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Transforming Agriculture in the Pilbara: Newman managed aquifer recharge (MAR) feasibility assessment

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Science Agency

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Executive summary

Transforming Agriculture in the Pilbara (TAP) is the Western Australian Government initiative aiming to identify a practical and achievable vision for medium-to-large-scale irrigated agricultural production in the Pilbara using water from mine dewatering operations ('mine dewater') and other in-situ water resources.

The Department of Primary Industries and Regional Development (DPIRD) has identified the Newman region as a likely region for future irrigation developments, subject to water availability and soil suitability.

DPIRD and CSIRO have jointly assessed the feasibility of using managed aquifer recharge (MAR) to store mine dewater in the Fortescue River alluvial fan aquifer in the Newman region. The aim of recharging the aquifer is to provide water supply for irrigated agriculture.

The potential source water for MAR is mine dewater located at the large BHP Billiton iron ore mines near Newman, sourced directly from within the mining area or from Ophthalmia Dam, into which BHP discharges mine dewater.

The objectives of the MAR assessment were to:

- assess the viability of using mine dewater for MAR to support development of irrigated agriculture, in keeping with national and state MAR guidelines.
- identify key risks of using mine dewater for MAR to supply water for irrigation, identify knowledge/investigations required to adequately assess risks, and define preventative measures to support approval of a MAR scheme for construction and commissioning (or to complete a pre-commissioning residual risk assessment).

This report is presented in two parts. Part 1 summarises the Fortescue River alluvial fan groundwater system previously reported by Schmid et al. (2022) and Donn et al. (2023) and describes the data available for the risk assessment. Part 2 uses the limited data available to assess the risks of potential MAR opportunities in the area. Due to data limitations, a regional risk assessment was undertaken rather than a site-specific risk assessment.

Key characteristics of the Fortescue groundwater system

- Data was sourced from the WA Government and BHP Billiton along with that produced as part of the TAP project. However, the assessment area is data poor with limited hydrogeological information. For example, only 34 observation bores in the 1670 km^2 study area had lithological descriptions and most of these are clustered around Ethel Gorge where MAR to support horticulture is unlikely to be feasible due to the complex hydrogeology/fault network, shallow groundwater, the presence of groundwater-dependent ecosystems, and the intensive mineral exploration activities which would likely disrupt agricultural development.

- The Fortescue River alluvial aquifer is characterised by an interbedded mix of clay, sand and gravel sediments, typical of alluvial deposits, and varying largely in thickness and extent. The alluvial deposits are deep in the MAR study area (at least 100 m in the south of the alluvial fan) with the neither the Wittenoom Dolomite nor basement intersected by recent drilling.
- The groundwater is deep, particularly in the centre of the fan where the depth to groundwater table reaches 40 mBGL, which reduces to the north, closer to the Fortescue Marsh, the main regional groundwater discharge zone, and to the south, close to Ethel Gorge, the main groundwater recharge zone.
- The thickness of the saturated layer of the alluvial aquifer reduces towards the groundwater discharge zone along the northern margins of the fan, which includes the southern edge of the Fortescue Marsh. In the north, the alluvial deposits are underlined by Wittenoom Dolomite and the two formations are likely to compose a single saturated layer of unknown thickness.
- The alluvial aquifer is recharged by rainfall infiltration (likely <10 mm/year) and localised recharge from the Fortescue River (>40 mm/year). Flows in the Fortescue River and subsequent recharge are influenced by mine dewatering operations, with contributions from both BHP Billiton Iron Ore (controlled discharge to and from Ophthalmia Dam) and Rio Tinto (via Kalgan Creek). The groundwater flow rate is about 10 m/year.
- The groundwater is relatively fresh and metal concentrations are generally low.

In refining the MAR assessment area, constraints for both MAR implementation and for suitability for irrigated horticulture were considered. The MAR risk assessment is based on a refined focus area that covers areas within southern extent of the Fortescue River alluvial fan. Several MAR scenarios were modelled to understand the impacts of MAR on the aquifer hydraulics. The findings are reflected in the key risks outlined below.

Key risks of implementing MAR in the Newman region

- Large volumes of water (we modelled from 5 GL to 50 GL per year) could be stored in the alluvial aquifer but not over the long-term (>5-10 years) without increasing the risk of inundation due to groundwater mounding.
- When storing large volumes, it is critical that the water is recovered (reused) on an annual basis, and that the MAR area is large enough to spread mounding and limit groundwater-level rise. The MAR area may be as much as 4000 ha for some scenarios, which may be prohibitive for development. Further investigation is required once specific MAR locations are chosen to define the suitable size for irrigated agriculture development.
- Inundation risks could be managed by limiting long-term storage through matching crop water requirements to the available dewater volume on an annual basis. This is managed by using available water directly for irrigation and when water is in excess of crop requirements directing it to the MAR scheme.

- The Fortescue River to the south of the agricultural area could be impacted by groundwater mounding associated with MAR.
- Further calibration and validation of the groundwater model is required to reduce the uncertainty of the modelled MAR scenario results.
- A BHP-supplied summary of mine water quality from three locations shows that mine dewater can exceed Cl, Na P, Fe, pH targets for irrigation. Salinity may exceed targets for irrigation of moderately sensitive crops but should be suitable for salt-tolerant crops and livestock watering. The water from Ophthalmia Dam could have high levels of phosphorus, pH and iron.
- Though groundwater quality data is limited, samples show that Cl, Na, P and B exceed targets for irrigation. In almost all samples, salinity exceeded the sensitive crop limit and in almost half of samples salinity exceeded the moderately sensitive crop limit.
- The risk of aquifer clogging requires further assessment and management.
- Pathogens, organic chemicals and radionuclides are unknown risks requiring additional information.

Additional water quality data will be sought to inform the maximal risk assessment and identify preventative measures to lower risks to an acceptable level. Site-specific soil and crop-specific requirements should be considered in the latter stages of feasibility assessment. To mitigate the risk of inundation, the cropping area should be determined from the crop water needs so that MAR water is not stored long-term in the alluvial aquifer.

1 Introduction

The Pilbara region in Australia's north-west (Figure 1-1) is a world-leading iron ore province and contains important deposits of gold, manganese, copper and uranium. It also provides onshore support and processing areas for offshore natural gas deposits (McFarlane, 2015).

The main land uses are vacant crown land, private grazing leases, grazing leases managed by mining companies, grazing leases managed by Indigenous groups, and reserves for parks and wildlife or other purposes (McFarlane et al., 2015). A very small area is privately-owned freehold land. The Western Australia Department of Primary Industries and Regional Development (DPIRD) has identified priority areas across the state where investigations are required to assess the capacity for developing irrigated agriculture and related businesses; the Pilbara region is one of these priority areas.

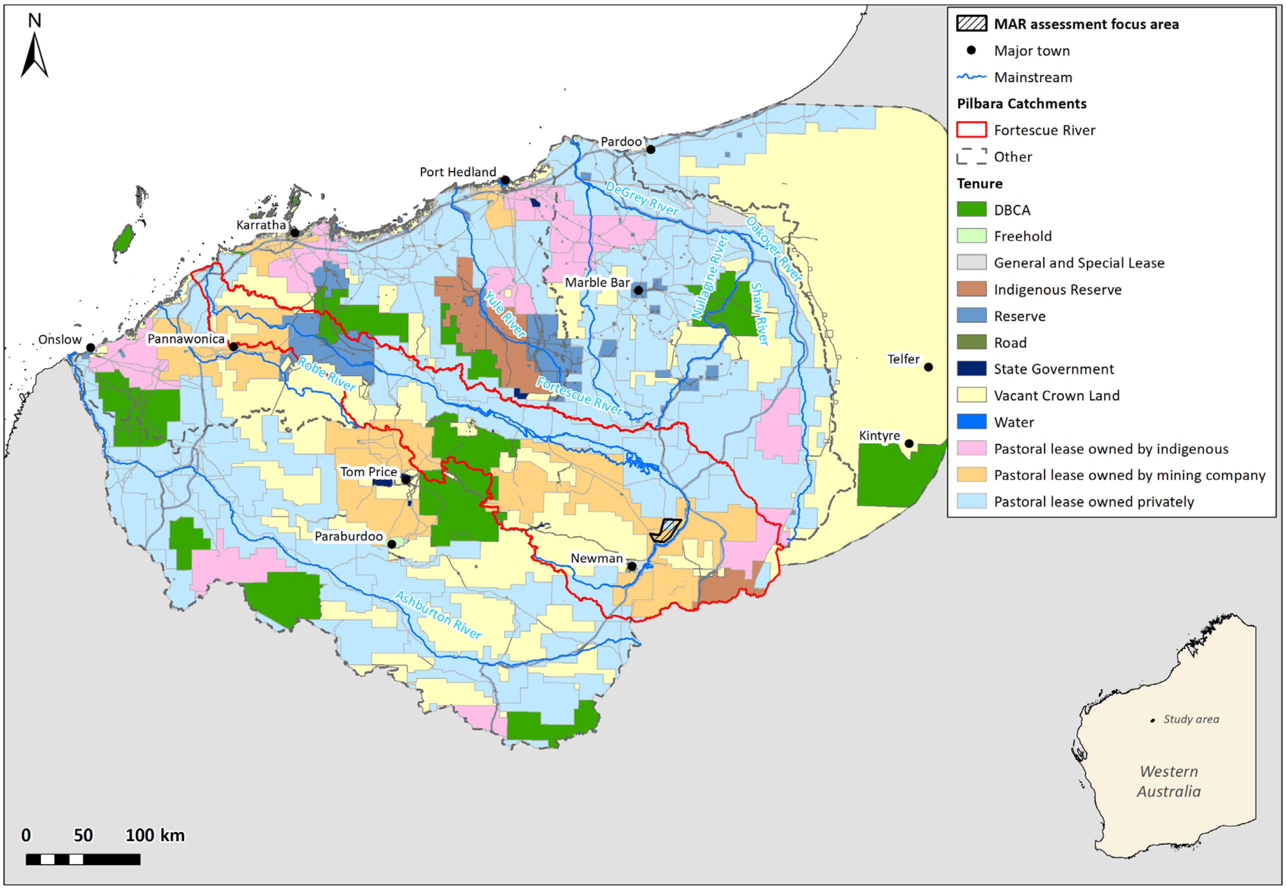

Figure 1-1 Location of study area in the upper Fortescue River catchment and land use in the Pilbara region. DCBA = land managed by the Department of Biodiversity, Conservation and Attractions. Adapted from (McFarlane et al., 2015)

As part of the DPIRD project titled 'Transforming Agriculture in the Pilbara, or TAP', the DPIRD and CSIRO have jointly investigated, for the Western Australian Government, opportunities for developing water resources in the Karratha-Hinterland, the De Grey catchment and the Newman region in the Pilbara. Each study area was identified as a likely region for future irrigation developments, subject to water availability and soil suitability.

In the Newman region, DPIRD commissioned an assessment of the potential for managed aquifer recharge (MAR) near Newman using surplus water resulting from mine dewatering as the water supply for irrigated agriculture.

The initial study area is located in the upper Fortescue River north of the town of Newman (defined by the groundwater model boundary in Figure 1-2). The initial area of interest for MAR extends north from Ethel Gorge and covers the upper Fortescue River floodplain and region to the east, including Jimblebar Creek and Carramulla Creek, coinciding with the airborne electromagnetic (AEM) survey area (Figure 1-2). This area was later refined (Section 2.5) as part of the project to include a smaller MAR assessment focus area (Figure 1-2). The potential source water for MAR is surplus mine water generated from dewatering operations (and referred to as ‘mine dewater’ in this report) at the large BHP iron ore mines near Newman, sourced directly from within the mining area or from Ophthalmia Dam (Figure 1-2). BHP is also interested in disposing of mine dewater from iron ore mining operations south of the AEM survey area (see BHP mining lease areas and miscellaneous licence area within the AEM survey area, Figure 1-2), which has resulted in collaboration between BHP and the DPIRD-CSIRO project team.

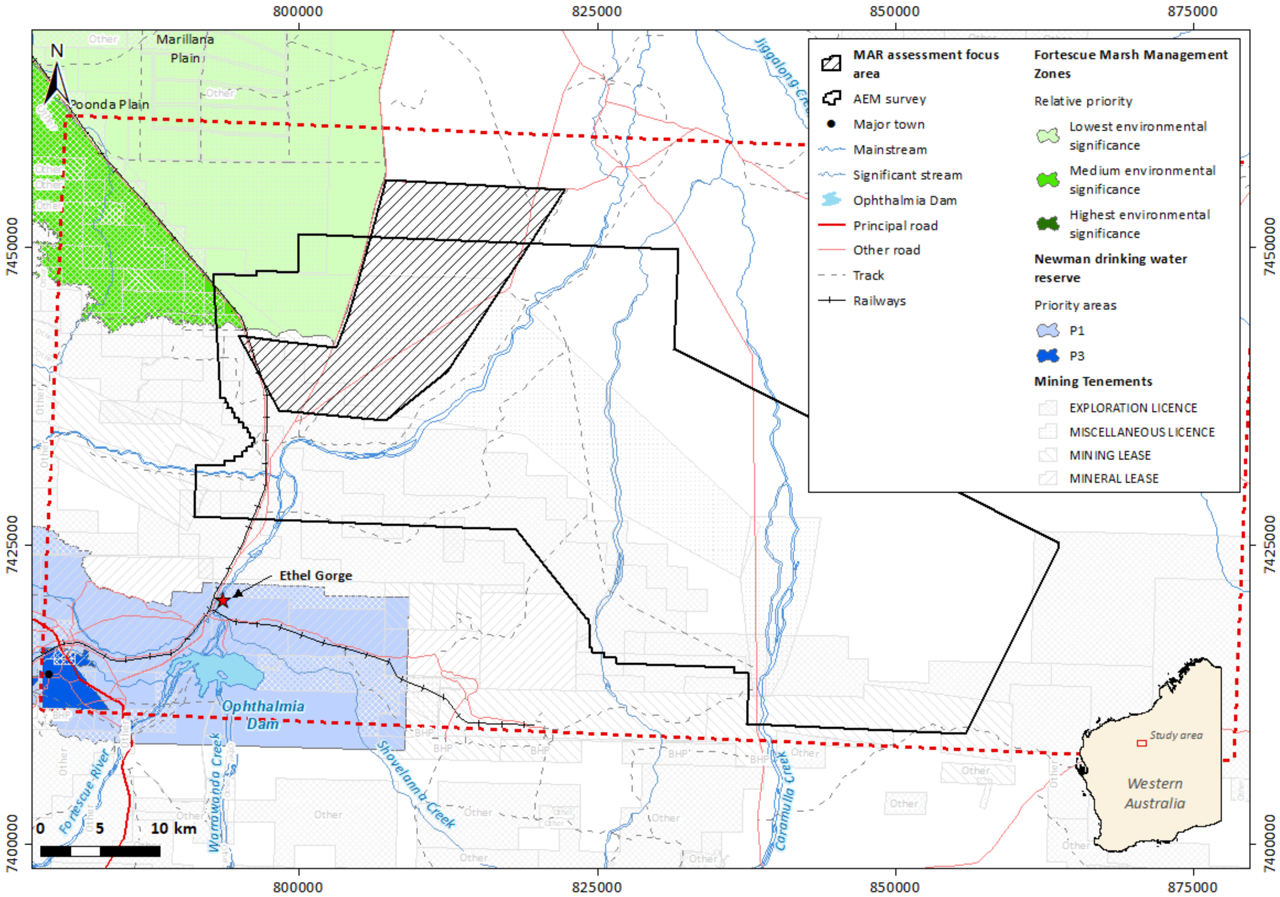

Figure 1-2 MAR feasibility assessment area showing mining operations (BHP and other companies) and environmental assets north of Newman. Groundwater model boundary is indicated by the red dashed polygon.

This assessment of MAR feasibility also assessed risks to environmental receptors of the mine dewater, including the Fortescue Marsh, riparian vegetation along the Fortescue River, and groundwater ecosystems. The assessment area abuts the Fortescue Marsh management zones of lowest and medium environmental significance (Marillana and Poonda Plains) but does not intersect the Newman Drinking Water Reserve (a public drinking water source area, or PDWSA) (Figure 1-2).

The objectives of the MAR assessment were to:

- identify focus area for MAR feasibility assessment within the initial larger area of interest for MAR
- assess the viability of MAR with mine dewater near Newman to support development of irrigated agriculture, in keeping with national and state MAR guidelines
- identify key risks associated with MAR with mine dewater for irrigation supply, and identify knowledge/investigation required to adequately assess risks and define preventative measures to support approval for construction and commissioning (or complete pre-commissioning residual risk assessment).

This report is presented in two parts. The first part describes the Fortescue River alluvial fan groundwater system and the data available for the risk assessment. Data was sourced from the WA Government and BHP Billiton along with that produced as part of the TAP project. For the completeness of this report information previously reported by Schmid et al. (2022) and Donn et al. (2023) is summarised in this section. The second part uses the available data to assess the risks of potential MAR opportunities in the area. Due to data limitations, a broader scale regional risk assessment was undertaken rather than a site-specific risk assessment.

Part 1 Groundwater system in the region and MAR modelling

Part 1 describes the groundwater system in the Fortescue alluvial fan, based on existing and newly acquired data. A revised groundwater conceptualisation was used to develop a numerical groundwater model, which was then used for assessing MAR. The MAR water was sourced from mine dewatering operations of BHP Billiton Iron Ore. The information created was used for the MAR risk assessment described in Part 2 of this report.

2 Conceptual groundwater model

Groundwater system characterisation within the Fortescue River alluvial fan north from Ethel Gorge (Newman, the eastern Pilbara) was carried out based on analysis of existing information and new data acquired by the DPIRD TAP team and supported by BHP Billiton Iron Ore (Donn et al., 2023).

- The investigation program included installation of boreholes, groundwater-level monitoring, and groundwater sampling for water quality analysis, including analysis of environmental tracers.
- The existing data included local surface and groundwater monitoring data (including those provided by BHP Billiton) and water quality data.
- An airborne electromagnetic (AEM) geophysical survey was interpreted in collaboration with BHP Billiton (Davis et al., 2020; 2021) and used as the basis of the aquifer geometry.

The assessment area was considered as a data-poor region with limited hydrogeological information. For example, only 34 observation bores in the 1670 km^2 study area had lithological descriptions (Apx Figure A.1). Furthermore, most of the bores with lithological descriptions are clustered around Ethel Gorge where MAR to support horticulture is unlikely to be feasible due to the complex hydrogeology/fault network, shallow groundwater occurrence, groundwater-dependent ecosystems occurrence, and the intensive mineral exploration activities which would likely disrupt agricultural development.

In addition to the AEM survey, data available to the study included new and previously available data on bore logs, depth to groundwater, and quality of ambient groundwater and MAR source water (mine dewater) (Table 2-1). The available data on the quality of mine dewater is representative of the water quality expected from different mine dewatering schemes in the region; however, the quality is likely to change during different stages of existing mine operations or development of new ore deposits. It is not possible from the existing data to predict how mine dewater quality will change as different mines/areas contribute to the overall quantity of mine dewater potentially available for MAR.

The investigation program enabled the characterisation of the local groundwater system to be advanced, including aspects related to aquifer structure and lithology, groundwater balance and quality. These aspects are outlined in the following sections with additional detail provided in Schmid et al. (2022) and Donn et al. (2023).

Table 2-1 Summary of data sources used in the Newman MAR feasibility assessment

Data type	Details	New/existing data	Source
Aquifer characterisation	AEM survey	New data	BHP/CSIRO - this project
	Drill logs, bore hole lithology	Existing data New data	Department of Water and Environmental Regulation (DWER) Water Information Reporting (WIR) Logs taken during DPIRD drilling program (5 locations) – this project (see Donn et al., 2023)
	Depth to groundwater	Existing data	DWER (WIR), BHP
Ambient groundwater quality	Predominantly salinity only, 15 shallow groundwater locations (stock wells/bore) DPIRD 2019	Existing data	DWER (WIR), DPIRD
	17 shallow (9) and deep (8) groundwater samples (October 2021) – 8 existing bores, 9 new bores (Donn et al., 2023)	New data	CSIRO – this project
Source water quality	Mine dewater surplus water quality 2009-2020 (2 locations; eastern and western summarised separately) Ophthalmia Dam water quality 2015-2020 (3 locations combined for summary)	Existing data	BHP
	One surface water sample below Ophthalmia Dam (October 2021) (Donn et al., 2023)	New data	CSIRO – this project
Hydraulic impacts	*Groundwater modelling of the Newman area for managed aquifer recharge assessment* (Schmid et al., 2022). Changes in hydraulic impacts from different MAR scenarios investigated.	New data	CSIRO – this project

2.1 The Fortescue alluvial fan aquifer

Within the extent of the AEM survey the thickness of the Fortescue alluvial aquifer increases from more than 100 m at the apex of the fan to less than 50 m at the Fortescue Marsh (Figure 2-1). The drilling program was able to define the depth of the basement in only a single bore (21NN04D, Apx Figure A.1), located on the western flank of the fan, where the depth to basement is approximately 80 metres below ground level (mBGL). Based on AEM data interpretation, the depth to basement was variable throughout the AEM survey area, with basement highs and lows potentially affecting groundwater flow paths.

Dolomites are likely to occur in the northern areas of the fan, as confirmed by the bore logs at 5 bores along the AEM transect shown in Figure 2-2. These bores are all north of the initial study area. It is possible that the alluvial fan aquifer and dolomite aquifer are hydraulically connected in this area. This is indirectly indicated by the similar groundwater levels and hydraulic heads in the shallow bores screened in the alluvial aquifer and deep bores screened in the dolomite (i.e. no vertical gradient), as well as a reduction in the longitudinal groundwater gradient in the northern area of the fan (Donn et al., 2023), potentially due to an increase in the transmissivity of the joint (alluvial fan and dolomite) aquifers.

Bore logs indicate that the alluvial aquifer is characterised by an interbedded mix of clay, sand and gravel sediments, typical of alluvial deposits, varying largely both vertically and spatially. This variability can lead to spatially localised confinement between more conductive layers. Confinement, identified from high frequency groundwater-level analysis, could be associated with such local confinement. However, the alluvial fan aquifer acts as a single aquifer layer.

Based on the nuclear magnetic resonance (NMR) data, it appears that lenses of perched water (high water content) may occur above the regional watertable, which is on average located at or below 30 mBGL in the newly drilled bores. Calcified and silicified deposits were observed in the shallow alluvial layers. This secondary deposition is common in the region and known to be associated with historical or present groundwater discharge zones. This indicated that groundwater level is likely to have been at more shallow positions in the past.

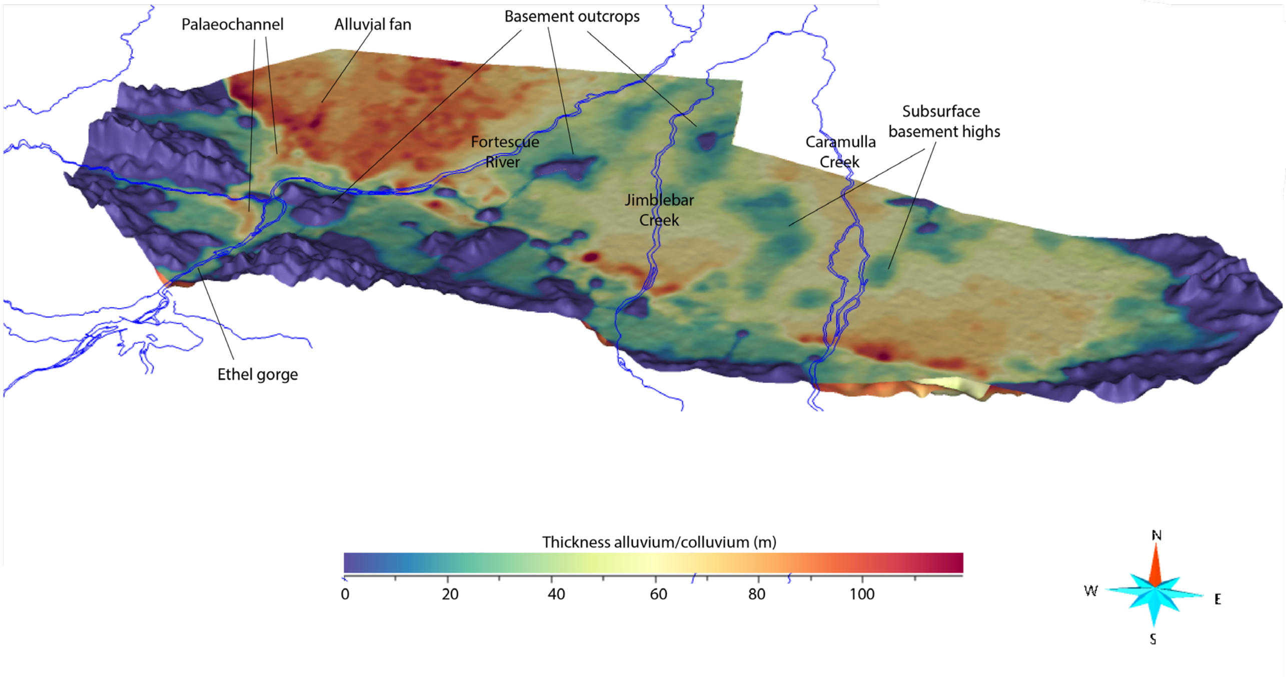

Figure 2-1 Isopach (thickness) map of the alluvium visualised in GoCAD-SKUA. Blue-purple colours indicate where the alluvium is absent (corresponding to basement outcrops). Adapted from Schmid et al. (2022)

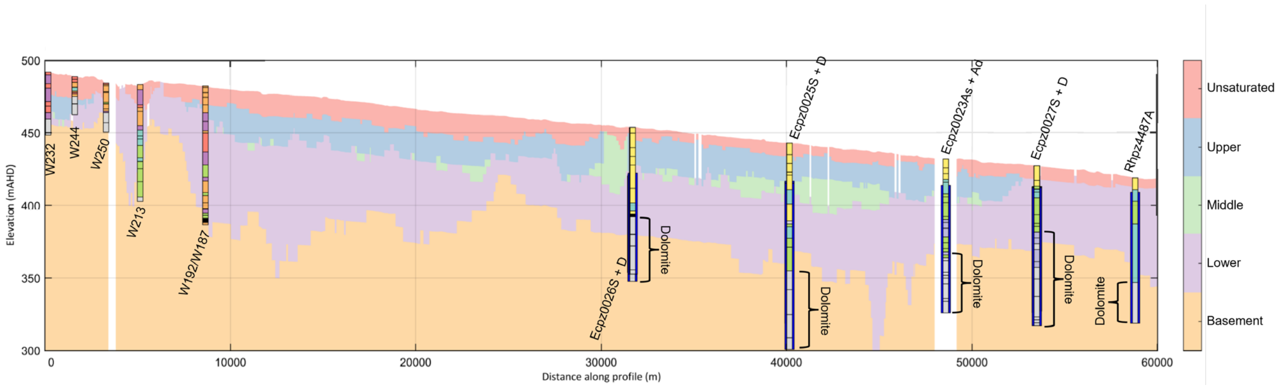

Figure 2-2 Aquifer layering interpreted from AEM survey transect (800001). The lithology of the 5 northernmost indicate that dolomite is overlain by alluvial sediments. Distance is from south to north from the apex of the alluvial fan towards the Fortescue Marsh, with the AEM transect location indicated in Figure 2-4.

