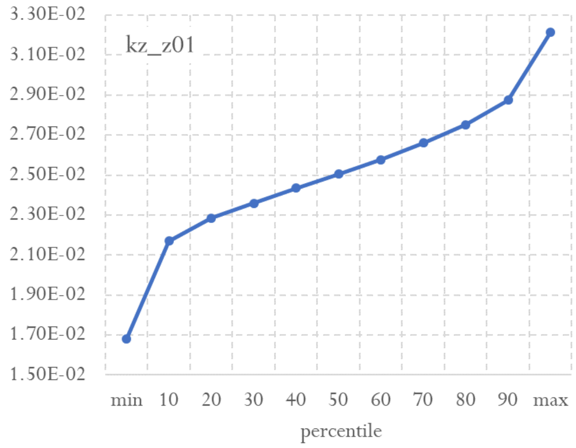
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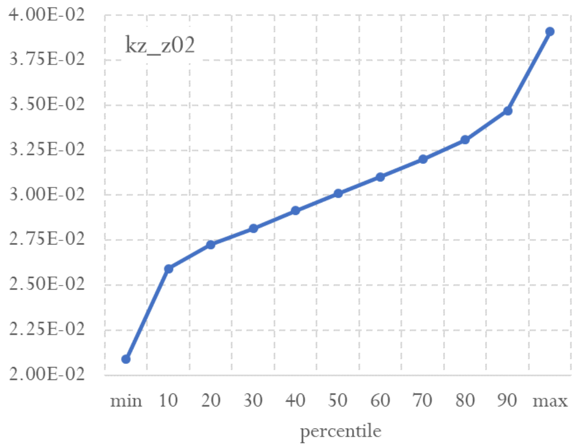
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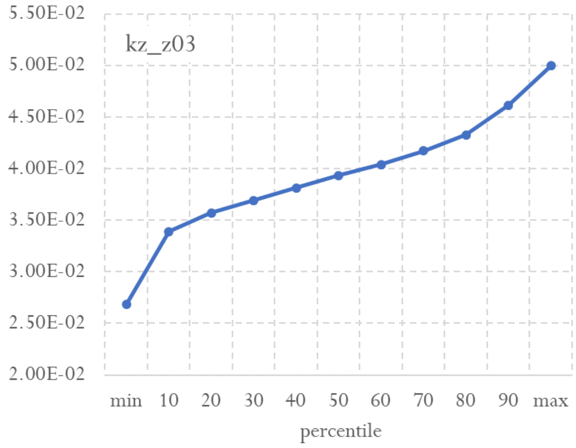
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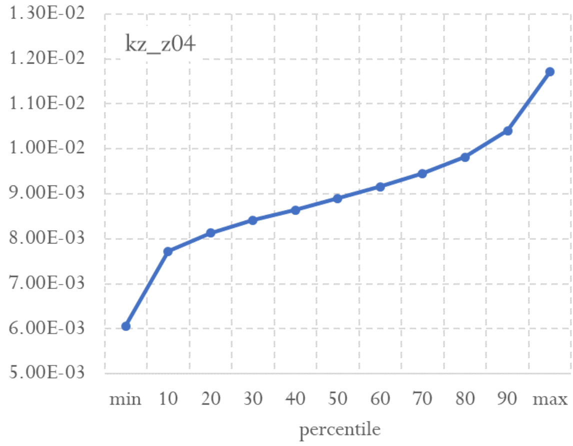
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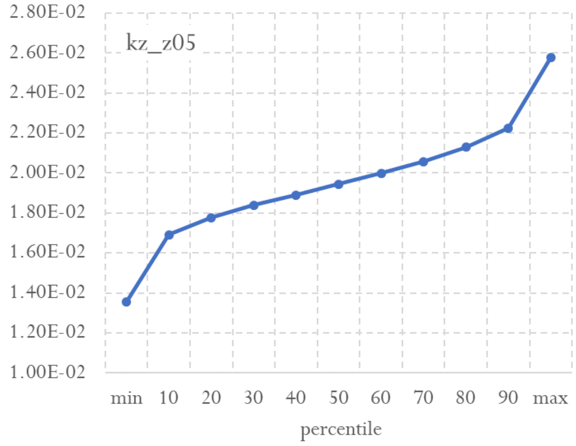
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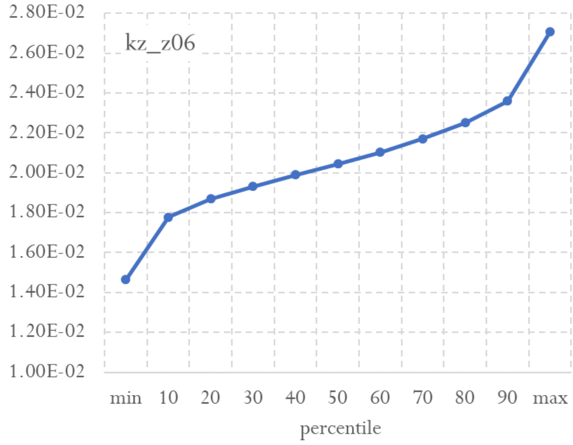
