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Report

Hydrogeological Assessment – Baseline Studies – Brookton and Mid Central Extended Mining Areas

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listen. think. deliver.

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Section 1 Introduction

1.1 Background

South32 Worsley Alumina Pty Ltd Join Venture (Worsley herein) operates an integrated bauxite mining and alumina refining operation located in Western Australia's south-west. The operation includes a bauxite mine located near Boddington, located approximately 130 kilometres south-east of Perth.

In 2005, Worsley was granted approval to expand its mining and processing operations, and subsequently, Ministerial Statement 719 (MS719) was granted. Under this approval, Worsley obtained conditional approval to mine in areas known as the Extended Mining Areas (EMAs). These areas include Brookton, Mid Central, Hotham North, Quindanning, and Morgan. Worsley are completing environmental studies within the EMAs as required by condition 8 of MS719..

Worsley has engaged CDM Smith Australia Pty Ltd (CDM Smith) to undertake a hydrogeological assessment of the Brookton and Mid-Central EMAs (the Project), having previously undertaken hydrogeological assessments for the Hotham North and Quindanning EMAs in 2023 (CDM Smith, 2023). These assessments are required to enable Worsley to meet its commitments prior to undertaking any operations in these areas and will be used to develop a water management plan for the EMAs. The plan will outline how Worsley will manage water resources in the Project area to minimise environmental impacts and ensure sustainable mining operations.

1.2 Mining Operations

Bauxite mining involves clearing vegetation, removal and stockpiling of topsoil and overburden, recovery of the ore and then backfilling with stockpiled overburden and re-contouring the landscape prior to rehabilitation (South32, 2021) (Figure 1-1). A comprehensive rehabilitation plan is implemented to restore the land to its original state or to a condition that is environmentally safe and stable.

Previous studies have suggested that land-clearing activities associated with mining can have significant impacts on groundwater and surface water systems (GHD, 2020). Changes in groundwater systems can include changes in water quality and quantity, groundwater mounding, alterations to natural drainage patterns, and potential contamination from mining waste products. Recognizing these potential impacts is important for maintaining, as much as possible, hydrogeological regimes so that environmental values (EVs) within the Project are protected.

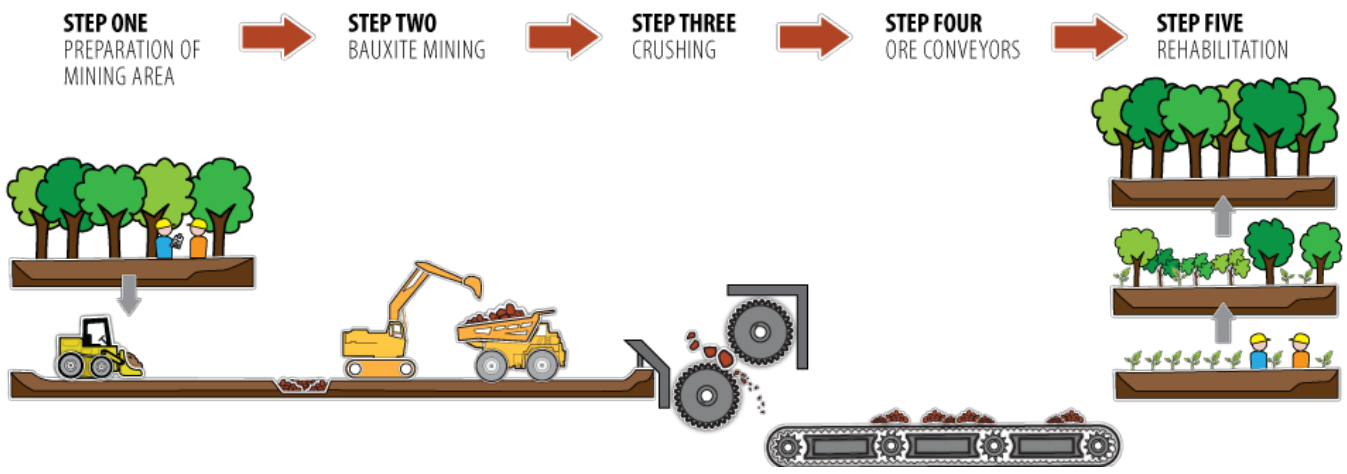

Figure 1-1 Bauxite mining process

1.3 Objective

The objective of this study is to undertake a series of work programs that will investigate the following matters contained in MS719:

- Condition 8-1 (11) groundwater systems and the occurrence and distribution of groundwater-dependent ecosystems; and
- Condition 8-1 (12) stream flow and quality and stream-dependent ecosystems.

The outcomes of this work will be used by Worsley to provide a report to the Environmental Minister, seeking regulatory approval to commence operations.

1.4 Scope of works

The Project area includes the EMAs (Brookton, Mid-Central, Hotham North, Quindanning, Morgans). Hydrogeological desktop assessments have already been completed by CDM Smith in 2023 for the Hotham North and Quindanning areas which recommended a series of monitoring bore installation works to improve the understanding of the hydrogeological regime in the area. The locations of all EMAs are provided in Figure 1-2.

A phased approach is adopted to accomplish the works and consists of the following:

- Phase 1: Desktop groundwater and surface water assessment, preliminary conceptual model, and gap analysis.
- Phase 2: Drilling, bore construction, testing, and monitoring.
- Phase 3: Final conceptual model and numerical modelling
- Phase 4: Impact assessment and final reporting

This report provides details on the desktop groundwater assessment (Phase 1) for the Brookton and Mid-Central EMAs with outcomes forming the basis for the drilling and field data collection program (Phase 2). The fieldworks will aim to reduce data gaps identified in the desktop assessment and enhance the understanding of the site's hydrogeological conceptualisation. It will also be used to inform the groundwater modelling (Phase 3) component which will assist in predicting the mine related impacts to groundwater EVs (Phase 4).

The Phase 1 desktop assessment scope of work includes the following:

- Present a concise summary of the current understanding of baseline hydrogeology, with the key knowledge gaps and uncertainties identified.
- Identify key EVs pertinent to the Project area.
- Recommendations detailing proposed drilling locations, target depths, methodologies for the installation of bores and to conduct tests to improve the understanding of the hydrogeological regime.
- Develop a preliminary monitoring plan to inform impact assessment studies.

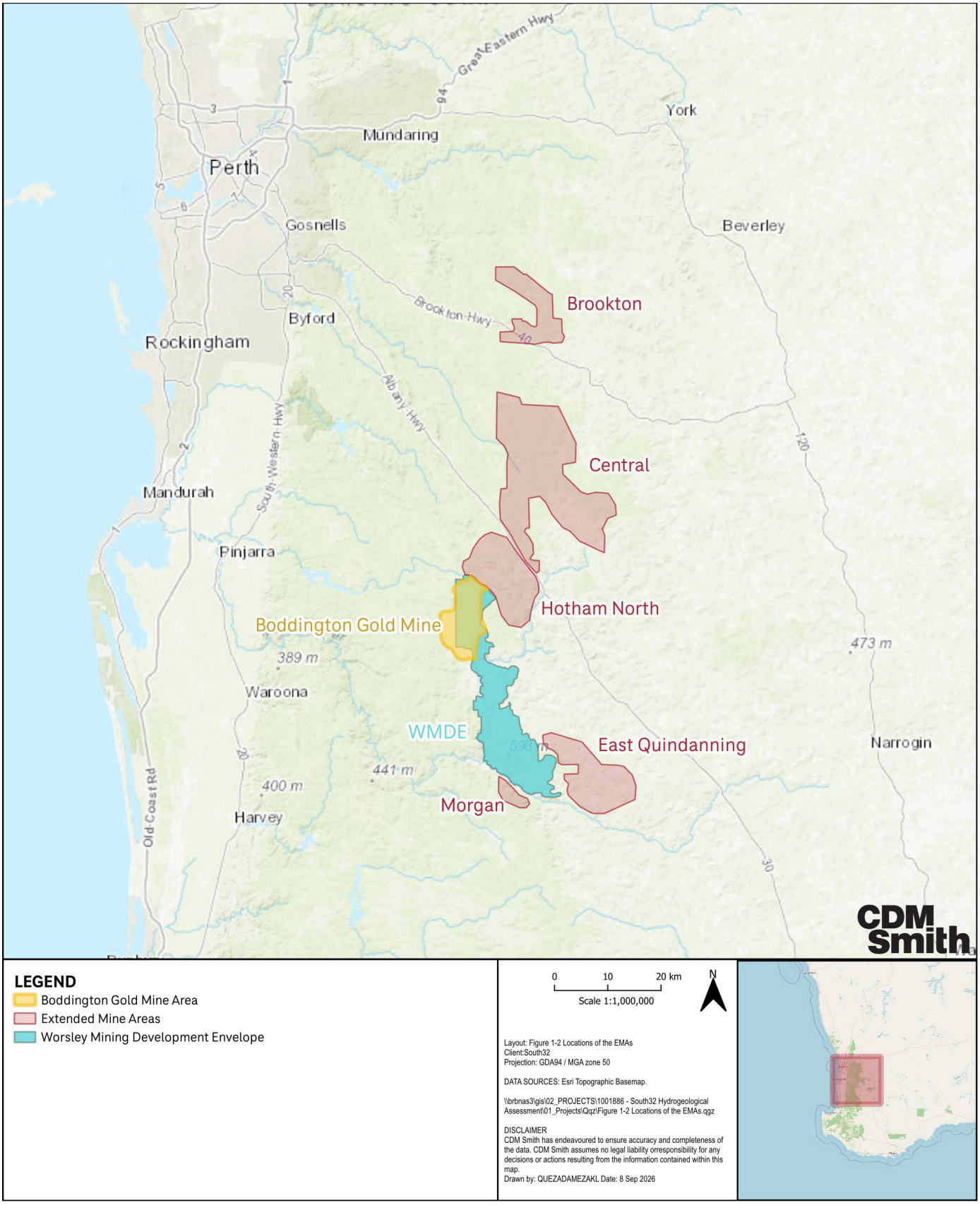

Figure 1-2 Locations of the EMAs

Section 2 Data Sources

This assessment of hydrogeological conditions across the Project area has been compiled based on public information and previous groundwater investigations undertaken (i.e., CDM Smith, 2023; GHD, 2020a). The primary sources are listed in Table 2-1 and referenced throughout this report.

Table 2-1 Key information sources for this assessment

Data	Source	Note
Groundwater level and salinity monitoring	Bureau of Meteorology (BoM) Groundwater Explorer, 2023	Groundwater flow behaviours and salinity trends in the Project area
Salinity mapping	Department of Water and Environment Regulation, 2018	Statewide mapping of groundwater salinity
Groundwater Dependent Ecosystem spatial files	BoM	Identification of potential groundwater dependent ecosystems within the Project area
Climate data	BoM, SILO	Regional setting review
Groundwater/surface water assessments, impacts assessments	CDM Smith, 2023	Hydrogeological assessments for the Quindanning and Hotham North Extended Mining Areas
	GHD, 2020	Assessment of bauxite mining impacts on the groundwater and surface water systems of the Worsley Mining Envelope
	Strategen, 2013	Environmental impact assessment for Newmont Boddington Gold
Government reports		
	Turner et al. 1997	Groundwater supply to the mining industry in the WA Goldfields
Regional studies	Waterhouse et al. 2013	Stratigraphic characterisation of the Beaufort River Paleochannel

Section 3 Regional setting

3.1 Climate

The Project area experiences a Mediterranean climate, which means the summer months (December to February) are hot and characterised by high evaporation. Winter months (June to August) are cooler, wetter and evaporation rates are lower. Average annual maximum daily temperatures are broad, ranging between 17 °C in winter to 33 °C in summer.

Daily rainfall and pan evaporation data are available from the BoM Station ID 9507 (Bannister), located within the Mid-Central EMA. Rainfall records have been selected for the period 1950-2023 and indicate an average annual rainfall of 605 mm/year with rainfall predominantly occurring in the winter months. Average annual pan evaporation for the period 1950-2022 was 1603 mm (SILO, 2023).