2.2 Water balance

Groundwater is deep, particularly in the centre of the fan. Here the depth to groundwater table reaches 40 mBGL, which reduces to the north, closer to the Fortescue Marsh, the main regional groundwater discharge zone, and to the south, close to Ethel Gorge, the main groundwater recharge zone (Figure 2-3).

The thickness of the saturated layer of the alluvial aquifer reduces towards the groundwater discharge zone along the northern margins of the fan. This zone includes the southern edge of the Fortescue Marsh. The thickness is more than 70 m in the south and reduces to less than 50 m. However, in the northern areas, the alluvial deposits are underlined by Wittenoom Dolomite. As mentioned above, two formations are likely to compose a single saturated layer with unknown total thickness, but likely greater overall transmissivity than elsewhere in the study region due to dolomite karstification. Unfortunately, pumping tests, which would have been conducted near newly installed bores only, were not possible within the project timeline.

The recharge mechanism is associated with rainfall infiltration and localised recharge from the Fortescue River. This river also receives discharge generated by mine dewatering operations, both from BHP Billiton Iron Ore (controlled discharge to and from Ophthalmia Dam) and Rio Tinto (via Kalgan Creek).

Based on a review of the literature (Schmid et al., 2022) and analysis of environmental tracers (Donn et al., 2023), diffuse rainfall recharge is likely to be less than 10 mm/year. Recharge was also corroborated by Donn et al. (2023) using the chloride mass balance method, based on rainfall and groundwater quality data. Based on this method, long-term net recharge in the study region was estimated to be less than 2 mm/year. At the same time, the localised recharge is at least an order of magnitude greater, occurring at the apex of the Fortescue River alluvial fan. Based on the environmental tracer analysis, localised recharge here is likely to be greater than 40mm/year (Donn et al., 2023).

Groundwater flow paths follow the topographic gradients towards the north-west and from the southern apex of the Fortescue River alluvial fan. The flow rate is approximately 10 m/year, which is in agreement with groundwater modelling (Schmid et al., 2022) and analysis of tracers (Donn et al., 2023).

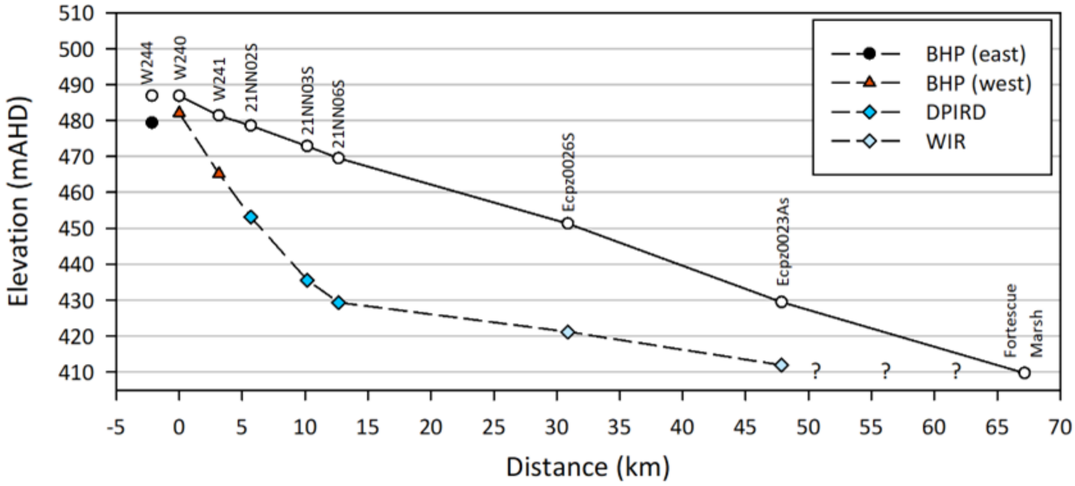

Figure 2-3 Groundwater-level elevations measured in October 2021

2.3 Groundwater quality

There is little ambient groundwater quality data in and around the MAR assessment focus area, and this is largely limited to groundwater salinity, with the distribution shown in Figure 2-4. Historical salinity data from the Department of Water and Environmental Regulation (DWER), Water Information Reporting (WIR) is clustered in the Ethel Gorge area and is largely in the range of 1,000–1,500 mg/L. However, this data was collected in the early 1980s and, as such, may not represent current groundwater salinities. Additional groundwater salinity data from the same source (DWER WIR) to the north of the study area shows slightly higher concentrations (1,500–2,000 mg/L). Recent sampling of shallow stock-water bores (DPIRD) shows lower salinity (<500 mg/L) along the Fortescue River, though salinity increases away from the influence of the river. Additional sampling by CSIRO (2021) from new and existing bores shows salinity predominantly in the 500–1,000 mg/L range, with salinity increasing along the flow path towards the Fortescue Marsh. A summary of samples collected from stock-water bores by DPIRD and groundwater bores by CSIRO are compared to water quality targets for agricultural use in Appendix A.2 (Apx Table A.1 and Apx Table A.2).

The 2019 stock-water bore census and CSIRO 2021 groundwater sampling indicate that groundwater is of mixed water type based on the major ion compositions (Apx Figure A.2), with lower salinity groundwater having lower proportions of sodium and chloride relative to the total cations and anions. However, sodium and chloride exceed sensitive crop targets where salinity is greater than ~500 mg/L TDS. The increase in the proportion of Na and Cl relative to other ions is potentially related to the deposition of carbonates, with calcite and dolomite saturation indices indicating saturation or supersaturation in the majority of groundwater samples (Donn et al., 2023). Compositionally, there is little difference between groundwater sampled from shallow and deep bores at the same location, indicating that the aquifer behaves as a single hydraulic unit.

Boron, total nitrogen, total phosphorus and reactive phosphorus also exceed target values in a small number of samples. Nitrate is the main nitrogen species, contributing to total nitrogen concentrations of up to 6.6 mg/L. This nitrate likely originates from near-surface biological fixation, which is subsequently flushed to the groundwater with recharge (Barnes et al., 1992), as nitrogen concentrations are low in the sole surface water sample analysed. Metal concentrations in the groundwater were generally low.

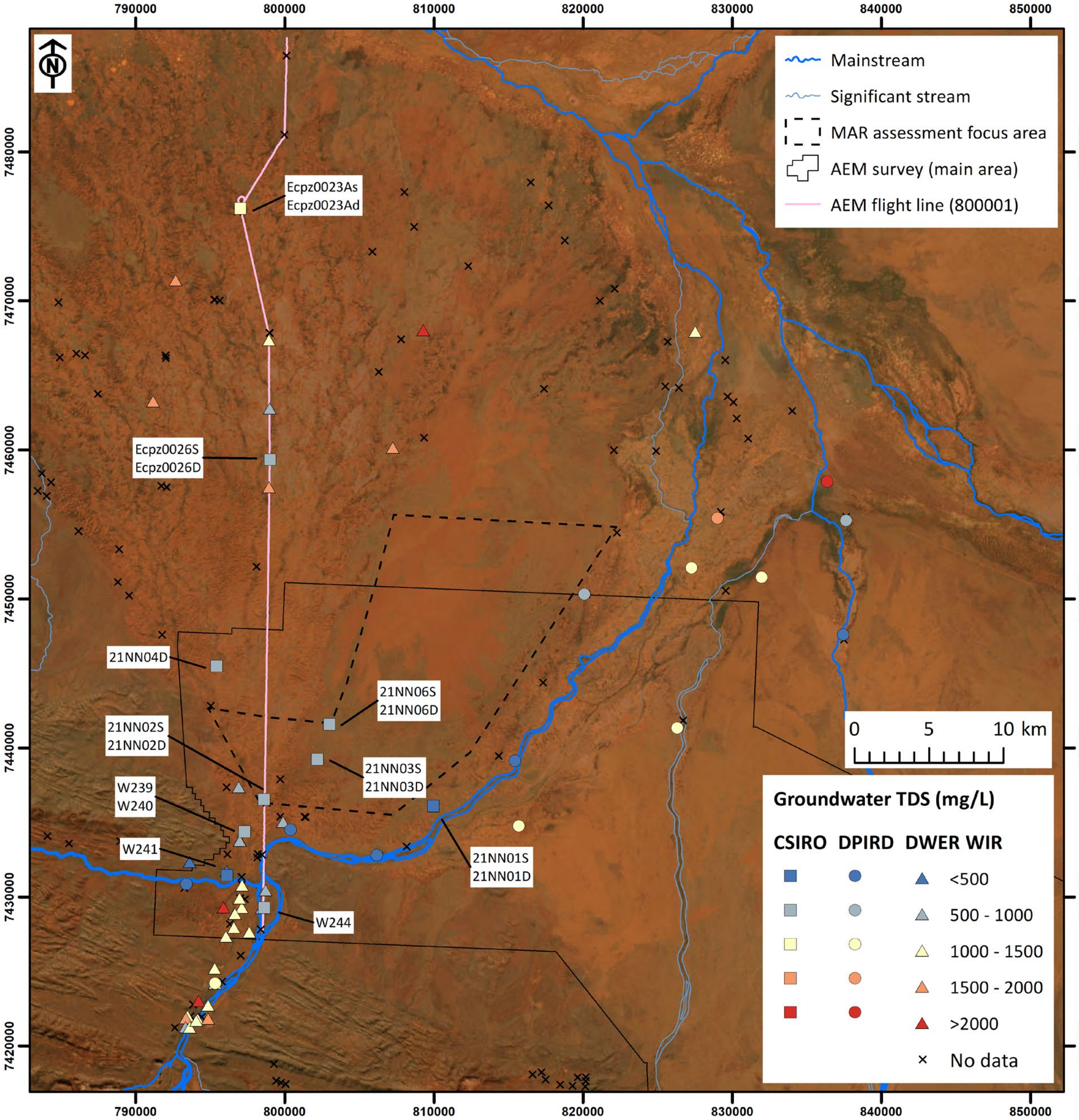

Figure 2-4 Distribution of groundwater salinity data from various sources. Sites sampled by CSIRO in October 2021 are labelled. The AEM survey area and focus area for MAR feasibility assessment are shown for reference.

2.4 Groundwater-dependent ecosystems

Significant environment assets exist in the vicinity of the study area, including Ethel Gorge and the Fortescue Marsh and associated management areas (Figure 1-2). However, within the immediate area of interest for MAR (MAR assessment focus area, Figure 2-5), groundwater-dependent vegetation or other groundwater-dependent ecosystems (GDEs) are unlikely to exist. According to the findings of the Pilbara Water Resource Assessment, only a few GDEs (soaks and pools) occur near the northern border of the study area, potentially indicating the presence of a groundwater discharge zone (Barron and Emelyanova, 2015).

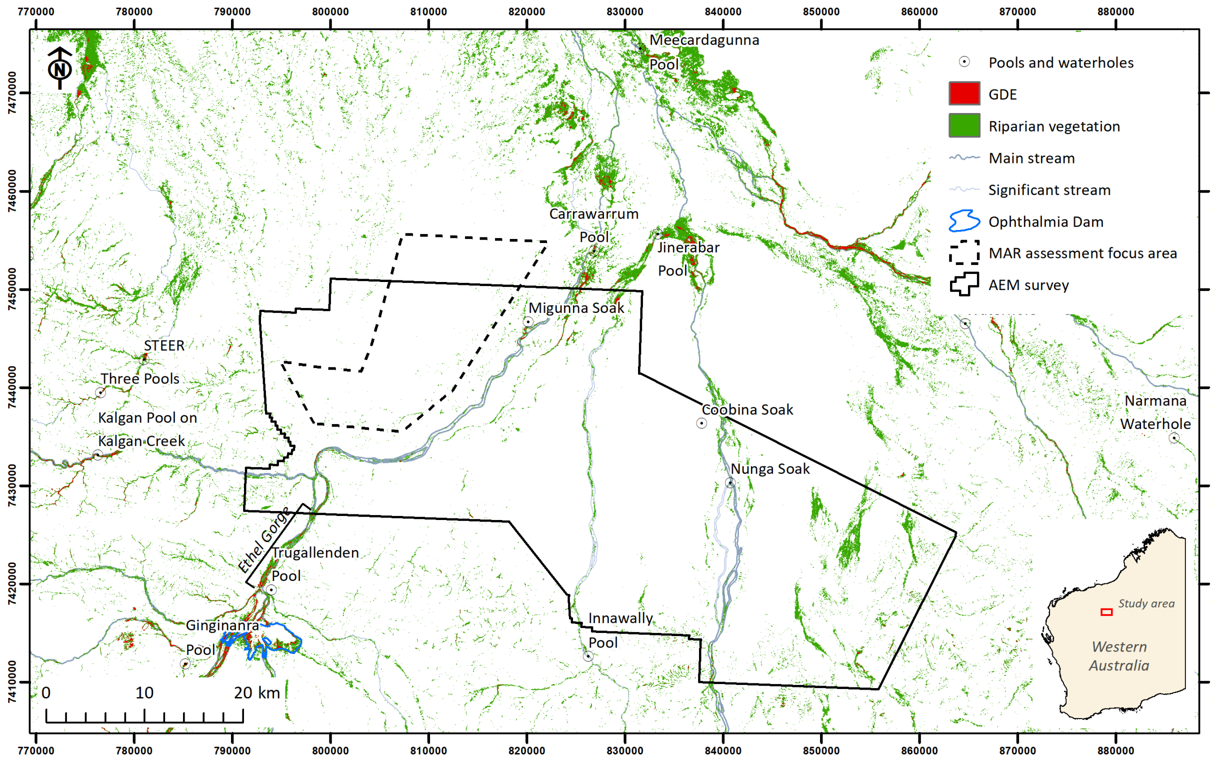

Figure 2-5 Riparian vegetation and groundwater-dependent ecosystems (GDEs) (soaks and pools) in the study area (Barron and Emelyanova, 2015)

2.5 Refinement of the MAR study area

Based on the AEM survey, Davis et al. (2021) identified several prospective areas for further investigations to validate relatively thick zones of low conductivity. These included areas on the Fortescue River alluvial fan (north of where the river runs west to east) and in the Jimblebar Creek area to the east. Due to resourcing constraints, the drilling program conducted to investigate these targets was restricted to sites on the Fortescue River alluvial fan. Thus, the MAR feasibility assessment was also restricted to this area, as verification of the AEM interpretation was not possible elsewhere due to the lack of existing bores.

In collaboration with the DPIRD project team, further constraints were considered, for either MAR implementation or suitability for irrigated horticulture, to further refine the MAR assessment area:

- The presence of soils suitable for irrigated agriculture – Most of the Fortescue River alluvial fan was classified in Class A1, i.e., land that has soil and landform characteristics that are rated as highly suited to irrigation making up more than 70% of its area (Figure 2-6) (Galloway et al., 2022).
- Suitable locations to store and recover water – As indicated above, the interpreted AEM data identified suitable locations to store and recover water based on the conductivity ranges and thicknesses (Davis et al., 2021).
- Protection of potential infrastructure (MAR and/or irrigation) – Avoiding the extreme flood hazard zone can help protect infrastructure (Figure 2-6).
- Maintenance of the natural groundwater flow regime – Irrigation and MAR zones should avoid areas within the Fortescue Marsh management zones (Figure 1-2) for which the management objectives state that the natural flow regime should be maintained (Environmental Protection Authority, 2013). This reduces risks to the environment from changes to the groundwater flow regime.
- Labour and transport availability – While outside the scope of this MAR risk assessment, the proximity of the prospective irrigation area to the town of Newman and a major transport route (Marble Bar Road / Great Northern Hwy) was also considered, in the context of labour supply and transport of crops to market.

The refined area selected for the focus area MAR risk assessment and the irrigation/MAR groundwater modelling scenarios of Schmid et al. (2022) is shown in Figure 1-2 and Figure 2-6.

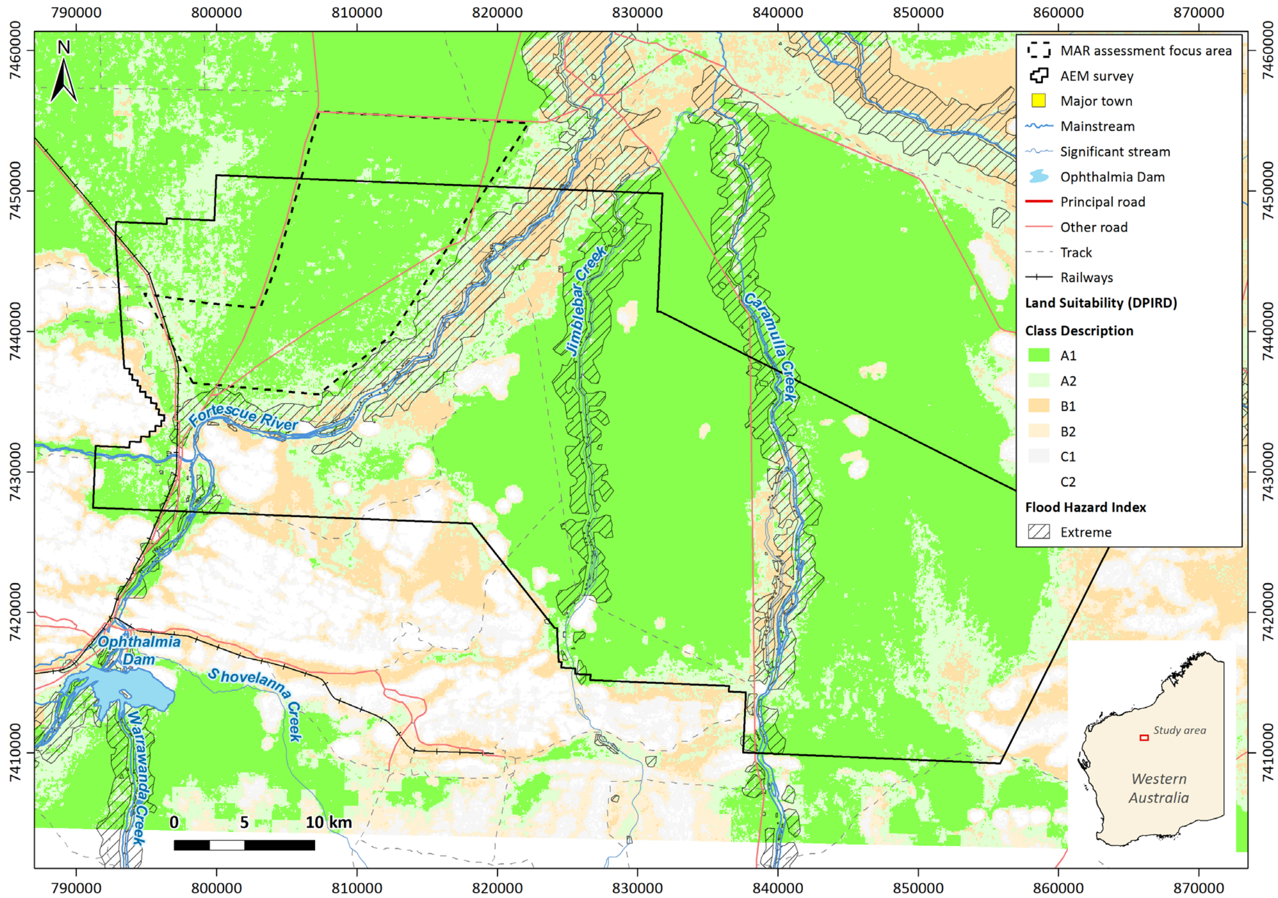

Figure 2-6 Soil suitability and extreme flood hazard risk in the Newman MAR feasibility assessment area

3 Groundwater model and MAR assessment scenarios

A conceptual numerical groundwater model was developed for the study area, encompassed by the coordinates: E:165000 N:7410000, and E:265000 N:7460000 (GDA94 zone 51). While this constitutes an area of 100 km by 50 km, the active model covers only 53% of this area (Figure 3-1). A single layer numerical model was developed based on the geological (bore stratigraphy) and geophysical data (AEM survey) and includes only the alluvial aquifer in the south-eastern part of the upper Fortescue River floodplain north of Ethel Gorge. The Fortescue Marsh is at least 30 km north of the model domain. Full details of the model development can be found in Schmid et al. (2022).

The groundwater model was used to assess likely aquifer hydraulic responses to MAR, with artificial recharge added directly to an unconfined alluvial aquifer within the model, without consideration of the method of introduction. The MAR modelling scenarios were limited to the MAR assessment focus area (Figure 3-1) with an emphasis in the south of this area and along the Marble Bar Road to limit potential impacts on the Fortescue Marsh. Modelled MAR scenarios were separated into two types:

- MAR with no agriculture – to assess impacts of high volumes of source water and the impact of longer-term water banking
- MAR with agriculture – 3 crops with different water requirements were assessed, with crop demand met first before the remaining water was directed to the aquifer as MAR or, if crop demands were not met, groundwater was abstracted.

The assessment considered a range of likely available mine dewater volumes (5–50 GL per year) assumed to be evenly distributed throughout the year, and a range of agricultural crops that are realistic representations of irrigated cropping options based on DPIRD's experience from field trials at Newman to date. Seasonal crop demands were used to calculate the water demand per hectare per month. These were then used to calculate the area under cropping, given the volume of source water available for each scenario.

For the no agriculture (MAR-only) case a range of source water volumes and MAR zone extents were tested resulting in a total of 24 scenarios based on combinations of the following:

- Source water volumes: 5, 10, 20, 30, 40, 50 GL/yr
- MAR zone extents: 100, 400, 900, 1600 ha

For scenarios that included agriculture the three crop types used were (1) winter maize for silage/summer fallow, (2) annual cropping rotation with oats (winter) and forage sorghum (summer) for hay, and (3) perennial cropping using lucerne for hay. A total of 126 MAR + agriculture scenarios were defined by the following:

- Cropping scenario: 1, 2, 3
- Source water volumes: 5, 10, 20, 30, 40, 50 GL/yr

- MAR zone extents: 100, 400, 900, 1600, 2500, 3600, 4900 ha

Further details on scenario development can be found in Schmid et al. (2022).

The results were used to explore risks and potential mitigation related to the extent of groundwater mound, waterlogging of the residual unsaturated zone above 3 mBGL (set by DPIRD as undesirable for agricultural reasons) and associated inundation risks. These results are discussed below with respect to MAR guidelines and in greater detail in Schmid et al. (2022).

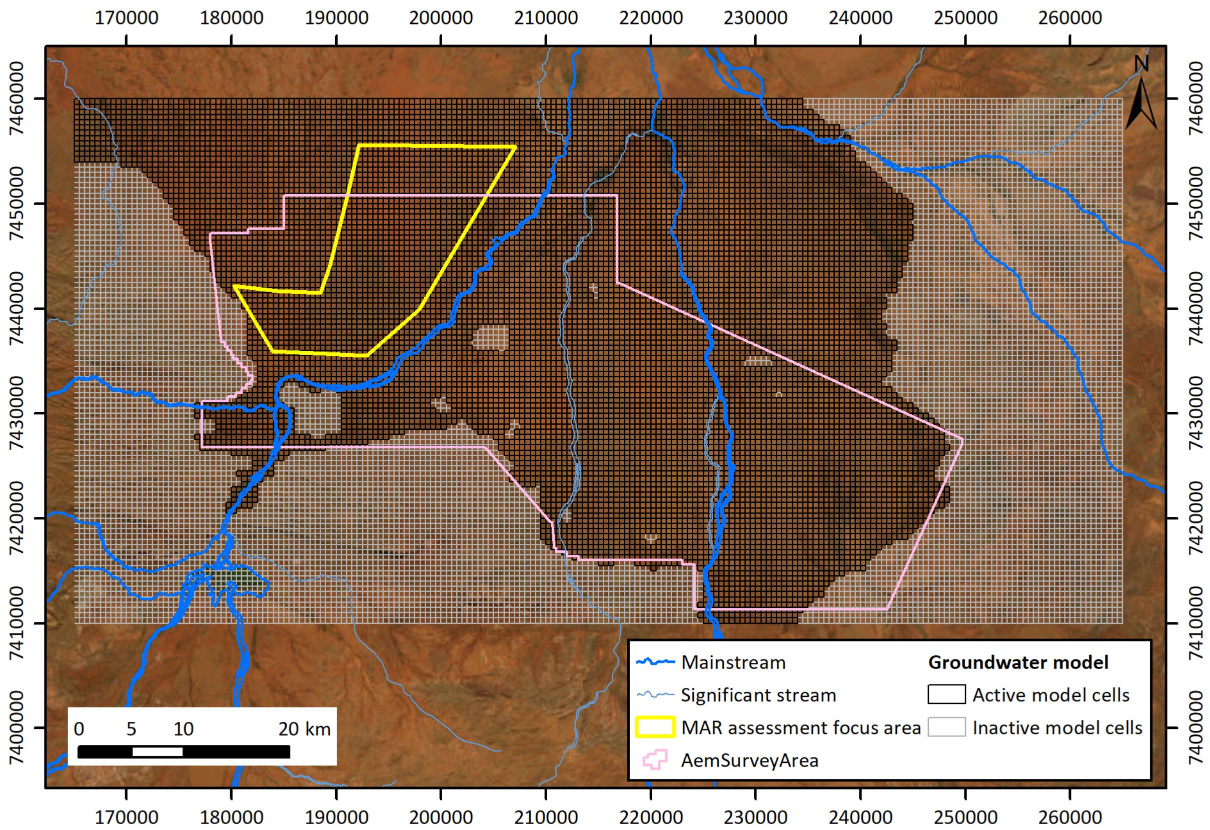

Figure 3-1 Extent of Newman groundwater model (Schmid et al., 2022), airborne electromagnetic survey area and MAR assessment focus area

3.1 Modelled aquifer hydraulic responses to MAR

Under natural conditions, the model predicted generally northerly groundwater flow. The time required for groundwater to travel from the southern extent of the alluvial fan to the Fortescue Marsh ~60 km to the north was in the order of hundreds of years. See pathlines in Figure 3-2, noting the Fortescue Marsh is a further 30 km north of the model boundary.