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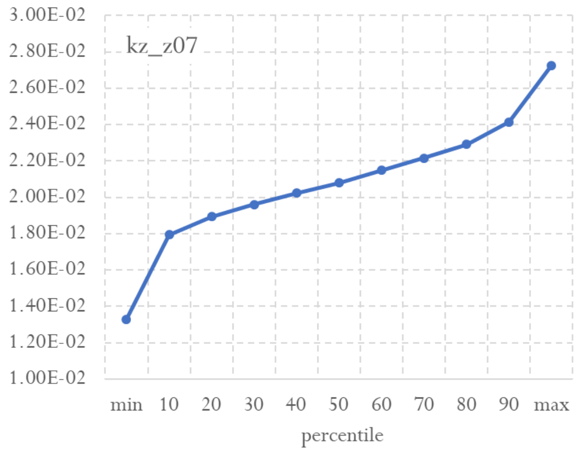
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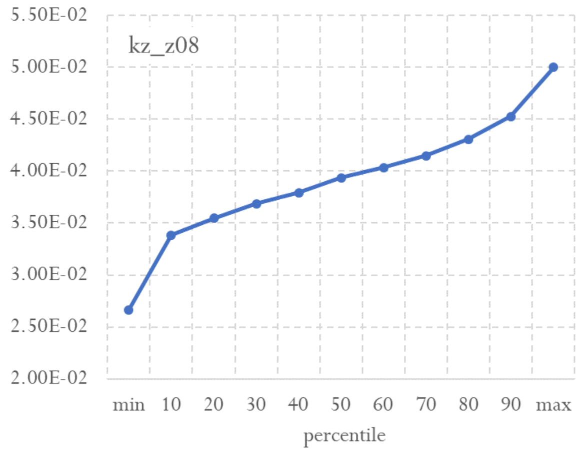
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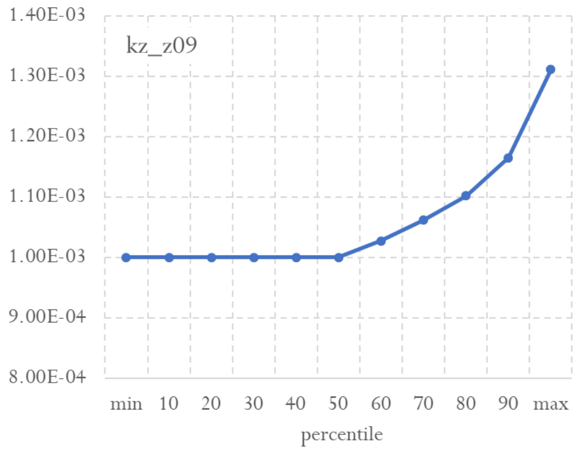
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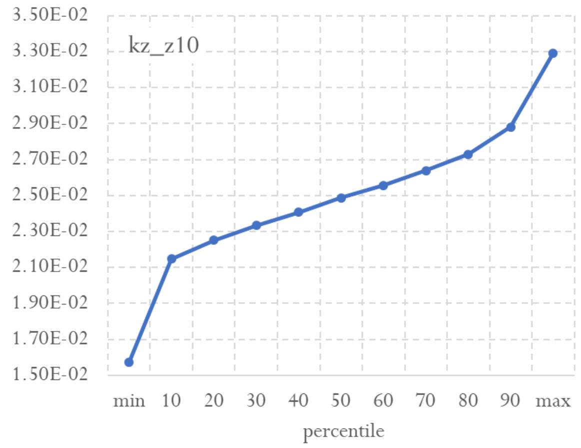
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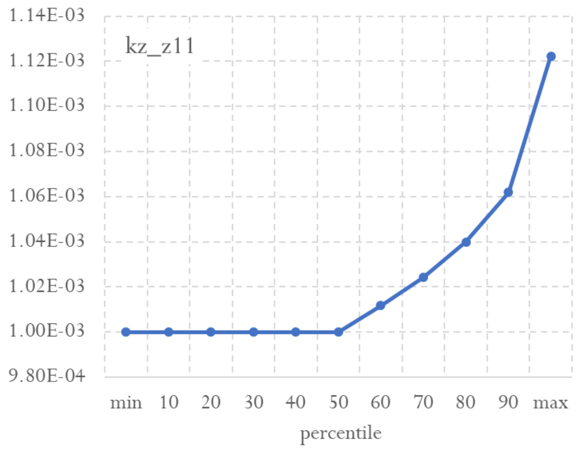
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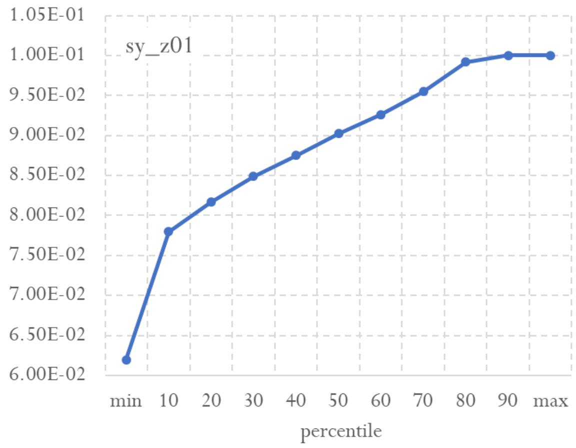