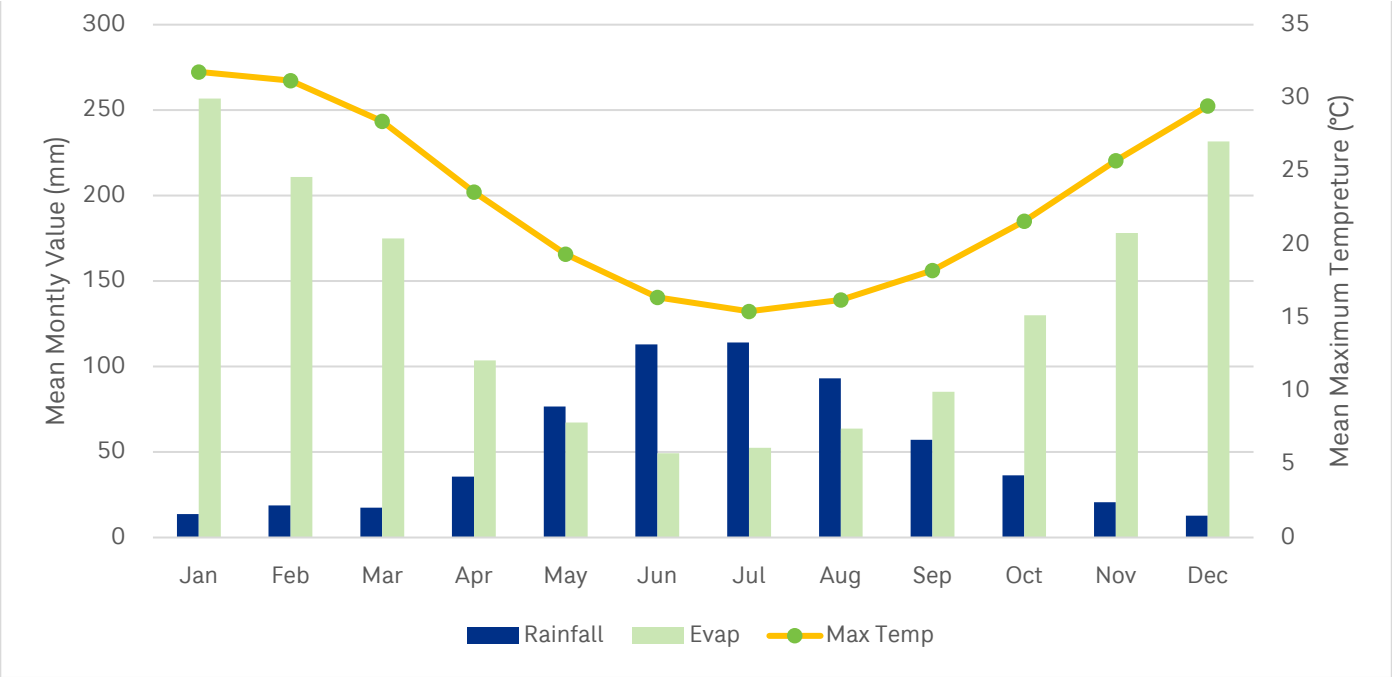

Figure 3-1 Rainfall (BoM) and evaporation (SILO) monthly averages for Bannister Station (No. 9507)

Long-term monthly rainfall and the Cumulative deviation from the mean (CDFM) are shown in the Figure 3-2. The data for this chart are acquired from the rainfall data obtained from Bannister station.

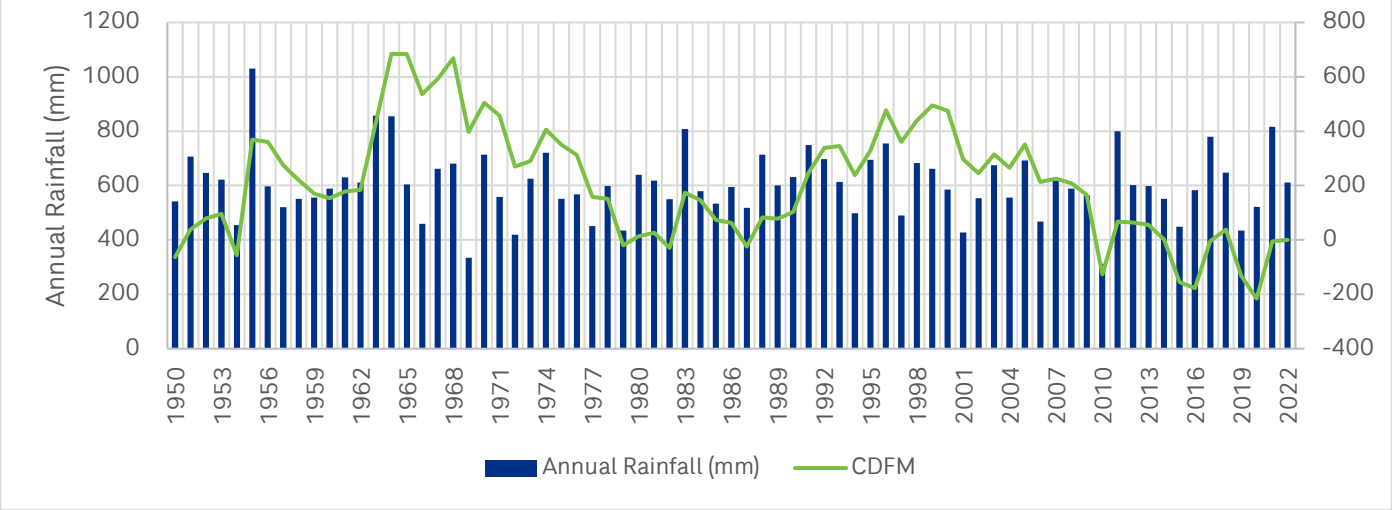

Figure 3-2 Long-term rainfall and CDFM for Bannister Station (No. 9507)

3.2 Land use

According to the catchment scale land use data for Australia (ABARES, 2020), the land area in the region is dominated by native forests, comprising 93, and 90% of the total land area for the Brookton, and Mid-Central EMAs, respectively. Other land uses in the area include nature conservation which make up 15% of the total land area, and dryland cropping (6% of total land area in Brookton).

3.3 Topography and Hydrology

3.3.1 Topography

Project topography is moderate to gently undulating, typically ranging from around 260 m to 430 m Above Height Datum (AHD) in Brookton and Mid-Central. Figure 3-3 shows the topographic relief across the Project area.

3.3.2 Hydrology

The Project area is characterised by multiple river catchments comprised of various perennial rivers and ephemeral surface water features. The area covers four major basins: Murray River, Avon River and Swan Coastal(Figure 3-3).

Watercourses in Brookton generally flow north-east towards the Breaking Brook River via several unnamed tributaries. Mid-Central is characterised by watercourses which flow in multiple directions.

A detailed description of hydrological data is presented in the surface water assessment for the Brookton and Mid-Central EMAs prepared by Alluvium Consulting.

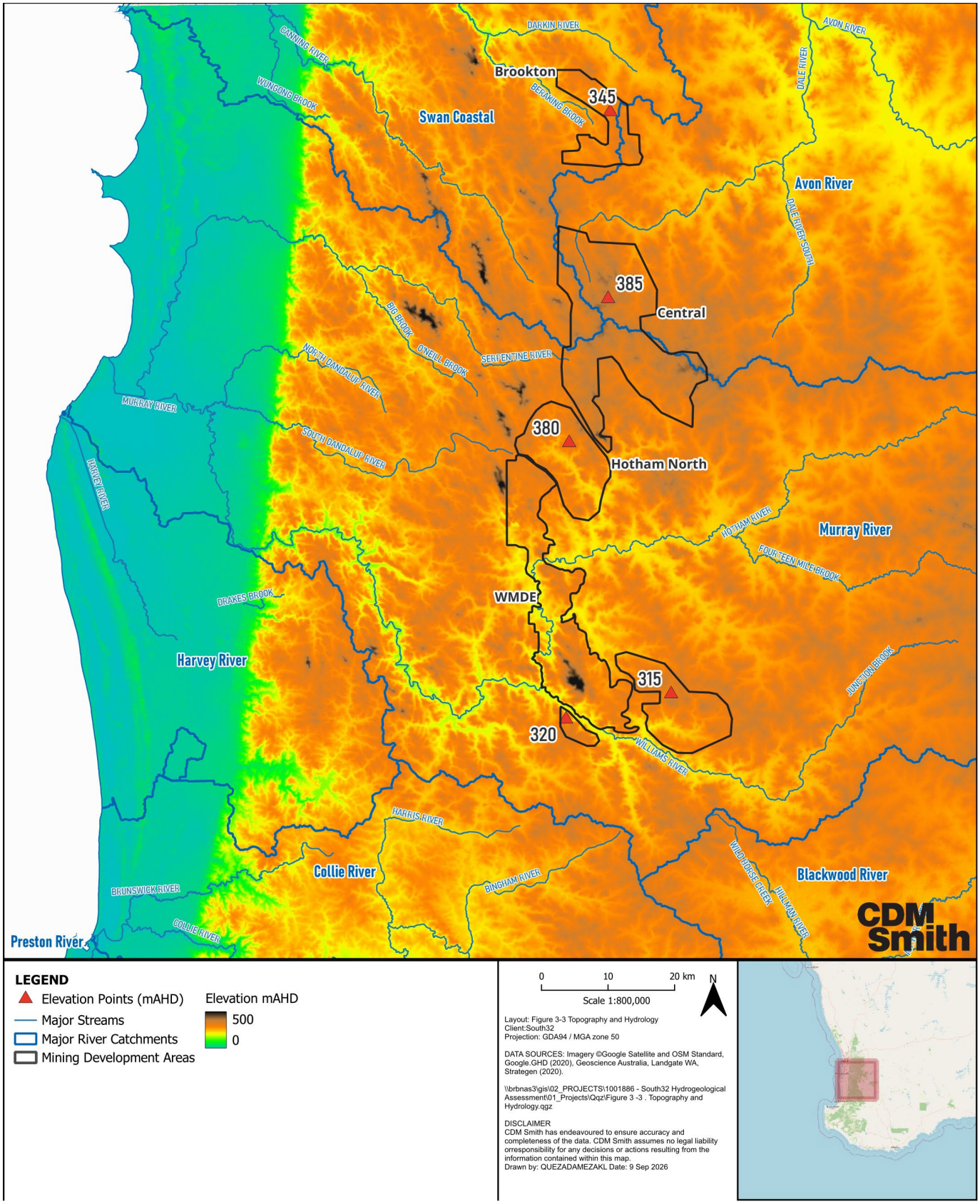

Figure 3-3 Topography and hydrology

3.4 Geology

The study area is located on the eastern side of the Darling Scarp, within the Southwest terrain of the Yilgarn Craton. The Yilgarn Craton is a significant geological feature characterised by its Archean age bedrock. This bedrock primarily comprises felsic intrusive rocks and high-grade metamorphic rocks, such as gneisses, as noted by Cassidy et al., 2006.

The fresh bedrock is overlain by a weathering profile up to 40 m thick, dominated by a quartz-rich granitic saprolite, commonly comprising a thin gritty basal layer overlain by a mottled and pallid zone clay-dominated horizon (Turner et al., 1997; Raper, 2005; Clarke et al., 2002; Strategen, 2013). The clay may contain thin lenses of gritty sand. The surface has been heavily lateritised, and a massive laterite 2 to 4 m thick generally caps areas of more gentle relief. The surficial lateritic cap comprises of nodular or pisolitic ferruginised material Cenozoic in age (Turner et al., 1997). The thin topsoil consists of laterite, colluvial sand and pisolitic gravel. The stratigraphy pertinent to the area is presented in Table 3-1 and the bedrock geology and surface geology are shown Figure 3-4 and Figure 3-5, respectively.

According to the weathering intensity index of Australia (Wilford in 2012), most EMAs in this region are categorised as “highly weathered”, noting that the intensity of weathering is not uniform across the region. It is comparatively lower in the southern parts of Hotham North and Quindanning.

