MINISTERS NORTH ECOHYDROLOGY

Prepared for

BHP IRON ORE

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Context and Purpose

BHP are investigating options to develop the Ministers North iron ore deposit in the Pilbara region of Western Australia. The deposit is located due north of MAC and south of Yandi, approximately 120km north-west of Newman in the central Pilbara.

The deposit is hosted in Brockman Iron Formation on a range of hills that strikes broadly east-west. The northern side of the range is marked by Marillana Creek and the associated Yandi paleovalley. The southern side of the range is marked by Yandicoogina Creek. Yandicoogina Creek deviates to flow due north, crossing the range at the eastern end of the deposit, and eventually joining Marillana Creek.

A riparian ecosystem has developed along Yandicoogina Creek that comprises Coolabah trees (*Eucalyptus victrix*), River Red Gums (*Eucalyptus camaldulensis*) and Silver Paper Bark trees (*Melaleuca argentea*). There are also permanent and semi-permanent pools. BHP now wish to gain an understanding of the potential consequence of groundwater level decline for the riparian ecosystem.

This Study

This report describes an initial review and preliminary ecohydrological conceptualisation undertaken by AQ2. The study included a review of existing BHP reports and data (hydrological investigations, groundwater monitoring and vegetation mapping). The review was complemented by a site reconnaissance visit.

The Ecohydrological System

The ecohydrological system is summarised in Figure ES1.

In the study area, the hydrological regime is ephemeral, with flow events occurring 2-3 times per year. Regional groundwater levels in the basement massif into which the creek is incised, decreased over the period of the monitoring record (from 2017 to present), which is believed to relate to rainfall trends. Notwithstanding, limited monitoring suggests groundwater levels in the creek alluvium have been stable, (other than for seasonal variation) over the same period; the depth to groundwater in the alluvial aquifer ranges between 0 mbgl and 5 mbgl. Transient and permanent pools are consistent with shallow groundwater levels.

Riparian vegetation occurs along the creek channel. In two areas, (Areas 1 and Area 3), this is characterised by a mesic progression of riparian vegetation from:

- *Eucalyptus victrix* ecotype (Ev-type). This ecotype comprises a low woodland of Eucalyptus victrix at low to moderate basal area. These areas are characterised by a grass understorey.
- *Eucalyptus camaldulensis* ecotype (Ec-type). This ecotype comprises a mid-woodland with *Eucalyptus camaldulensis* as the primary species. *Eucalyptus victrix* forms a subordinate species at its upstream margins while *Melaleuca argentea* is a subordinate species at its downstream margins. This ecotype includes *Acacia tumida* and *A. coriacea* as mid storey species. Extensive *Gossypium robinsonii* occurs in slightly elevated areas on the margins of the creek.

- *Melaleuca argentea* ecotype (Ma-type). This ecotype comprises a high woodland to open-forest of *Melaleuca argentea* with subordinate *Eucalyptus camaldulensis.* This ecotype includes *Acacia tumida* and *A. coriacea* as mid storey species and extensive *Typha domingensis* in areas of both permanent and transient pools. Extensive *Gossypium robinsonii* occurs in slightly elevated areas on the margin of the creek.

It is inferred that the Ev ecotype does not rely on consistent access to groundwater and is not groundwater dependent, based on relatively low observed basal area and clear indications of historical water stress. The Ec ecotype may facultatively use groundwater although periods of water stress are also inferred. The Ma ecotype is likely to have an obligate groundwater dependence. It is likely that the mesic progression mirrors a progression in higher water demands for the Ma type compared to the Ev type and less tolerance for dry (i.e., low-matric pressure) conditions.

Risks and Recommendations

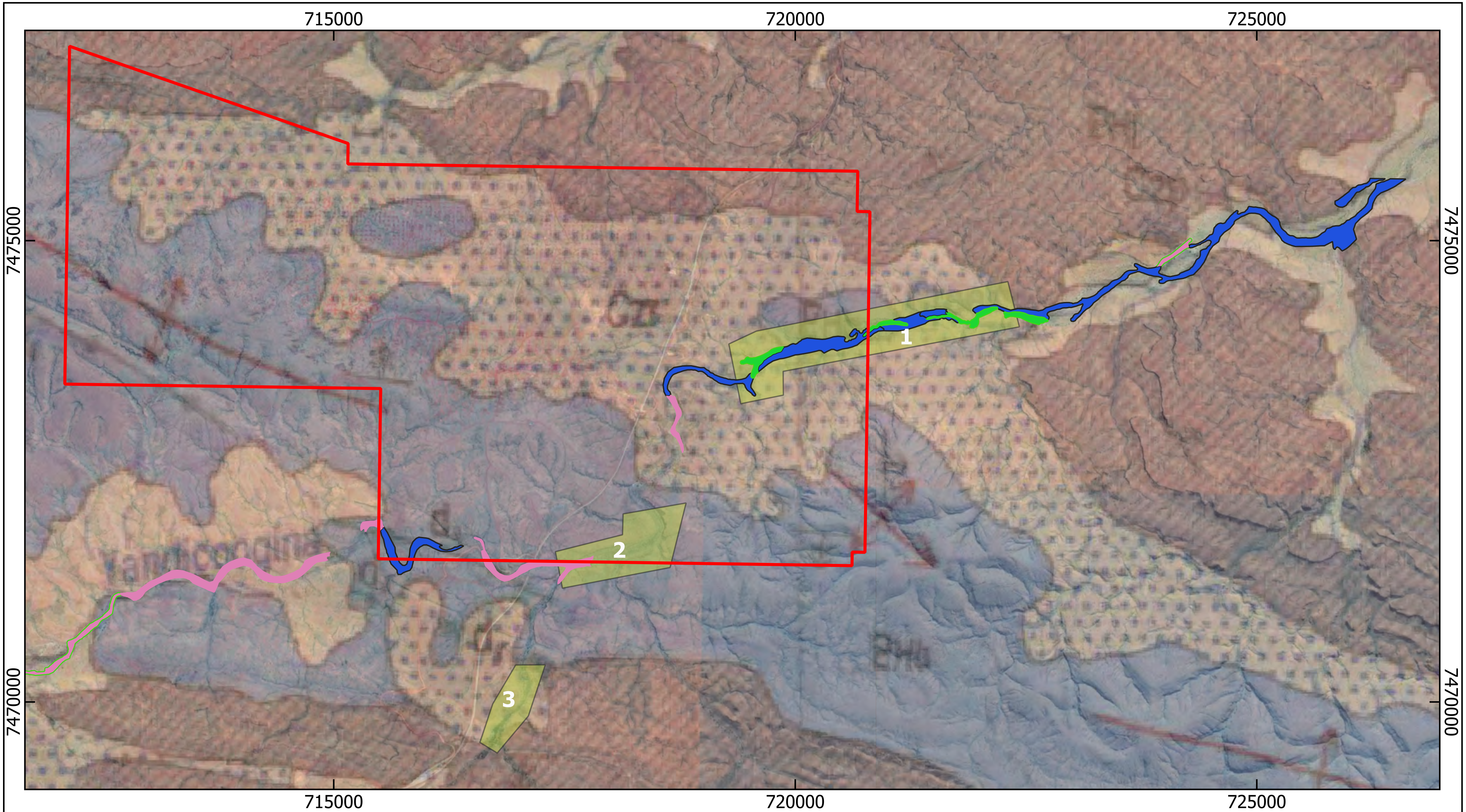
It is believed the key approval and operational risks relate to:

- Limited quantification and modelling of the ecohydrological systems. Specifically:
  - Quantified metrics to describe the systems and allow determination of evapotranspiration demands.
  - Determination of baseline conditions taking account of evidence for historical water stress and recruitment.
- Confirmation (through quantification) of the suitability of Area 3 to provide an analogue for Area 1.
- Impacts from reduced groundwater levels related to future mine-dewatering; recent pumping tests show there is hydraulic connection between the alluvial aquifer and the Ministers North mining area.
- A wider potential impact footprint than anticipated because uncertainties and limitations mean there is in fact a stronger link between vegetation and groundwater, over a wider area, than inferred during this initial study.

Recommendations are summarised in Table ES1.