With no agricultural use of the source water (100% of water is stored in the aquifer), inundation resulting from the aquifer storage capacity being exceeded was observed when 20 GL/year was applied to a 100-ha recharge zone (Figure 3-3a). Increasing the MAR zone size, however, reduced the area of inundation. Further increases in recharge volumes (≥ 30 GL/year) resulted in increased inundation even at large (up to 1600 ha) MAR zone sizes (Figure 3-3b). However, based on particle tracking, groundwater travel times to the Fortescue Marsh were still several hundred years.

Since crop water requirements were met first in the agriculture scenarios, less water was available for MAR relative to a similar source water volume for the no-agriculture scenarios. On a month-to-month basis, water was either recharged when in excess of crop requirements or recovered to satisfy additional crop needs. For some scenarios, on an annual basis, the sum monthly recharge and recovery was equal, so no impact was observed on groundwater levels.

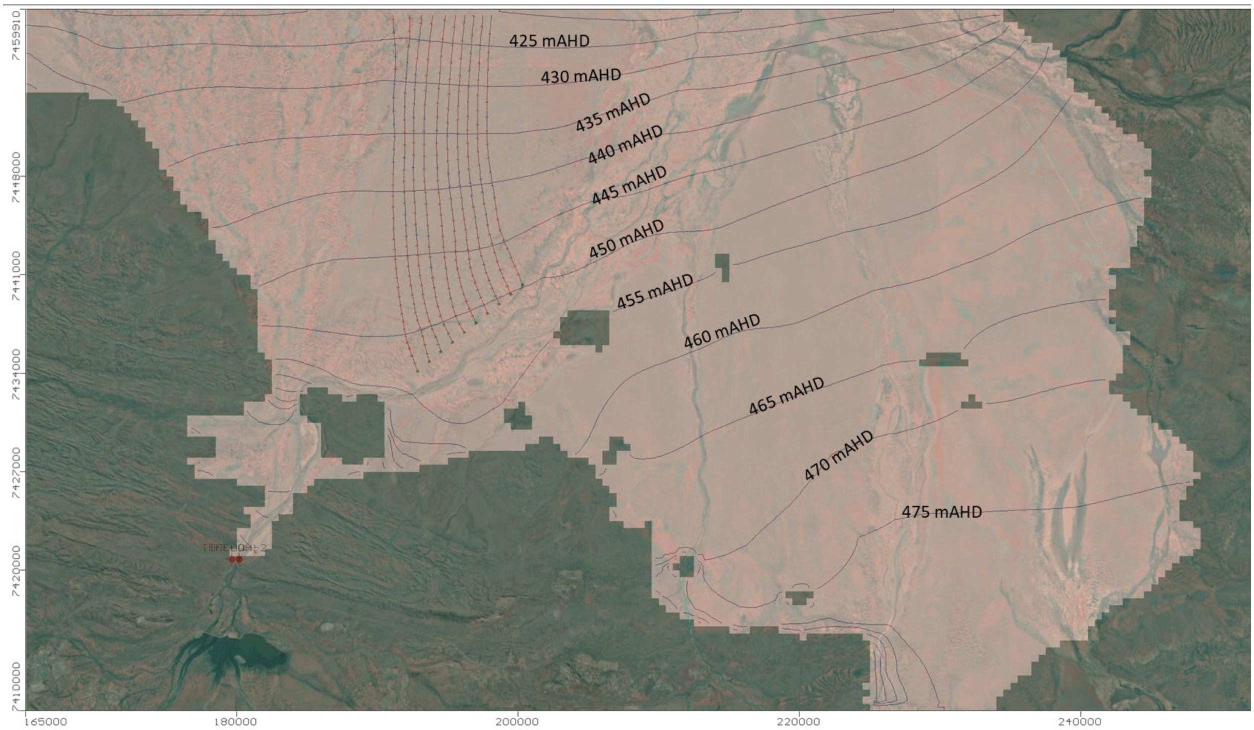

Figure 3-2 Flow field for steady-state run using final parameter values and (forward) pathlines obtained from advective particles. Each mark in each pathline represents a 10-year period. Source: Schmid et al. (2022) Figure 4-15,

However, in some MAR+agriculture scenarios more water was recharged than recovered on an annual basis. In these scenarios, groundwater tables rose over the 10-year modelling period. Changes in groundwater level were observed, especially with small MAR zones and relatively large water volumes, though these changes are reduced by increases to the MAR zone areas. If the total volume of water recharged via MAR was not subsequently recovered, inundation could occur, comparable to the no-agriculture scenarios where water is banked in the aquifer.

While the conceptualisation of the groundwater model did not include groundwater-surface water interaction, the groundwater mounds associated with MAR could interact with the Fortescue River to the south and east of the MAR zones. This mainly occurs when groundwater mounds form due to banking of mine dewater in the aquifer. An extreme example based on a no-agriculture scenario is shown in Figure 3-3b.

Also, with increasing MAR zone size, MAR water may also migrate beneath the Fortescue Marsh Management Zone to the northwest of the MAR assessment focus area (e.g. Figure 3-3b), especially if MAR water is banked within the aquifer.

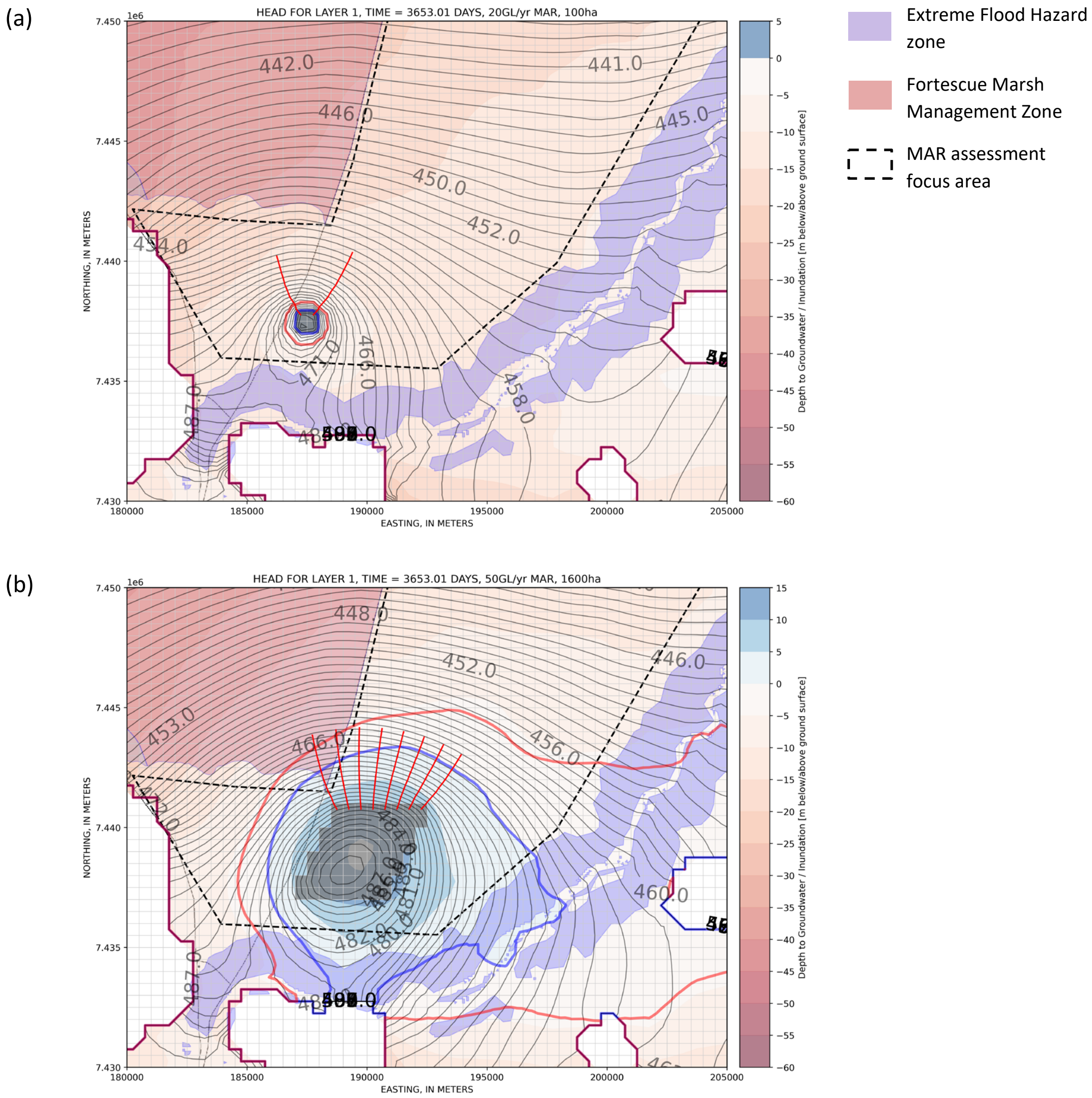

Figure 3-3 Aquifer response to a MAR volume for the no-agriculture scenario with (a) 20 GL/year delivered in a 100-ha MAR zone and (b) 50 GL/year in a 1,600-ha MAR zone. Blue contour lines contain area of inundation (expression of groundwater at ground surface), red contours indicate the waterlogged areas where groundwater is within 3 m of the ground surface, and red lines show the 10-year travel path for particles released from the northernmost cells of the MAR zone at time zero. Adapted from Schmid et al. (2022)

4 Source water quality

A BHP-supplied summary of mine water quality from three locations — Ophthalmia Dam, and mine dewater (Apx Figure A.3) derived from mining activities to the west and east of the Fortescue River — is compared to water quality targets for agricultural use in Appendix A.3 (Apx Table A.3, Apx Table A.4 and Apx Table A.5). Water quality targets for agricultural use include long-term and short-term trigger values for 100 and 20 years of irrigation, respectively, and livestock drinking water quality guidelines (ANZECC-ARMCANZ, 2000). Health guidelines are presented for consideration of the risk from ingestion of sprays from irrigation.

The median electrical conductivity (EC) for the three locations varies from 900 to 1700 µS/cm (~600–1,100mg/L) and the 95th percentile EC varies from 1,200 to 2,000 µS/cm (~800–1,300 mg/L TDS). Notably, this indicates that salinity may exceed targets for irrigation of moderately sensitive crops (1,400 µS/cm, see Appendix A.3) but is expected to be suitable for salt-tolerant crops and livestock watering which have a higher threshold.

The available data also indicates there is considerable variability in the salinity of dewater, though groundwater also shows a similar variability (Apx Figure A.4 and Apx Figure A.5).

While the various source waters have a mixed water type (Apx Figure A.4 and Apx Figure A.5), sodium and chloride exceed targets for sensitive crops at higher salinities (>~700 mg/L). However, both sodium and chloride concentrations are acceptable or marginally greater than the targets for moderately sensitive crops. Of the four crops suggested by DPIRD, maize, sorghum and lucerne are considered to be moderately tolerant crops (ANZECC-ARMCANZ, 2000) to both chloride and sodium with all source water samples falling below the respective guideline values (700 mg/L and 460 mg/L, respectively).

Aside from salinity, the data indicates some potential for high phosphorus, along with high pH and iron from Ophthalmia Dam only. The 95th percentile phosphorus concentration in water from the eastern mining operations exceeds only the stringent long-term trigger value guideline of 0.05 mg/L to minimise bioclogging of irrigation equipment only. Higher values were reported for Ophthalmia Dam, falling within the range given for the short-term trigger value for phosphorus of 0.8–12 mg/L. This highlights the need to consider the impacts of phosphorus on crop yield, though, considering the high iron oxide content of the soils, phosphorus impacts may be reduced due to adsorption.

Source water iron concentrations should be examined in relation to crop toxicity and the risk of aquifer clogging due to filtration (particulate iron) or precipitation (soluble iron).

High pH should be assessed in relation to the potential for fouling of agricultural systems or the aquifer itself (i.e. chemical clogging in the aquifer due to precipitation of carbonate minerals). Preliminary geochemical assessment indicates the source water is saturated with respect to carbonate minerals, with saturation indices >1 for calcite, aragonite and dolomite.

Part 2 MAR risk assessment

The following risk assessment addresses Section 3.2 (*risk assessment*) in the WA MAR Guidelines (Department of Water and Environmental Regulation, 2021a). The feasibility of MAR is being investigated as an option for irrigated agriculture in the region since high evaporation rates result in the loss of water and evaporative concentration of mine dewater stored in Ophthalmia Dam. In addition to this increased iron ore mining is increasing the volume of dewater above the 25 GL capacity of Ophthalmia Dam. As this is a regional pre-feasibility assessment of MAR potential, there is insufficient information available to undertake a *hydrogeological assessment* (Section 3.1 of the guidelines) or provide information on the *operating strategy* (Section 3.3 of the guidelines). Further to this the lack of soil infiltration or aquifer pump test data only a general MAR setup is considered without assessment of the most appropriate method of recharge.

5 Risk-based MAR scheme development

5.1 Risk assessment methodology

This assessment of MAR feasibility using mine dewater is guided by the National Water Quality Management Strategy and, in particular, the *Australian guidelines for water recycling: Managed aquifer recharge* (‘the MAR Guidelines’) (NRMMC-EPHC-NHMRC, 2009) and the *Australian and New Zealand Guidelines for fresh and marine water quality* (‘the ANZECC guidelines’) (ANZECC-ARMCANZ, 2000). The MAR Guidelines guide the development of the MAR scheme, which is outlined below (Section 5.1.1) along with any additional state specific guidance (Section 5.1.2).

5.1.1 Australian MAR Guidelines

The MAR Guidelines apply a staged approach to risk-based project development (Figure 5-1).

Stage 1 is an entry-level assessment using existing information to determine the viability and likely degree of difficulty associated with project development and the information requirements to proceed with the next stage of assessment. The simplified assessment process is intended for small-scale projects with low inherent risk (i.e. domestic-scale projects for non-potable use) and is not applicable to the scale of project under investigation here.

Stage 2 is an iterative process of investigations and risk assessment to identify risks and appropriate preventative measures to reduce these risks to an acceptable level. Stage 2 concludes with a pre-commissioning residual risk assessment. Potential schemes of low residual risk can proceed to Stage 3, which is construction and commissioning of a MAR scheme, and then finally Stage 4, operation under a risk management plan.

This assessment of the feasibility of MAR using mine dewater for agricultural water supply aims to progress through Stage 1 and Stage 2 of the MAR Guidelines. However, as there is insufficient data to complete the Stage 1 and Stage 2 assessment process, this report instead demonstrates the assessment process using available data, to identify the knowledge gaps for further assessment. Theoretical sites considered for the Stage 2 assessment were informed by new borehole installation and groundwater modelling within the MAR assessment focus area.

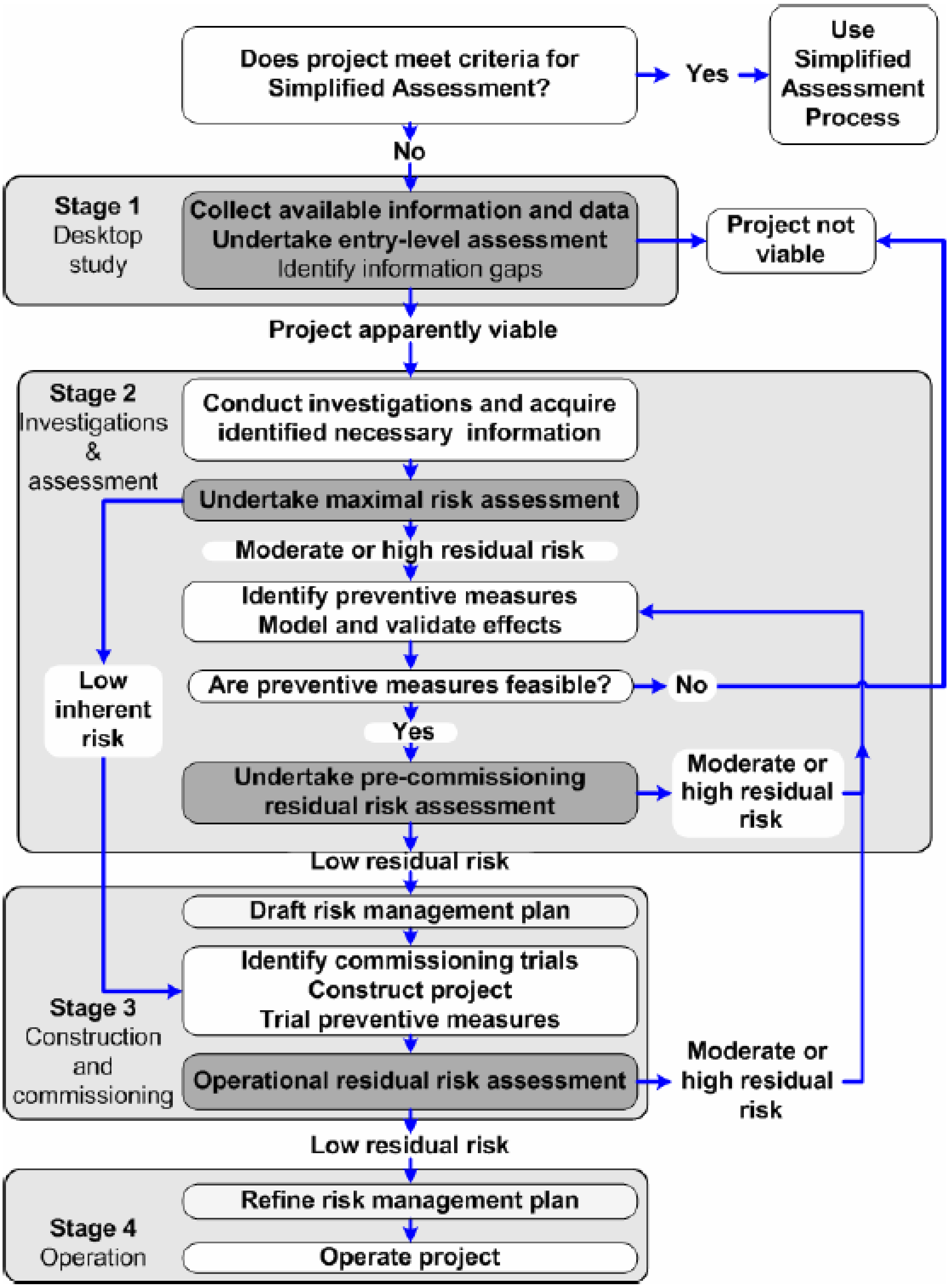

Figure 5-1 Risk assessment stages in MAR scheme development (NRMMC-EPHC-NHMRC, 2009)

Water quality target values

The water quality of potential source water for MAR and ambient groundwater quality was compared to appropriate water quality target values to assess risks associated with intended use/s. While the intention is for recovered water to be used for agricultural irrigation, livestock watering suitability was also assessed.

The ANZECC guidelines address water quality requirements for environmental protection relevant to agricultural use (i.e. crop, soil, livestock, receiving water bodies, aquifer). The ANZECC Guidelines have recently been updated to a web-based framework (ANZG, 2018), but the update refers to the water quality guidance for primary industries in the previous version (ANZECC-ARMCANZ, 2000).

Other impact pathways are the risk to human health through ingestion of food crops or irrigation sprays. For this purpose, the *Australian Drinking Water Guidelines* provide water quality requirements for human health protection (NHMRC-NRMMC, 2011).

Comparing 95th percentile values (or 5th percentile values for acidic pH) to water quality target values is a conservative approach to risk management. For some hazards, an indicative water quality target was adopted for use in this assessment. For example, the risk associated with the salinity of irrigation water depends on the soil and crop type and, therefore, salinity targets for sensitive and moderately sensitive crops used here were estimated using a leaching fraction of 0.33 (loam and light clay soils) (Figure 5-1). Site-specific soil and crop-specific requirements should be considered in latter stages of feasibility assessment.

Table 5-1 Plant salt-tolerance categories in relation to irrigation water salinity for loam and light clay soils with a leaching fraction of 0.33

Plant salt-tolerance groupings	Average root zone salinity EC_{SE}(DS/M)	Water or soil salinity rating	Irrigation water salinity, assuming leaching factor 0.33		Example crop species within salt-tolerance groupings
			EC (µS/cm)	~TDS (mg/L)* based on EC	
Sensitive crops	<0.95	Very low	<690	<500	turnip
Moderately sensitive crops	0.95–1.9	Low	690–1,400	500–1000	almond, grape, onion, potato, bean, carrot, lettuce
Moderately tolerant crops	1.9–4.5	Medium	1400–3300	1000–2000	date, fig, olive, cucumber, brassicas, peanut, tomato, lucerne
Tolerant crops	4.5–7.7	High	3300–7000	2000–5000	cotton, rhodes grass, sorghum, wheat zucchini
Very tolerant crops	7.7–12.2	Very high	7000–8900	5000–6000	barley, pistachio, ryegrass

EC_{se}=electrical conductivity of soil extract; * estimated using EC (µS/cm) x 0.67=TDS (mg/L) (ANZECC-ARMCANZ 2000)

Components of a MAR scheme

The MAR Guidelines describe 7 components that can be identified within any MAR scheme, regardless of the type of scheme (NRMMC-EPHC-NHMRC 2009). They recognise that MAR can be incorporated with engineered treatment within a treatment train. Each component represents a step where water quantity or quality impacts can be assessed and managed as required. It is not necessary that each of the 7 components is required for a specific MAR scheme; for example, treatment prior to recharge or end use may not be necessary. These 7 components are described in Table 5-2 and illustrated in Figure 5-2 for an infiltration basin and an injection well scheme.

Table 5-2 The 7 components of every MAR scheme

Component	Example
1. Capture zone	• Mine dewater point/s or pipeline • Ophthalmia Dam
2. Pre-treatment	• Detention to allow for sedimentation of particulate matter • Engineered treatments (filtration) to produce source water suitable for recharge
3. Recharge	• Infiltration basin/s • Injection bore/s
4. Subsurface storage	• The aquifer that water is stored in and where passive treatment may occur
5. Recovery	• Recovery bore • Intentional discharge to a groundwater-dependent ecosystem
6. Post-treatment	• Engineered treatments to produce water suitable for its intended use (most applicable to drinking water supply)
7. End use	• Irrigation • Aquatic ecosystem support

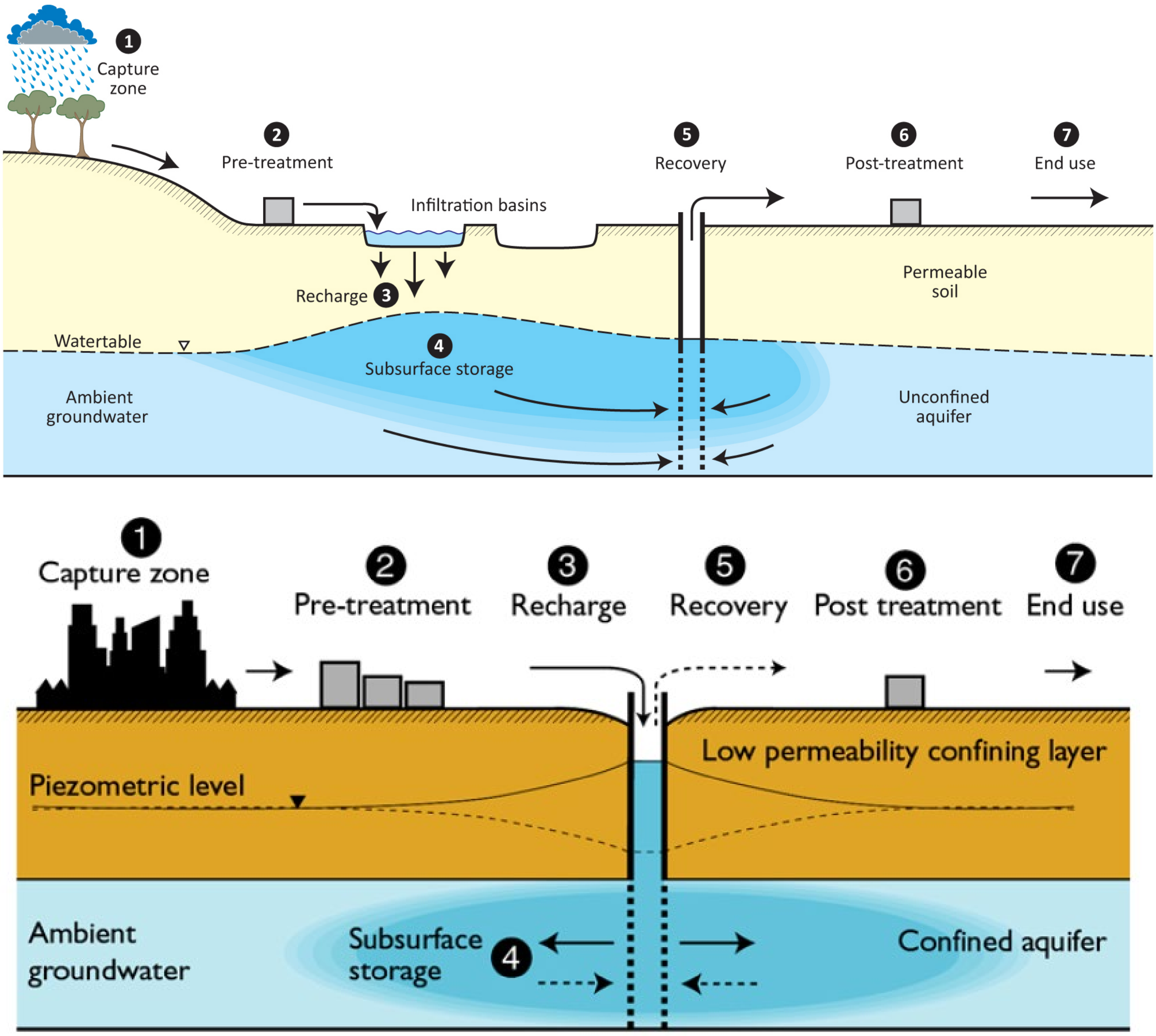

Figure 5-2 Schematic diagram of an infiltration basin and an injection well scheme. The 7 components can be described for all MAR schemes. Each represents a step where water quantity or quality impacts can be assessed and managed as required. The components are described in Table 5-2.