Cenozoic-aged sediments also occur as paleochannel infill in the greater Project area. Paleochannel networks hosted with palaeovalleys are present over much of Australia and reflect different depositional environments and climates. Mapped paleochannels in the Project area are shown in Figure 3-4. The buried paleochannels comprise channel-fill sands, gravels, silts, and clays and generally overlie weathered bedrock (Waterhouse et al. 1994).

Table 3-1 Stratigraphic description of Project area geology

Age	Symbol	Province	Description
Quaternary	Qrc	n/a	Colluvium and/or residual deposits, sheetwash, talus, scree; boulder, gravel, sand; may include minor alluvial or sand plain deposits, local calcrete and reworked laterite.
Cenozoic	Cza	n/a	Nakina Formation; Weakly lithified claystone, conglomerate and sandstone in upward-fining cycle; cross-bedded, fluviatile sands.
Cenozoic	Czc	n/a	Undifferentiated consolidated Cenozoic sedimentary rocks; sandstone, limestone, conglomerate, siltstone, duricrust; commonly ferruginised or silicified; may be poorly consolidated, highly weathered, and dissected by present day drainage.
Cenozoic	Czl	n/a	Ferruginous duricrust, laterite; pisolitic, nodular, vuggy; may include massive to pisolitic ferruginous subsoil, mottled clays, magnesite, reworked products of ferruginous and siliceous duricrusts, calcrete, gossan; residual ferruginous saprolite.
Archaean	Ag	Yilgarn Craton	Undifferentiated felsic intrusive rocks, including monzogranite, granodiorite, granite, tonalite, quartz monzonite, syenogranite, diorite, monzodiorite, pegmatite. Locally metamorphosed, foliated, gneissic. Local abundant mafic and ultramafic inclusions.
Archaean	An	Yilgarn Craton	Banded granitic gneiss (monzogranitic to granodioritic), quartzofeldspathic gneiss with mafic bands, migmatite, granofels, mafic and felsic granulites, hypersthene-plagioclase-quartz granulite; schist, pelitic or mafic granofels.
Archaean	Am	n/a	Diopside-epidote-plagioclase-microcline-titanite, with local garnet, magnetite and quartz; South-west Gneiss Terrane.

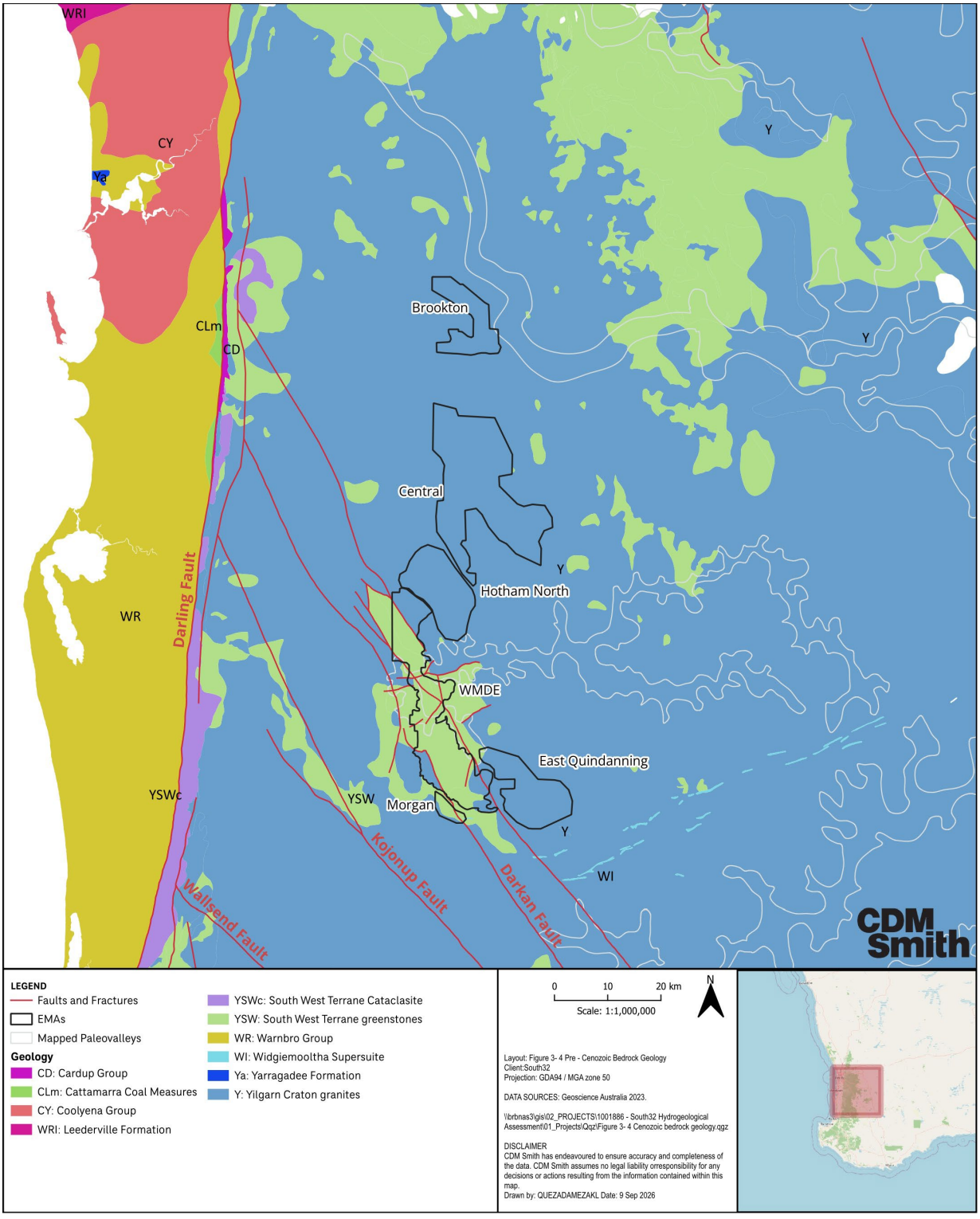

Figure 3-4 Pre-Cenozoic bedrock geology

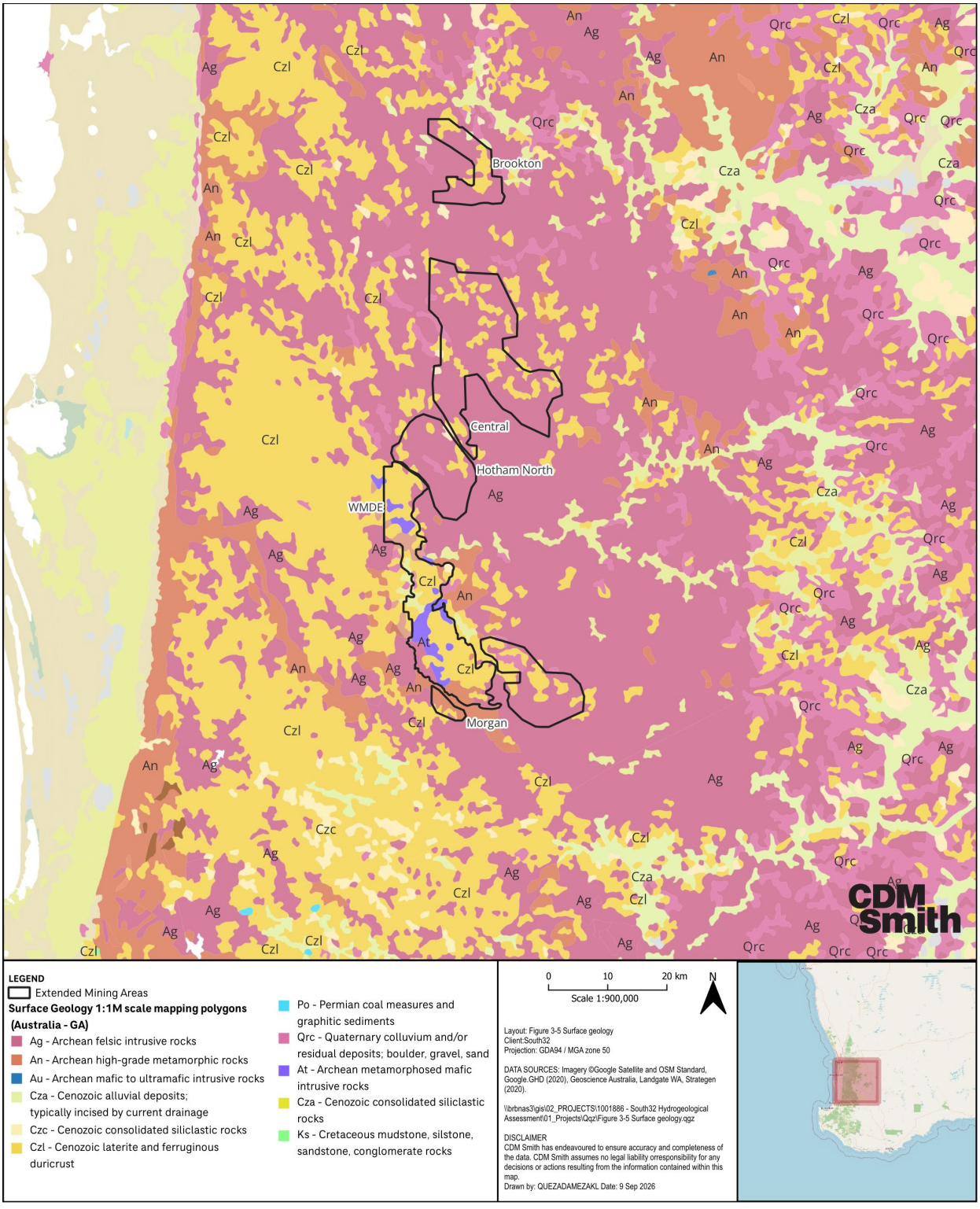

Figure 3-5 Surface geology

Section 4 Hydrogeological baseline

4.1 Datasets

The latest publicly available groundwater data has been obtained from the BoM groundwater explorer database. A total of 129 bores are identified within the greater Project area, most of which are situated in proximity to Mid-Central. These data have been assessed together with data collected from hydrogeological investigations undertaken in neighbouring sites (e.g. Strategen, 2013; Global Groundwater, 2020) and regional reviews (Turner et al., 1997).

Table 4-1 shows the total number of groundwater bores in each EMA (gathered from BoM) separated by purpose. The registered bores and groundwater monitoring locations for Brookton and Mid-Central are shown in Figure 4-1.

Table 4-1 Groundwater bores within 10 km of Brookton and Mid-Central

EMA	Monitoring	Water supply	Irrigation	Stock and domestic	Dewatering	Exploration	Other	Unknown	Total
Brookton	16	2	-	-	-	-	-	9	27
Mid-Central	31	1	-	1	-	-	-	69	102

4.2 Hydrostratigraphy

4.2.1 EMAs

The hydrostratigraphy of the Project area has been defined through previous studies (e.g. Strategen 2013; GHD, 2020; CDM Smith, 2023) and comprises three main hydrostratigraphic units (HSUs, youngest to oldest):

- **Shallow Weathered Zone**: The topsoil is typically 0.1 m thick and contains gravel, sand and organic matter. This is underlain by a gravelly soil layer of 0.5 to 8 m thick and a high hydraulic conductivity (Strategen, 2013).
  - The weathered profile comprises lateritic cap rock and shallow gravely to sandy sediments, which host a seasonal aquifer with significant storage, infiltration, and flow capability (GHD, 2020a). The thickness of the lateritic cap is variable (1 – 5 m thick) but is reduced or absent in places such as eroded hill slopes and may be substantially thicker in areas of extensive erosion (Strategen, 2013; Global Groundwater, 2020).
  - As a shallow aquifer, it is highly responsive to rainfall patterns (Strategen, 2013). Groundwater flow and storage are likely controlled by secondary porosity formed from post-depositional processes.
- **Deep Weathered Zone**: Comprised of decomposed granite weathering profile and gravel at the base of the shallow weathered profile. At the base of the weathering profile, the partly weathered/saprolitic basal zone is more permeable than the overlying pallid and mottle zone (Clarke et al., 2002).
  - The interface between the saprolite and upper bedrock surface hosts the main aquifer in the Project area (Global Groundwater, 2020). The permeable section is a thin layer at the base of the weathering profile, often in the saprock (Turner et al., 1997). The base of the weathering profile is around 8 times more permeable than the rest of the saprolite and forms a key aquifer (Clarke et al., 2002). The base of the weathered zone is more granular than the mottled and pallid zone clays. The highly permeable section is typically 7 and to 15 m thick (Strategen, 2013).
  - Geological structures in the basement, such as dykes, fault zones and quartzite beds, may control groundwater flow in the saprolitic aquifers (Clarke et al., 2002). Groundwater flow and storage are likely controlled by secondary porosity formed from post-depositional processes.