Table ES1 Summary of Recommendations

Recommendation	Risk Addressed	Outcome	Activity
Ecohydrological field surveys	Qualitative conceptual model No ability to quantify and predict impacts.	Quantified vegetation metrics to support estimates of evapotranspiration and modelling. Data to support determination of tree-water sources.	Field surveys covering: - vegetation density (by species) measured as Stand Basal Area - Predawn and midday leaf water potential measurements in representative transects
Ecohydrological quantified conceptual model and water balance model	Unanticipated impacts because vegetation uses groundwater. Impacts from other operations inseparable from Fortescue impacts. Baseline inappropriately defined due to historical time-variance.	Assessment of impacts and long-term baselines to support approvals and on-going compliance.	Quantify conceptual model with field data. Develop numerical ecohydrological model to predict: - historical baselines - confirm water sources required by the riparian system and predict impacts related to Fortescue operations.
Specific comparison of modelling of Area 1 and Area 3 to confirm Area 3 is an analogue location	Natural changes in Area 1 related to climate are assigned to mining-induced change Limited time-series baseline.	Confirmation Area 3 can be used as a non-impact analogue location	Comparison of ecohydrological characteristics from field work and modelling between Area 1 and Area 3.
BHP Groundwater modelling to predict groundwater level change in the Yandicoogina alluvial aquifer	Changes to groundwater levels in the alluvial aquifer and implications for vegetation / management / mitigation strategies	Time series of groundwater level changes as an input to predictive ecohydrological modelling	BHP internal groundwater modelling programme
Expansion of groundwater monitoring network	Uncertainty over spatial / temporal depth to water in riparian area and spatial thickness of alluvium	Geometry of alluvial aquifer and range groundwater levels (that influence both root depth and PAW)	BHP monitoring bore drilling and installation of loggers
Ecohydrological monitoring	No baseline conditions against which to measure Fortescue impacts. Impacts related to Iron Valley are confused with Fortescue operations.	Establish baseline conditions Monitoring on-going changes related Iron Valley operations (prior to Fortescue start).	Regular (seasonal) monitoring of: - vegetation condition - LWP to provide a measure of tree water status



Location Map

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Ministers North Project Area

Vegetation Mapping

Ec-type

Ev-type

Ma-type

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AUTHOR: DGS

DRAWN: LDS

DATE: 04/03/2022

Report No: 006a

Revision: A

JOB No: 408

NOTES & DATA SOURCES:

Aerial image from Bing, Microsoft.

FIGURE ES1:
Major Ecotypes

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1 INTRODUCTION

1.1 Context and Purpose

BHP are investigating options to develop the Ministers North iron ore deposit in the Pilbara region of Western Australia. The deposit is located due north of MAC and south of Yandi, approximately 120km north-west of Newman in the central Pilbara.

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A riparian ecosystem has developed along Yandicoogina Creek that comprises Coolabah trees (*Eucalyptus victrix*), River Red Gums (*Eucalyptus camaldulensis*) and Silver Paper Bark trees (*Melaleuca argentea*). There are also permanent and semi-permanent pools. BHP now wish to gain an understanding of the potential consequence of groundwater level decline for the riparian ecosystem. This report describes an initial review and preliminary ecohydrological conceptualisation undertaken by AQ2.

1.2 Project Area

The project area is illustrated in Figure 1.1.

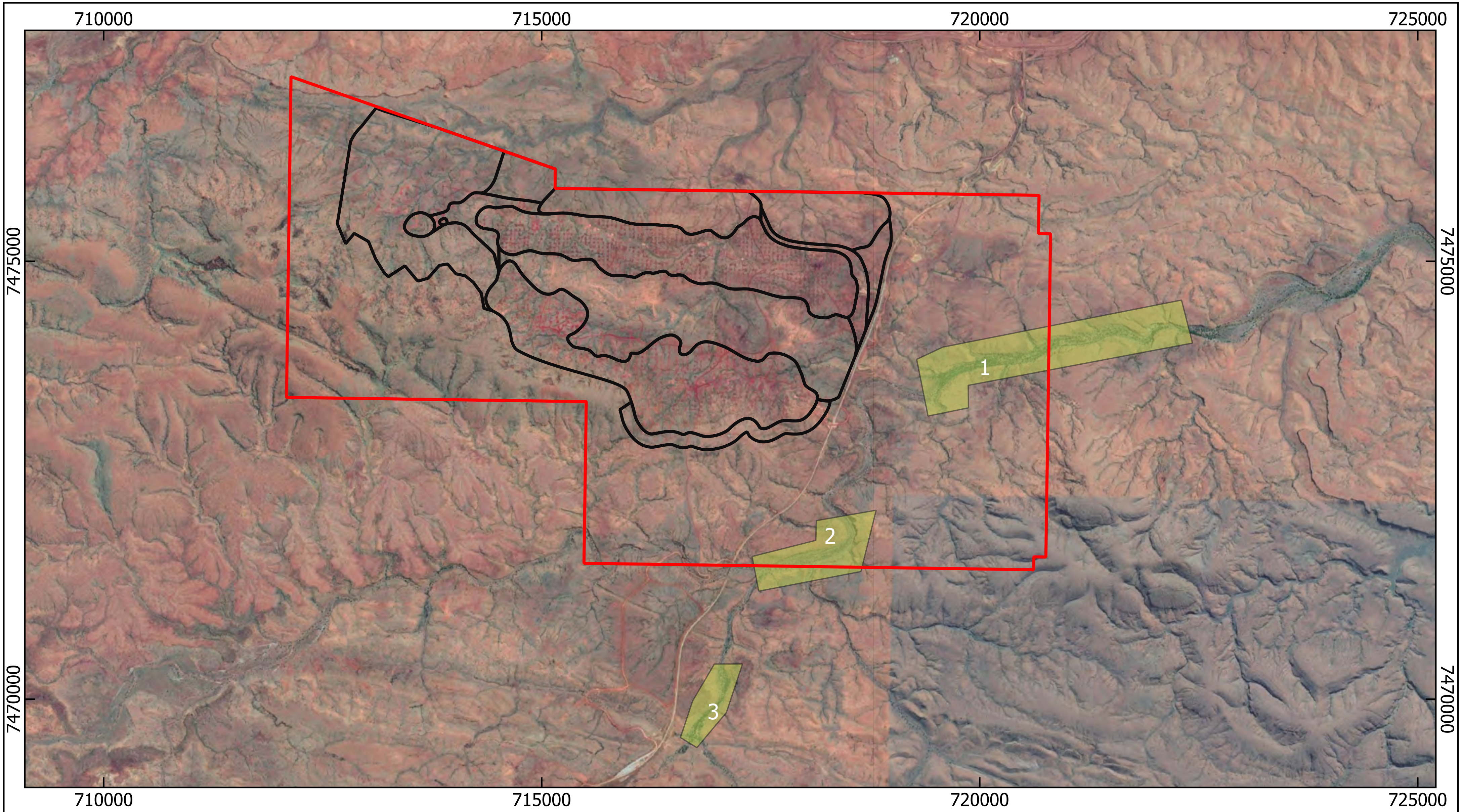
1.3 Physiography

1.3.1 Regional Geology and Hydrogeology

The study area lies within the Hancock Range between Mining Area C (to the south) and Yandi (to the north). The Hancock Range is a region of rugged hills and ranges comprising rocks of the Hamersley Group, a succession of banded iron formation (BIF), dolomite, shale, chert, and felsic volcanic rocks intruded by dolerite sills and dykes (Macphail and Stone 2004). The range forms the hinterland of the Yandicoogina Creek catchment.

Yandicoogina Creek flows through the range in a well incised channel / gorge. The gorge is characterised by shallow groundwater levels, pools and significant riparian vegetation in a location approximately 1.5km from the deposit. Preliminary indications are that in places, the pools are groundwater-fed, and the vegetation is phreatophytic; the presence of mature *Melaleuca argentea* trees suggests obligately so. The pools and incision occur where the creek passes through the Brockman Iron Formation adjacent to the NW/SE trending Wirriba Anticline which influences mineralisation. The incised creek channel is partially infilled with Cenozoic detrital sediments.

Groundwater levels at the Ministers North deposit have been in decline since ~2017; it is uncertain whether this decline is natural or related to the large-scale dewatering at Yandi as the decline in groundwater levels corresponds to a series of low-rainfall years and to the start of dewatering at the E7 pit; as discussed later in this report, a rainfall-related recession appears more likely. The Ministers North deposit extends below the water table and dewatering would be required to mine the entire resource, which may result in more significant declines in groundwater levels in the riparian area.



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Ministers North Project Area

Work Areas From Site Reconnaissance

Disturbance Area

0 1 2 km

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AUTHOR: DGS DRAWN: LDS DATE: 04/03/2022	Report No: 006a Revision: A JOB No: 408	**NOTES & DATA SOURCES:** Aerial image from Bing, Microsoft.	**FIGURE 1.1:** **Project Area**

1.3.2 Yandicoogeena Creek Catchment Hydrology

The Yandicoogeena Creek catchment covers an area of approximately 150km^2 to the location of the pools adjacent to Ministers North Deposit. Yandicoogina Creek consists of a well incised valley with little flood plain development. Most of the creek channel is activated by 1:5-year ARI flood and events larger than this, predominantly increase flow depth rather than flow width. The catchment is highly responsive with hydrological modelling suggesting that most flood events will pass in less than 24 hours; thus, frequent prolonged inundation is unlikely to occur.