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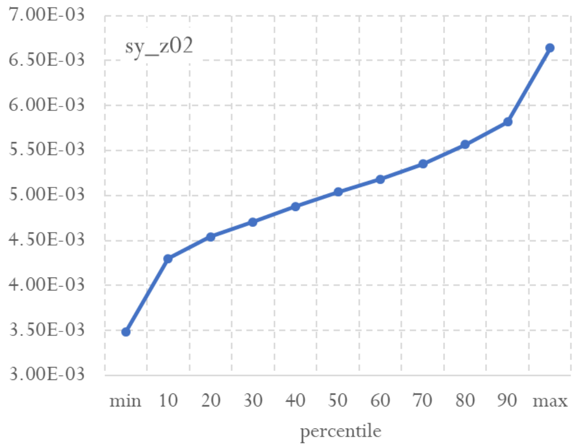

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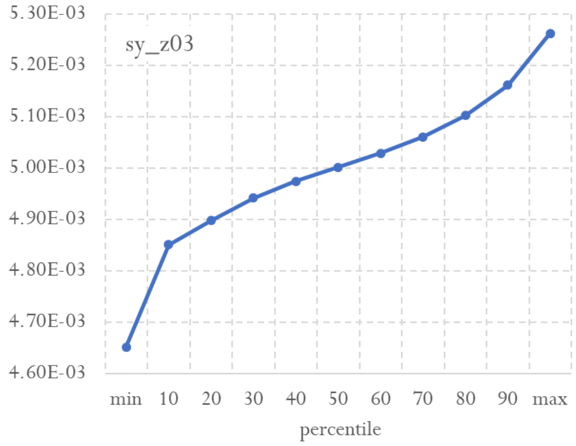

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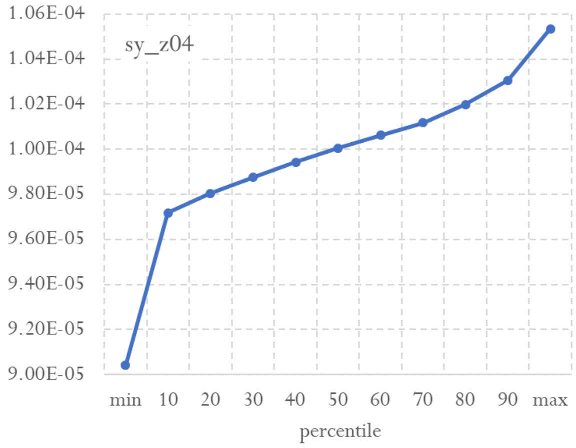
percentile



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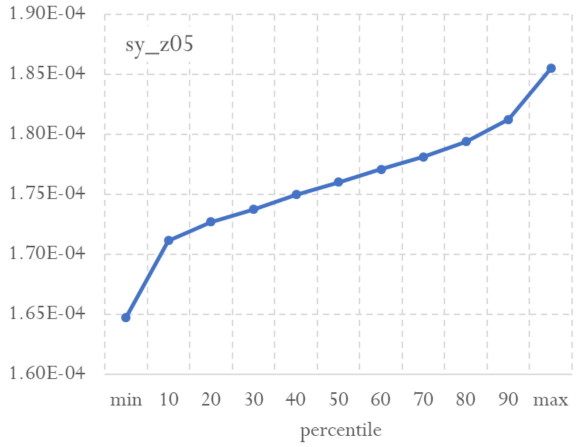