- **Fractured bedrock aquifer**: Groundwater may be present in the fresh bedrock fractures or joints. These fractures generally remain open in the upper 10 to 15 m of fresh bedrock (Strategen, 2013) and may persist for 30 to 40 m around faults (Turner et al., 1997). The aquifer permeability, yield and storage are dependent on fracture development and their connectivity.
  - Where fractures are well-connected and open, these may be fast draining and locally have high transmissivity, thus leading to low residence times (Turner et al., 1997; Global Groundwater,2020). The fractured rock aquifer is hydraulically connected to the saprolitic aquifers in the deep weathered profile (Turner et al., 1997). Typically, this is a minor local aquifer however where connected fractures permit, high yielding bores of up to 22 l/s have been reported (Global Groundwater, 2020).
  - There are southeast trending dolerite dykes and hydraulic conductivity is higher parallel to the dykes (Strategen, 2013). Groundwater flow and storage is controlled by secondary fracture derived porosity (Global Groundwater, 2020).

4.2.2 Paleochannel networks

All paleochannel networks are located outside of the EMAs in the Project area. However, they can still be hydraulically connected to the local hydrogeology and be impacted by mining-related activities. Groundwater exploration drilling programs undertaken in the Beaufort Paleochannel found the paleochannel to be comprised of up to 65 m of interbedded sands, clayey sands, carbonaceous clays and silts (Waterhouse, et al. 1994).

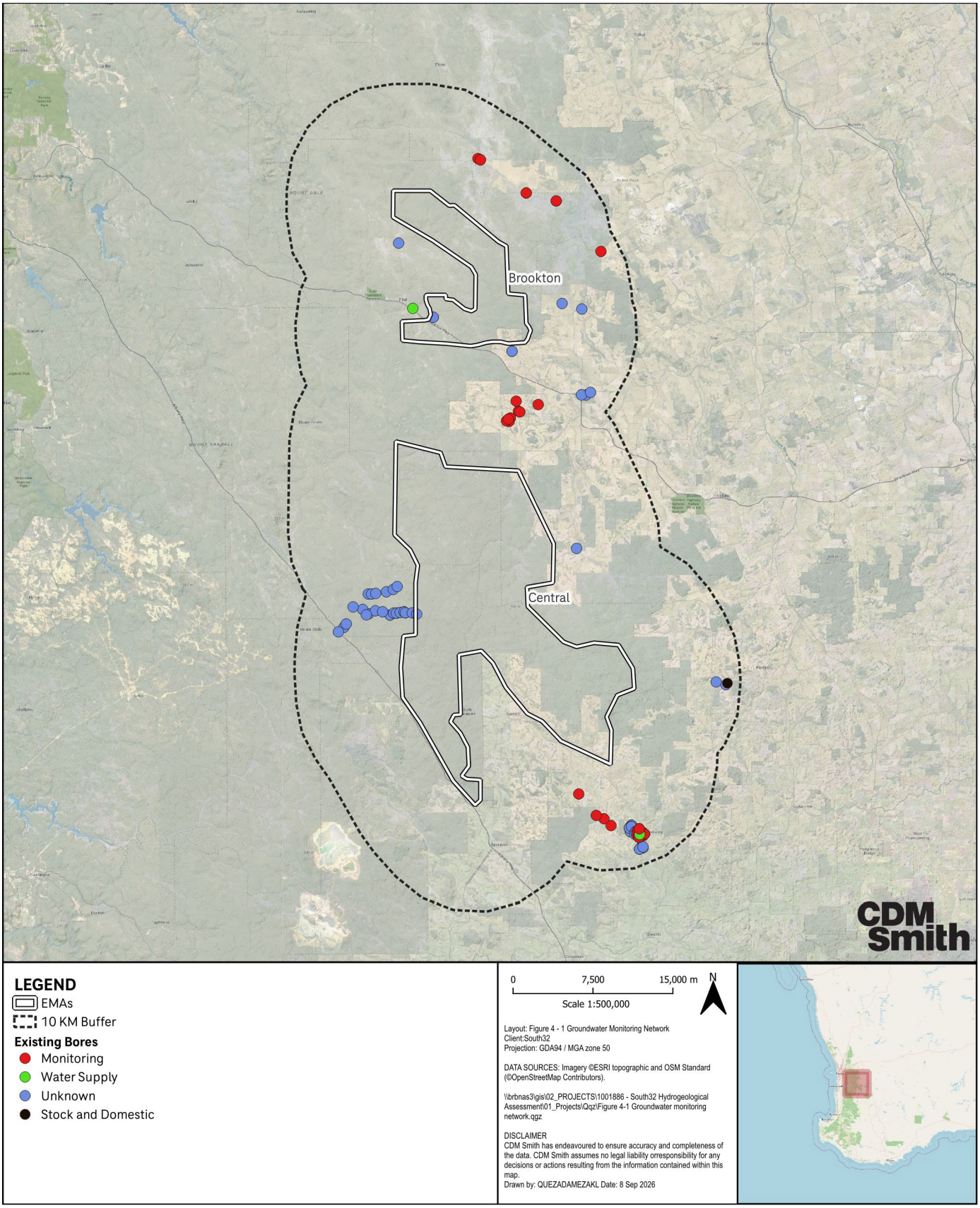

Figure 4-1 Groundwater monitoring network

4.3 Groundwater levels and flow

4.3.1 Groundwater flow

There is insufficient groundwater monitoring data across Brookton and Mid-Central to confidently determine groundwater flow directions. However, it is likely that groundwater migrates from topographic highs towards discharge areas. This may include rivers which surround the EMA (e.g. Darkin River), groundwater springs and production bores.

Nearby mining operations (e.g. Boddington) has also resulted in significant drawdown and the formation of potentiometric depressions due to dewatering.

4.3.2 Groundwater levels

The area's groundwater level assessments are data-constrained. In both Brookton and Mid Central EMAs, no groundwater level measurements exist. Moreover, within the 10-kilometer buffers, scant groundwater measurements have been taken, none of which form a comprehensive time series. The groundwater measurements closest to these two EMAs indicate depths not exceeding 10 mbgl. While the hydraulic characteristics of the current aquifers may not be conducive to yielding a substantial water supply, the shallow water table suggests the likelihood of proximity rather than immediate availability of groundwater for use within these specific areas. None of these measurements originate directly from the EMAs, emphasising an existing data gap in determining the depth to the groundwater within these EMAs.

4.4 Groundwater recharge and discharge

Groundwater recharge will occur predominantly via rainfall infiltration to sediments and, possibly to a lesser extent, to outcropping and sub-cropping bedrock. The rate of recharge will be constrained by evapotranspiration losses from the soil reservoir. Recharge in the area is likely to be greater on the upper slopes where more permeable soils are typically found (Clarke et al., 2002), and in areas where rainfall exceeds evaporation rates (Figure 4-3). Further, it is likely that only higher intensity/duration rainfall events that result in surface ponding and flow will result in significant recharge, with rainfall from lesser events evaporating prior to or soon after infiltration.

Diffuse recharge to the basement across the Project area is expected to be low given the relatively thick, low permeability surficial cover and saprolite (weathered) zone. Given the above, the groundwater in the higher permeability fracture zone is unlikely to be receiving significant recharge via infiltration or throughflow from the low permeability basement rocks.

Discharge from fractured basement rocks is likely restricted to throughflow and areas of groundwater abstraction (e.g. dewatering at Boddington Gold Mine). Groundwater flows down gradient towards depressions where it may discharge to stream courses, hillslope seeps, or by evaporation and usage by vegetation in swampy areas (Kern, 1987; GHD, 2020a; Nulsen, 1998). There are no recorded wells actively pumping in Brookton and Mid Central.

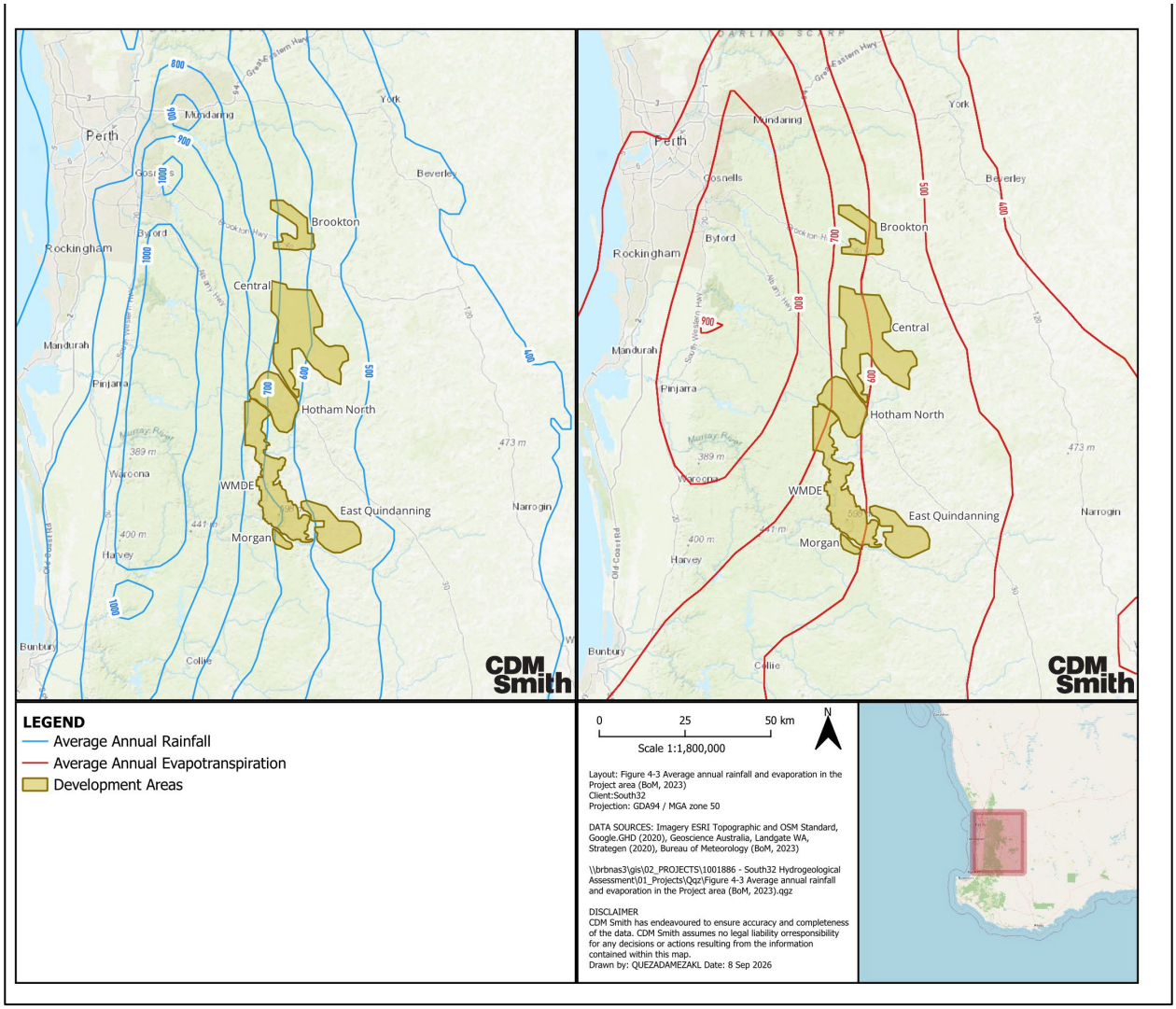

Figure 4-2 Average annual rainfall and evaporation in the Project area (BoM, 2023)

4.5 Hydraulic properties

Hydraulic data for the Project area are generally sparse. Aquifer parameters for the Project area are limited to field investigations undertaken in the Marradong and Saddleback areas in the neighbouring WMDE (i.e., GHD, 2020a; Global Groundwater).