5.1.2 Western Australia MAR Guidelines

The Western Australia Department of Water and Environmental Regulation, DWER, has developed a policy and guidelines to facilitate the approval of socially and environmentally acceptable MAR proposals (‘the WA MAR Guidelines’) (Department of Water and Environmental Regulation, 2021b; 2021a). The WA MAR Guidelines adopt a risk management framework consistent with the national guidance (see Section 5.1) and incorporating state legislative requirements. This policy states that scheme approval will only be granted “provided potential impacts on the environment, water uses, and public health are determined to be acceptable” (Department of Water and Environmental Regulation, 2021b).

Storage of dewatering excess into an aquifer and subsequent abstraction for use is covered by the WA MAR Guidelines, though the specifics of any proposed scheme will have to be assessed. The WA Guidelines are specific to the current water and environmental legislation in Western Australia and are consistent with the MAR Guidelines, which address risks to public health and the environment.

Selected requirements of the WA MAR Guidelines were assessed in addition to the risk assessment under the national guidelines. The aim was to describe the implications of the WA MAR Guidelines for development of MAR using mine dewater for agricultural use in the vicinity of Newman, while identifying knowledge gaps for further assessment.

5.2 Stage 1 Entry-level risk assessment

The Stage 1 entry-level assessment consists of (i) viability and (ii) degree of difficulty assessments. The viability assessment is a screening tool to assess the basic requirements for MAR and indicates that MAR using mine dewater in the assessment area is viable (Table 5-3).

Table 5-3 Entry-level assessment part 1 - viability

Attribute	General response related the MAR assessment focus area
1 Intended water use	
Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	Yes – water resource to support economic development, specifically irrigated agriculture
2 Source water availability and right of access	
Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	Yes – mine dewater or surface water from Ophthalmia Dam Distance from source water to MAR scheme and end use is an economic consideration. It is unclear as to the consistency of supply and water quality from Ophthalmia Dam varies seasonally.
3 Hydrogeological assessment	
Is there at least one aquifer at the proposed MAR site capable of storing additional water?	Yes – surficial aquifer of the Fortescue River alluvial fan, which may be connected to the karstic aquifer in the Wittenoom Formation >100 m deep in the study area
Is the project compatible with groundwater management plans?	Yes – assessment area does not intersect groundwater protection area proscribed by the Newman Water Reserve (PDWSA, Department of Water (2014)), and environmental value of aquifer is primary industries
4 Space for water capture and treatment	
Is there sufficient land available for capture and treatment of the water?	Yes – mine dewater is an available waste stream that is already captured as it requires management/disposal, and the assessment area is undeveloped
5 Capability to design, construct and operate	
Is there a capability to design, construct and operate a MAR project?	Yes – consultants can be engaged as required
	If Y to all, continue to entry level assessment part 2

The degree of difficulty assessment is intended to provide information about the amount of effort in investigations required to achieve public health and environmental approvals. It is useful as an early warning of the nature of investigations required. For this assessment, the degree of difficulty assessment (Table 5-4) has been used to highlight:

- where sufficient information exists (green highlight)
- where additional information is required to determine if interventions will be required to support scheme approval (amber highlight)
- where existing information identifies a risk to be managed and additional information is required to inform the intervention strategy (red highlight).

Table 5-4 Entry-level assessment part 2 - degree of difficulty

Question	General response related to 2 potential locations for MAR
1 Source water quality with respect to groundwater environmental values	
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Yes – source water salinity is of similar range to the ambient groundwater. Seasonality of source water needs to be assessed.
2 Source water quality with respect to recovered water end use environmental values	
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	No – salinity, Cl, Na, P, Fe (Ophthalmia Dam), and pH (Ophthalmia Dam) can exceed irrigation targets. Source-specific quality data is required for mine dewater. Seasonality of source water and impact of surface storage (i.e. Ophthalmia Dam) needs to be assessed.
3 Source water quality with respect to clogging	
Is source water of low quality, for example any of: total suspended solids, total organic carbon and total nitrogen >10 mg/L, And is soil or aquifer free of macropores?	Yes - source water can be low quality (total suspended solids (TSS) >10 mg/L). Soil properties are uncertain, though the alluvial aquifer is unlikely to contain macropores. Source-specific quality data is required for mine dewater. Seasonality of source water and impact of surface storage (i.e. Ophthalmia Dam) needs to be assessed.
4 Groundwater quality with respect to recovered water end use environmental values	
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No – salinity, Cl, Na, N, P, Fe and B can exceed irrigation targets. However, ambient groundwater quality was assessed over a large area. Further site-specific ambient groundwater quality data is required to fully assess this.
5 Groundwater and drinking water quality	
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – not in the assessment area
6 Groundwater salinity and recovery efficiency	
Does the salinity of native groundwater exceed: (a) 10,000 mg/L, or (b) the salinity criterion for uses of recovered water?	(a) No (b) Yes - salinity exceeds sensitive crop limit (690 µS/cm / 343 mg/L) in 85% of groundwater samples (n = 32) and exceeds moderately sensitive crop limit (1400 µS/cm / 705 mg/L) in 47% of samples. Further site-specific groundwater quality and crop sensitivity data is required to fully assess the salinity constraints on recovery efficiency.
7 Reactions between source water and aquifer	
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	Unknown – pH can be high in source water, redox status of groundwater varies (DO 0–7.9 mg/L), nitrate was present in both the source water (temporally variable) and groundwater (spatially variable), and phosphorus is high in the source water. Further site-specific groundwater quality data, aquifer mineralogy and geochemistry, and source-specific quality data for mine dewater is required to fully assess this.
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries	
Are there other groundwater users, groundwater-connected ecosystems or a property boundary near (within 100-1000 m) the MAR site?	Unknown. Specific MAR location/s are yet to be determined. Groundwater is used for stock watering (unlicensed). Connectivity to groundwater-connected ecosystems is unknown, though modelling indicates that groundwater

Question	General response related to 2 potential locations for MAR
	mounds may interact with the Fortescue River depending on the location and operation of the MAR scheme.

9 Aquifer capacity and groundwater levels	
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Unconfined, watertable depth varies from ~5 mBGL to ~40 mBGL across the study area with shallower groundwater tables closer to Ethel Gorge. The impact will depend on the location and operation of the MAR scheme and irrigated agriculture.
10 Protection of water quality in unconfined aquifers	
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No
11 Fractured rock, karstic or reactive aquifers	
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Unknown – connection to karstic aquifer (Wittenoom Formation >100 m deep for bores installed in 2021) and geochemistry of the whole aquifer sequence is unknown (no data collected).
12 Similarity to successful projects	
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	Yes – to the north but within the Pilbara groundwater allocation plan area
13 Management capability	
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – water and environmental risk management
14 Planning and related requirements	
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	Unknown, land planning changes may be required to alter the land use from the current pastoral lease to one appropriate for MAR

5.3 Stage 2 Investigations and risk assessment

Stage 2 of the MAR Guidelines assessment process is an iterative process of investigations and risk assessment to identify risks and appropriate preventative measures to reduce these risks to an acceptable level. Stage 2 concludes with a pre-commissioning residual risk assessment.

The entry-level assessment identified several aspects that require additional information to assess requirements for interventions or preventative measures, as follows:

- Water quality evaluation of suitability for irrigation end use
    - source-specific source water evaluation, including the impact of storage (if applicable) and seasonality
    - ambient groundwater, with respect to spatial variability and to investigate whether quality varies temporally
- Water quality evaluation for clogging risk and treatment requirements
- Geochemical evaluation to assess reactions between source water and aquifer, and implications for irrigation use or clogging
- Hydrogeological evaluation to assess potential impacts on other groundwater users, connectivity to groundwater-connected ecosystems or the underlying karstic aquifer, and losses to the aquifer due to recovery efficiency.

However, these investigations are site-specific and, first, the potential MAR scheme locations and types (i.e. injection versus infiltration) needs to be determined, the source water availability and volumes need to be quantified, and crop type and their specific water quality requirements need to be understood.

In the interim, this report uses existing information and data produced as part of the TAP project to demonstrate the maximal risk assessment process for the focus area for MAR feasibility assessment. This process determines the inherent risk in the absence of any preventative measures and aims to further identify the aspects of the potential schemes that require additional information. Undertaking a preliminary maximal risk assessment at this early stage in development aims to maximise the opportunity to collect necessary information to progress beyond this regional assessment.

5.4 Maximal risk assessment

The maximal risk assessment addresses both water quality hazards, hydrogeological hazards and those associated with energy use. These are briefly summarised in Table 5-5, followed by additional information for each of the MAR hazards.

Seven water quality hazards — pathogens, inorganic chemicals, salinity/sodicity, nutrients, organic chemicals, turbidity/particulates and radionuclides — were assessed using BHP-supplied water quality data for the two mine dewater sampling locations (western summary in Apx Table A.3; eastern summary in Apx Table A.4) and for water from Ophthalmia Dam (3 sites combined; summary in Apx Table A.5).

Groundwater quality data (Section 2.3) used for this assessment was obtained from existing data sources or collected as part of this study. Due to data limitations and the broad scale of the MAR assessment focus area, the maximal risk assessment could only be partially completed.

The hydrogeological hazards are assessed using literature data and data produced as part of the TAP project.

Table 5-5 Partial maximal risk assessment summary for Newman MAR using mine dewater (based on BHP-supplied existing water quality data for western and eastern dewater locations and water from Ophthalmia Dam)

MAR Hazards	**Maximal risk assessment – mine dewater**		
	Endpoints: pathway		
	Human (spray ingestion, consumption food products): irrigation	**Environment (soil and crops): irrigation**	**Environment (aquifer): MAR**
Pathogens – No data available for source water or groundwater, pathogens unlikely in mine dewater (groundwater) but may be introduced during surface storage (Ophthalmia Dam). Ophthalmia Dam water is prone to contamination by a range of viruses, bacteria, toxic algae and other harmful microorganisms (Shire of East Pilbara, 2020). Groundwater in unconfined aquifers may be contaminated by livestock grazing, though the likelihood is low due to the low stocking rates (except around stock watering points where cattle congregate), and thick unsaturated zone where attenuation may occur.	**U**	**L**	**L**
Inorganic chemicals – Mine dewater can exceed Cl, Na P, Fe, pH targets for irrigation. Other inorganic chemical concentrations in dewater generally meet targets for irrigation. For groundwater, Cl, Na, P and B exceed targets for irrigation. The potential for inorganic chemicals to mobilise from the aquifer following storage and recovery is an unknown to be addressed.	**L**	**H**	**U**
Salinity and sodicity – Mine dewater and groundwater can exceed electrical conductivity / TDS targets for moderately sensitive crops and groundwater salinity is brackish at a number of locations in the study area. Salinity is considered low risk for ingestion due to small volume/frequency. Further analysis of the soils is required to determine if they are sensitive to sodicity-related issues.	**L**	**H**	**U (location dependent)**
Nutrients: nitrogen, phosphorous and organic carbon – Phosphorus may affect crop yield or result in bioclogging of irrigation infrastructure.	**L**	**H**	**L**
Organic chemicals – No data for mine dewater, Ophthalmia Dam water or groundwater.	**U**	**U**	**U**
Turbidity and particulates – In mine dewater or released from the aquifer as a result of MAR operations, they may cause clogging of aquifer or irrigation infrastructure.	**L**	**U**	**H**
Radionuclides – Gross alpha and beta screening in 1 sample < target value; needs to be confirmed in additional samples.	**U**	**U**	**U**
Pressure, flow rates, volumes and groundwater levels – Groundwater model indicated that inundation may occur if MAR zone is too small. Initial analysis of high frequency water levels indicate that deep bores may be			**U**

MAR Hazards	Maximal risk assessment – mine dewater Endpoints: pathway		
	Human (spray ingestion, consumption food products): irrigation	Environment (soil and crops): irrigation	Environment (aquifer): MAR
confined. Further hydrogeological characterisation is required to determine if confining beds/layers exist in alluvium and the type of MAR required (injection versus infiltration). Additional data is required to refine the groundwater model and reduce uncertainty.			
Contaminant migration in fractured rock and karstic aquifers – The alluvial aquifer is thick (at least 100 m). Its connection with fractured dolostone and fault zone/s remains uncertain in the south of the Fortescue River alluvial fan, though unlikely to impact shallow MAR schemes.			**U**
Aquifer dissolution and stability of well and aquitard – Needs hydrogeological and geochemical characterisation, though is unlikely to be a concern in siliceous aquifers. Confining beds/layers were indicated in initial analysis of high frequency water levels, though further investigation is required to assess the spatial continuity within the alluvial aquifer.			**U**
Aquifer and groundwater-dependent ecosystems – Needs hydrogeological characterisation and a more detailed groundwater model that includes surface water interaction to assess impact.			**U**
Energy demand and greenhouse gas generation – Unable to assess as the MAR scheme design has not been conceptualised, hence not assessed under this risk assessment.			**U**

L low risk; **U** unknown risk; **H** high risk

Pathogens

Pathogens can pose a risk to human health through ingestion of spray during irrigation or consumption of food crops irrigated with contaminated source water. No data was available for microbial hazards in source water or groundwater. It is unlikely that mine dewater (extracted from confined aquifers) contains pathogen hazards, but surface storage (i.e. Ophthalmia Dam) may introduce microbial hazards (Shire of East Pilbara, 2020). Pathogen risks are uncertain and require confirmation of source water and groundwater quality. Preventative measures to reduce the risk of pathogenic hazards include reducing exposure (i.e. limiting public access during irrigation, subsurface irrigation) and water treatment (disinfection).

Inorganic chemicals

Inorganic chemical hazards include major ions, metals, metalloids and gases. Available water quality data indicates that source water and groundwater may, on occasion, exceed chloride and sodium targets for sensitive and moderately sensitive crops (Appendix A.2 and A.3). The data also indicates some potential for high phosphorus, iron and pH.

Other inorganic chemical concentrations (e.g. heavy metals) in mine dewater and in groundwater samples generally meet targets for irrigation. However, the potential for mobilisation of inorganic chemicals from the aquifer sediments is unknown and needs to be investigated on MAR site-specific aquifer sediments.

Inorganic chemical concentrations typically meet the health-based targets for drinking water, which is relevant to ingestion of sprays. Despite unknown potential for mobilisation of inorganic chemicals from the aquifer, inorganic chemicals are considered a low risk for ingestion due to the small volume and low frequency of potential ingestion.

Salinity and sodicity

It is likely that mine dewater will exceed the salinity target for sensitive and moderately sensitive crops. Groundwater salinity is spatially variable — fresher groundwater is associated with recharge from the Fortescue River, while brackish groundwater occurs in the Fortescue River alluvial fan aquifer. The impact of mixing between source water and groundwater on the quality of water to be recovered for irrigation remains to be assessed, pending further MAR site selection and the spatial/temporal variability in the source water and the spatial variability in the groundwater.

It will be necessary to understand the temporal and spatial variability in salinity of the source water available for MAR, as it may be necessary to set salinity limits for use in MAR and agriculture. Salinity limits may restrict the use of source water from Ophthalmia Dam at certain locations or at certain times of the year. Salinity and sodicity impacts of irrigating with mine dewater require further evaluation and must consider the irrigation water quality, soil properties, rainfall, irrigation demand, leaching fraction, root zone salinity, plant response and watertable management (ANZECC-ARMCANZ, 2000).

Salinity is considered a low health risk for ingestion due to the small volume and low frequency of potential ingestion.

Nutrients: nitrogen, phosphorus and organic carbon

Phosphorus concentrations may affect crop yield or result in bioclogging of irrigation infrastructure.

Organic chemicals

There was no data available for organic chemical concentrations in mine dewater, in water from Ophthalmia Dam or in groundwater. This risk remains to be assessed. However, given the remote location and the likely absence of widespread use of pesticides, herbicides and other organic chemical and industrial activities, the risks may be low.

Turbidity and particulates

Particulates are likely to be present in mine dewater and may also be released from the aquifer. Particulates and turbidity may cause clogging of the aquifer or irrigation infrastructure. Management strategies for clogging include prevention (or minimisation) through treatment (i.e. filtration or sedimentation) or remediation (i.e. periodic scraping of the infiltration basin surface or well backflushing). Prevention is recommended but may need to be complemented by some level of remediation.

Radionuclides

Gross alpha and beta radionuclide screening were reported for one sample of mine dewater, suggesting that the risk of radionuclide hazards in the source water is low. However, this remains to be confirmed through additional source water and groundwater samples.

Pressure, flow rates, volumes and groundwater levels

The target aquifers for MAR are thought to be unconfined, and, while the presence of clay layers was confirmed in the lithology logs, their extent and continuity remains to be determined. In addition, analysis of high frequency water level monitoring data indicated that deep bores in the study area were likely to be confined (Donn et al., 2023), which may affect the MAR opportunities. Pump tests should be conducted to determine whether the clay layers observed and water level analysis relate to confinement within the alluvial aquifer.

When considering the potential for lower cost MAR in unconfined aquifers, shallow watertables (<4 mBGL) should be avoided due to the risk of waterlogging and/or salinisation as a result of the watertable rise associated with recharge. Groundwater monitoring data in 2021 (Section 2.2) show that the depth to groundwater varies in the study area from ~5 mBGL to 40 mBGL.

Groundwater modelling also indicated that storing large volumes of mine dewater is likely to result in watertable rise and most likely inundation. However, if the irrigated agriculture and MAR scheme is managed so that the aquifer is used only for short-term storage (<10 years) during times of excess source water, then it is likely that watertable rise will be minimal. Further development of the groundwater model is required to reduce uncertainty, especially in the area of interest for irrigation/MAR which is data poor.

Contaminant migration in fractured rock and karstic aquifers

The target aquifer in the study area is the Fortescue River alluvial fan which is >100 m thick in the MAR assessment area. To the north of the study area, the aquifer is connected with the deeper dolomites of the Wittenoom Formation, which are often karstic; however, this connection has not been confirmed in the MAR assessment area (Donn et al., 2023). Interactions with the Fortescue Fault and the Poonda Fault could not be confirmed with the available data.

Connection to preferential flow paths means that stored water may travel further from the point of recharge and the attenuation zone may be larger than in a porous aquifer, though this is unlikely if MAR targets the shallow alluvial aquifer. Further investigation is required to understand the connection between the alluvial aquifer and underlying formations.

Aquifer dissolution and stability of well and aquitard

Recent drilling conducted as part of the project did not indicate that carbonates were present within the alluvial sediments. Thus, it is unlikely that aquifer dissolution would occur within the timeframe of a MAR operation.

Aquifer and groundwater-dependent ecosystems

Groundwater modelling suggests that under the worst-case scenarios where MAR water is not recovered for agricultural use (i.e. irrigation), groundwater could intersect the Fortescue River to the south and east of the MAR zone (Schmid et al., 2018). This risk is mitigated if all the MAR water stored in the aquifer is reused for agriculture. The scenarios that were run under these conditions resulted in no interaction with the Fortescue River because the resulting groundwater mound expanded and contracted on an annual basis. Since groundwater-surface water interaction has not been conceptualised in the groundwater model, further investigation is required to determine the potential impacts and the conditions under which groundwater-surface water interaction occurs (i.e. how much banked water over what period will result in discharge to the Fortescue River).

Due to the regional groundwater flow towards the north and mounding can occur due to MAR, recharged water could migrate into the Fortescue Marsh Management Zone. It is not clear how this mounding might affect the environmental areas of lowest significance (Marillana Plain) and medium significance (Poonda Plain), especially if the groundwater remains below the rooting zone of native vegetation.

Long term, it is unlikely that MAR within the study area will affect the Fortescue Marsh due to the long groundwater travel times, which increase when MAR water is used on an annual basis.

Energy and greenhouse gas considerations

Options considered for the MAR scheme will need to consider the energy requirements of alternative recharge, recovery and source water supply options.

Infiltration techniques targeting surficial deposits, while generally cheapest, may not be viable due to the high clay content of surficial soils. Further investigation is required to determine infiltration rates of soils in the study area.

If infiltration is not viable, deeper well-injection techniques will need to be considered, which have higher energy costs, for pumping.

Other factors that need to be considered in the MAR scheme conceptual design are the energy requirements to transfer water to and from the MAR scheme location, and to recover the water for irrigation.

5.5 Operational considerations

Economics

Uncertainty about the costs and benefits of MAR is hindering its uptake (Maliva, 2014; Parsons et al., 2012; Ross and Hasnain, 2018). However, it is generally understood that MAR schemes using infiltration to recharge unconfined aquifers cost less than schemes using bore injection to target deeper, confined systems due to typically lower cost of construction and lower energy requirements (Ross and Hasnain, 2018). Using recycled wastewater in MAR costs more than using excess surface water because the wastewater must be treated before it is used.

An evaluation of 21 MAR schemes in 5 countries reported levelised costs of $270/ML for infiltration schemes with surface water, $630/ML for injection bore schemes with surface water, $2,100/ML for infiltration schemes with recycled water and $2,000/ML for injection bore schemes with recycled water (Ross and Hasnain, 2018). Australia’s largest and oldest MAR scheme, which uses infiltration basins to recharge up to 45 GL of surface water per year in the Burdekin Delta, has a levelised cost of $80/ML (Dillon et al., 2009).

Clearly, site selection and scheme configuration (MAR type) decisions affect the overall economic viability of MAR. In this evaluation of MAR feasibility using mine dewater, the focus is on lower cost MAR configurations that may be suited to agricultural end use. Therefore, priority is given to infiltration-based schemes (i.e. infiltration basins), although, based on initial drilling, soils in the study area may not be suitable for infiltration.

To minimise pipeline costs, later stages of assessment will need to consider affordable drilling depth for groundwater extraction, proximity to the source of water for recharge, and the demand for irrigation water.

Infrastructure requirements

Groundwater modelling indicated that substantial MAR areas may be required to mitigate the risk of groundwater mound development. While there is considerable uncertainty about the model parameterisation, it indicates that infrastructure requirements may be high. It should be noted that the groundwater model does not consider how the water is introduced to the aquifer, so further investigation is required to assess the potential MAR type (i.e. infiltration or well injection).

The infiltration surface area required to recharge 5–50 ML/day of dewater (1.8–18 GL/year) was estimated at 2–200 hectares (Table 5-6). This estimate is intended to indicate the surface footprint required for various scheme scales. It assumes that each surface is operated for half a year, which allows maintenance to be undertaken in the remainder of the year. Infiltration rates of 500 mm/day and 50 mm/day were used to represent highly and moderately permeable soils, respectively. Assuming a nominal basin surface area of 1 ha, up to 200 basins may be required for a large scheme in moderately permeable soils, with half the basins in operation at any one time. The maximum infiltration rate required needs to be assessed based on the volume of source water available and the crop requirements, which will reduce the volume that is required to be recharged via MAR.

Based on the parameters used for the groundwater modelling, one crop type had a 6-month fallow period (Schmid et al., 2022). For this crop and the 50 GL/year case, 137 ML/day was required to be infiltrated over this 6-month fallow period. This would equate to up to 550 basins of 1-hectare each (6% to 13.5% of the area under cropping for this scenario).

It is recommended that the infiltration rate through the unsaturated zone is determined for each potential MAR injection area. It is important to assess the presence and extent of clay layers that inhibit infiltration. Lithological logs from recent drilling indicates that clays are present in the profile, which may prevent infiltration.

Table 5-6 Approximate infiltration basin surface area required for recharge in moderately to highly permeable soils (assuming 182 days use per year, which allows for duplication of infiltration capacity to allow for maintenance)

ML/day	GL/year	Infiltration surface area (ha) **Highly permeable soils** **(based on 500 mm/day infiltration rate and 182 days use/year)**	Infiltration surface area (ha) **Moderately permeable soils** **(based on 50 mm/day infiltration rate and 182 days use/year)**
5	1.8	2	20
10	3.65	4	40
20	7.3	8	80
50	18.3	20	200
137	50	55	550

Well injection rates are yet to be determined. Assuming an injection rate of 15 L/s equates to injection of approximately 1.3 ML/day per well. Recharge targets of 5–50 ML/day of mine dewater equates to 4–39 injection wells if continuous injection is feasible. The feasibility of MAR using injection wells requires additional understanding of the hydraulic properties of target aquifers.

Clogging

The most common operational issue affecting recharge rate in MAR operations is aquifer clogging which can be a result of biological, physical, and/or chemical processes (Martin, 2013). Clogging can be managed by source water control (e.g. treating the recharge water or diverting water with high turbidity) or maintaining the MAR scheme (e.g. scraping the infiltration basin, regularly backflushing injection wells). Prevention through control of source water quality is recommended as it is the most cost-effective solution for clogging, but it is unlikely to prevent all clogging processes.

In infiltration-based MAR schemes, the infiltration surface can be rejuvenated by removing the 'clogging' layer and replacing it with new material, as required. It is common for infiltration basins to be operated sequentially to allow for maintenance periods, which in turn increases the infiltration surface area required in a scheme (as discussed above). The potential for soil compaction during mechanical rejuvenation of the infiltrated surface also needs to be considered for basin maintenance.

For injection wells, maintenance is more challenging and therefore higher quality water is required for sustainable injection than for infiltration-based MAR schemes. Operational remediation strategies for well injection techniques include regular backflushing, airlift redevelopment, vacuuming, chemical treatment, scrubbing, or well enlargement, all of which require understanding of the nature of clogging (Martin, 2013).

Recovery efficiency

The recovery efficiency of a MAR scheme is defined as the proportion of recovered water that is of suitable quality for its intended use (NRMMC-EPHC-NHMRC 2009). The recovery efficiency was not tested within the groundwater model due to the inherent uncertainties in the model. Generally, recovery is limited by the salinity of the recovered water. When fresh water is stored in an aquifer with groundwater salinity above the target for use, mixing between the ambient groundwater and the source water for recharge will affect the volume that can be recovered and the recovery efficiency of the scheme.

Mixing and recovery efficiency is influenced by the hydrogeology of the site and how the scheme is managed. It is essential first to understand the hydrogeological variables when assessing the feasibility of MAR at a potential location. Hydrogeological variables include aquifer thickness, transmissivity, porosity, dispersivity, diffusivity, hydraulic gradient, and groundwater quality (salinity) (NRMMC-EPHC-NHMRC 2009). The potential for mobilisation of salts stored within the soil profile should also be considered in infiltration schemes.