1.3.3 Ecology

Pools occur along the creek channel. Some pools are transient whereas others are (semi) permanent. The key riparian trees within the system comprise *Melaleuca argentea*, *Eucalyptus camaldulensis* and *Eucalyptus victrix*. *Melaleuca argentea* is restricted to areas around perennial pools, coexisting with *Eucalyptus camaldulensis* which extended further upstream towards the area of transient pools where they are interspersed with *Eucalyptus victrix*. The creek also hosts riparian vegetation where surface water drainage is focussed even in the absence of pools. These areas are characterised by *Eucalyptus victrix.*

The riparian zone is most densely vegetated in the areas of transient and permanent pools. Here it is also characterised by a mid-storey dominated by *Acacia tumida* and marginal *Gossypium robinsonii* and an understorey of various grasses; *Cypress sp*. and *Typha domingenisis* in the wetter areas around pools.

2 EXISTING WORK AND SITE RECONNAISSANCE

2.1 BHP Drilling and Monitoring Data

BHP have data from 51 hydrogeological investigation bores associated with the Ministers North project; at least one water level measurement is available from 34 of these and time-series monitoring is available from many. Bore locations are shown in Figure 2.1. Most of these bores are drilled directly into the Brockman Iron Formation. Three bores are drilled into the Cenozoic Detritals that infill the creek channel (although in marginal locations and not in the low flow channel). Details of the monitoring bores in Yandicoogina Creek are summarised in Table 2.1.

Table 2.1: Monitoring Bores in Yandicoogina Creek

Bore	Easting (mE)	Northing (mN)	Elevation (mAHD)	Depth (m)	Monitoring Start	Water Level (mAHD)		Range (m)	Avg Depth (mbgl)
						Max	Min		
HMN0015M	719338	7473589	569.2	42	12/11/2020	562.16	561.86	0.296	7.2
HMN0016M	719341	7473597	569.1	75	12/11/2020	561.45	561.16	0.297	7.8

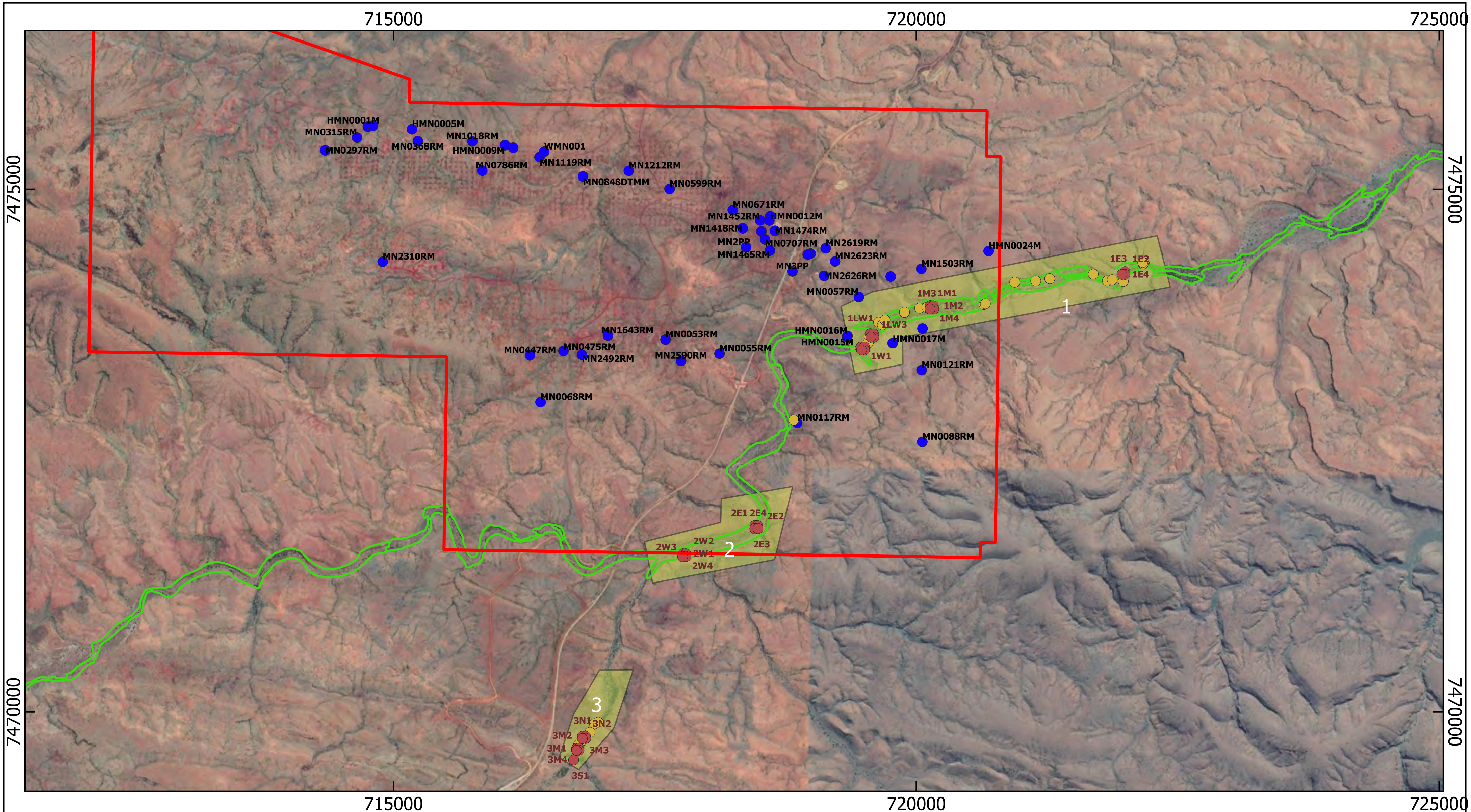
2.2 BHP Technical Reports and Investigations

BHP have developed a conceptual hydrogeological model for the Ministers North deposit (BHP 2019). This report included information gleaned from a site reconnaissance where it was postulated that shallow groundwater levels in the alluvial aquifer are sustained by seepage from the surrounding basement (where groundwater occurs at higher elevations than in the incised creek valley). Specific hydraulic connection between the orebodies and the alluvial aquifer was not considered in this model.

BHP have also compiled a summary of regional water level trends (BHP 2021). It is clear from this review that regional groundwater levels have been in recession since 2017. The reason for this is not confirmed and it may relate to regional dewatering at Yandi (to the north) or the natural response to rainfall changes. (It is noted in Section 3.1.2 later in this report that rainfall since 2017 has been significantly below the recent average and so a natural response appears likely).

BHP undertook a long-term pumping test on the Ministers North deposit in 2022 (RPS 2022). The data show that pumping from Ministers North South deposit for 30 days caused between 0.1 m and 0.2 m of drawdown in the creek-valley aquifer. Water that was discharged during the pumping test, was reinjected in Ministers North, North. The recharge mound did not extend towards Yandicoogina Creek, and it was postulated that the Keystone Fault acts as a hydraulic barrier. The pumping and injection tests suggest some hydraulic connection between the southern orebody and the alluvial aquifer with the potential for greater drawdown during long-term dewatering of the southern orebody.

BHP undertook an assessment of potential hydrological impacts related to the project (Stantec 2018). This work included 2D-modelling flood modelling, including relatively frequent flood events (1:2 ARI and 1:5 ARI). The modelling suggests that due to the incised nature of the channel with defined banks, most of the channel, in the main areas of riparian vegetation, would be inundated during a 1:5 yr ARI. However, the modelled hydrographs suggest the periods of inundation would be less than 24-hours.



Location Map

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Legend

- Ministers North Project Area
- Work Areas From Site Reccy
- NDVI Analysis Points
- Site Reccy Photo Points
- Monitoring Bores

0 1 2 km

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AUTHOR: DGS DRAWN: LDS DATE: 04/03/2022	Report No: 006a Revision: A JOB No: 408	**NOTES & DATA SOURCES:** Aerial image from Bing, Microsoft.	**FIGURE 2.1:** **Existing Data**

Data and mapping are available from two vegetation surveys undertaken by BHP (Biologic 2020 and Onshore 2018). Relevant survey areas are shown in Figure 2.1. Vegetation surveys confirm the distribution of riparian vegetation within Yandicoogina Creek and identify the broad community composition. Three broad riparian types can be discerned from the vegetation surveys:

- *Eucalyptus* low woodland - *Eucalyptus victrix* dominant communities along the channel.
- *Eucalyptus* mid to low woodland – *Eucalyptus camaldulensis* dominant communities with *Eucalyptus victrix.*
- *Melaleuca* woodland / open forest – *Melaleuca argentea* dominant communities with *Eucalyptus camaldulensis*.