Table 4-2 provides a summary of hydraulic parameters derived from aquifer test analyses in the greater Project area. The data indicate that the fractured bedrock aquifer is highly heterogeneous with transmissivities (T) ranging between 1 and 75 m^2/d. Conversely, airlift development for bores at Boddington Gold Mine suggests that hydraulic conductivities for the weathered and fractured upper bedrock are relatively low, ranging from 0.0003 to 0.04 m/day, with an average of 0.003 m/day (Global Groundwater, 2020).

Table 4-2 Summary of aquifer parameters in the Project area

Aquifer/lithology	Hydraulic conductivity, K (m/d)	Transmissivity, T (m^2/d)	Storativity, S
Deep weathered zone	0.0003 – 0.04[1]	2 – 20[2]	-

Aquifer/lithology	Hydraulic conductivity, K (m/d)	Transmissivity, T (m^2/d)	Storativity, S
Fractured bedrock	-	1 – 75[2]	-
Nakina Formation[3]	0.12	-	-

Notes: 1. Global Groundwater, 2020
2. GHD, 2020a

4.6 Water quality

Publicly available hydrogeochemical data is generally limited for the Project. According to statewide mapping of groundwater salinity (DWER, 2018), there is a general west to east trend of increasing salinity for the Brookton and Mid-Central EMAs with salinity ranging from 500 to 7000 mg/L (Figure 4-4).

In the surrounding regions, groundwater salinity decreases west of the Project area and increases to the east (> 35,000 mg/L). It is possible the elevated groundwater salinity in the east is due to modified land uses and agricultural practices in the region. Southwestern Western Australia has been affected by dryland salinity due to land-clearing practices leading to rising water tables and elevated groundwater salinity (Raper et al., 2013).

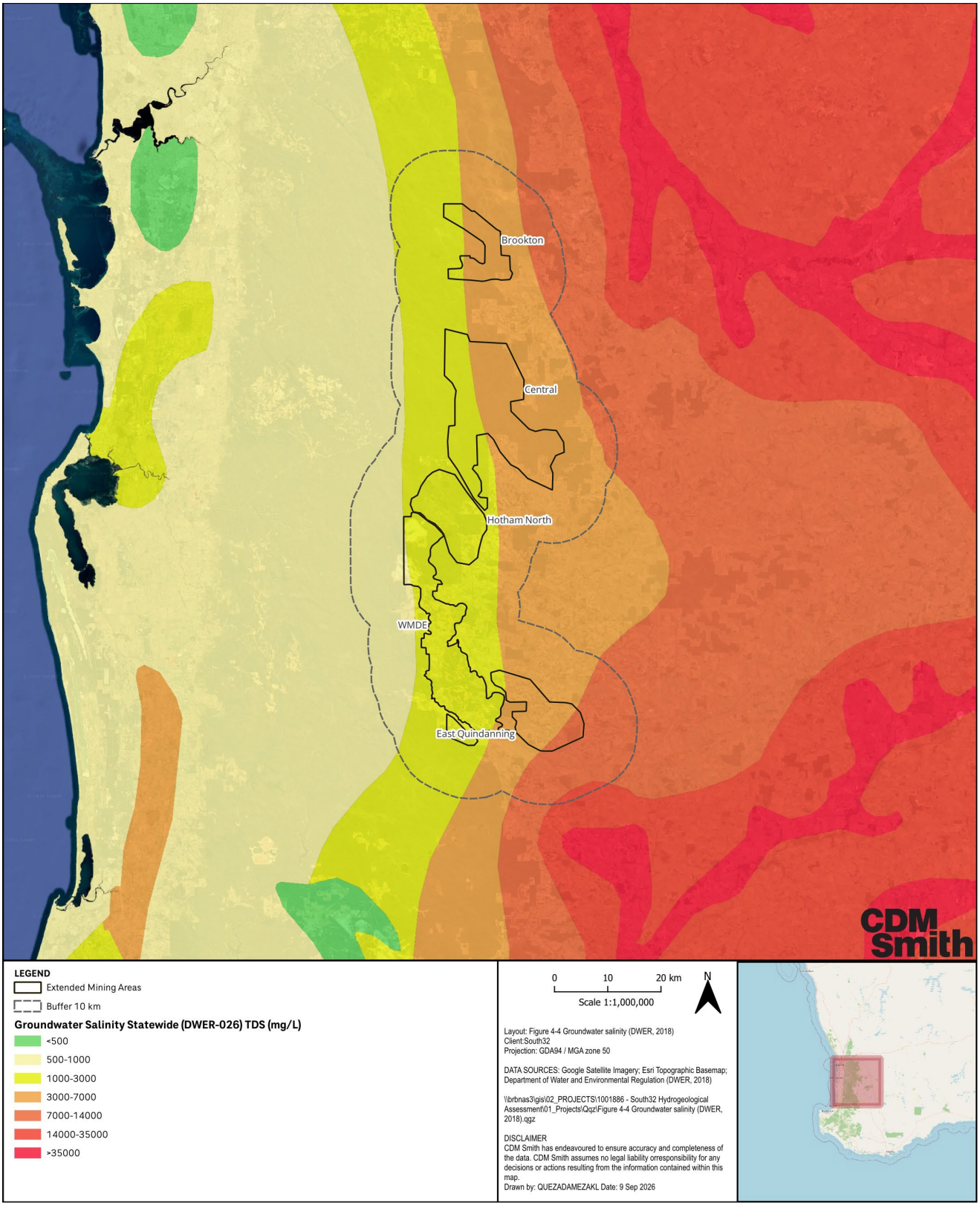

Figure 4-3 Groundwater salinity (DWER, 2018)

4.7 Conceptual hydrogeological model

The available hydrogeological data have been used to construct hydrogeological cross-sections over the Project area to assist in the understanding of the hydrogeological processes and conceptualisation of the Project area's HSUs. Cross sections for Brookton and Mid-Central are presented in Figure 4-5 and Figure 4-6, respectively. In the absence of data, thicknesses of stratigraphic units have been inferred. Final conceptual sections will be provided in Phase 3 and Phase 4 of the assessment after the completion of field works (Phase 2).

Key features of the preliminary hydrogeological conceptualisation are as follows:

- The Project area comprises three main HSUs
  - Shallow weathered profile comprised of a lateritic cap rock and shallow gravelly to sandy sediments
  - Deeper weathered zone comprised of saprolitic clays (up to 70 m thick), grading to more permeable saprock (7 to 15 m thick)
  - Fractured rock comprised of fresh mafic volcanics and granite; aquifer permeability and yield are dependent on fracture development and their connectivity
- Only a small proportion of rainfall will likely infiltrate topsoil and percolate downwards until it reaches the water table and recharge the groundwater system; recharge is likely to be greater on the upper slopes where more permeable soils are typically found
- Groundwater recharge is likely to be greater in areas where rainfall rates exceed evaporation
- Evapotranspiration of infiltrating soil water and shallow water tables and through flow in the fractured bedrock contributes to groundwater discharge
- Nearby mining operations in Boddington Gold Mine has resulted in significant drawdown and the formation of potentiometric depressions due to dewatering. There is no link has been observed between drawdowns and Worsley activities in the study area.
- There is a general west to east trend of increasing salinity, ranging from 500 to 7000 mg/L.

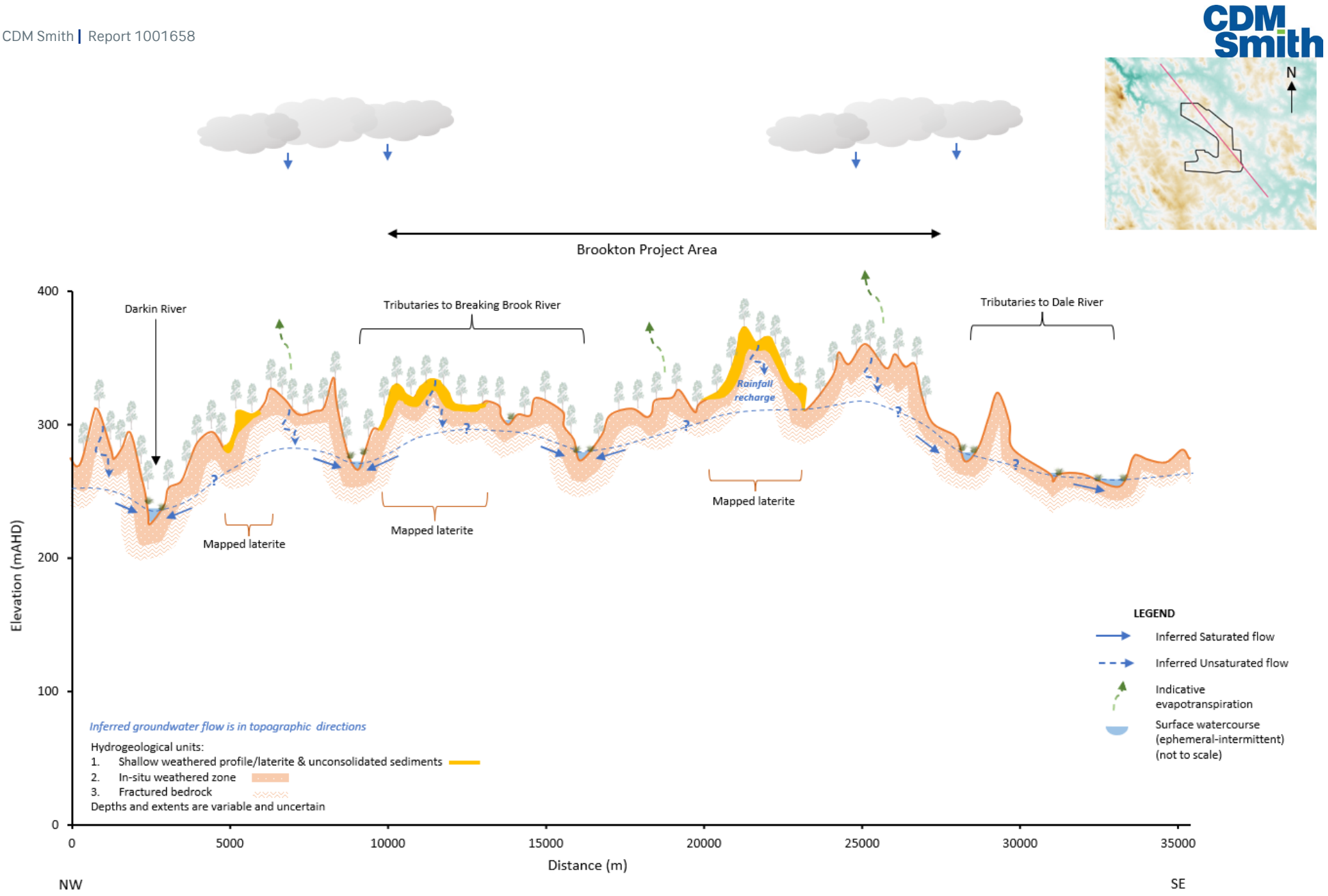

Figure 4-4 Preliminary hydrogeological conceptual model (Brookton)