The design and operation of the MAR scheme can then be tailored to minimise mixing (as required) and maximise recovery efficiency. Management variables include well design, infiltration, injection and recovery rates, injection and recovery volumes, residence time in the aquifer, and location of recovery well/s (NRMMC-EPHC-NHMRC 2009).

5.6 Western Australian specific requirements

Further to the risk assessment outlined above, specific requirements are outlined in the WA MAR Guidelines. These largely outline how a MAR scheme will be managed in Western Australia. Based on the information above, the implications for MAR schemes in the study area are briefly outlined in Table 5-7. These implications are general in nature and need to be addressed more thoroughly for any proposed MAR scheme.

Table 5-7 Requirements of WA MAR Guidelines in relation to the Newman MAR feasibility assessment

Requirement	Implications for Newman MAR
Source water	
Proponents must consider the impacts of using water from a particular source and obtain approvals for access and use from relevant agencies. The taking of water for the purpose of recharging an aquifer should not adversely impact the environment, water users or public health.	The source proposed is mine dewater which would otherwise need to be disposed of to the environment. This needs to be worked through with whoever is supplying the dewater.
Recharge	
Proponents must demonstrate that the impacts of recharge upon the environment, water users and public health will be acceptable.	That environmental impact is acceptable needs to be demonstrated. As demonstrated above in the risk assessment, the remote location should minimise impacts on water users and public health. A site-specific hydrogeological evaluation is required.
The infiltration or injection of water into an aquifer should not unacceptably impact the quantity or quality of water resources, ecosystems, water users or public health.	Development needs to be in accordance with MAR Guidelines to manage risks to environment and public health.
For proposals without abstraction, proponents must demonstrate the environmental or mitigation benefits of the proposal for it to be considered as MAR.	Not relevant as it is expected that water will be abstracted for irrigation.
Within public drinking water source areas, MAR may be supported with conditions on water and environmental licences if water infiltrated or injected into an aquifer is treated to drinking water standard.	Not relevant as proposed MAR locations are not within the Newman Water Reserve (PDWSA).
Recovery	
Where recharge water is to be abstracted for subsequent use, proponents must demonstrate that it will be available for abstraction when required, and that the impacts of abstraction upon the environment, water users and public health will be acceptable.	Sufficient hydrogeological information is needed to underpin decision-making about whether recharge water is available for abstraction. Groundwater model was used to predict mounding and distribution of recharge under the influence of abstraction. However, due to the large cell size, local effects could not be determined. Impacts on the environment also need to be assessed based on hydrogeological information pertaining to drawdown associated with pumping. A hydrogeological evaluation is required.
Recovery of recharge water will only be allowed after water has been injected or infiltrated.	It is proposed that source water will be recharged when in excess of irrigation demand with subsequent abstraction during times of irrigation deficit.
Recovery volumes must not exceed recharge or banked volumes and must take losses and potential impacts of abstraction into account.	Recovery efficiencies need to be assessed based on source water and groundwater quality. Irrigated agriculture should be designed to not exceed recharge. A hydrogeological evaluation is required.
Any abstraction exceeding recharge volumes will require a separate licence to take water and as this water will be taken	This was not tested as part of the risk assessment and determining this would be up to the individual scheme

Requirement	Implications for Newman MAR
from existing water resources, the required volume must be available under the allocation limit.	design. Irrigated agriculture operations could be designed to avoid this.
Recovery volumes must be estimated as part of the hydrogeological assessment. The department will determine appropriate recovery volumes for licensing purposes based on estimates provided by the proponent in their hydrogeological assessment, as well as other management considerations.	Preliminary groundwater modelling undertaken within the TAP project (Schmid et al., 2022) suggest that this requirement is unlikely to be met due to the high level of uncertainty. Refinement of the groundwater model requires additional data. A hydrogeological evaluation is required.
Managing recharge and recovery volumes	
Recharge and recovery operations should ideally be undertaken within the same aquifer to ensure they are hydraulically connected.	This assessment considers only the aquifer hosted by the alluvium of the Fortescue River alluvial fan aquifer. This is the only likely aquifer as the alluvium is up to 100 m thick.
Connection between recharge and recovery operations must be demonstrated by the proponent as part of the hydrogeological assessment of the proposed MAR operations.	This is beyond the scope of this assessment as no site has been selected and pump test data is not available to inform this. It will need to be considered should MAR be progressed in the Newman study area.
Recharge and recovery volumes will be managed separately to existing allocation limits for water resources since MAR contributes an additional input to a groundwater resource. Allocation limits do not need to be amended as a result of MAR recharge or recovery.	This is an operational consideration and needs to be implemented.
Recharge and recovery volumes must be metered (or where this is not possible, measured), and must take losses into account (e.g. evaporation from infiltration basins).	This is an operational consideration and needs to be implemented.
MAR management zones	
MAR management zones may be required to facilitate the licensing of bores/works and management of water quality and quantity. Proponents must consider the need for a MAR management zone in consultation with the department and, where required, include a proposed management zone in their hydrogeological assessment. The management zone boundary and any sub-zones will be assessed and approved on a case-by-case basis, based on the proponent's hydrogeological assessment, requirements of other agencies, and any other relevant information.	Discussions with DWER suggest that the MAR management zone is likely to be defined by the hydrogeological responses (mounding) and the area impacted by the transport of artificially recharged water (plume) Sufficient hydrogeological information is needed to underpin decision-making about the extent of this zone (beyond the scope of this preliminary feasibility assessment, applicable to subsequent detailed scheme-scale feasibility assessment). Preliminary groundwater modelling provides an initial assessment of the extent of the MAR management zone but will need to be refined with model advancement. A hydrogeological evaluation is required.

6 Conclusion

The assessment of MAR pre-feasibility undertaken builds on existing and new data collected as part of this project along with pre-feasibility groundwater modelling results. It provides a regional rather than a site-specific context on the viability of MAR, because of the scarcity of data and the large scale of the irrigated agriculture/MAR scenarios that were modelled to utilise large volumes of mine dewater (5–50 GL/year).

Recommended investigations developed from the entry-level degree of difficulty assessment and the maximal risk assessment are summarised in Table 6-1. The investigations required include further hydrogeological evaluation, aquifer geochemical characterisation and more comprehensive water quality assessments of the ambient groundwater and the mine dewater available for recharge.

A range of potential irrigated agriculture/MAR scenarios were investigated using the groundwater model. Recovery of MAR water on an annual basis was critical to preventing inundation due to groundwater mounding, along with increasing the MAR zone to spread out the mound. Once specific MAR locations are chosen, further investigation is required to optimise recovery and any potential for water banking, either in the short-term (few years) or long-term (> 10 years). This further investigation requires the groundwater model uncertainty to be reduced through better understanding of the alluvial aquifer hydraulic properties and calibration targets in the area of interest for irrigated agriculture.

Assessment of BHP's water quality data for mine dewater identified salinity, sodium, chloride, iron, phosphorus and pH as potential concerns for the suitability of recovered water for agricultural use, and their potential impacts on the receiving environment (surface soils or aquifer). Mixing the mine dewater with groundwater in the Fortescue alluvial fan may further limit the use of recovered water for irrigation, depending on the groundwater salinity, which varies spatially.

While there are no suspended solid target values for irrigation use, total suspended solids (TSS) greater than 10 mg/L is considered a low quality water that can result in aquifer clogging in MAR (NRMMC-EPHC-NHMRC, 2009). A 95th percentile TSS concentration in mine dewater of 9–26 mg/L suggests the risk of aquifer clogging requires further assessment and management.

Therefore, inorganic chemicals, salinity and sodicity, nutrients and turbidity are assessed as high risks to the environment, resulting from MAR and agricultural use.

There is no water quality data to assess the risks of pathogens or organic chemicals and only one sample to screen for radionuclide activity. As a result, pathogens, organic chemicals and radionuclides are unknown risks requiring additional information.

Additional water quality data will be sought to inform the maximal risk assessment and identify preventative measures to lower risks to an acceptable level. Site-specific soil and crop-specific requirements should be considered in the latter stages of feasibility assessment. To mitigate the risk of inundation, the cropping area should be determined from the crop water needs so that MAR water is not stored long-term in the alluvial aquifer.

Table 6-1 Summary of investigations required to address knowledge gaps

Investigation required	Relevant to degree of difficulty questions	Rationale
Hydrogeological evaluation	8, 9, 11	• Insufficient information to assess impacts on other groundwater users or groundwater-connected ecosystems. However, pre-feasibility groundwater modelling indicates that groundwater mounding may impact the Fortescue River if mine dewater surplus is stored long-term (>5 years) in the alluvial aquifer. Due to long groundwater travel times the Fortescue Marsh is unlikely to be impacted. • Modelling indicates that groundwater mounding and inundation occurs if the MAR zone is too small and mine dewater is stored long-term (>5 years). Clay layers were observed in the lithology logs, but there is still insufficient information on the hydraulic properties of the aquifer to refine the one layer used in the groundwater model or determine localised influences of the clay layers. • There was insufficient information available to support a solute transport model to assess salinity impacts, though groundwater sampling indicated that salinity varied spatially.
Aquifer geochemical characterisation	7, 11	• Insufficient information to assess the potential for reactions between the source water and the aquifer. Site-specific information on aquifer mineralogy and geochemistry is required.
Water quality assessment – source water	2, 3, 7	• Source water is unlikely to meet water quality targets for irrigation use. Understanding the spatial and temporal variability in source water quality is necessary to determine preventative measures to manage risks (e.g. set salinity limits for use in MAR, using source water from certain locations only or at certain times of the year). • Source water likely to cause clogging - source water treatment (i.e. settling, filtration) and maintenance (basin scraping, well backwashing) requirements need to be determined. • Insufficient information to assess the potential for reactions between the source water and the aquifer. Site-specific information on aquifer mineralogy is required.
Water quality assessment - groundwater	4, 6, 7	• Installation of new groundwater bores enabled the assessment of groundwater quality; however, it was found to vary spatially, especially salinity. • Since a wide range of groundwater salinity was observed (250–1,500 mg/L) in the study area, further investigation is required during site-specific investigations. Recovery efficiency may be affected depending on the differences in groundwater and source water salinity. • Insufficient information to assess the potential for reactions between the source water and the aquifer. Site-specific information on aquifer mineralogy is required.

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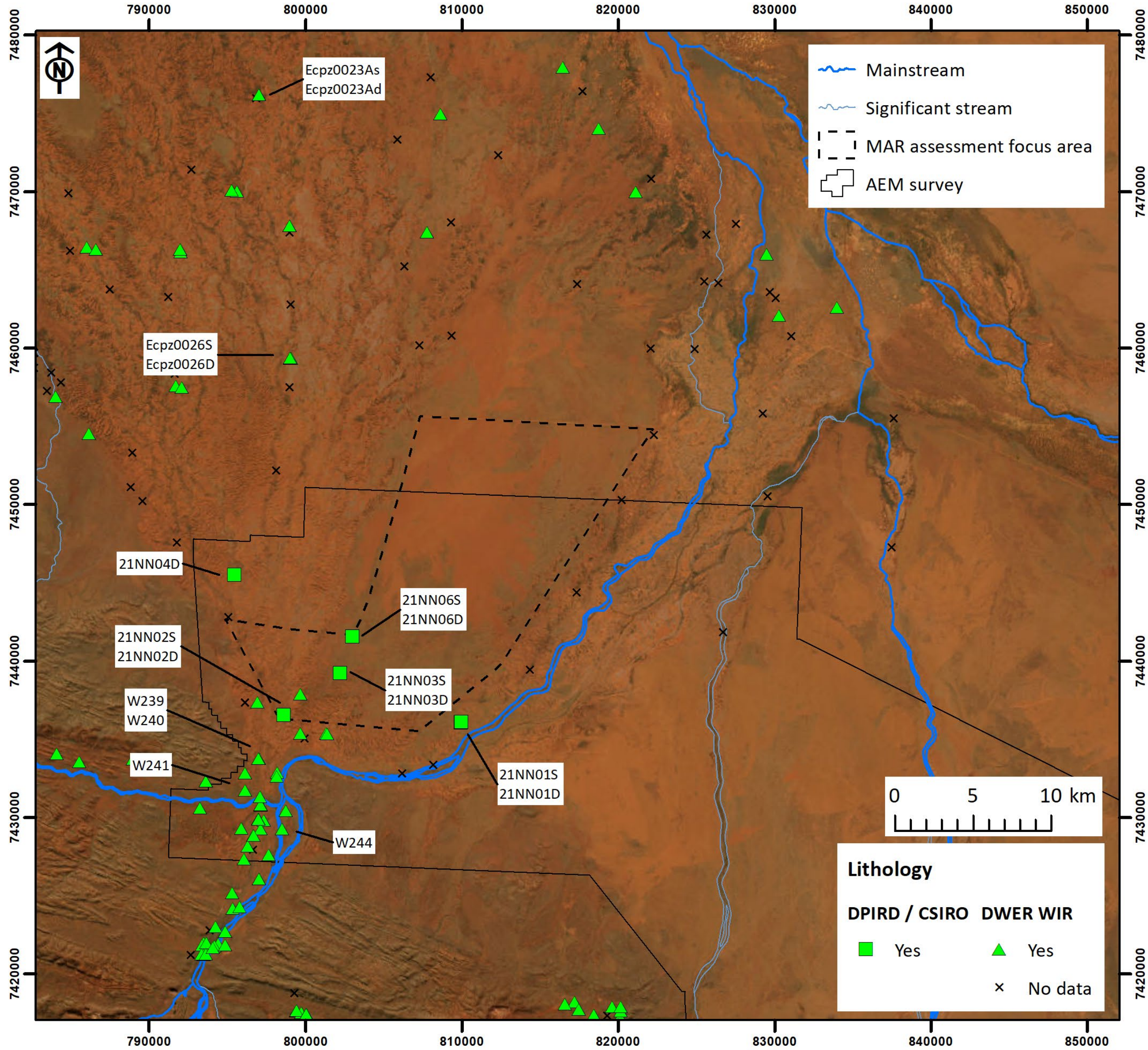
Appendix A Available data

A.1 Bore data in assessment area



Apx Figure A.1 Distribution of bores with lithological descriptions in the study area

A.2 Groundwater quality summary

Apx Table A.1 Water quality data summary for stock-water bores sampled by DPIRD in September 2019

Parameter mg/L unless stated	Guideline values Drinking (health) †	 Irrigation ‡	 Livestock ‡	Groundwater (stock-water bores) Count	 Minimum	 5th percentile	 Median	 95th percentile	 Maximum
General physico-chemical									
Temperature-field (degrees C)				15	26.7	26.7	28.8	30.1	30.2
pH-lab (pH units)		6.5–8.5		15	7.7	7.7	7.8	8.0	8.4
pH-field (pH units)				15	6.4	6.5	7.3	7.5	7.5
Suspended Solids									
Turbidity (NTU)									
Free Chlorine									
Chemical Oxygen Demand									
Carbonaceous biochemical oxygen demand (CBOD5)									
Salinity									
Electrical conductivity (EC-lab) (µS/cm)		crop dependent; 690 # (sensitive crops), 1400 # (moderately sensitive crops)		15	310	390	**1520**	**3210**	**3990**
EC-field (µS/cm)				15	390	500	**1800**	**3790**	**4720**
Total Dissolved Solids (TDS-lab)			animal dependent; 2000 (poultry), 4000 (beef cattle)	15	260	295	860	1810	**2300**
TDS-field									
Inorganic chemicals									
Total Alkalinity as CaCO3				15	105	122	232	467	468
Bicarbonate				15	128	149	283	569	570
Carbonate				15	<1	<1	<1	<1	<1
Chloride		crop dependent; 175 (sensitive crops), 350 (moderately sensitive crops), 750 (increased cadmium uptake)		15	16.0	36.3	159	**666**	**770**
Fluoride	1.5	1 (LTV), 2 (STV)	2	7	0.08	0.10	0.27	0.88	0.92
Sulfate			1000	15	8.00	11.0	110	329	505

Parameter	Guideline values			Groundwater (stock-water bores)					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Calcium			1000	15	18.8	22.9	47.3	103	106
Magnesium				15	12.1	18.3	48.9	108	156
Potassium				15	3.8	3.9	17.8	52.8	74.1
Sodium		crop dependent; 115 (sensitive crops), 230 (moderately sensitive crops)		15	14.5	15.6	**163**	**381**	**520**
Aluminium		5 (LTV), 20 (STV)	5	15	<0.005	<0.005	<0.005	<0.005	0.006
Arsenic	0.01	0.1 (LTV), 2 (STV)	0.5	15	<0.001	<0.001	<0.001	<0.001	<0.001
Barium				15	0.025	0.027	0.046	0.215	0.320
Beryllium	0.06	0.1 (LTV), 0.5 (STV)		15	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Boron	4	0.5 (LTV), crop dependent; 1 (sensitive crops STV)	5	15	0.08	0.08	0.31	**0.95**	**1.40**
Cadmium	0.002	0.01 (LTV), 0.05 (STV)	0.01	15	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Chromium		0.1 (LTV), 1 (STV)	1	15	<0.0005	0.00076	0.0025	0.0097	0.0100
Hexavalent Chromium									
Cobalt		0.05 (LTV), 0.1 (STV)	1	15	<0.0001	<0.0001	<0.0001	<0.0001	0.0004
Copper	0.05	0.2 (LTV), 5 (STV)	0.5 (sheep)	15	<0.0001	0.0002	0.0005	0.0029	0.0034
Iron		0.2 (LTV), 10 (STV)			<0.005	<0.005	<0.005	9.2	**11**
Iron-soluble		0.2 (LTV), 10 (STV)							
Manganese		0.2 (LTV), 10 (STV)	0.2 (LTV), 10 (STV)	15	<0.0001	0.0001	0.0004	0.17	0.45
Mercury	0.001	0.002	0.002						
Molybdenum	0.05	0.01 (LTV), 0.05 (STV)	0.15	15	<0.001	<0.001	<0.001	0.001	0.002
Nickel	0.02	0.2 (LTV), 2 (STV)	1	15	<0.001	<0.001	<0.001	0.004	0.004
Lead	0.01	2 (LTV), 5 (STV)	0.1	15	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Lithium		2.5							
Selenium	0.01	0.02 (LTV), 0.05 (STV)	0.02	15	<0.001	<0.001	0.002	0.005	0.005
Silica				15	19	32	69	91	110
Silver	0.1								
Strontium									
Tin				15	<0.0001	<0.0001	<0.0001	<0.0001	0.0002

Parameter	Guideline values			Groundwater (stock-water bores)					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Titanium									
Uranium	0.017	0.01 (LTV), 0.1 (STV)	0.2	15	<0.0001	0.0003	0.0019	0.0046	0.0063
Vanadium		0.1 (LTV), 0.5 (STV)		15	<0.0001	0.0009	0.0057	0.0124	0.013
Zinc		2 (LTV), 5 (STV)	20	15	<0.001	<0.001	0.002	0.052	0.061
Nutrients									
Ammonia as N				15	<0.01	<0.01	<0.01	0.03	0.03
Nitrate	50		400	15	0.02	0.18	3.9	17	23
Nitrite	3		30	7	<0.01	<0.01	<0.01	<0.01	0.02
Total Kjeldahl Nitrogen									
Nitrogen-total		5 (LTV), 25-125 (STV)		7	0.13	0.19	4.3	**21**	**23**
Phosphorus-total		0.05 (LTV), 0.8-12 (STV)		7	<0.005	<0.005	<0.006	0.008	0.008
Reactive Phosphorus as P (mg/L)		0.05 (LTV), 0.8-12 (STV)		15	<0.01	<0.01	0.02	0.03	0.03
Total Organic Carbon									
Dissolved Organic Carbon				7	<1.0	<1.0	<1.0	<1.0	1.0
Pathogens									
E.coli (cfu/100 mL)	0								
Thermotolerant coliforms (cfu/100 mL)	0	10 (raw food crops in contact with irrigation water)							
Organic chemicals									
Radionuclides									
Gross alpha (Bq/L)		0.5							
Gross beta (excluding K-40) (Bq/L)		0.5							

† NMRC-NRMMC (2011)

‡ ANZECC-ARMCANZ (2000)

upper bound of tolerance estimated using a leaching fraction of 0.33 which is applicable to loam and light clay soils; LTV (long-term trigger value) = 100 years irrigation; STV (short-term trigger value) = 20 years irrigation; **bold** values exceed a guideline value

* TSS, TN or TP > 10 mg/L is considered a clogging risk in MAR (NRMMC-EPHC-NHMRC, 2009)

Apx Table A.2 Water quality data summary for groundwater bores sampled by CSIRO in October 2021

Parameter mg/L unless stated	Guideline values Drinking (health) [†]	Irrigation [‡]	Livestock [‡]	Groundwater (stock-water bores) Count	Minimum	5^{th} percentile	Median	95^{th} percentile	Maximum
General physico-chemical									
Temperature-field (degrees C)				17	29.9	30.5	31.5	35.8	36.5
pH-lab (pH units)		6.5–8.5		17	7.1	7.3	7.6	7.7	7.8
pH-field (pH units)				17	4.0	6.2	7.2	7.3	7.3
Suspended Solids									
Turbidity (NTU)									
Free Chlorine									
Chemical Oxygen Demand									
Carbonaceous biochemical oxygen demand (CBOD5)									
Salinity									
Electrical conductivity (EC-lab) (µS/cm)		crop dependent; 690 [#] (sensitive crops), 1400 [#] (moderately sensitive crops)		17	438	545	**1620**	**2830**	**2860**
EC-field (µS/cm)				17	447	557	**1620**	**2860**	**2880**
Total Dissolved Solids (TDS-lab)			animal dependent; 2000 (poultry), 4000 (beef cattle)	17	250	290	790	1420	1500
TDS-field									
Inorganic chemicals									
Total Alkalinity as CaCO3				17	146	164	278	335	365
Bicarbonate				17	178	200	339	410	445
Carbonate				17	<1	<1	<1	<1	<1
Chloride		crop dependent; 175 (sensitive crops), 350 (moderately sensitive crops), 750 (increased cadmium uptake)		17	27	67	273	**623**	**638**
Fluoride	1.5	1 (LTV), 2 (STV)	2	17	0.21	0.37	0.64	0.81	0.91
Sulfate			1000	17	19.0	31.0	140	262	270
Calcium			1000	17	15.5	26.7	59.8	81.4	91.7
Magnesium				17	12.7	22.6	58.3	73.8	80.4
Potassium				17	4.1	4.3	8.7	23.9	26.4

Parameter	Guideline values			Groundwater (stock-water bores)					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Sodium		crop dependent; 115 (sensitive crops), 230 (moderately sensitive crops)		17	36.9	47.1	**167**	**362**	**363**
Aluminium		5 (LTV), 20 (STV)	5	17	<0.005	<0.005	<0.005	<0.005	0.006
Arsenic	0.01	0.1 (LTV), 2 (STV)	0.5	17	<0.001	<0.001	<0.001	0.008	0.010
Barium				17	0.003	0.005	0.050	0.144	0.160
Beryllium	0.06	0.1 (LTV), 0.5 (STV)		17	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Boron	4	0.5 (LTV), crop dependent; 1 (sensitive crops STV)	5	17	0.140	0.188	0.310	0.476	0.500
Cadmium	0.002	0.01 (LTV), 0.05 (STV)	0.01	17	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Chromium		0.1 (LTV), 1 (STV)	1	17	<0.0005	<0.0005	0.0024	0.0092	0.0100
Hexavalent Chromium									
Cobalt		0.05 (LTV), 0.1 (STV)	1	17	<0.0001	<0.0001	<0.0001	0.0020	0.0024
Copper	0.05	0.2 (LTV), 5 (STV)	0.5 (sheep)	17	<0.0001	<0.0001	0.0002	0.0009	0.0010
Iron		0.2 (LTV), 10 (STV)							
Iron-soluble		0.2 (LTV), 10 (STV)		17	<0.005	<0.005	<0.005	**0.638**	**0.820**
Manganese		0.2 (LTV), 10 (STV)	0.2 (LTV), 10 (STV)	17	0.0001	0.0001	0.018	0.700	0.860
Mercury	0.001	0.002	0.002	17	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Molybdenum	0.05	0.01 (LTV), 0.05 (STV)	0.15	17	<0.001	<0.001	<0.001	0.003	0.003
Nickel	0.02	0.2 (LTV), 2 (STV)	1	17	<0.001	<0.001	<0.001	0.003	0.003
Lead	0.01	2 (LTV), 5 (STV)	0.1	17	<0.0001	<0.0001	0.0001	0.0008	0.0009
Lithium		2.5		17	0.0002	0.00036	0.001	0.0027	0.0031
Selenium	0.01	0.02 (LTV), 0.05 (STV)	0.02	17	<0.001	<0.001	<0.001	0.002	0.002
Silica				17	14.0	20.4	45.0	65.8	73.0
Silver	0.1			17	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Strontium				17	0.110	0.118	0.290	0.374	0.430
Tin				17	<0.0001	<0.0001	<0.0001	<0.0001	0.0002
Titanium				17	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Uranium	0.017	0.01 (LTV), 0.1 (STV)	0.2	17	<0.0001	0.0002	0.0018	0.0078	0.0078
Vanadium		0.1 (LTV), 0.5 (STV)		17	0.0002	0.00068	0.0042	0.0114	0.013
Zinc		2 (LTV), 5 (STV)	20	15	<0.001	<0.001	0.003	0.012	0.013