2.3 Other Relevant Literature

2.3.1 Tree Root Response to Changes in Water Regime

Root Function

Little work has been published regarding the characterisation of the root systems of Pilbara riparian species. However, the root system is the mediator between a tree and its water and nutrient source (notwithstanding the complimentary function of mycorrhizal fungi). Understanding how the root system responds to changes in the water regime is of fundamental importance in predicting how the vegetation may change.

Global synthesis of plant root distribution data has shown that for most species about 50% of the root biomass occurs in the first 80 cm of soil, 95% in the first 200 cm, and only a minor percentage (if any) in deeper soil layers (Schenk 2008; Schenk & Jackson 2002, 2005). This reflects the primary importance of infiltrated rainfall in replenishing plant-available soil water. However, particularly in seasonally water-limited environments, some woody plants develop deep and expansive root systems (i.e., up to tens of meters) as a functional drought stress avoidance strategy (Schenk and Jackson 2002; Maeght et al. 2013).

In particular, the root systems of desert phreatophytes have a remarkable ability to adapt to water availability and groundwater dynamics (e.g., Naumburg et al., 2005; Orellana et al., 2012), resulting in vertically optimised active roots that respond to water table dynamics (Wang et al 2018). The dominant water sources for arid-zone tree transpiration can rapidly alternate between soil water during periods of infiltration and groundwater during the dry periods (Gou & Miller, 2014) and this plasticity minimises the energy costs of acquiring water (Schymanski et al 2008). In arid-zone riparian trees, the hydraulic conductivity of deep roots can be 30-times greater than shallow roots as a physiological adaption to allow high rates of transpiration from depth using only a small proportion of the overall root mass (e.g., Pate et al 2020).

Application to the Pilbara

The major Pilbara riparian species commonly have dimorphic root systems, consisting of expansive shallow lateral roots and a large taproot capable of penetrating to a considerable depth (to reach the deeper vadose zone or capillary fringe where groundwater is shallow). Extensive lateral roots and large tap and sinker roots on a *Eucalyptus victrix* are shown in Plate 1 from Weeli Wolli Creek adjacent to Nyidinghu. For contrast, the shallower and finer (predominantly) lateral roots of an adjacent *Acacia citrinoviridis* can be seen.

Plate 1: Extensive Lateral Roots and Sinker (Tap) Roots

Root Depth

Vadophytic *Eucalyptus victrix* on Coondewanna Flats (~50km southwest of the study area, within the Weeli Wolli Creek drainage basin) were shown to use water from around 5 mbgl following an infiltration event and water from between 15 mbgl and 20 mbgl after a prolonged dry period (AQ2 2015), clearly showing the dimorphic nature of the root distribution and ability of *Eucalyptus victrix* to develop a deep and plastic root system when environmental conditions are conducive. Loomes (2014) presents data that suggests that, in the Pilbara, *Eucalyptus camaldulensis* and *Melaleuca argentea* are characterised by shallower root systems than *Eucalyptus victrix* which is consistent with the more mesic tendency of these species.

The seasonal water level variation in Pilbara creek-aquifers commonly ranges up to 2 m. This means there may be a water level decline, at the end of the wet season, of up to 2 m, occurring over the 9-month dry season; this rate of decline may exceed the growth rate of the roots. Indeed, Argus et al (2015) found the roots of *Eucalyptus camaldulensis* seedlings did not grow at all in the first month after waterlogging. Thus, where a tree is using groundwater, a portion of the root system must persist in the zone that is periodically saturated such that water extraction from this zone can be readily initiated as the water level declines, without requiring the seasonal growth of roots. A portion of the roots must therefore persist in saturated and anoxic conditions for periods of time and phreatophytic tree roots evolve aerenchyma and adventitious roots to allow tolerance of anoxic conditions (Argus et al 2015, Wang et al 2018).

However, root function will not persist under prolonged periods of saturation (e.g., Argus 2018). After a threshold time, oxygen stress will result in root death and truncation. Based on leaf water potential, tree health monitoring, and the excavation of trenches to measure roots, in Kangeenarina Creek (West Pilbara), where surface water discharge has resulted in consistently shallow groundwater levels AQ2 (2019) concluded:

- Root truncation was observed in the zone that had become saturated for more than 12 months.
- Due to surface water discharge, the water table had been maintained at a consistent level and active (i.e., live) roots existed within upper portions of the capillary fringe but not very close to the observed water table. There was a separation between the deepest roots and saturated conditions of around 15 cm.

Root Growth

There are no published data on the rates of long-term root growth for Pilbara riparian trees. Phreatophytic trees in southwest WA (e.g., *Melaleuca raphiophylla*) have been shown to support rates of root advance of up to around 0.25 m/yr (e.g., Sommer and Froend 2014). AQ2 derived similar rates of root growth for Kangeenarina Creek (*Melaleuca argentea* and *Eucalyptus camaldulensis),* empirically derived from the onset of water stress (as measured by leaf water potential) and rates of groundwater decline (AQ2 2019). By contrast, Argus et al (2015) report that *Eucalyptus camaldulensis* seedlings were able to recover root-water-uptake functionality quickly following waterlogging; but that this was not accompanied by marked root growth. However, in this case, post-flood monitoring only covered 1 month and the trees were transplanted and not in a natural setting. It is possible that the soil remained too moist to stimulate growth or that other stimuli (such as symbiotic mycorrhizal fungi) are lost on transplantation.

Root growth also requires that meristem cells on the root apices can be activated. There is evidence that meristem functionality may decline with tree age (Shishkova e al 2008) i.e., more mature trees may be less adaptable to changes in root-zone water dynamics.

There may also be inter-species variations in meristem cell function following waterlogging. Trees less adapted to waterlogging may also be less adapted to the maintenance of meristem cell function under oxygen stress associated with waterlogging (Kreuzwieser and Rennenberg 2014). The processes are potentially complicated and relate to the physical loss of meristem cells through truncation and hormonal changes within the tree in response to waterlogging (Phukan et al 2016).

In practice, this means following a period of waterlogging, *Eucalyptus victrix* may be less able to respond to a water level decline than *Eucalyptus camaldulensis* or *Melaleuca argentea*; and those younger trees may be better able to respond than mature trees for whom the roots have become determinant either through senescence or previous waterlogging events.

Notwithstanding the potential for root plasticity and growth, there are also species limits on maximum root depth (e.g., Orellana et al 2012). Loomes (2014) has specifically considered the maximum depth at which Pilbara riparian species may use groundwater.

Root characteristics, interpreted from Loomes (2014) and AQ2 (2015), are summarised in Table 2.2.

Table 2.2: Riparian Vegetation Root Characteristics

Species	Environmental Conditions					Water Use	
	Min GW Depth (mbgl)	Avg GW Depth (mbgl)	Max Root depth (mbgl)	Avg WL Range (m)	Flooding tolerant	Turgor Loss (kPa)	GW Use
Melaleuca argentea	0	2	5	2.5	high	-2500	Obligate
Eucalyptus camaldulensis	0	5	10	3	medium	-3500	Facultative
Eucalyptus victrix	0	n/a	20	4	low	-5500	Facultative

Notes:
All parameters are typical values and do not take account of outliers
Avg WL Range = common range in seasonal high to seasonal low
Flooding tolerance = ability to tolerate periods of prolonged water logging
Min GW Depth = each species will have a period for which 0 mbgl DTW can be tolerated (Ma>Ec>Ev)
Turgor loss = minimum midday LWP at risk of embolism
Ma obligate GW use is in context of semi-arid Pilbara setting
Note Loomes 2014 only provide data from mesic site with shallow GW whereas E. victrix is noted from other areas with lower depth to water.

2.4 Recent Observations and Site Reconnaissance

2.4.1 Overview

An ecohydrological site reconnaissance was completed between Tuesday 5th October and Thursday 7th October 2021 in the project area. The site reconnaissance focussed on three broad areas: the northern, central, and southern riparian zones within the creek (Areas 1, 2 and 3). These are illustrated on Figure 2.1.

The reconnaissance involved visual observations only and no measurements or samples (of soil or vegetation) were taken. Consequently, the inferences made from the field observations are based on experience and “professional judgement” rather than data; they have been used to underpin working hypotheses and identify areas for future data collection.