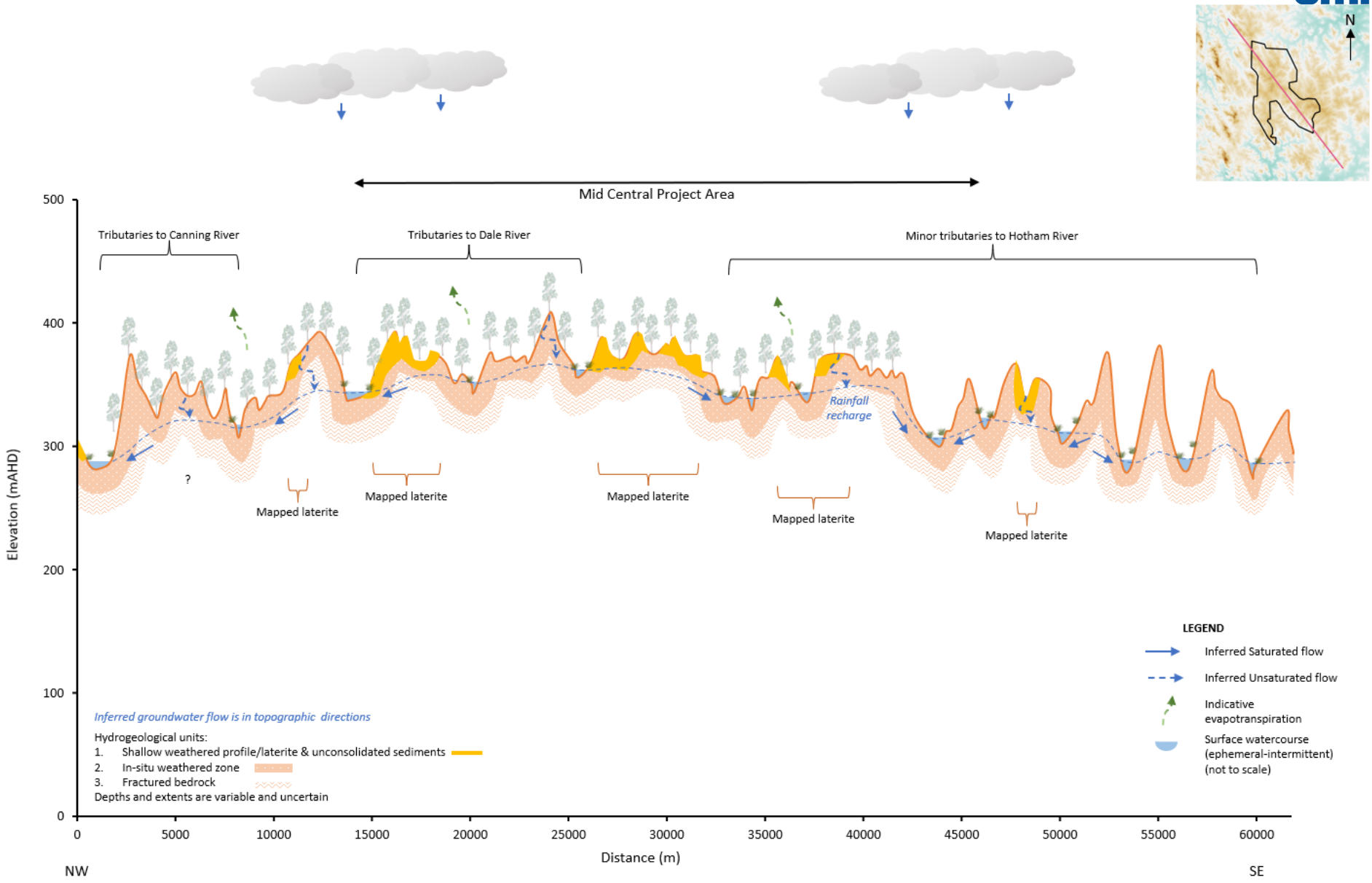

Figure 4-5 Preliminary hydrogeological conceptual model (Mid-Central)

Section 5 Environmental Values

5.1 Overview

Any changes to physical and quality aspects of groundwater resources, or to the physical characteristics of groundwater systems as a consequence of development of the Project have the potential to adversely affect existing and possible future EVs that are exposed to these changes. Two broad categories of EVs are defined under the *Environmental Protection Act 1986:*

- Ecosystem health
- Beneficial use

Table 5-1 presents the EVs identified by WA EPA (2018) as well as indication of whether they have been identified in the Project area. The following sections present an overview of existing and possible future groundwater EVs that might be exposed to changes to the groundwater baseline. They include all groundwater EVs identified within a 10 km radius of the EMAs (including Hotham North and Quindanning).

Table 5-1Identified Project area environmental values

Environmental value[1]		Brookton		Mid-Central		Hotham North		Quindanning	
			< 10 km		< 10 km		< 10 km		< 10 km
Ecosystem health	RAMSAR listed wetlands	☒	☒	☒	☒	☒	☒	☒	☒
	Conservation category or Resource enhancement wetlands[2]	☑	☑	☑	☑	☒	☒	☒	☒
	Directory of Important Wetlands in Australia wetlands	☒	☒	☒	☒	☒	☒	☒	☒
	Environmental Protection Policies wetlands	☒	☒	☒	☒	☒	☒	☒	☒
	Wild rivers	☒	☒	☒	☒	☒	☒	☒	☒
	Poorly represented wetlands in Conservation reserves system	☒	☒	☒	☒	☒	☒	☒	☒
	Springs and pools	☒	☒	☒	☒	☒	☒	☒	☒
	Ecosystems supporting significant flora, vegetation and fauna[3]	☒	☑	☑	☑	☑	☑	☑	☑
	Ecosystems supporting significant amenity, recreation and cultural values[4]	☒	☑	☒	☑	☒	☒	☒	☒

Environmental value[1]		Brookton		Mid-Central		Hotham North		Quindanning	
			< 10 km		< 10 km		< 10 km		< 10 km
	Saline lakes, estuaries and near shore ecosystems	☒	☒	☒	☒	☒	☒	☒	☒
	Downstream marine ecosystems	☒	☒	☒	☒	☒	☒	☒	☒
Beneficial use	Drinking water supplies	☑	☑	☑	☑	☑	☑	☒	☒
	Significant current or potential water supplies	☑	☑	☑	☑	☑	☑	☒	☒
	Water supplies supporting commercial activities (mining, pastoral, etc)	☑	☑	☑	☑	☑	☑	☑	☑
	Inland water with high levels of active and passive recreation including multiple use wetlands	☒	☒	☒	☒	☒	☒	☒	☒
	Waterbodies	☒	☑	☑	☑	☒	☑	☒	☑

Notes: ☒ - no ☑ - yes ☐ - unknown

1. WA EPA (2018)
2. Waterways Conservation Act Management Areas under the *Waterways Conservation Act 1976*
3. Bureau of Meteorology Groundwater Dependent Ecosystem Atlas (2023)
4. Collaborative Australian Protected Areas Database (DCCEEW, 2022)

5.2 Ecosystem health

The following provides details of possible ecosystem EVs in and around the Project area:

Terrestrial Groundwater Dependent Ecosystems

The BoM Groundwater Dependent Ecosystem (GDE) Atlas (BoM, 2023) indicates there is high potential for GDEs to occur across most of the Project area. Mapped potential terrestrial GDEs are provided in Figure 5-1. The mapped high potential GDEs in the Project area are typically associated with drainage features, rivers and their tributaries. Vegetations associated with ephemeral drainage lines are unlikely to be groundwater dependent.

Aquatic Groundwater Dependent Ecosystems

High potential aquatic GDEs are mapped across most of the Project area and are associated with wetlands and rivers (e.g., Darkin River in Brookton and Serpentine River in Mid-Central). Most high potential GDEs are located within 10 km of the respective EMAs. Mapped potential aquatic GDEs are shown in Figure 5-1.

Conservation areas

The Project area is within 10km of several conservation areas listed under the Collaborative Australian Protected Areas Database (DCCEEW, 2022) including Wandoo conservation park within 10 km of Brookton and Lupton conservation park within 10 km of Mid-Central.

5.3 Beneficial use

Drinking water supplies

All EMAs (apart from Quindanning and Morgans) are located within Public Drinking Water Source Areas (PDWSA) and in areas classified under the *Metropolitan Water Supply, Sewerage and Drainage Act 1909* (MWSSD Act) as delineated by the Department of Water and Environmental Regulation (DWER) in Western Australia. The MWSSD Act aims to protect proclaimed catchment areas and water reserves which provide the state's public drinking water source. It is likely elevated groundwater salinity limits the use of groundwater for human consumption in the Project area.

Stock and domestic water supplies

A search of the BoM groundwater explorer identified over 100 registered groundwater bores within 10 km of the respective mining areas, 1 of which are used for domestic and stock purposes.

Mining activities

The Boddington Gold Mine (located adjacent to Hotham North) is a use of groundwater with requirements up to 29 GL/year for ore processing, dust suppression and domestic purposes (Strategen, 2013). Water is sourced from mine dewatering and groundwater inflow to pits (4 to 10 GL/year), rainfall/runoff harvesting (5 to 15 GL/year) and abstraction from Hotham River (2 to 10 GL/year) (Strategen, 2013).

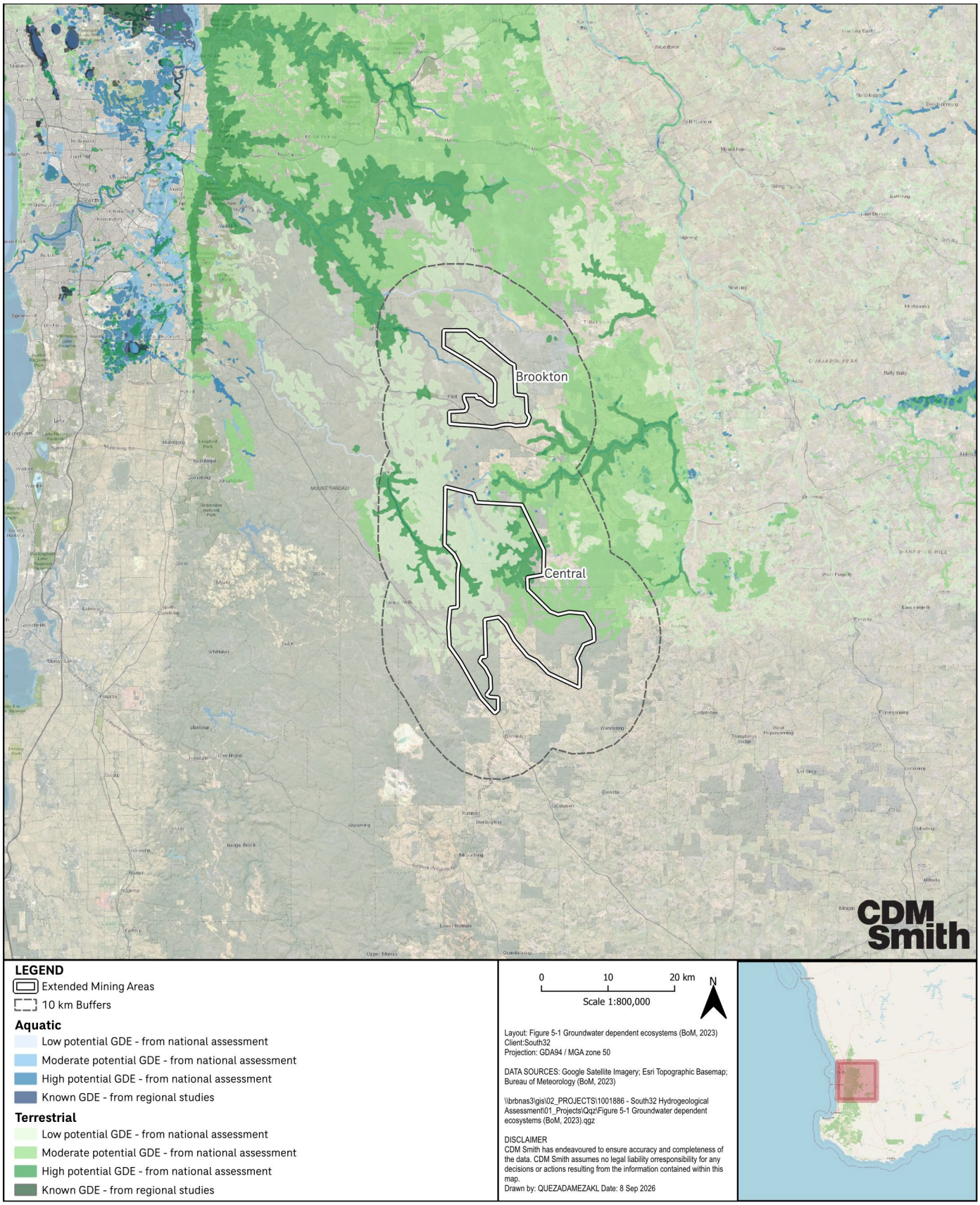

Figure 5-1 Groundwater dependent ecosystems (BoM, 2023)

Section 6 Gap analysis

Information about the hydrogeology in the study area is constrained due to the scarcity of groundwater resources. In the northern EMAs, there is a notable lack of drilled wells. A thorough evaluation of existing data has revealed several critical gaps that need addressing. The following table provides details about the known data gaps and the methodology to address the gaps.