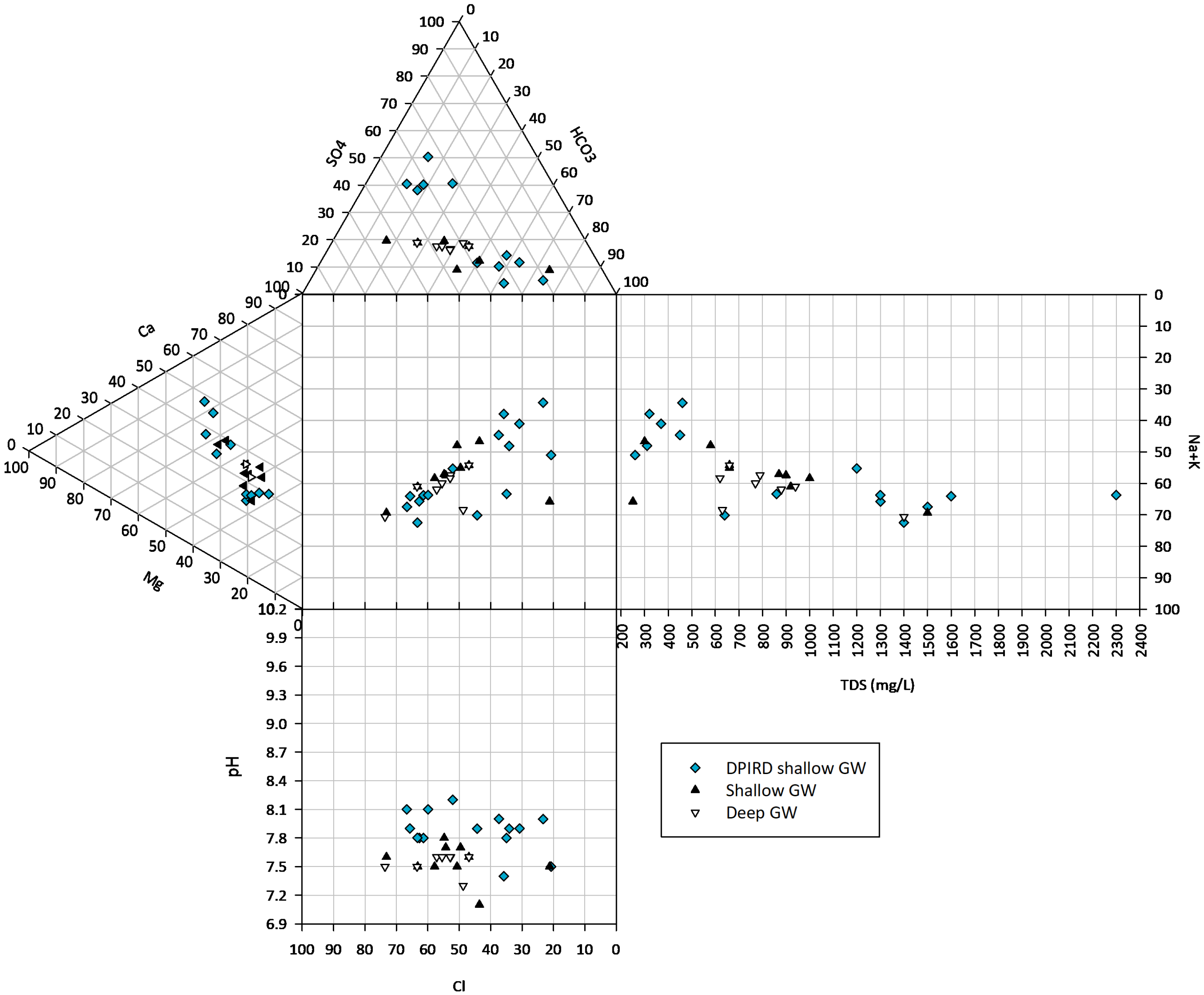
Parameter	Guideline values			Groundwater (stock-water bores)					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Nutrients									
Ammonia as N				17	<0.01	<0.01	<0.01	<0.01	<0.01
Nitrate	50		400	17	0.03	0.046	0.98	5.48	5.80
Nitrite	3		30	17	<0.01	<0.01	<0.01	<0.01	0.01
Total Kjeldahl Nitrogen									
Nitrogen-total		5 (LTV), 25-125 (STV)		17	0.03	0.09	1.50	**6.20**	**6.60**
Phosphorus-total		0.05 (LTV), 0.8-12 (STV)		17	<0.005	<0.005	0.019	**4.60**	**6.10**
Reactive Phosphorus as P (mg/L)		0.05 (LTV), 0.8-12 (STV)		17	<0.01	<0.01	0.01	**4.44**	**5.90**
Total Organic Carbon									
Dissolved Organic Carbon				7	<1.0	<1.0	<1.0	4.7	5.0
Pathogens									
E.coli (cfu/100 mL)	0								
Thermotolerant coliforms (cfu/100 mL)	0	10 (raw food crops in contact with irrigation water)							
Organic chemicals									
Radionuclides									
Gross alpha (Bq/L)		0.5							
Gross beta (excluding K-40) (Bq/L)		0.5							

† NMRC-NRMMC (2011)

‡ ANZECC-ARMCANZ (2000)

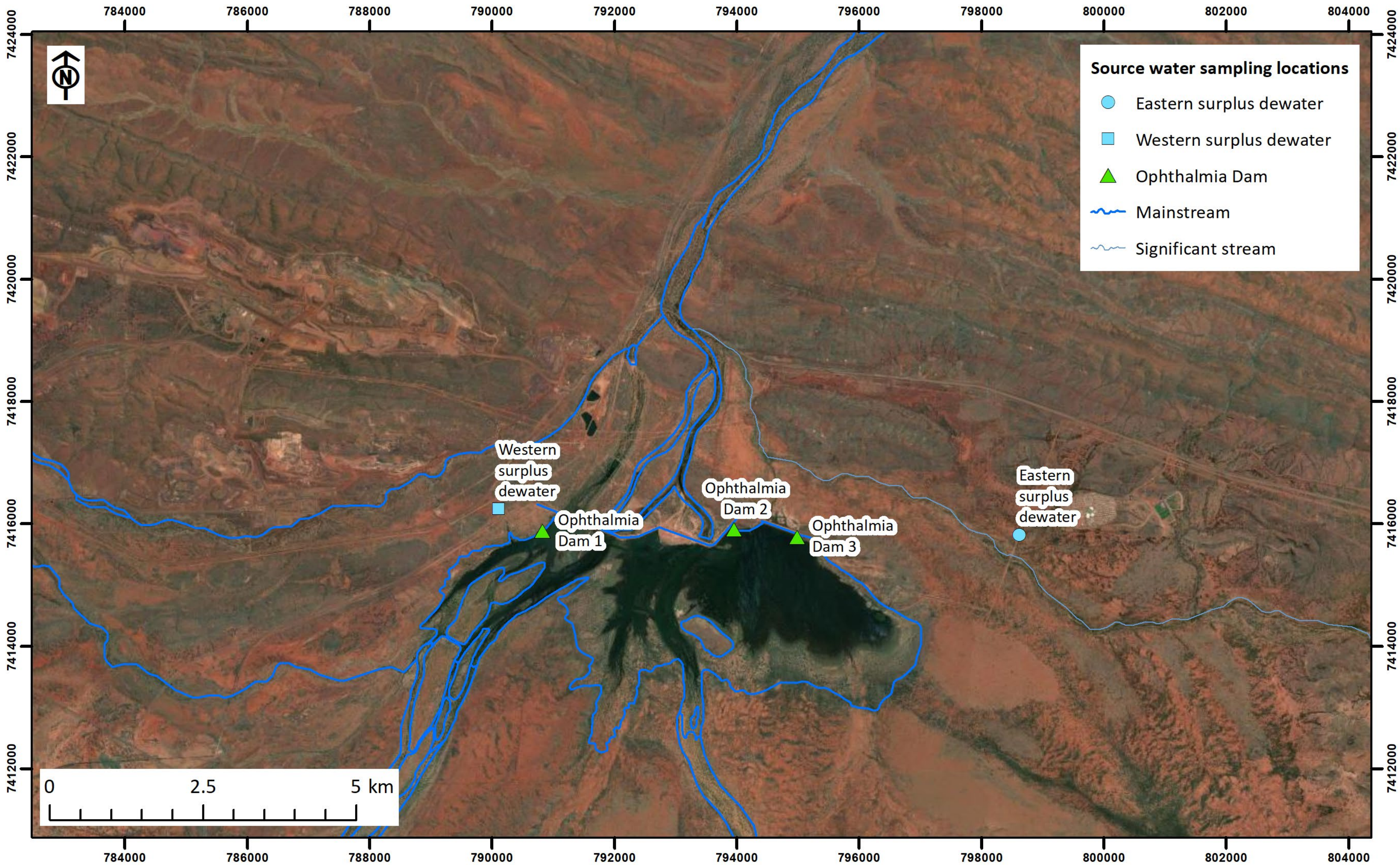
upper bound of tolerance estimated using a leaching fraction of 0.33 which is applicable to loam and light clay soils; LTV (long-term trigger value) = 100 years irrigation; STV (short-term trigger value) = 20 years irrigation; **bold** values exceed a guideline value

* TSS, TN or TP > 10 mg/L is considered a clogging risk in MAR (NRMMC-EPHC-NHMRC, 2009)



Apx Figure A.2 Durov diagram showing cation and anion composition of groundwater (GW) in relation to pH and total dissolved solids (TDS) for the shallow groundwater samples collected from stock bores in September 2019 (DPIRD shallow GW) and from CSIRO groundwater sampling in October 2021 (shallow and deep GW)

A.3 Source water quality summary



Apx Figure A.3 Location of BHP surplus mine dewater and Ophthalmia Dam sampling locations

Apx Table A.3 Water quality data summary for western surplus mine dewater

Parameter	Guideline values			Western surplus mine dewater					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
General physico-chemical									
Temperature-field (degrees C)									
pH-lab (pH units)		6.5–8.5		42	7.7	7.7	7.8	8	8.4
pH-field (pH units)									
Suspended Solids				42	<1	<1	<1	9	43 *
Turbidity (NTU)									
Free Chlorine				15	<0.1	<0.1	<0.1	<0.1	0.1
Chemical Oxygen Demand				15	<10	<10	<10	20	26
Carbonaceous biochemical oxygen demand (CBOD5)									
Salinity									
Electrical conductivity (EC-lab) (µS/cm)		crop dependent; 690 # (sensitive crops), 1400 # (moderately sensitive crops)		42	**980**	**1005**	**1665**	**2018**	**2460**
EC-field (µS/cm)									
Total Dissolved Solids (TDS-lab)			animal dependent; 2000 (poultry), 4000 (beef cattle)	42	540	90	1000	1320	1540
TDS-field									
Inorganic chemicals									
Total Alkalinity as CaCO3				42	230	261	311	333.8	360
Bicarbonate				31	280	300	380	410	430
Carbonate				23	<5	<5	<5	<5	<5
Chloride		crop dependent; 175 (sensitive crops), 350 (moderately sensitive crops), 700 (moderately tolerant crops), 750 (increased cadmium uptake)		42	130	150	**270**	**365**	**462**
Fluoride	1.5	1 (LTV), 2 (STV)	2	26	0.2	0.4	0.6	0.6	0.6
Sulfate			1000	33	74	83	160	189	190
Calcium			1000	42	48	54	74	93	96
Magnesium				42	49	50	77	90	97

Parameter	Guideline values			Western surplus mine dewater					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Potassium				42	5.8	5.9	7.4	10	14
Sodium		crop dependent; 115 (sensitive crops), 230 (moderately sensitive crops), 460 (moderately tolerant crops)		42	66	76	**150**	**208**	**254**
Aluminium		5 (LTV), 20 (STV)	5	42	<0.005	<0.005	<0.005	0.01	0.02
Arsenic	0.01	0.1 (LTV), 2 (STV)	0.5	42	<0.001	<0.001	<0.001	0.002	0.004
Barium				39	0.017	0.0179	0.022	0.0317	0.044
Beryllium	0.06	0.1 (LTV), 0.5 (STV)							
Boron	4	0.5 (LTV), crop dependent; 1 (sensitive crops STV)	5	18	0.21	0.23	0.30	0.37	0.47
Cadmium	0.002	0.01 (LTV), 0.05 (STV)	0.01	42	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Chromium		0.1 (LTV), 1 (STV)	1	38	<0.001	<0.001	<0.001	<0.001	<0.001
Hexavalent Chromium				6	<0.004	<0.004	<0.004	<0.004	<0.004
Cobalt		0.05 (LTV), 0.1 (STV)	1						
Copper	0.05	0.2 (LTV), 5 (STV)	0.5 (sheep)	42	<0.001	<0.001	<0.001	0.002	0.004
Iron		0.2 (LTV), 10 (STV)		12	<0.005	<0.005	0.0055	0.0164	0.023
Iron-soluble		0.2 (LTV), 10 (STV)		30	<0.005	<0.005	<0.005	0.050	0.050
Manganese		0.2 (LTV), 10 (STV)	0.2 (LTV), 10 (STV)	42	<0.001	0.001	0.007	0.020	0.020
Mercury	0.001	0.002	0.002	42	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Molybdenum	0.05	0.01 (LTV), 0.05 (STV)	0.15	39	<0.001	<0.001	<0.001	0.0011	0.002
Nickel	0.02	0.2 (LTV), 2 (STV)	1	42	<0.001	<0.001	<0.001	<0.001	0.001
Lead	0.01	2 (LTV), 5 (STV)	0.1	42	<0.001	<0.001	<0.001	<0.001	<0.001
Lithium		2.5							
Selenium	0.01	0.02 (LTV), 0.05 (STV)	0.02	38	<0.001	<0.001	<0.001	0.01	0.01
Silica				39	16	18	26	36	45
Silver	0.1								
Strontium									
Tin									
Titanium									

Parameter	Guideline values			Western surplus mine dewater					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Uranium	0.017	0.01 (LTV), 0.1 (STV)	0.2						
Vanadium		0.1 (LTV), 0.5 (STV)		9	<0.001	<0.001	<0.001	<0.001	<0.001
Zinc		2 (LTV), 5 (STV)	20	42	<0.005	<0.005	<0.005	0.17	0.76
Nutrients									
Ammonia as N				15	<0.005	0.005	0.02	0.09	0.13
Nitrate	50		400	31	<0.05	1.2	2.7	4.3	12
Nitrite	3		30	10	<0.05	<0.05	<0.05	<0.05	<0.05
Total Kjeldahl Nitrogen				23	<0.05	<0.05	0.12	0.48	0.5
Nitrogen-total		5 (LTV), 25-125 (STV)		40	0.29	0.37	0.76	2.0	2.8
Phosphorus-total		0.05 (LTV), 0.8-12 (STV)		39	<0.01	<0.01	0.02	**0.06**	**0.09**
Reactive Phosphorus as P (mg/L)		0.05 (LTV), 0.8-12 (STV)		21	<0.005	<0.005	0.019	0.024	0.028
Total Organic Carbon									
Dissolved Organic Carbon									
Pathogens									
E.coli (cfu/100 mL)	0								
Thermotolerant coliforms (cfu/100 mL)	0	10 (raw food crops in contact with irrigation water)							
Organic chemicals									
Radionuclides									
Gross alpha (Bq/L)		0.5							
Gross beta (excluding K-40) (Bq/L)		0.5							

† NMRC-NRMMC (2011)

‡ ANZECC-ARMCANZ (2000)

upper bound of tolerance estimated using a leaching fraction of 0.33 which is applicable to loam and light clay soils; LTV (long-term trigger value) = 100 years irrigation; STV (short-term trigger value) = 20 years irrigation; **bold** values exceed a guideline value

* TSS, TN or TP > 10 mg/L considered a clogging risk in MAR (NRMMC-EPHC-NHMRC, 2009)

Apx Table A.4 Water quality data summary for eastern surplus dewater. When the sample size is 1 then the measured value shown as median.

Parameter	Guideline values			Eastern surplus mine dewater					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
General physico-chemical									
Temperature-field (degrees C)									
pH-lab (pH units)		6.5–8.5		1			8.1		
pH-field (pH units)									
Suspended Solids				1			<5		
Turbidity (NTU)				1			<0.5		
Free Chlorine									
Chemical Oxygen Demand									
Carbonaceous biochemical oxygen demand (CBOD5)									
Salinity									
Electrical conductivity (EC-lab) (µS/cm)		crop dependent; 690 # (sensitive crops), 1400 # (moderately sensitive crops)		1					**1200**
EC-field (µS/cm)									
Total Dissolved Solids (TDS-lab)			animal dependent; 2000 (poultry), 4000 (beef cattle)	1			660		
TDS-field									
Inorganic chemicals									
Total Alkalinity as CaCO3				14	240	247	250	260	260
Bicarbonate				14	290	297	310	320	320
Carbonate									
Chloride		crop dependent; 175 (sensitive crops), 350 (moderately sensitive crops), 700 (moderately tolerant crops), 750 (increased cadmium uptake)		14	110	129.5	160	**190**	**190**
Fluoride	1.5	1 (LTV), 2 (STV)	2	14	0.3	0.3	0.3	0.4	0.4
Sulfate			1000	14	65	67	75	104	110
Calcium			1000	13	57	57	61	64	64

Parameter		Guideline values		Eastern surplus mine dewater					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Magnesium				13	51	51	55	57	57
Potassium				13	11	11.6	12	13	13
Sodium		crop dependent; 115 (sensitive crops), 230 (moderately sensitive crops), 460 (moderately tolerant crops)		13	48	54	65	91	97
Antimony	0.003								
Aluminium		5 (LTV), 20 (STV)	5	11	<0.005	<0.005	<0.005	0.014	0.021
Arsenic	0.01	0.1 (LTV), 2 (STV)	0.5	11	<0.001	<0.001	<0.001	<0.001	<0.001
Barium				11	0.023	0.0235	0.025	0.030	0.030
Beryllium	0.06	0.1 (LTV), 0.5 (STV)							
Boron	4	0.5 (LTV), crop dependent; 1 (sensitive crops STV)	5	11	0.19	0.19	0.2	0.3	0.3
Cadmium	0.002	0.01 (LTV), 0.05 (STV)	0.01	11	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Chromium		0.1 (LTV), 1 (STV)	1	13	<0.001	<0.001	<0.001	<0.001	<0.001
Hexavalent Chromium									
Cobalt		0.05 (LTV), 0.1 (STV)	1						
Copper	0.05	0.2 (LTV), 5 (STV)	0.5 (sheep)	11	<0.001	<0.001	<0.001	<0.001	<0.001
Iron		0.2 (LTV), 10 (STV)		12	0.005	0.010	0.032	0.070	0.086
Iron-soluble		0.2 (LTV), 10 (STV)		1			<0.005		
Manganese		0.2 (LTV), 10 (STV)	0.2 (LTV), 10 (STV)	11	<0.001	<0.001	0.004	0.014	0.016
Mercury	0.001	0.002	0.002	10	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Molybdenum	0.05	0.01 (LTV), 0.05 (STV)	0.15	11	<0.001	<0.001	<0.001	<0.001	<0.001
Nickel	0.02	0.2 (LTV), 2 (STV)	1	11	<0.001	<0.001	<0.001	<0.001	<0.001
Lead	0.01	2 (LTV), 5 (STV)	0.1	11	<0.001	<0.001	<0.001	<0.001	0.001
Lithium		2.5							
Selenium	0.01	0.02 (LTV), 0.05 (STV)	0.02	11	<0.001	<0.001	<0.001	<0.001	<0.001
Silica				14	17	17	18	19	20
Silver	0.1			1			<0.001		
Strontium									

Parameter	Guideline values			Eastern surplus mine dewater					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Tin									
Titanium									
Uranium	0.017	0.01 (LTV), 0.1 (STV)	0.2						
Vanadium		0.1 (LTV), 0.5 (STV)							
Zinc		2 (LTV), 5 (STV)	20	11	<0.005	<0.005	<0.005	0.0065	0.007
Nutrients									
Ammonia as N									
Nitrate	50		400	14	0.17	0.36	1.1	6.4	10
Nitrite	3		30	13	<0.05	<0.05	<0.05	<0.05	<0.05
Total Kjeldahl Nitrogen									
Nitrogen-total		5 (LTV), 25-125 (STV)							
Phosphorus-total		0.05 (LTV), 0.8-12 (STV)		1			<0.02		
Reactive Phosphorus		0.05 (LTV), 0.8-12 (STV)							
Total Organic Carbon				1			<0.2		
Dissolved Organic Carbon				1			<0.2		
Pathogens									
E.coli (cfu/100 mL)	0								
Thermotolerant coliforms (cfu/100 mL)		10 (raw food crops in contact with irrigation water)							
Organic chemicals									
Radionuclides									
Gross alpha (Bq/L)		0.5		1			0.066		
Gross beta (excluding K-40) (Bq/L)		0.5		1			0.061		

† NMRC-NRMMC (2011)

‡ ANZECC-ARMCANZ (2000)

upper bound of tolerance estimated using a leaching fraction of 0.33 which is applicable to loam and light clay soils; LTV (long-term trigger value) = 100 years irrigation; STV (short-term trigger value) = 20 years irrigation; **bold** values exceed a guideline value

Apx Table A.5 Water quality data summary for Ophthalmia Dam. When the sample size is 1 then the measured value shown as median.

Parameter	Guideline values			Ophthalmia Dam (3 locations combined)					
mg/L unless stated	**Drinking (health) [†]**	**Irrigation [‡]**	**Livestock [‡]**	**Count**	**Minimum**	**5th percentile**	**Median**	**95th percentile**	**Maximum**
General physico-chemical									
Temperature-field (degrees C)									
pH-lab (pH units)		6.5–8.5		49	8.2	8.2	**8.9**	**9.8**	**10**
pH-field (pH units)				42	7.1	7.8	**8.9**	**9.9**	**10**
Suspended Solids				31	<1	<1	9	26	35
Turbidity (NTU)				29	0.8	2	5	21	77
Free Chlorine									
Chemical Oxygen Demand									
Carbonaceous biochemical oxygen demand (CBOD5)									
Salinity									
Electrical conductivity (EC-lab) (µS/cm)		crop dependent; 690 [#] (sensitive crops), 1400 [#] (moderately sensitive crops)							
EC-field (µS/cm)				42	140	160	**900**	**1800**	**4300**
Total Dissolved Solids (TDS-lab)			animal dependent; 2000 (poultry), 4000 (beef cattle)	49	360	490	700	900	960
TDS-field				42	95	110	610	1200	**2900**
Inorganic chemicals									
Total Alkalinity as CaCO3				49	130	140	210	270	280
Bicarbonate				49	11	26	170	310	340
Carbonate				49	<5	<5	30	80	90
Chloride		crop dependent; 175 (sensitive crops), 350 (moderately sensitive crops), 700 (moderately tolerant crops), 750 (increased cadmium uptake)		49	86	113	**230**	**306**	**340**
Fluoride	1.5	1 (LTV), 2 (STV)	2	49	0.2	0.3	0.4	0.5	0.5
Sulfate			1000	49	42	60	94	180	190
Calcium			1000	48	9.3	11	24	54	56

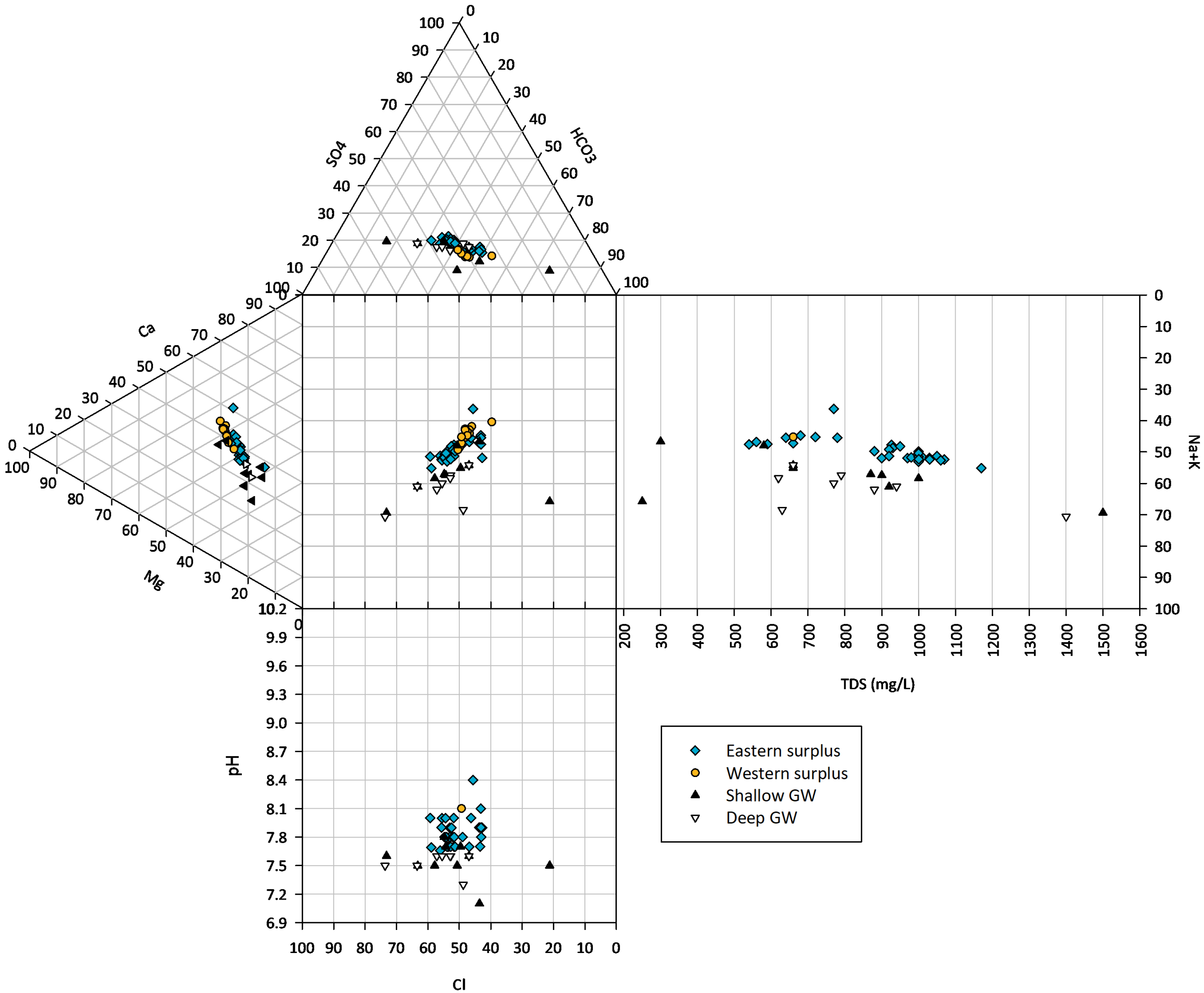
Parameter	Guideline values			Ophthalmia Dam (3 locations combined)					
mg/L unless stated	Drinking (health) †	Irrigation ‡	Livestock ‡	Count	Minimum	5th percentile	Median	95th percentile	Maximum
Magnesium				48	28	46	73	91	98
Potassium				48	4.5	6.3	15	22	23
Sodium		crop dependent; 115 (sensitive crops), 230 (moderately sensitive crops), 460 (moderately tolerant crops)		48	43	66	100	**140**	**160**
Antimony	0.003			48	<0.001	<0.001	<0.001	<0.001	<0.001
Aluminium		5 (LTV), 20 (STV)	5	48	<0.005	<0.005	<0.005	0.022	0.033
Arsenic	0.01	0.1 (LTV), 2 (STV)	0.5	48	<0.001	<0.001	<0.001	<0.001	0.002
Barium				48	0.001	0.006	0.03	0.06	0.07
Beryllium	0.06	0.1 (LTV), 0.5 (STV)		48	<0.001	<0.001	<0.001	<0.001	<0.001
Boron	4	0.5 (LTV), crop dependent; 1 (sensitive crops STV)	5	48	0.18	0.21	0.31	0.41	0.42
Cadmium	0.002	0.01 (LTV), 0.05 (STV)	0.01	48	<0.001	<0.001	<0.001	<0.001	<0.001
Chromium		0.1 (LTV), 1 (STV)	1	48	<0.001	<0.001	<0.001	<0.001	<0.001
Hexavalent Chromium									
Cobalt		0.05 (LTV), 0.1 (STV)	1	48	<0.001	<0.001	<0.001	<0.001	<0.001
Copper	0.05	0.2 (LTV), 5 (STV)	0.5 (sheep)	48	<0.001	<0.001	<0.001	<0.001	<0.001
Iron		0.2 (LTV), 10 (STV)		70	0.015	0.027	0.15	**1.2**	**4.6**
Iron-soluble		0.2 (LTV), 10 (STV)		55	<0.005	<0.005	0.012	0.072	**0.62**
Manganese		0.2 (LTV), 10 (STV)	0.2 (LTV), 10 (STV)	24	<0.001	<0.001	0.001	0.13	0.22
Mercury	0.001	0.002	0.002	46	<0.00005	<0.00005	<0.00005	<0.00005	<0.00005
Molybdenum	0.05	0.01 (LTV), 0.05 (STV)	0.15	48	<0.001	<0.001	0.001	0.002	0.002
Nickel	0.02	0.2 (LTV), 2 (STV)	1	48	<0.001	<0.001	<0.001	<0.001	<0.001
Lead	0.01	2 (LTV), 5 (STV)	0.1	1			<0.001		
Lithium		2.5							
Selenium	0.01	0.02 (LTV), 0.05 (STV)	0.02	48	<0.001	<0.001	<0.001	<0.001	0.002
Silica				31	1.4	1.6	9.2	15	16