Key inferences from the site reconnaissance are:

- Over much of their area, the riparian systems appear to be dynamic (i.e., subject to a wide range in water availability). There are relatively small areas where hydrological conditions converge to provide more persistent water availability (through shallow groundwater) and in these areas, more stable conditions are implied (based on species combination and an increased extent of mature trees); there is the potential for these areas to act as refugia.
- There is a progression in community over-storey composition associated with this inferred variability in water persistence (*Eucalyptus victrix* being dominant in the most dynamic areas and *Melaleuca argentea* being dominant in the most stable areas). This is consistent with the three broad riparian communities identified in the vegetation surveys.
- In dynamic areas, at least two (possibly three) recruitment events are inferred. By analogy elsewhere in the Pilbara (e.g., AQ2 work for Fortescue in Zalamea Creek, 2020), the earliest

recruitment event is believed to have been between 1995 and 2000 and corresponds to the start of a prolonged wet period in the Pilbara climate. The other two recruitment events are inferred to be more recent than this (as the trees are smaller), with the smallest cohort of recruits being perhaps 2 – 3 years old. The density of mature trees is considerably less than the recruits (based on tree-count) and so it appears that the current level of recruitment within the system is not the historical norm (and all the recruits may not be sustained). The relative contribution to basal area of mature trees or recruits has not been determined.

- A history of periodic water stress can be inferred from visible characteristics of the mature trees in the more dynamic areas (typically *Eucalyptus camaldulensis* and *Eucalyptus victrix*); such characteristics include stress cracks on trunks (that have healed), limb embolism / failure and epicormic growth. A history of fire is also inferred for the northern riparian zone where Melaleuca argentea trees appear to have also been affected.
- A northern (i.e., the main) riparian area (Area 1) and a southern riparian area (Area 3) have been identified with broad similarities with respect to species-mix and ecotype. Both areas show evidence of historical drought stress and appear to be currently on a drying trend.

The recruitment cohorts that are observed and the degree of dynamism that is inferred over much of the system presents challenges in defining baseline conditions and in determining whether future changes will be mining-related or fall within the natural range of the systems. The parallel drying trajectory of the northern and southern areas suggests this maybe a regional mesic recession.

2.4.2 Detailed Observations

The location of detailed observations and photographs are shown in Figure 2.1. The following detailed observations were made:

- Consistent with the vegetation surveys and mapping, the primary tree species within the riparian areas vary (refer to Plates 2 to 4) and a progression in species composition related to wetness or permanence of water availability is inferred:
    - Less dense areas are characterised by *Eucalyptus victrix* (at low to moderate basal area); these areas are inferred to experience the greatest range in water availability.
    - More dense areas of vegetation comprise a mixed community of *Eucalyptus camaldulensis* with subordinate *Eucalyptus victrix.*
    - In places, *Eucalyptus camaldulensis* and *Melaleuca argentea* become codominant (and *Eucalyptus victrix* is largely absent in these areas).
    - The wettest areas are characterised by *Melaleuca argentea* dominance.
- The areas of *Melaleuca argentea* dominance are associated with the presence of pools (at the time of the site visit). These pools were characterised by mature marginal trees and dense stands of *Typha domingensis, Cyperus vaginatus* and *Schoenoplectus subulatus.* There are no trees growing within the pools themselves, which implies surface water is sufficiently persistent to prevent recruitment within the currently inundated area and encourage *Melaleuca argentea* growth on the banks of the pools.

Plate 2: *Eucalyptus victrix* dominant drainage line

Plate 3: *Eucalyptus camaldulensis* co-dominant channel vegetation

Plate 4: *Melaleuca argentea* dominant channel vegetation

- The areas with *Eucalyptus camaldulensis* dominant or codominant are associated with pools that are currently dry; BHP have installed data loggers in some of these transient pools.
- In the areas where *Eucalyptus camaldulensis* and *Eucalyptus victrix* were dominant, a series of historical water stress events is inferred (Plates 5 and 6):
  - Aged hydraulic stress cracks are visible on the trunks of many trees. In most cases, these have healed suggesting they are historical.
  - Epicormic growth is also apparent, with large differences in the size of epicormic branches implying the underlying stress-trigger has occurred on more than one previous occasion.
  - Some trees have evidence of hydraulic failure of tree limbs (likely to be due to embolism in xylem during water stress events). In some cases, branchlets have fallen from the limbs (or the limb has partially fallen) implying a long period of time since the limb failure occurred. In other cases, a dense network of branchlets remains on the limb, suggesting failure was relatively recent.

Plate 5: *Eucalyptus camaldulensis* with generations of limb failure indicating historical water stress

Plate 6: Eucalyptus victrix with water stress cracks (healed)

- The areas with a significant proportion of *Eucalyptus victrix* did not appear to be associated with significant permanent surface water. This is consistent with *E. victrix* reduced ability to produce aerenchyma and maintain root meristem function under wet conditions (i.e., *E. victrix* does not tolerate water logging well and tends to be outcompeted *by Eucalyptus camaldulensis* under periodic waterlogged conditions.).
- Some other species that commonly associate in areas of persistent water availability in Pilbara riparian systems were not noted in abundance. In-channel benches and the channel margins hosted dense stands of *Acacia tumida* and *Gossypium robinsonii* with minor *Acacia coriacea subsp. pendens* (Plate 7); these species are most commonly associated with surface water focussing along drainage lines. *Melaleuca glomerata* was restricted in distribution, *Sesbania formosa* was only noted in two locations and other mesic *Acacia spp (e.g., A. ampliceps or A. citrinoviridis)* were absent.

Plate 7: Riparian trees (Ma) in channel and *Acacia tumida* / *Gossypium robinsonii* scrub on bench

- The channel and banks are characterised by generally coarse-grained material suggesting a high-energy flow regime; this would be expected given the confined nature of the channel with limited opportunity for overbank flow (Plate 8). There are some in-channel benches forming as anabranches and these comprise silty loam with a large fraction of vegetation litter. These in channel benches host recruits of riparian trees at their lowest elevations and of *Acacia tumida* where the elevation is slightly higher.

Plate 8: Channel Bed (coarse material) and in-channel bench (with an older cohort of Ma recruits)

- In some areas where silty loam was exposed in the sides of the creek bank, there were potential indications of lateral water seepage indicated by salt staining. The salt staining indicates the evaporation of seepage water for a prolonged period. Potentially, this may indicate the lateral movement of groundwater from the surrounding basement, draining into the channel. Plate 9 illustrates this.

Plate 9: Salt Staining and potential lateral seepage (indicated by still damp alluvium)

- The southern and northern areas are similar:
    - Both areas transition from a dynamic (i.e., not persistently wet) environment characterised by *Eucalyptus victrix* through to a stable wet zone characterised by *Melaleuca argentea.*
    - Both areas have pools that occur adjacent to basement cliffs.
    - There is the potential that these pools are fed by groundwater seepage from the BIF that forms the cliffs.
    - Both areas also have evidence of transient pools within the "dynamic area" that are currently dry (e.g., As indicated by stained low points in the channel, dead algal mats, and dead stands of *Typha spp*. and *Cypress spp*.).
- Importantly, the southern area is 5km south of the northern area (i.e., 5km more distant from the Yandi mining operation). The potentially parallel drying-trajectory implies the mesic-recession that is inferred from drying pools may be a regional response (to climate) rather than a local response to dewatering impact.
- Notwithstanding these similarities, the extent of this environment is greater in the northern area than the southern.
- The central area is characterised by significantly lower density riparian overstorey, with Eucalyptus victrix dominant (Plate 10). There is a transient pool in this area that is monitored by BHP, and this was dry at the time of the reconnaissance visit. The ecohydrology and morphology of the Central area (Area 2) is different to the Northern and Southern areas and appears much more likely to result from surface water focussing and frequent replenishment of the vadose zone (rather than groundwater use).

Plate 10: The central riparian zone

3 CLIMATE AND WATER REGIME

3.1 Rainfall and Evapotranspiration

3.1.1 Overall Context

In areas where rainfall data is sparse (spatially or temporally), generated rainfall data are available from the SILO database where SILO is a meteorological dataset managed by the Science Delivery Division of the Department of Science, Information Technology, Innovation, and the Arts (DSITIA). SILO can provide daily historical weather estimates from 1889 to present, for any location in Australia to the closest 0.05° latitude/ longitude.

An assessment of the long-term annual rainfall totals for the project area has been undertaken using the SILO data from the period from 1900-2020, for the location -22.8 degrees south and 119.10 degrees east. The annual average rainfall over the period is 321 mm per year. A Budyko model (e.g., Trancoso et al 2016, Budyko 1974) has been used to characterise the energy / water balance for the project area and to provide an estimate of catchment-scale actual evapotranspiration (which will control the type of vegetation that can sustainably develop). Summary data are shown in Table 3.1.