Table 6-1 Identified Data Gaps and areas for further investigation.

Data Gap / Area for Investigation	Methods to Address the gap
Incomplete Understanding of Groundwater Dynamics	- Drilling monitoring bores to assess groundwater depth and flow directions and monitor temporal trends. - Developing and calibrating a numerical groundwater model
Uncertain Extent and Depth of Existing Aquifers	- Drilling monitoring bores to determine the extent and depth of existing aquifers- - Developing and calibrating a numerical groundwater model
Ambiguity Surrounding Paleo Valleys' Impact on Northern EMAs	- Drilling and sampling from groundwater monitoring bores, and if evidence found, assess the extent and magnitude of Paleo valleys' effects on groundwater systems using a calibrated groundwater model
Lack of Comprehensive Data on Groundwater Fluctuations over Time	- Drilling monitoring bore installations and quarterly groundwater observations to collect time series data on fluctuations
Incomplete Hydraulic Characterization of Aquifers	- Conducting slug tests or other methods to estimate hydraulic characteristics of aquifers through drilling monitoring bores. - Developing a groundwater model and calibrating hydraulic parameters
Surface water / Groundwater interactions	- Studying the influence of surface water features and their fluctuations on groundwater through drilling monitoring bores
Inaccurate Estimates of Water Usage and Extraction Rates	- Utilizing existing resources for accurate estimation of water usage and extraction rates - Developing and calibrating a groundwater model for precise estimation
Limited Knowledge on Groundwater Quality and Seasonal Variations	- Quarterly groundwater sampling from monitoring bores to monitor and assess changes in groundwater quality in different seasons

Data Gap / Area for Investigation	Methods to Address the gap
Impact of Various Groundwater Usages and Activities	- Developing and calibrating a groundwater model, conducting in-depth studies using existing reports and studies, and communicating with other groundwater users to analyse the impact of activities other than planned mining activities

Section 7 Monitoring bore locations

As outlined in the previous section, drilling and installing groundwater monitoring bores is recommended. The number and placement of these bores has been determined to provide sufficient data for creating a groundwater elevation map to determining groundwater flow directions and to inform the understanding of surface water/groundwater interactions. While spatial coverage of bores has been the priority, accessibility via established roads has been a factor in choosing drilling locations.

While the bores have been positioned to encompass the necessary details required for the groundwater model and groundwater impact assessment studies, the data acquired during the drilling campaign might reveal the need for additional bores in later stages to augment the study findings.

7.1 Brookton

In the Brookton Area, 11 drilling locations have been selected (Table 7-1 and Figure 7-1). The primary objectives for these bores include studying the geology, determining groundwater depth at each site, and verifying the presence of paleo valleys. These bore placements align with the low-potential GDEs mapped in the area, with efforts made to position monitoring bores near these zones whenever feasible. All monitoring bore sites in these areas are conveniently accessible via established roads, simplifying location access, while enough spatial coverage has been maintained.

Table 7-1 Proposed drilling locations in Brookton

ID	Depth (m)	Easting[1]	Northing[1]	Access	Target	Purpose
MB_1	10 to 40	447850	6443835	Yarra road	Bottom of Weathered Rock	Geology setting - Groundwater depth and quality, Low potential GDE, a Reference point for paleo valleys should any paleo valleys be detected in the east side of EMA.
MB_2	10 to 40	451532	6442496	Korner Road and Sullivan Road Junction	Bottom of Weathered Rock	Geology setting - Groundwater depth, Low potential GDE
MB_3	10 to 40	450701	6439110	Korner Road	Bottom of Weathered Rock	Geology setting - Groundwater depth and quality, Low potential GDE, Groundwater Interaction with Beraking Brook
MB_4	10 to 40	456302	6438981	Catchment Road	Bottom of Weathered Rock	Geology, Groundwater depth and quality, Low-potential GDE. Reference point for geology if any paleo valleys detected in southern parts of this EMA.
MB_5	10 to 40	453996	6436203	Willies Road	Bottom of Weathered Rock	Geology setting - Groundwater depth and quality, Low potential GDE.

ID	Depth (m)	Easting[1]	Northing[1]	Access	Target	Purpose
MB_6	20 to 60	458387	6434387	Local access from Edison Mills Road	Bottom of Weathered Rock, and if paleochannels detected, the base of paleochannels.	Geology of paleo valleys, Groundwater depth and quality, low-potential GDEs.
MB_7	10 to 40	451593	6433033	Flint Road	Bottom of Weathered Rock	Geology, Groundwater depth and quality
MB_8	10 to 40	455207	6432529	Darkin Road	Bottom of Weathered Rock	Geology, Groundwater depth and quality, Low potential GDEs
MB_9	10 to 40	447373	6431541	Local access from Metro Road	Bottom of Weathered Rock	Geology, Groundwater depth and quality, low potential GDEs.
MB_10	20 to 60	458942	6430860	Noonan Road	Bottom of Weathered Rock, and if paleochannels detected, the base of paleochannels.	Geology of paleo valleys, Groundwater depth and quality, low-potential GDEs.
MB_11	10 to 40	453147	6429788	Local access from Brookton highway	Bottom of Weathered Rock	Geology, Groundwater depth and quality

Notes: 1. GDA 1994 MGA Zone 50

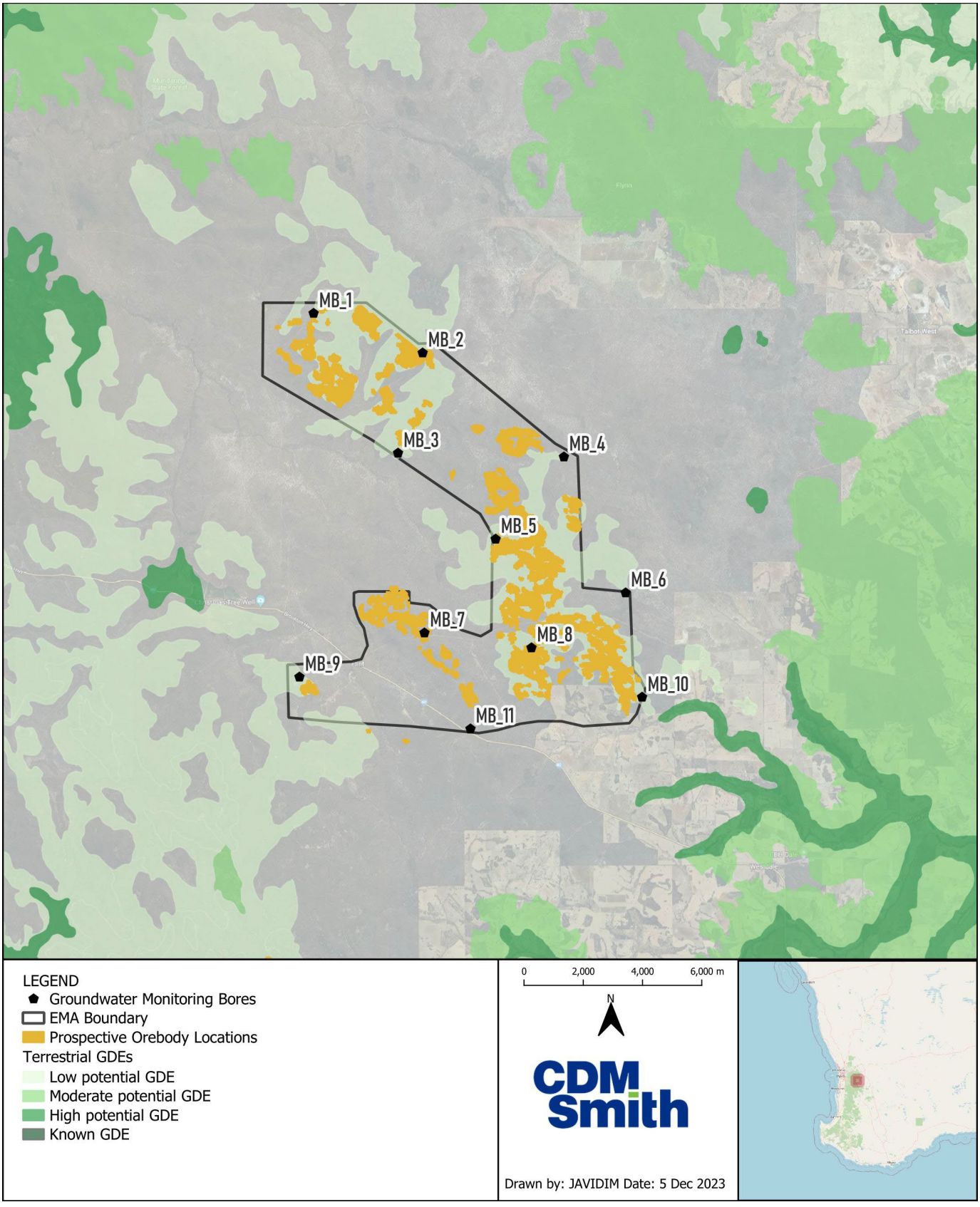

Figure 7-1 Proposed monitoring bore locations in Brookton

7.2 Mid Central

A total of 18 drilling locations have been selected for drilling in the Mid Central EMA (Table 7-2 and Figure 7-2). The selection of these locations was based on the high potential GDEs and the network of surface streams that have been identified in this EMA. Other factors such as different land uses, spatial variability, and accessibility were also taken into consideration while selecting these bore locations.