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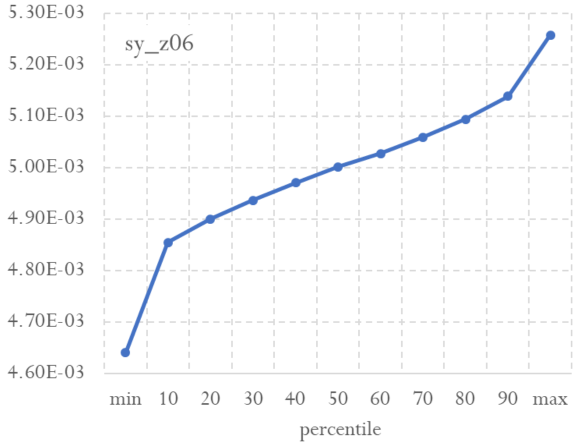

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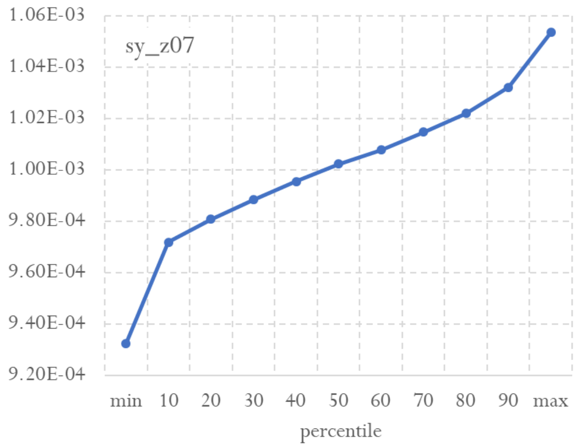

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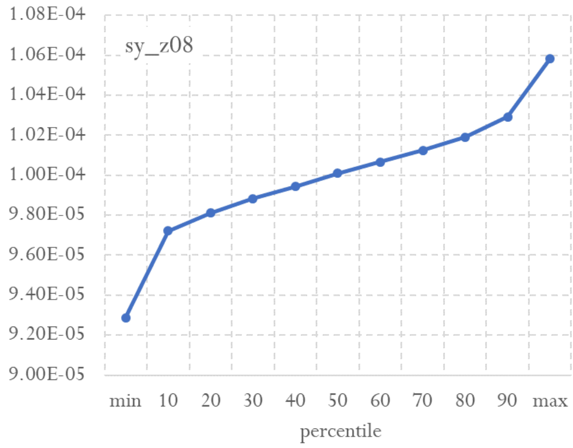
percentile



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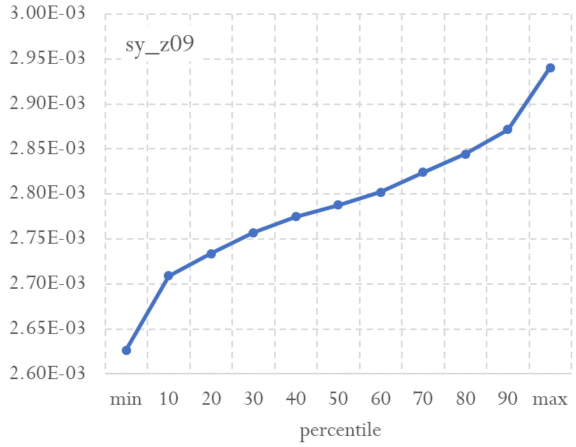

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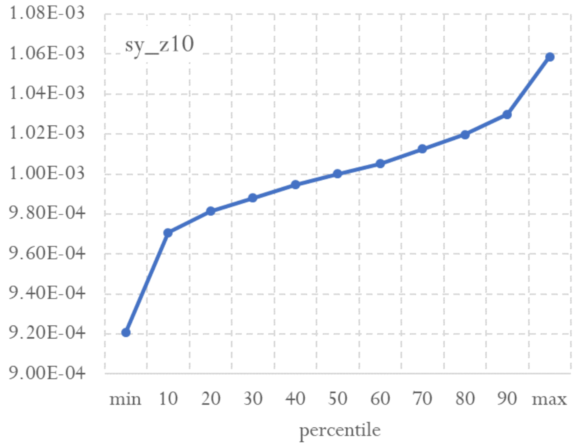

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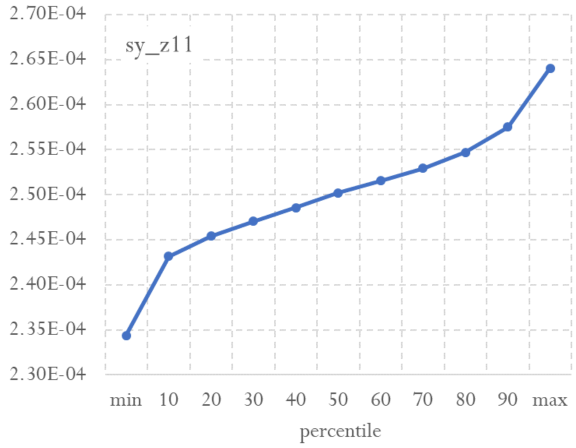

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2.35E-04
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percentile