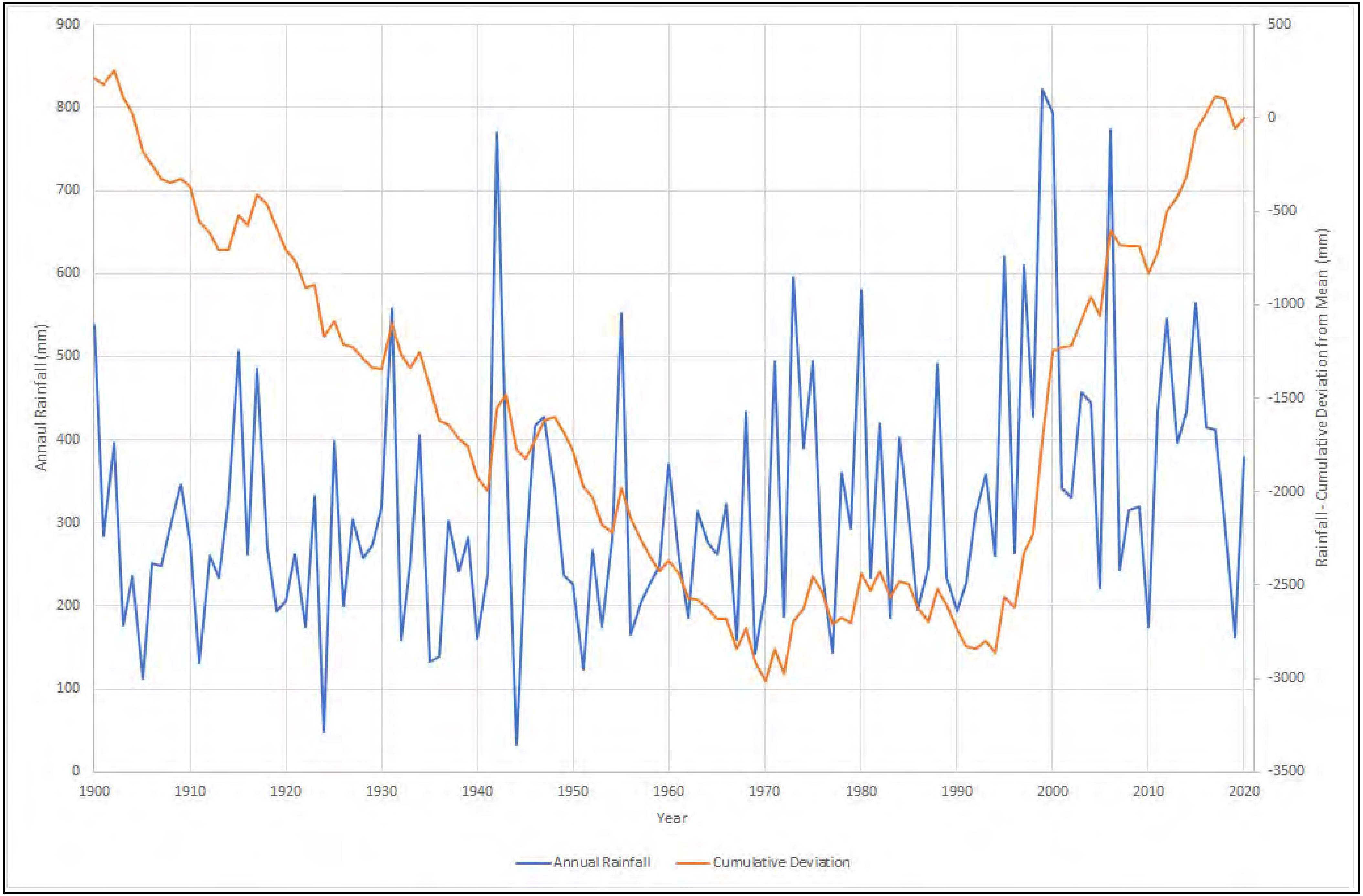
Table 3.1: Ecohydrological Setting

Period (Years)	Type Conditions	PET (mm/yr)	Average Rainfall (mm/yr)	Aridity Index	Budyko ET Estimates (mm/yr) Average	Average ET/Precip (%)	ET var. from avg (%)
Overall Average	Long-term	3400	321	10.6	320.3	99.7%	0.0%
1900 - 1970	Dry	3400	278	12.2	278.1	99.8%	-13.2%
1971 - 1994	Average	3400	327	10.4	326.6	99.7%	2.0%
1995 - 2020	Wet	3400	431	7.9	429.6	99.5%	34.1%

Notes:
Aridity Index 5 - 20 = Arid (based on United Nations Formula AI = Precip/PET)
SILO Data for -22.8 degS, 119.3 degN
Budyko estimates of ET provide a catchment-wide average and are not representative of areas where water is "focussed"
Overall average is derived from the SILO record over the period 1900 to 2020 and used as a baseline
ET variation is calculated by comparing average ET for a defined period against the overall average
Type Conditions is a qualitative descriptor that describes the average rainfall for a defined period with respect to the long-term
Budyko ET estimate is average of Budyko, Ol'Dekop and Schreiber methods

These annual data are shown plotted in Figure 3.1. Figure 3.1 also shows cumulative deviation from the long-term average rainfall. A deviation moving in an increasingly negative direction indicates drier than average conditions; an increasingly less negative (or positive) deviation indicates wetter than average conditions. Three broad periods can be defined:

- From 1900 until approximately 1970, there is an increasingly negative deviation from the long-term average rainfall, which indicates a dry period. Over this time only, average rainfall was 278 mm/yr (compared with 321 mm/yr as the long-term SILO average rainfall).
- For a 25-year period from 1970 to 1994, actual rainfall was close to the long-term average. Average rainfall over this period was 327 mm/yr.
- From 1995 to the present, the cumulative deviation became increasingly less negative indicating a wetter than average period. Average rainfall over this period was 431 mm/yr.



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F:\408\3.C&R\[006a Figs&Tabs.xlsx]Figure 3.1

Longterm Rainfall Trends FIGURE 3.1

The aridity index (ratio of potential evapotranspiration to rainfall) ranges between 7.9 and 12.2 over the period and although all can be classified as arid, there is a significant variation in aridity depending on rainfall trends.

The Budyko estimate of ET provides an assessment of the actual annual average evapotranspiration across the catchment. The Budyko model predicts that actual evapotranspiration in the study area is water-limited (not energy limited) and under these conditions, actual evapotranspiration will approximate precipitation (i.e., almost all available water will be lost through evapotranspiration). This is consistent with the low rates of runoff and groundwater recharge in the Pilbara (e.g., CSIRO 2015).