Table 7-2 Proposed drilling locations in Mid-Central

ID	Depth	Easting	Northing	Access	Target	Purpose
MB_12	10 to 40	448112	6418356	Local access from McCallum Road	Bottom of Weathered Rock	Geology, Recharging effects from Dale River, Groundwater Levels
MB_13	10 to 40	457155	6417831	Local access from Pike Road	Bottom of weathered Rock	Geology setting, agricultural activities recharge monitoring, Groundwater depth and quality.
MB_14	10 to 40	451372	6413722	Metro Road	Bottom of Weathered Rock	Geology setting - Groundwater depth and quality, Low potential GDE
MB_15	10 to 40	446310	6413443	Local access from Water shed Road	Bottom of Weathered Rock	Geology, High potential GDE, Groundwater depth and quality
MB_16	10 to 40	455999	6411605	Local Access from Pikes Road	Bottom of Weathered Rock	Geology, High Potential GDE, Groundwater depth and quality
MB_17	10 to 40	461038	6411372	Local access Thompson Road	Bottom of Weathered Rock	Geology, High Potential GDEs, Groundwater depth and quality, Agriculture effect on groundwater levels and quality
MB_18	10 to 40	448397	6408596	Pikes Road	Bottom of Weathered Rock	Geology, High potential GDE, Groundwater depth and quality
MB_19	10 to 40	454098	6407013	Metro Road	Bottom of Weathered Rock	Geology, High potential GDE, Groundwater depth and quality
MB_20	10 to 40	458286	6405950	Lindy Ln	Bottom of Weathered Rock	Geology, High Potential GDEs, Groundwater depth and quality
MB_21	10 to 40	454478	6403542	Local access from Metro Road	Bottom of Weathered Rock	Geology, low and Medium potential GDE
MB_22	10 to 40	447064	6400896	Old Coach Road	Bottom of Weathered Rock	Geology, Groundwater levels, potential recharges from Serpentine River
MB_23	10 to 40	462332	6399901	South Road	Bottom Of weathered Rock	Geology, Groundwater Level, Moderate Potential GDEs
MB_24	10 to 40	468708	6398439	Heartbreak Road	Bottom Of weathered Rock	Geology, Moderate Potential GDEs, Groundwater depth and quality

ID	Depth	Easting	Northing	Access	Target	Purpose
MB_25	10 to 40	463774	6396510	Ricks Road	Bottom of weathered Rock	Geology setting, agricultural activities recharge monitoring, Groundwater depth and quality.
MB_26	10 to 40	451655	6396281	Local access from North Banister - Wandering Road	Bottom of Weathered Rock	Geology, Groundwater depth and quality, High potential GDEs
MB_27	10 to 40	458530	6395729	Ricks Road	Bottom of weathered Rock	Geology, Surface water/Groundwater interaction studies, Groundwater levels and groundwater quality
MB_28	10 to 40	466478	6390587	Mission Road	Bottom Of weathered Rock	Geology, Recharge Estimation from Agriculture and Cream Creek, groundwater depth and quality, Potential GDEs nearby
MB_29	10 to 40	454244	6387442	Access from Albany Highway	Bottom of Weathered Rock	Geology, Groundwater depth and quality, and low potential GDEs

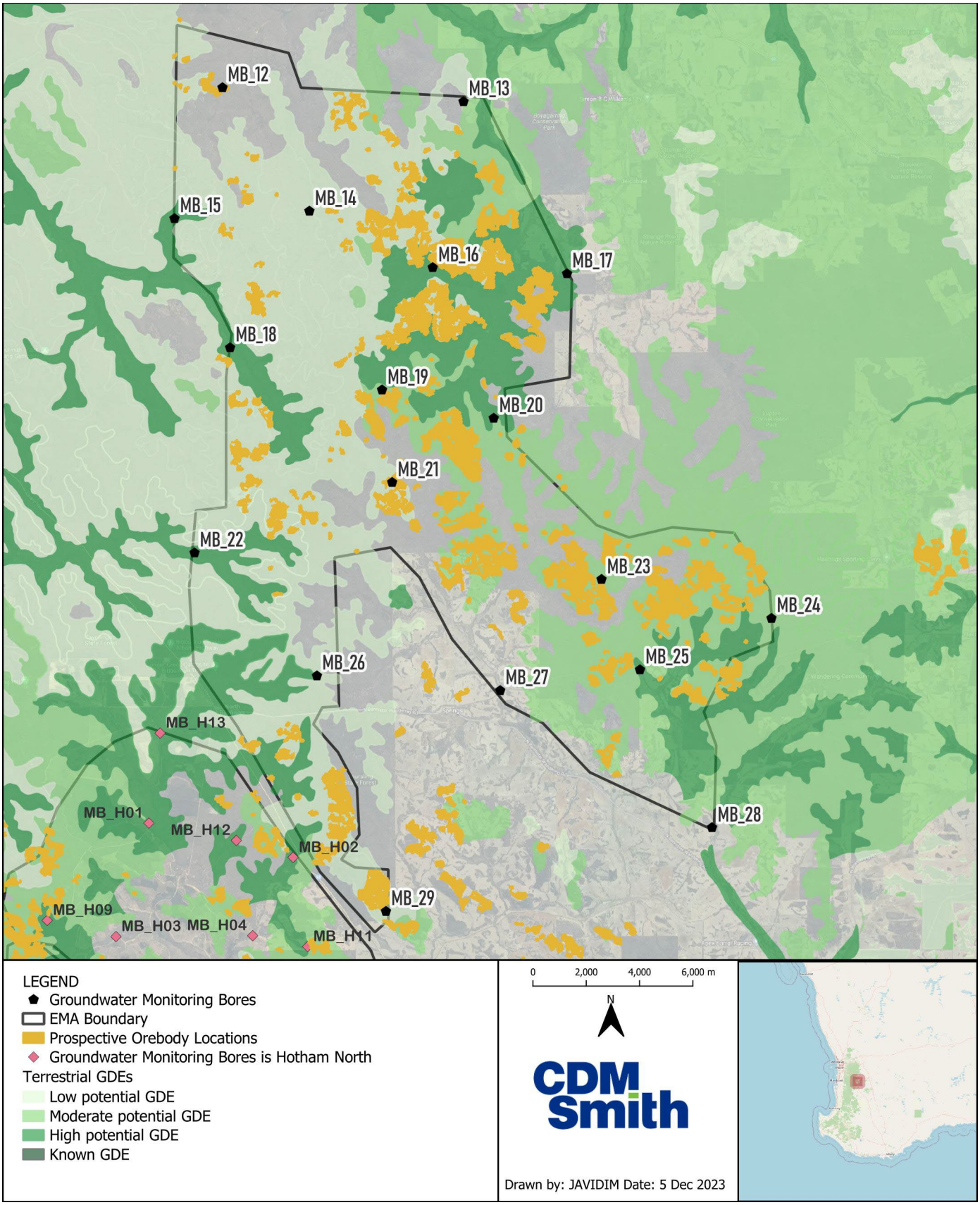

Figure 7-2 Proposed monitoring bore locations in Mid-Central

Section 8 Bore installation and construction requirements

8.1 Monitoring Bore Installation Methodology

All groundwater bores will be installed as per the "Minimum Construction Requirements for Water Bores in Australia". Although largely dependent on-site specific ground conditions, a general method of borehole construction and piezometer installation is summarised as follows:

- A Class 2 qualified driller will be required for the installation of the monitoring bores.
- A diameter hole of 155 mm would be sufficient for the holes as it is recommended that only one 50 mm diameter piezometer is to be installed in each hole.
- The groundwater monitoring bore will be constructed by carefully lowering 50 mm uPVC screen/end cap and casing into the open hole. The drilling rig should have suitable slips/elevators set up to hold the weight of the piezometer while it is being installed.
- Once the casing is installed within the bore, the gravel filter pack (2-5mm quartz gravel) shall be tremmied into place within the well screen section and to a minimum of 1 m above the screen. A bentonite seal is then emplaced, and the bore is then completed by backfilling and sealing with concrete grout at the surface. It is important that the placement of all backfilling material, gravel packs and seals must be carefully undertaken at a controlled rate with appropriate settlement times to ensure placement at the correct depth and avoid bridging at higher levels within the hole.
- Each groundwater monitoring bore shall be developed after installation has been completed to clear residual drill fluid and cuttings from the piezometer. This can be done by using compressed air to lift the water column to surface. Airlifted water should be run through a V-notch weir to determine yields.
- Once constructed the bore should have an end cap and lockable bore monument installed. It is recommended that the monument be grouted in place and well-marked.

A proposed preliminary schematic for each borehole has been provided in Appendix A. Geological logging is necessary prior to confirming the installation specification of each monitoring bore to ensure the bore screen is located in the correct lithology/aquifer. Final bore design will be confirmed by the hydrogeologist in the field during installation based on field conditions.

The hydrogeologist's duties include geological logging of drill cuttings, recording v-notch yields and water quality parameters during drilling, advising on bore construction parameters to meet the Project requirements and confirmation that bores are airlift developed after drilling until produced water was clear, free of fines and water quality parameters had stabilised.

8.2 Monitoring Bore Materials

The following materials are proposed for the drilling and piezometer installation:

- Drilled at 155 mm for a 50 mm uPVC CL 12 or 18 casing thread jointed PVC specific to environmental assessments.
- Sufficient casing centralisers
- 50mm uPVC CL 12 or 18 slotted screen (<1mm slot width)
- Piezometer end caps to prevent ingress of particulate matter to the piezometers
- Filter pack comprising uniformly graded, clean gravel pack with diameter between 2 – 5 mm
- Borehole sealant (bentonite pellets) and cement based grout
- Bore cap, monuments and locks to cover and protect the bore and any installed equipment

8.3 Testing and Groundwater Sampling

8.3.1 Slug Testing

Following the installation of the monitoring bores, it will be necessary to perform a slug or rapid displacement test on each monitoring bore to determine aquifer hydraulic conductivity. The results of the slug tests should be analysed using software packages to calculate hydraulic conductivity.

8.3.2 Groundwater Sampling Methodologies

Groundwater sampling will be required following the installation of the monitoring bores and bore development. Representative groundwater samples are to be collected following stabilisation of field water quality parameters. Low flow method of sampling should be adopted as part of the groundwater sampling methodology. Low flow methods minimise the impact of the sampling method on the aquifer and are more likely to obtain a representative sample, while some high flow pumps can sometimes induce water chemistry changes.

Prior to groundwater sampling a standing water level should be measured for each bore.

Field water quality analysis should include at a minimum electrical conductivity, pH, and temperature.

Collected groundwater samples will need be stored in laboratory supplied bottles and, where required, field filtered (i.e. dissolved metals). Samples will be sent to a NATA accredited laboratory after each sampling event in accordance with industry standard chain of custody (COC) protocols.

It is recommended sampling of the bores should be undertaken quarterly to capture seasonal variations. Groundwater monitoring is recommended near the end of the wet season when groundwater levels are likely to be at their highest and near the end of the dry season when groundwater levels are likely to be at their lowest.

8.3.3 Quality Management Processes

Groundwater sampling is to be conducted in accordance with:

- Geoscience Australia (2009) “Groundwater Sampling and Analysis – A Field Guide” (record 2009/27)
- The Australian/New Zealand Standard Water quality – “Sampling, Part 1: Guidance on the design of sampling programs, sampling techniques and the preservation and handling of samples” (AS/NZS 5667.1:1998)
- The Australian/New Zealand Standard Water quality – “Sampling, Part 11: Guidance on sampling of groundwaters” (AS/NZS 5667.11)

For QA/QC purposes, blind duplicate samples are to be collected at each site monitoring network location and at a minimum 1:10 ratio basis. All monitoring field equipment should be calibrated in accordance with the manufacturer's specifications.

8.3.4 Laboratory Analysis

The following analysis is based on the South32 Water Management Plan (South32, 2020) which details the monitoring to be undertaken. The representative samples taken from the bores shall be analysed for the following parameters:

- Standing water level measurement.
- pH, electrical conductivity, total dissolved solids, hardness and alkalinity.
- Fluoride, nitrate and nitrite, Silicon as SiO2.
- Major cations and anions. Na, K, Ca, Mg, Fe, SO4, Cl.
- Filtered and unfiltered metals (Al, As, B, Bo, Be, Cd, Cr, Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, Se, U, Zn).
- Cyanide.
- TRH and BTEXN.

Stock watering has been identified as a potential beneficial use of groundwater and Table 8-1 lists the livestock water guidelines values.

Table 8-1 Livestock Drinking Water Guideline Values

Parameter	ANZECC, 2000 Guideline Stock Drinking Water
TDS (mg/L)	4,000–5,000 (Beef Cattle)
Calcium (mg/L)	1,000
Fluoride (mg/L)	2
Sulfate (mg/L)	1,000
Nitrate (mg/L)	1,500
Nitrite (mg/L)	30
Aluminium (mg/L)	5
Arsenic (mg/L)	0.5
Boron (mg/L)	5
Cadmium (mg/L)	0.01
Chromium (mg/L)	1
Cobalt (mg/L)	1
Copper (mg/L)	1 (Beef Cattle)
Lead (mg/L)	0.1
Mercury (mg/L)	0.002
Molybdenum (mg/L)	0.15
Nickel (mg/L)	1
Selenium (mg/L)	0.02
Uranium (mg/L)	0.2
Zinc (mg/L)	20

Section 9 References

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