Parameter	Guideline values			Ophthalmia Dam (3 locations combined)					
mg/L unless stated	**Drinking (health) †**	**Irrigation ‡**	**Livestock ‡**	**Count**	**Minimum**	**5th percentile**	**Median**	**95th percentile**	**Maximum**
Silver	0.1								
Strontium									
Tin				48	<0.001	<0.001	<0.001	<0.001	<0.001
Titanium				48	<0.001	<0.001	<0.001	<0.001	0.001
Uranium	0.017	0.01 (LTV), 0.1 (STV)	0.2						
Vanadium		0.1 (LTV), 0.5 (STV)		48	<0.001	<0.001	0.003	0.01	0.011
Zinc		2 (LTV), 5 (STV)	20	48	<0.005	<0.005	<0.005	<0.005	<0.005
Nutrients									
Ammonia as N				49	<0.01	<0.01	0.01	0.47	0.83
Nitrate	50		400	76	<0.05	<0.05	0.12	0.64	1.1
Nitrite	3		30	75	<0.005	<0.005	<0.005	0.14	0.24
Total Kjeldahl Nitrogen									
Nitrogen-total		5 (LTV), 25-125 (STV)							
Phosphorus-total		0.05 (LTV), 0.8-12 (STV)		93	<0.02	<0.02	0.04	**0.38**	**3.1**
Reactive Phosphorus		0.05 (LTV), 0.8-12 (STV)		56	<0.005	<0.005	<0.005	<0.005	0.009
Total Organic Carbon									
Dissolved Organic Carbon				49	1.5	2.1	3.6	7.3	13
Pathogens									
E.coli (cfu/100 mL)	0								
Thermotolerant coliforms (cfu/100 mL)		10 (raw food crops in contact with irrigation water)							
Organic chemicals									
Radionuclides									
Gross alpha (Bq/L)		0.5							
Gross beta (excluding K-40) (Bq/L)		0.5							

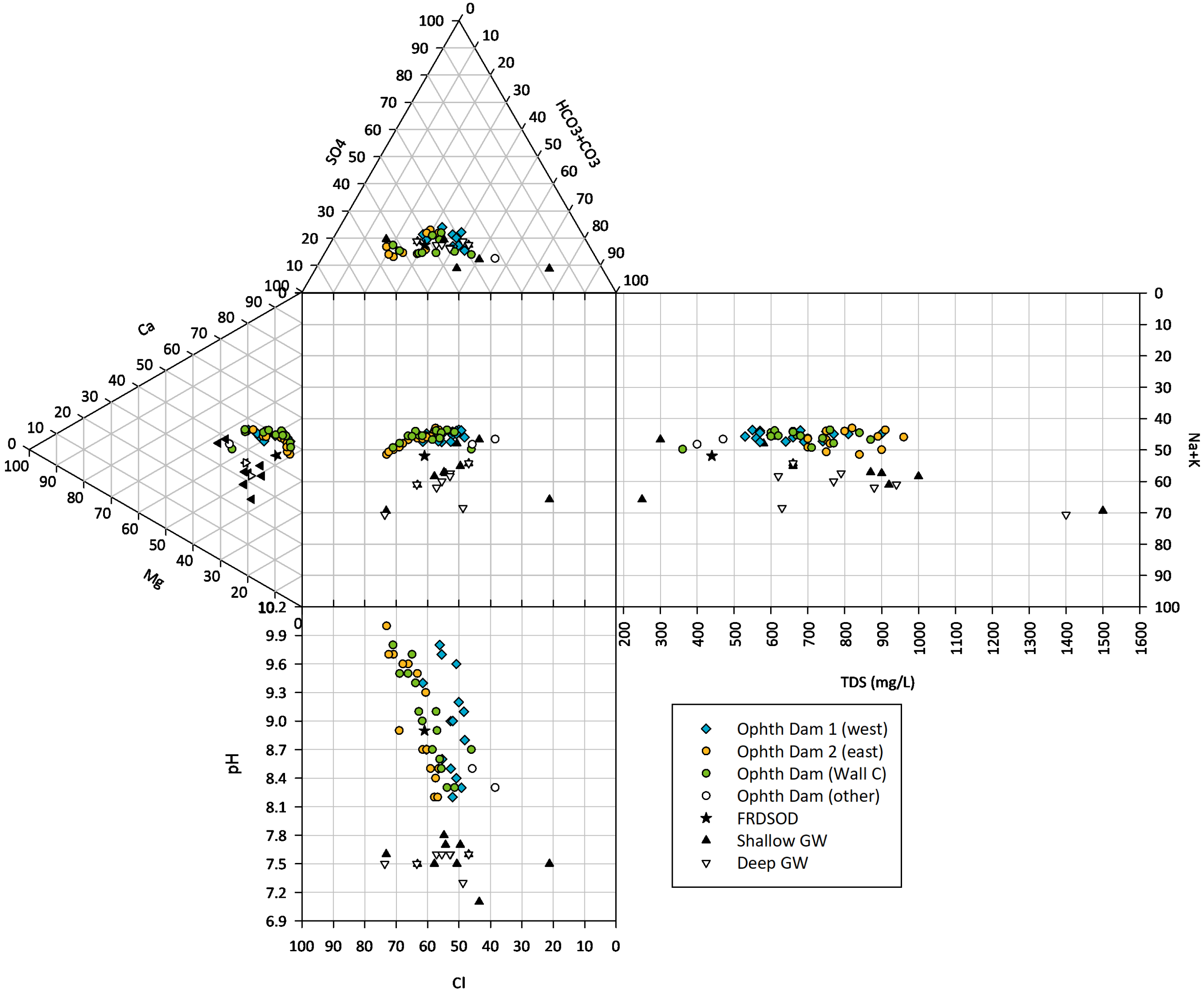
† NMRC-NRMMC (2011)

‡ ANZECC-ARMCANZ (2000)

upper bound of tolerance estimated using a leaching fraction of 0.33 which is applicable to loam and light clay soils; LTV (long-term trigger value) = 100 years irrigation; STV (short-term trigger value) = 20 years irrigation; **bold** values exceed a guideline value



Apx Figure A.4 Durov diagram showing cation and anion composition of groundwater (sampled in October 2021 CSIRO; shallow and deep GW) and source water (mine water surplus, data courtesy of BHP) in relation to pH and total dissolved solids (TDS)



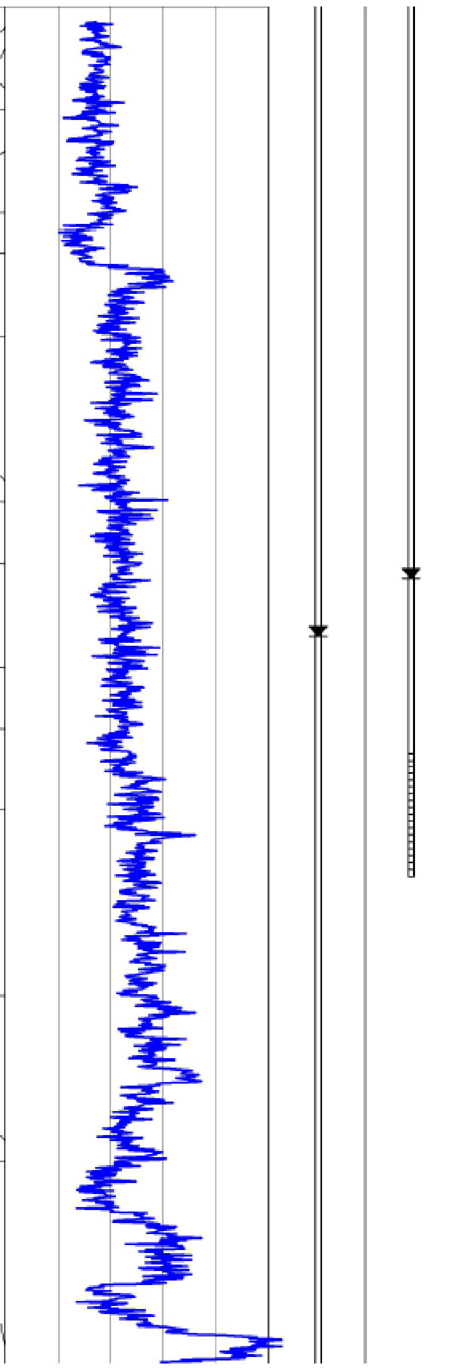
Apx Figure A.5 Durov diagram showing cation and anion composition of groundwater (sampled in October 2021 CSIRO; shallow and deep GW) and source water (Ophthalmia Dam, data courtesy of BHP) in relation to pH and total dissolved solids (TDS)

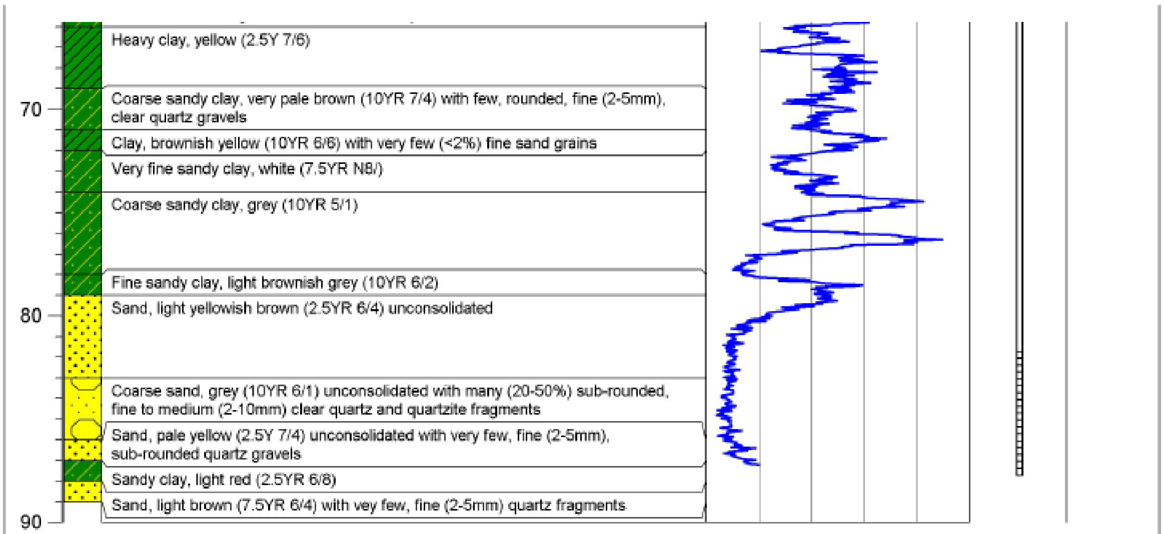
Appendix B Lithology logs for bores installed by DPIRD, 2021

Lithological logs for bores installed by DPIRD in June and August 2021 as part of the TAP project. Locations are shown in Apx Figure A.1.

Bore name/s: 21NN01D & S	**Supervisor/s:** J. Simons		Department of Primary Industries and Regional Development
Org:	**Project:** TAP		
Date: 08/06/2021	**Catchment:** Fortescue	**Sub-catchment:** Ethel Ck	
Location: Ethel Creek Station			
Datum: GDA94 **Zone:** 51	**Location QC:** GPS	**AHD (m):**	**E (m):** 195571 **N (m):** 7436201
Landholder: BHP		**Land use:** Pastoral	
Landform / Soil description: Plain		**Year cleared:**	

Depth (m)	Lithology description
0	Clay loam, red (2.5YR 4/6)
	Sandy clay loam, dark red (10R 3/6)
	Clay, red (10R 4/6)
	Sandy loam, reddish brown (2.5YR 4/4), cemented
	Sandy clay loam, red (2.5YR 4/6) with very few (<2%), large (up to 30mm) sub-rounded ironstone gravels
	Coarse sand to very coarse sandy loam, red (2.5YR 4/6) with very few, medium (5-25mm) sub-rounded gravels, mixed lithology
10	Calcrete, light yellowish brown (10YR 6/4), very hard
	Fine sandy clay loam, yellowish red (5YR 5/6)
	Sandy clay loam, yellowish red (5YR 5/6) with very few, small (2-5mm) sub-rounded quartz gravels
20	
	Calcrete, yellowish red (5YR 5/6)
	Gravels, many (20-50%), small to medium (2-10mm), sub-rounded in red (2.5YR 4/6) clay loam sandy
	Gravels, many, medium (5-20mm), sub-rounded, mixed lithology in red (2.5YR 4/6) loam fine sandy to coarse sand loam
30	
	Gravels, many, small to medium (2-10mm), in red (2.5YR 4/6) clay loam to silty clay loam
	Sandy clay, red (2.5YR 4/6) with few (2-10%), small to medium (2-15mm) sub-rounded gravels
40	Fine sandy clay with very few, small to medium (2-10mm) sub-rounded gravels
	Gravels, very many (50-90%), medium (5-20mm), sub-rounded in coarse sandy clay, dark red (2.5YR 3/6)
50	
	Clay, dark red (2.5YR 3/6)
	Medium clay, light grey (10YR 7/1)
60	
	Sandy clay, very dark greyish brown (2.5Y 3/2) with very few, fine (2-5mm), sub-rounded, manganese coated ferricrete pisolites



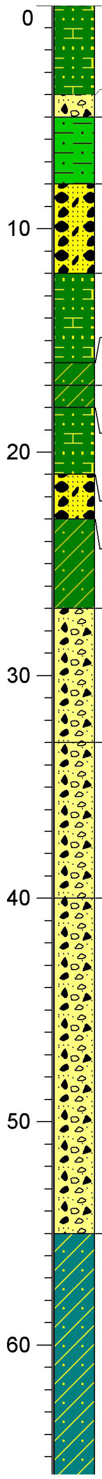


Driller: Austral	**Drill method:** AirCore	**Drill bit diam. (mm):** 130
Depth drilled (m): 89 (D) 42 (S)	**Casing length (m):** 88.14 (D) 42.7 (S)	**Casing AGL (m):** 0.42 (D) 0.49 (S)
Casing diam. (mm): 50 (D) 50 (S)	**Casing type:** PVC PN12	**Casing installation QA:** Good
Screen length (m): 6.0 (D) 6.0 (S)	**Screened interval (mBGL):** 82.14-88.14 (D) 36.7-42.7 (S)	
Screen type: PVC PN12 0.5mm slots	**Annulus seal:** Bentonite	**Filter pack:** 8/16 gravel
SWL date: 21/06/2021	**SWL (mBGL):** 30.1 (D) 27.8 (S)	**Yield (L/s):** 0.48 (D) 0.2 (S)
Material screened: Sands (D)	**EC (mS/m):** 134 (D) 46 (S)	**pH:** 7.18 (D) 7.5 (S)

Notes: 21NN01D was drilled using a hammer bit from 0 - 53.5m and then AirCore bit from 53.5m to EOH.

Bore name/s: 21NN02D & S	**Supervisor/s:** R. Paul	Department of Primary Industries and Regional Development – Government of Western Australia
Org:	**Project:** TAP	
Date: 22-25/06/2021	**Catchment:** Fortescue	**Sub-catchment:** Ethel Ck
Location: Ethel Creek Station		
Datum: GDA94 **Zone:** 50	**Location QC:** GPS **AHD (m):**	**E (m):** 798611 **N (m):** 7436553
Landholder: BHP		**Land use:** Pastoral
Landform / Soil description: Plain		**Year cleared:**

Depth (m)	Lithology description	Gamma (cps) 0–200	Bore design: Deep, Shallow Piezometers



Silty clay, dark reddish brown (2.5YR 3/4), sandy, very few (<2%) fine (2-4mm) sub-rounded gravels ironstone pisolites. @ 4-5m gravels (2-10mm)

Gravels, many (20-50%) fine to medium (2-20mm) sub-rounded

Silty clay loam, dark red (2.5YR 3/6)

Gravelly sandy loam, red (2.5Yr 4/6), with many (20-50%) sub-rounded gravels (5-30mm) mixed lithology

Clay loam sandy, red (2.5YR 4/6) with very few (<2%) fine (2-5mm) rounded gravels

Sandy clay, yellowish red (5YR 4/6) with very few (<2%) large (20mm) sub-rounded gravel fragments

Fine sandy clay, yellowish red (5YR 5/6) with grey clay lenses and very few (<2%) large (up to 70mm) sub-rounded pebbles/gravels

Silty clay, red (2.5YR 4/6), sandy, fine-coarse grained, sub rounded to rounded, mainly quartz, between 18 to 19m very few (<2%) large (up to 70mm) sub-rounded pebbles/gravels

Silt loam, yellowish red (5YR 4/6) with many (20-50%) sub-rounded coarse (up to 70mm) gravels/ large pebbles

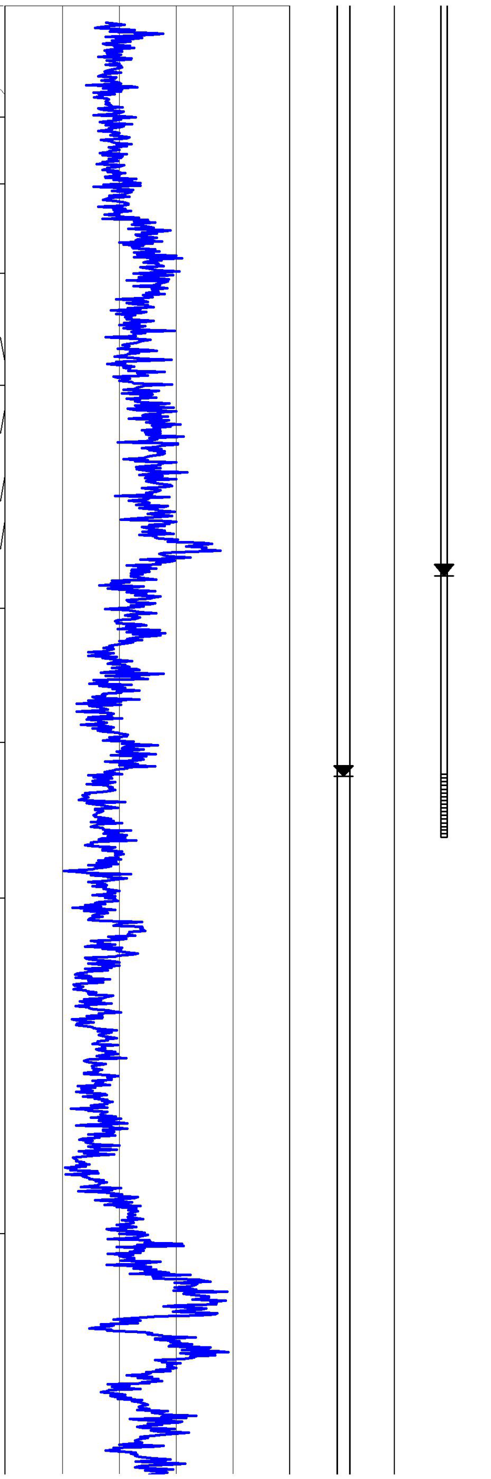
Fine sandy clay, dark red (2.5YR 3/6)

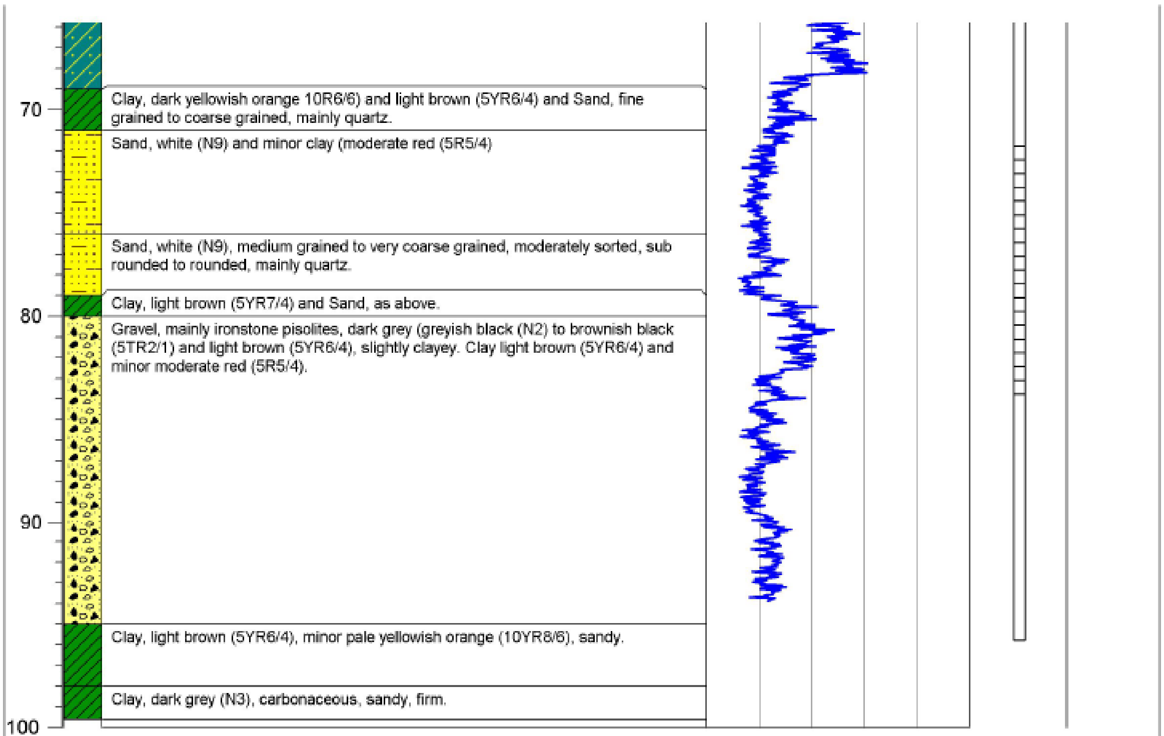
Gravels, very abundant (50-90%), large (up to 70mm) sub-rounded to rounded, poorly sorted within a red (2.5YR 4/6) silty clay matrix

Gravels, mainly banded ironstone and clay, moderate red (5R 5/6).

Gravels, mainly banded ironstone, sub-rounded and Clay, white (N9) and moderate red (5R5/6).

Clay, sandy, white (N9), greyish orange (10YR7/4) and moderate reddish orange (10R6/6). Clay firm, plastic, sand fine grained to medium grained, sub rounded to rounded, mainly quartz.