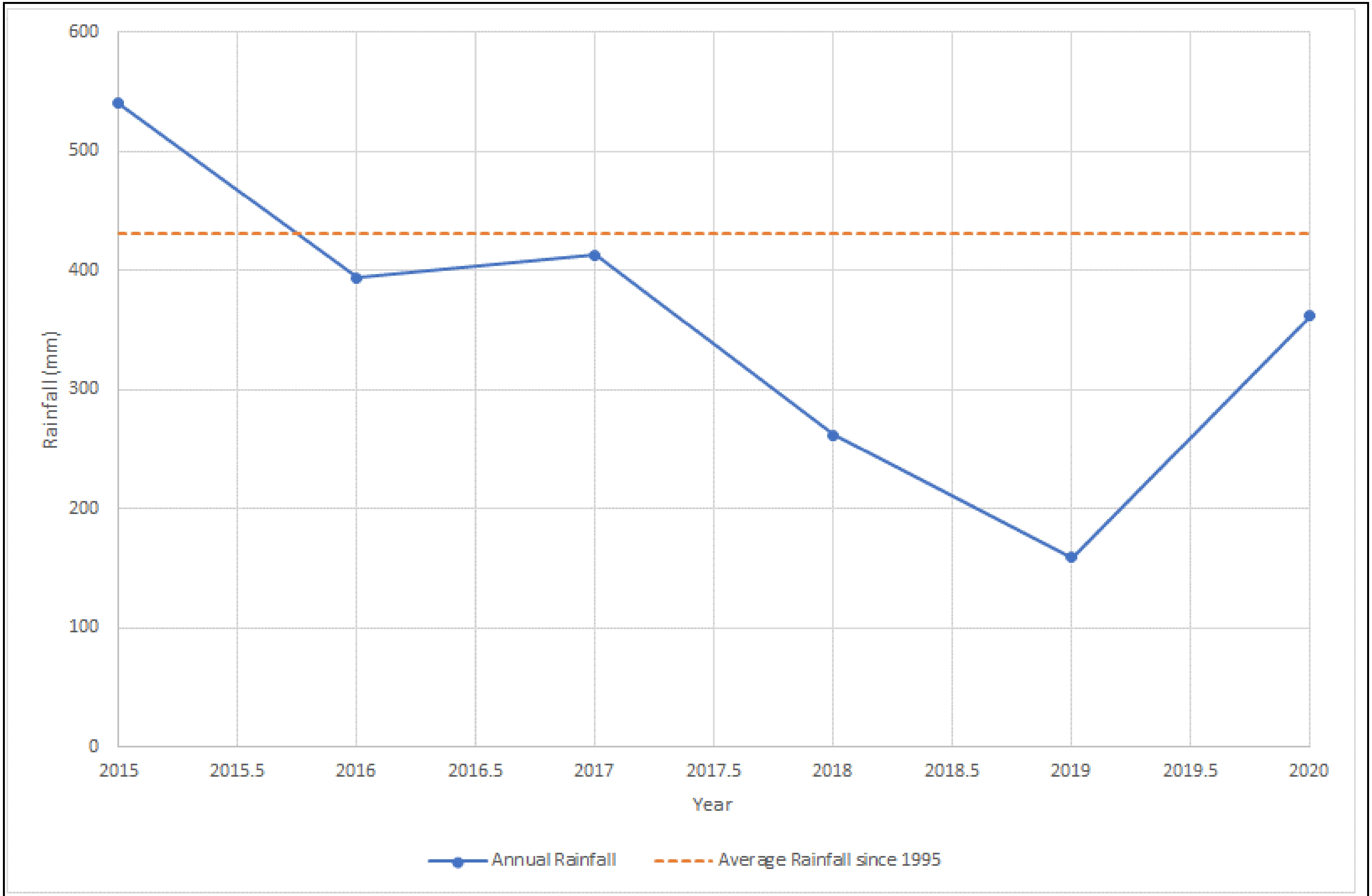
Although annual average rainfall has varied over the 100-year period, the climate has remained arid and water-limited with respect to evapotranspiration. Notwithstanding the water limitation, there is estimated to have been a significant increase (>50%) in actual ET due to the increased rainfall (when comparing the driest period between 1900 and 1970 and the wettest period between 1995 to current); this increase in actual ET will manifest as increased vegetation density (potentially both in stem-size and leaf area of existing vegetation and in new vegetation recruitment). Thus, there are likely to have been significant changes in vegetation structure and density across the catchment over the last 100 years. Consequently, baselines are likely to be time varying.

The ET trends noted above occur at a “whole-of landscape” scale. Drainage concentrates into receiving areas in the landscape – drainage lines, creeks and claypans – and these are characterised by disproportionate infiltration, recharge (both in magnitude and frequency) and shallower groundwater levels. Because receiving environments are the endpoints of water movement through the landscape, they typically comprise less than 5% of the total landscape and are areas where the catchment water yield is focussed. Consequently, they are characterised by increased water availability (even through prolonged dry periods) which means receiving areas:

- Maybe stable and subject to less change in water availability than the catchment-scale Budyko estimates imply.
- Function as refugia and support rare environmental and cultural values that result from riparian vegetation, periodic pools and associated habitat and aesthetic values.

3.1.2 Recent Trends

Annual rainfall for the project area since 2015 is summarised in Table 3.2 and shown in Figure 3.2. Also shown is the recent wet-period average annual rainfall (derived from SILO data for the period since 1995 i.e., 431 mm per year).



Recent Rainfall Trends FIGURE 3.2

F:\408\3.C&R\[006a Figs&Tabs.xlsx]Figure 3.2

Table 3.2: Recent Rainfall Trends

Parameter (mm)	2015	2016	2017	2018	2019	2020
Annual Rainfall	564.1	415.6	411.8	302.1	162.1	379.3
Recent average	431	431	431	431	431	431
Deviation from average	133	-15	-19	-129	-269	-52
% Deviation	31%	-4%	-4%	-30%	-62%	-12%
Cumulative Deficit	133	118	99	-30	-299	-350

Years 2016 to 2020 all experienced rainfall below the recent average; 2019 was 62% below the recent average. Cumulatively, between 2016 and 2020 a moisture deficit of 350 mm has accumulated when compared to average moisture availability since 1994.

Section 3.3 describes monitoring that shows that regional groundwater levels have been on a declining trend since 2017. This corresponds with the period of accumulating moisture deficit. It is possible the decline in groundwater levels represent natural adjustment after a period of high annual rainfall between 1994 and 2015. Observations during the site reconnaissance (Section 2) were also consistent with periods of water stress.

3.2 Surface Water

Relatively frequent flood events are an important control on riparian vegetation both with respect to seed distribution and water availability. Commonly, the major riparian tree species in the Pilbara, occur within the 1:2 or 1:5 ARI flood levels. Although these represent surface water controls, riparian trees may also use groundwater within this inundation zone. However, in the Pilbara, even with shallow groundwater, riparian trees rarely occur outside of the 1:5 ARI flood zone.

The Yandicoogina Creek channel in the Ministers North area is incised and defined by steep banks. Modelling shows that much of the channel will be activated by a 1:5-year ARI event (Stantec 2018). This is consistent with the distribution of riparian vegetation across much of the channel width with limited unvegetated overbank areas.

BHP telemetry monitoring of pools in the channel between September 2019 and December 2021 (~2 years) shows 5 occasions when runoff was initiated, and pool levels increased. The start of the time series also appears to be receding from a recent event and so approximately 6 runoff events in 2-years is implied. The infiltration from each of these flow events will replenish the vadose zone. Groundwater monitoring in bores HMN0015M shows groundwater rises closely following the pool level rises (and inferred runoff events) which implies this infiltration is sufficient to result in groundwater recharge. It would appear that vadose zone replenishment and groundwater recharge occur on 2 – 3 occasions per year.

3.3 Groundwater

3.3.1 Hydrostratigraphy

Table 3.3 summarises the regional hydrostratigraphy. The local hydrogeology is summarised in a review of the Ministers North Conceptual Hydrogeology (BHP 2019). Of principal interest in the study area, mineralisation is hosted in the Brockman Iron Formation. The Yandicoogina Creek channel is incised through this and infilled with an undetermined sequence and thickness of Tertiary Detritals and alluvium. Where monitoring bores have been drilled into Cenozoic sediments on the margins of the creek channel, they are up to 25m thick (e.g., HMN0015).

The ecohydrological system along the creek is hosted by the alluvial and detrital aquifers and these are the focus of the current study. No specific data are available on the hydraulic properties of the alluvium. However, commonly in other Pilbara Creek systems, the alluvium comprises poorly sorted gravel, matrix supported in low-permeability, fine grained material (silt and clay), which will provide high levels of PAW from the vadose zone. This is consistent with drilling at HMN0015 where the sediments comprise clay with gravel / cobbles. High permeability gravel aquifers can occur within this fine-grained alluvium associated with sedimentary deposition in active flow channels.

3.3.2 Hydrogeological Connection

Generally, the Brockman Iron Formation is of low permeability except where mineralised. Nonetheless, where head differences are large, seepage through the Brockman Iron Formation may occur; in this case from the elevated massif towards the lower-elevation creek alluvium.

Moreover, recent pumping tests (RPS 2022) show hydraulic connection extending from the Ministers North South-deposit into the area of the creek (due either to direct connection with the alluvial aquifer or through depressurisation of the basement and associated drainage response in the alluvial aquifer. The extent of drawdown in the alluvial aquifer ranged between 0.1 m and 0.2 m after 30 days of pumping. This implies there may be enhanced permeability (and hydraulic connection) from the orebody extending under the creek. Enhanced permeability may result from an extension of the sub-grade mineralisation shell or structural permeability related to deformation along the Wirriba Anticline.