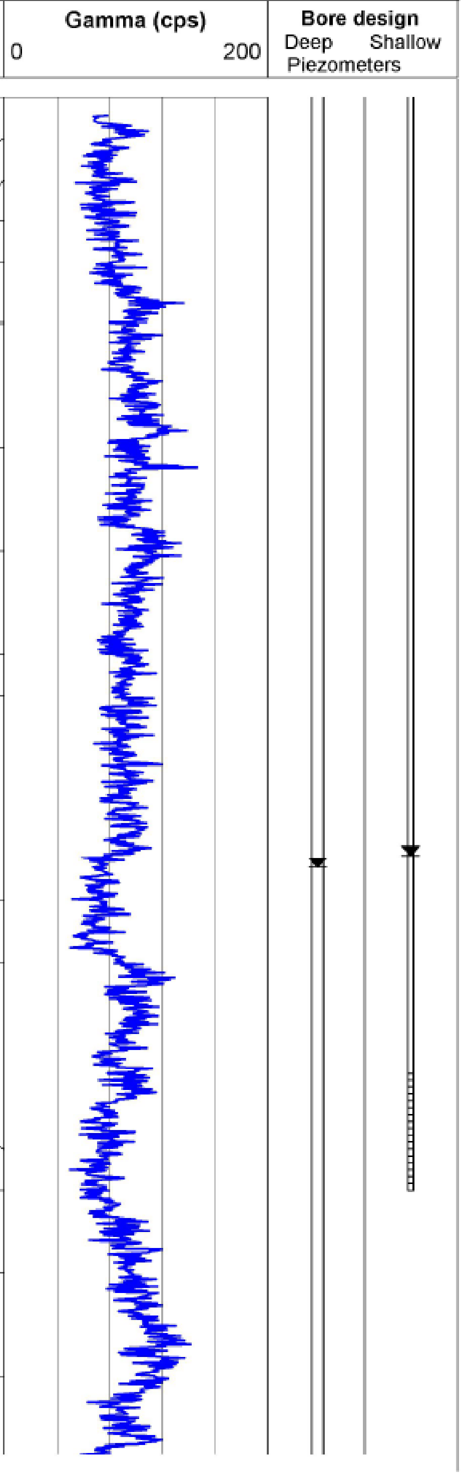


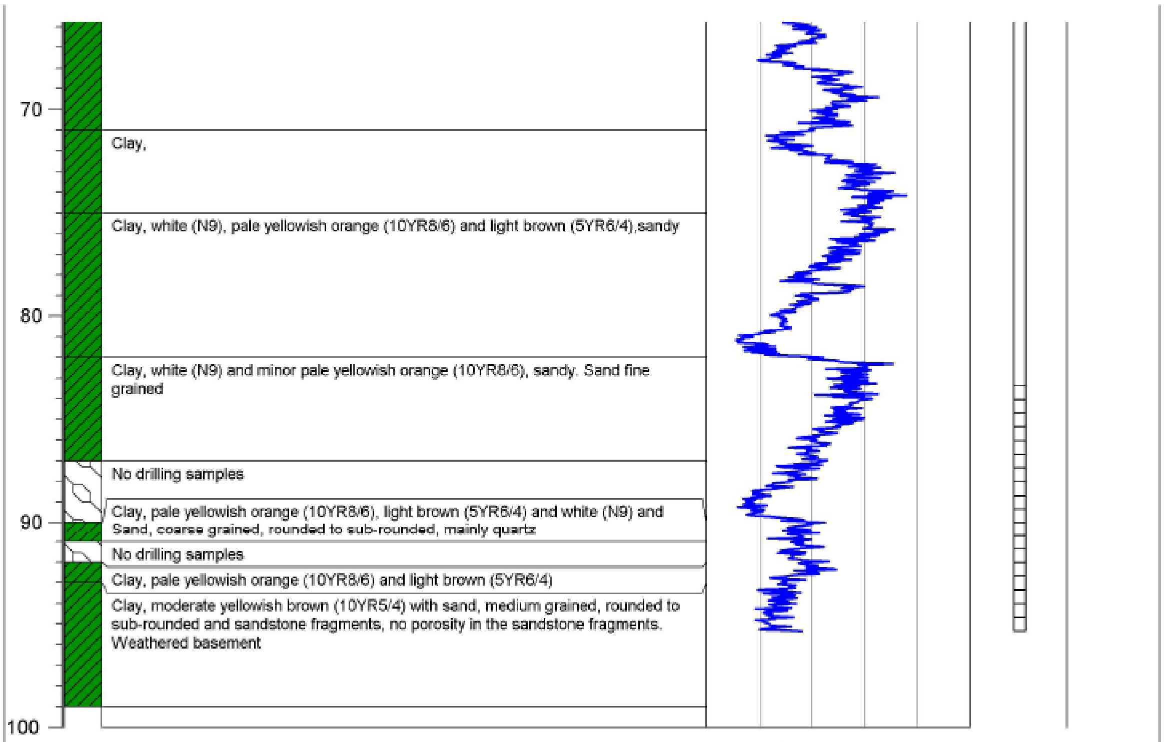
Driller: Austral	**Drill method:** Mud rotary	**Drill bit diam. (mm):** 213
Depth drilled (m): 99.4 (D) 48 (S)	**Casing length (m):** 96.4 (D) 37.9 (S)	**Casing AGL (m):** 0.64 (D) 0.65 (S)
Casing diam. (mm): 100 (D) 50 (S)	**Casing type:** PVC PN12	**Casing installation QA:** Good
Screen length (m): 12.0 (D) 3.0 (S)	**Screened interval (mBGL):** 71.76-83.76 (D) 34.25-37.25 (S)	
Screen type: PVC PN12 0.5mm slots	**Annulus seal:** Bentonite	**Filter pack:** 8/16 gravel
SWL date: 02/09/2021	**SWL (mBGL):** 34.53 (D) 25.53 (S)	**Yield (L/s):** 0.4 (D) 0.45 (S)
Material screened: Sands	**EC (mS/m):** 165 (D) 210 (S)	**pH:** 7.22 (D) 7.33 (S)

Notes:

Bore name/s: 21NN03D & S	**Supervisor/s:** R. Paul		Department of Primary Industries and Regional Development
Org:	**Project:** TAP		
Date: 15-20/06/2021	**Catchment:** Fortescue	**Sub-catchment:** Ethel Ck	
Location: Ethel Creek Station			
Datum: GDA94 **Zone:** 50	**Location QC:** GPS **AHD (m):**	**E (m):** 802194	**N (m):** 7439224
Landholder: BHP		**Land use:** Pastoral	
Landform / Soil description: Plain		**Year cleared:**	

Depth (m)	Lithology description
0	Sandy clay loam, red (10R 4/6) with common (10-20%) fine (2-6mm) sub-rounded gravels
	Sandy clay, red (10R 4/6) with many (20-50%) coarse (2-60mm) sub-rounded gravels, poorly sorted, mixed lithology
	Ferricrete (red brown hard pan), weak red (10R 4/4) hard, cemented
	Loam fine sandy red (2.5YR 4/6) @ 8m cemented band of ferricrete
10	Coarse sandy clay loam, yellowish red (5YR 5/6) with many sub-rounded fine gravels. @10m Hard cemented red-brown hard pan
	Sandy clay loam, red (2.5YR 4/6), @11m foam injected, @13m band of gravels, coarse (up to 30mm), sub-rounded, poorly sorted, mixed lithology
20	Gravels, coarse (up to 50mm), sub-rounded, poorly sorted, mixed lithology
	Silty clay loam (fine sandy), red (2.5YR 4/6) with very few (<2%) fine (2-6mm) sub-rounded gravels
	As above with common (10-20%) coarse (up to 60mm) sub-rounded gravels
30	Silty clay, red (10YR 4/6) with very few, medium (6-20mm) sub-rounded gravels
40	Gravels many (20-50%) coarse (20-60mm), sub-rounded, poorly sorted within coarse sandy clay
	Light clay, white (5YR 8/1) with bands of red (2.5 YR 4/6) and yellowish red (5YR 5/6) silty clays. @ 50m band of highly polished, sub-rounded 5-15mm gravels.
50	Light clay, light grey (5YR 7/1), @51m band of ferricrete, hard, dark reddish brown (5YR 3/2)
	Clay, light brown (5YR6/4), minor pale yellowish orange (10YR8/6) and very minor white (N9)
60	Clay, light brown (5YR6/4), pale yellowish orange (10YR8/6) and very minor white (N9)
	Clay, pale yellowish orange (10YR8/6), light brown (5YR6/4) and minor white (N9), sandy. Sand fine grained



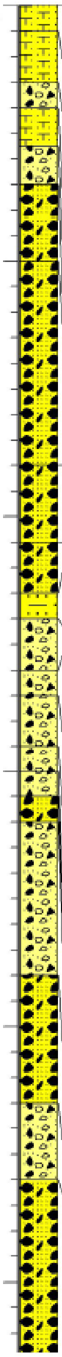


Driller: Austral	**Drill method:** Mud rotary	**Drill bit diam. (mm):** 213
Depth drilled (m): 99.4 (D) 53 (S)	**Casing length (m):** 96 (D) 53.7 (S)	**Casing AGL (m):** 0.65 (D) 0.70 (S)
Casing diam. (mm): 100 (D) 50 (S)	**Casing type:** PVC PN12	**Casing installation QA:** Good
Screen length (m): 12.0 (D) 6.0 (S)	**Screened interval (mBGL):** 83.35-95.35 (D) 47.0-53.0(S)	
Screen type: PVC PN12 0.5mm slots	**Annulus seal:** Bentonite	**Filter pack:** 8/16 gravel
SWL date: 02/09/2021	**SWL (mBGL):** 37.38 (D) 36.76 (S)	**Yield (L/s):** 0.38 (D) 0.17 (S)
Material screened: Clay	**EC (mS/m):** 137 (D) 183 (S)	**pH:** 6.45 (D) 7.26 (S)

Notes:

Bore name/s: 21NN03D & S	**Supervisor/s:** R. Paul	Department of Primary Industries and Regional Development
Org:	**Project:** TAP	
Date: 03-07/08/2021	**Catchment:** Fortescue **Sub-catchment:** Ethel Ck	
Location: Ethel Creek Station		
Datum: GDA94 **Zone:** 50	**Location QC:** GPS **AHD (m):**	**E (m):** 795435 **N (m):** 7445503
Landholder: BHP		**Land use:** Pastoral
Landform / Soil description: Plain		**Year cleared:**

Depth (m)	Lithology description	Gamma (cps) 0–200	Bore design



0
- Silt, sandy, moderate reddish brown (10R6/6), sands fine to medium grained, sub-rounded to rounded, mainly quartz
- Silt, sandy, with minor gravel (up to 20mm), reddish brown (10R5/6).
- Gravel (BIF, chert and quartz) and Sand and Silt, pale reddish brown (10R5/4). Sand fine to very coarse grained, sub-rounded to rounded, mainly quartz
- Silt, sandy, with minor gravel (up to 20mm), reddish brown (10R5/6).

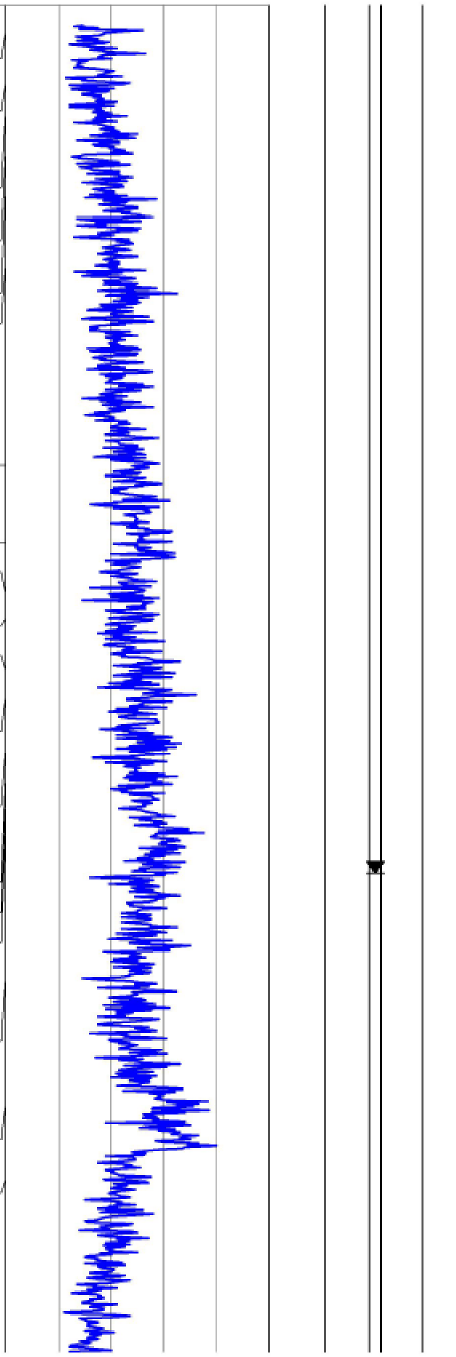
10
- Gravel (up to 40mm), sandy, silty, pale reddish brown (10R5/4) and black (N1), sands rounded mainly quartz
- Silt, sandy, gravelly (up to 10mm), pale reddish brown (10R5/4)
- Silt, sandy, gravelly (10-20mm), light brown (5YR5/4). Sand fine to medium grained, sub-rounded to rounded, mainly quartz
- Sand and Gravel (up to 20mm), silty, reddish brown (10R6/4)

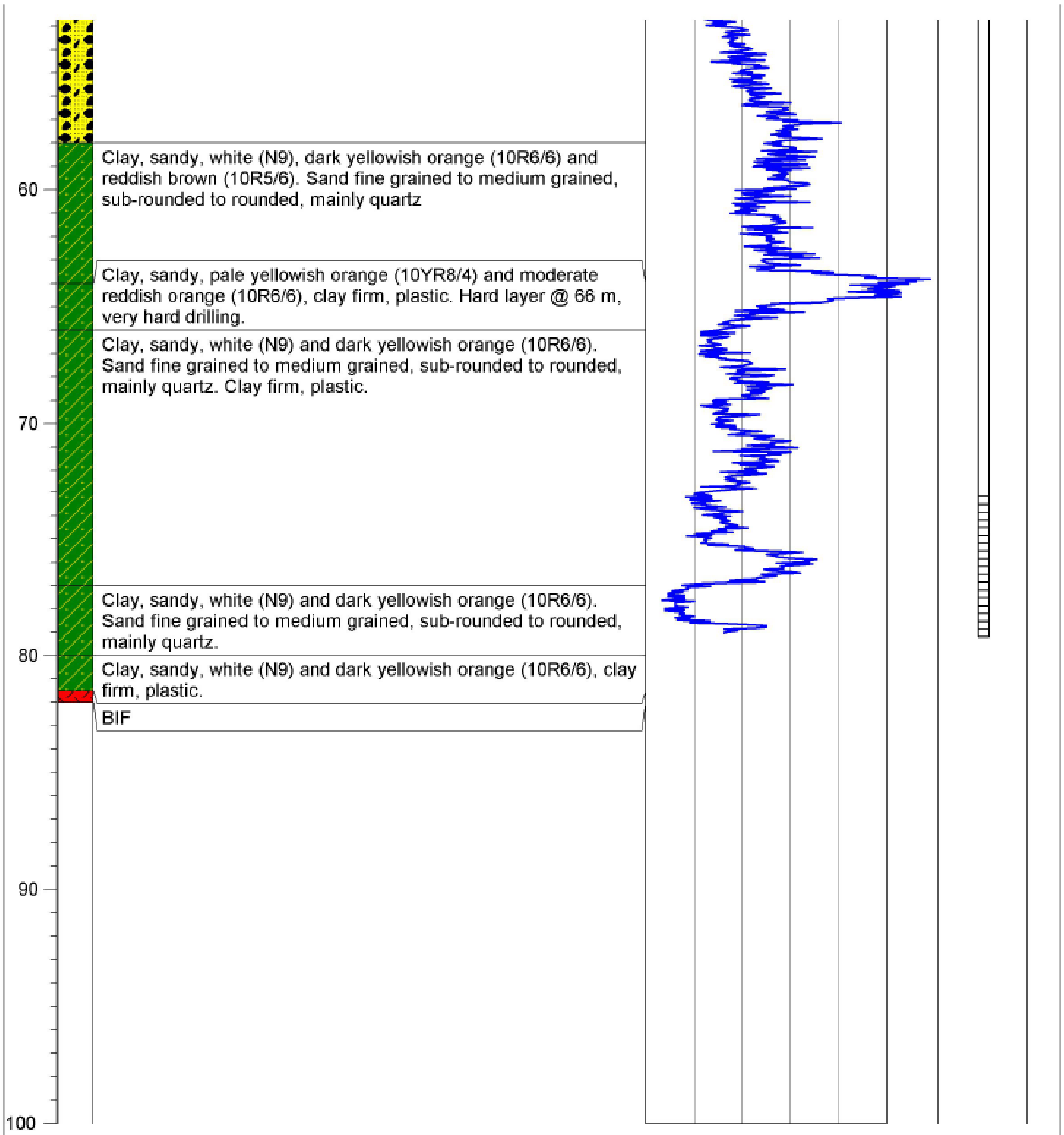
20
- Sand and Gravel (up to 10mm), silty, light brown (5YR5/6)
- Silt, sandy, minor gravel (up to 20mm), reddish brown (10R5/6). Sand mainly fine grained to medium grained, mostly quartz
- Gravel (up to 50mm), mainly ironstone and chert
- Gravel (up to 50mm), mainly ironstone and chert. Gravel and Silt, sandy fine grained, friable, layers of moderate reddish brown (10R4/6) and moderate yellowish orange (10R6/6)

30
- Gravel (up to 40mm), light brown (5YR5/6). Gravel and Silt, sandy fine grained, friable, layers of moderate reddish brown (10R4/6) and moderate yellowish orange (10R6/6)
- Gravel (up to 50mm), silty, moderate brown (5Y5/4). Gravel and Silt, sandy fine grained, friable, layers of moderate reddish brown (10R4/6) and moderate yellowish orange (10R6/6)
- Gravel (up to 50mm), silty, moderate brown (5Y5/4)
- Gravel, silty, dark reddish brown (10R3/6).
- Gravel (mostly 5-10 mm but up to 20mm) sub-rounded and silt, sandy, moderate reddish brown (10R4/6). Sand mainly fine grained to medium grained, sub-rounded to rounded, mainly quartz

40
- Silt, gravelly (mostly 5-10 mm but up to 20mm) sub-rounded, sandy, moderate reddish brown (10R4/6). Sand mainly fine grained to medium grained, sub-rounded to rounded, mainly quartz
- Gravel (up to 10mm), ironstone and chert, sub-rounded to rounded within a silty, moderate reddish brown (10R4/6) matrix
- Silt and Gravel (up to 10mm), sandy, reddish brown (10R4/4). Silt sandy, fine grained to medium grained, indurated, friable

50



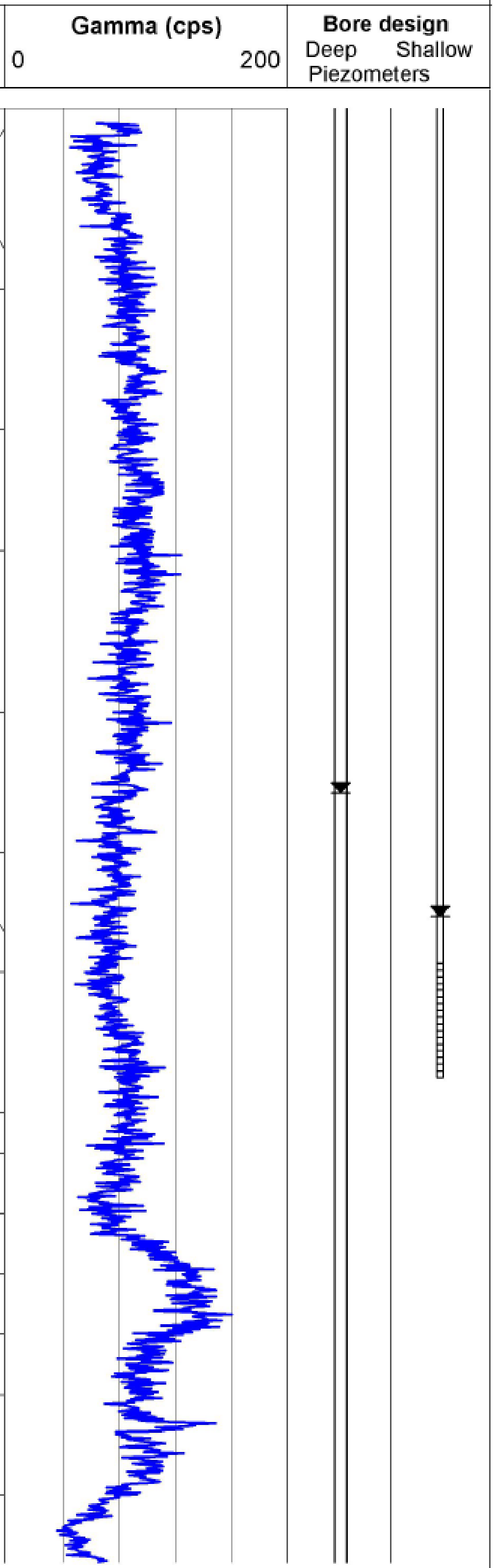


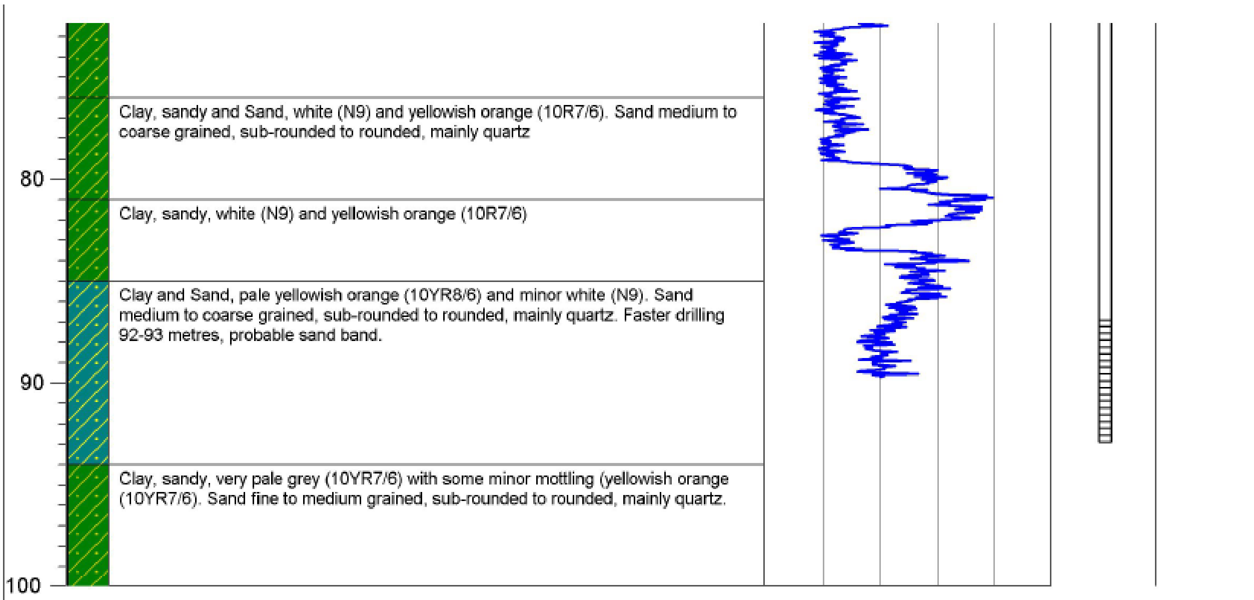
Driller: Austral	**Drill method:** Mud rotary	**Drill bit diam. (mm):** 213
Depth drilled (m): 82	**Casing length (m):** 79.78	**Casing AGL (m):** 0.60
Casing diam. (mm): 100	**Casing type:** PVC PN12	**Casing installation QA:** Good
Screen length (m): 6.0	**Screened interval (mBGL):** 73.18-79.18	
Screen type: PVC PN12 0.5mm slots	**Annulus seal:** Bentonite	**Filter pack:** 8/16 gravel
SWL date: 02/09/2021	**SWL (mBGL):** 34.01	**Yield (L/s):** 0.9
Material screened: sandy clay	**EC (mS/m):** 187	**pH:** 7.09

Notes:

Bore name/s: 21NN06D & S	**Supervisor/s:** R. Paul		Department of Primary Industries and Regional Development
Org:	**Project:** TAP		
Date: 27-31/08/2021	**Catchment:** Fortescue	**Sub-catchment:** Ethel Ck	
Location: Ethel Creek Station			
Datum: GDA94 **Zone:** 50	**Location QC:** GPS	**AHD (m):**	**E (m):** 803003 **N (m):** 7441572
Landholder: BHP		**Land use:** Pastoral	
Landform / Soil description: Plain		**Year cleared:**	

Depth (m)	Lithology description
0	Silt, sandy, moderate reddish brown (10R5/6). Sand fine to medium grained
	Gravel, silty, moderate red (5R5/4) and dusky blue (5PB3/2). Gravels up to 50mm, sub-rounded to rounded, poorly sorted, includes BIF, quartz and chert
	Silt, sandy, moderate reddish brown (10R5/6). Sand fine grained to medium grained, mainly quartz
10	Silt, sandy, minor gravel (up to 20mm), moderate reddish brown (10R5/6). Sand fine to coarse grained, mainly quartz
	Silt and Gravel, moderate reddish brown (10R5/6). Gravel content increasing with depth with last metre drilled mostly gravel.
20	
	Silt, sandy, minor gravel, moderate reddish brown (10R4/6). Sand fine to medium grained, mainly quartz
30	Silt, sandy, minor gravel (up to 10mm), moderate red (5R3/4). Sand mainly fine to medium grained, mostly quartz
	Silt and gravel, moderate reddish brown (10R5/6)
40	Gravel, silty, pale reddish brown (10R5/6). Gravel sub-rounded to rounded, up to 10mm
	Gravel and Silt, pale reddish brown (10R5/6). Gravel content decreasing with depth
50	Silt with minor gravel (up to 10mm), moderate reddish brown (10R4/6)
	Clay, sandy, silty, yellowish orange (10YR7/6) and moderate reddish brown (10R6/6). Sand fine to medium grained, mainly quartz.
	Clay, sandy and minor gravel (up to 5mm), moderate reddish brown (10R5/6) and white (N9). Sand fine to medium grained, mainly quartz
60	Clay, sandy, with minor gravel (up to 20mm), white (N9) and dark orangish brown (10R6/6). Sand fine to medium grained
	Clay, sandy, with minor gravel (up to 20mm), moderate reddish orange (10R5/6), dark orangish brown (10R6/6) and white (N9)
	Clay, sandy, yellowish grey (5Y7/2) and minor yellowish orange (10YR7/6). Clay very stiff
70	Clay, sandy, white (N9) and yellowish orange (10R7/6)





Driller: Austral	**Drill method:** Mud rotary	**Drill bit diam. (mm):** 213
Depth drilled (m): 106 (D) 50 (S)	**Casing length (m):** 93.2 (D) 48.8 (S)	**Casing AGL (m):** 0.3 (D) 0.57 (S)
Casing diam. (mm): 100 (D) 50 (S)	**Casing type:** PVC PN12	**Casing installation QA:** Good
Screen length (m): 6.0 (D) 6.0 (S)	**Screened interval (mBGL):** 86.9-92.9(D) 42.23-48.23 (S)	
Screen type: PVC PN12 0.5mm slots	**Annulus seal:** Bentonite	**Filter pack:** 8/16 gravel
SWL date: 02/09/2021	**SWL (mBGL):** 34.02 (D) 40.16 (S)	**Yield (L/s):** 0.20 (D) 0.08 (S)
Material screened:	**EC (mS/m):**	**pH:** 7.16 (D) 7.24 (S)

Notes:

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