Table 3.3: Regional Hydrostratigraphic Summary

Age	Group	Formation	Member	Lithological Description	Hydrogeological Description	Notes
Cainozoic	Recent Alluvium			Silt, sand, and gravel.	Hosts creek pools and riparian vegetation. Variable permeability depending on fines.	Primary unit of interest; predominantly silt and clay with channelised coarse gravel
	Cenozoic Detritals (CzD)	CzD3		Haematitic silt and clay (becoming scree on valley sides).	Generally, aquitard (some aquifer potential depends on clast-size)	Aquifer / aquitard sequence in hydraulic connection with overlying alluvium.
		CzD2		Clay / channel iron deposits (CID) / calcrete / silcrete.	Aquifers in CID/Calcrete/Silcrete. Notably orebody aquifers in CID	
		CzD1		Magnetite and haematite pisolite & alluvial deposits / scree on MBSV valley sides.	Aquifer potential depends on clast-size; higher in coarse alluvial deposits	Presence unknown and limited deep subcrop
Proterozoic	Hamersley Group	Weeli Wolli		Banded iron formation (BIF), shaly BIF / shale / jaspilite.	Low permeability. Commonly forms low permeability surrounds to CID paleochannels	Outcrop with creek incised through this unit.
		Brockman Iron	Yandicoogina	Interbedded chert and shale locally intruded by dolerite sills.	Low permeability	At outcrop with creek incised through this unit; primary mining target at Iron Valley
			Joffre	BIF with minor shale bands. Major ore-host.	Aquifer potential limited to orebody aquifers; low where not mineralised	
			Whaleback Shale	Interbedded shale, chert, and BIF.	Low permeability	
			Dales Gorge	Interbedded BIF and shale. Major ore-host.	Aquifer potential limited to orebody aquifers; low where not mineralised	
		Mount McRae Shale		Graphitic and chloritic shale interbedded with BIF. (Notably Colonial Chert unit. *)	Low permeability with localised aquifers associated with Colonial Chert Member which often affects footwall in Brockman orebodies	Outcrop
		Mount Sylvia		Shale, dolomite, and BIF bands.	Low permeability with localised aquifers associated with Bruno's Band (chert)	Outcrop
		Wittenoom	Bee Gorge	Calcareous shale and dolomite.	Low - high permeability depending on weathering and fracturing in dolomite	Limited to subcrop in Fortescue Valley - deep aquifer / aquitard sequence
			Paraburdoo	Dolomite – locally with karstic characteristics.	Regional aquifer where karstic (typically where sub cropping and dipping in MBSV setting); low permeability where karst has not developed.	
			West Angela	Shale-BIF-chert-dolomite. Locally manganiferous.	Aquifer potential in some zones assoc with manganese/dolomite	

3.3.3 Groundwater Levels

Figure 3.3 presents an estimate of groundwater levels for 2019. The contours suggest that Yandicoogina Creek acts as a regional "drain" through the groundwater surface that is developed in the surrounding Brockman Iron Formation massif. The following comments are made:

- Groundwater levels decline from 565 mAHD at the upstream end of the project area to 552 mAHD at the downstream end of the study area. Flow broadly follows the topography and valley system.
- A steep hydraulic gradient is inferred towards the creek with groundwater levels declining by around 10m near through the basement towards the channel. Importantly, this means significant changes in the regional water table may not have a large impact on groundwater levels in the gorge which is likely to act as a "fulcrum" point. Groundwater levels in the gorge are like to be relatively stable.
- The depth to groundwater in the gorge is not well defined. However, the presence of (semi) permanent pools in places suggest it is at or very close to the ground surface in some areas. The measured water level in bore HMN0015 is ~7 mbgl (Table 2.1). This bore is in a slightly elevated location on an alluvial terrace and the depth to water in the low-flow area nearby is likely to be less than 7 m; a visual estimate was made during the site visit of around a 2 m elevation difference. Thus, it appears that depth to water will vary along the channel and be in the range 0 to 5 mbgl in the more densely vegetated riparian areas.

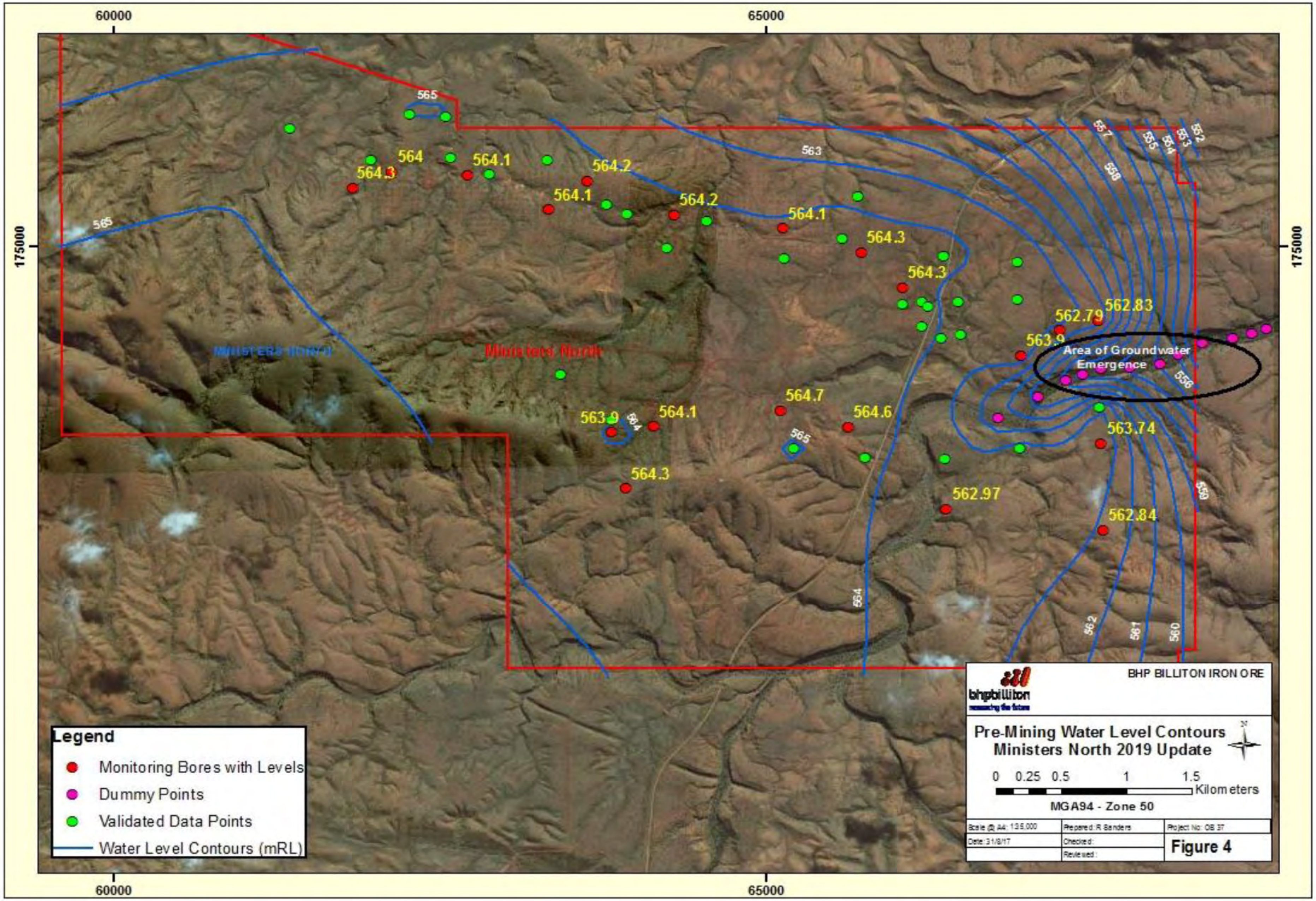
3.3.4 Groundwater Levels and Time

Hydrographs are shown in Figure 3.4.

The regional monitoring bores show groundwater decline since 2017. This corresponds with a period of relatively low rainfall and an accumulating moisture deficit. Although climate seems like a likely cause for decline, the period also corresponds with changes in BHP's dewatering at Yandi.

Monitoring data are not available specifically for the alluvial aquifer that infills the channel. Only two monitoring bores appear to have encountered Cenozoic Detritals while the remainder are drilled into basement associated with dewatering investigations for the orebody. The two monitoring bores that encountered Cenozoic Detritals (HMN0015 and HMN0016) are screened predominantly against underlying basement. Additionally, the time series data from these bores is only available from late 2020. Nonetheless, they do not show the trend of declining water levels that is visible in the regional bores. Rather, they show recession periods interspersed with rises that are associated with larger rainfall events and correspond to the rises in pool water levels (Pool hydrographs are also shown in Figure 3.4). This implies that rainfall recharge (at least for events above a certain threshold) is an aspect of the alluvial aquifer.

The incision of the creek channel and steep hydraulic gradient supporting groundwater levels in the channel likely explains why the bores that are exposed to creek alluvium do not show the same long-term trend. The creek invert is likely to act as a drainage level, about which regional water levels pivot (i.e., a fulcrum). However, this stability in groundwater level in the alluvial aquifer is likely to be preserved only for the small range in groundwater levels that are experienced under natural conditions. The recent pumping tests show that larger stresses on the basement aquifer will have an impact in the alluvial aquifer also.



Notes Figure from BHP (2019): Ministers North Conceptual Hydrogeological Model

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Estimated 2019 Groundwater Levels FIGURE 3.3

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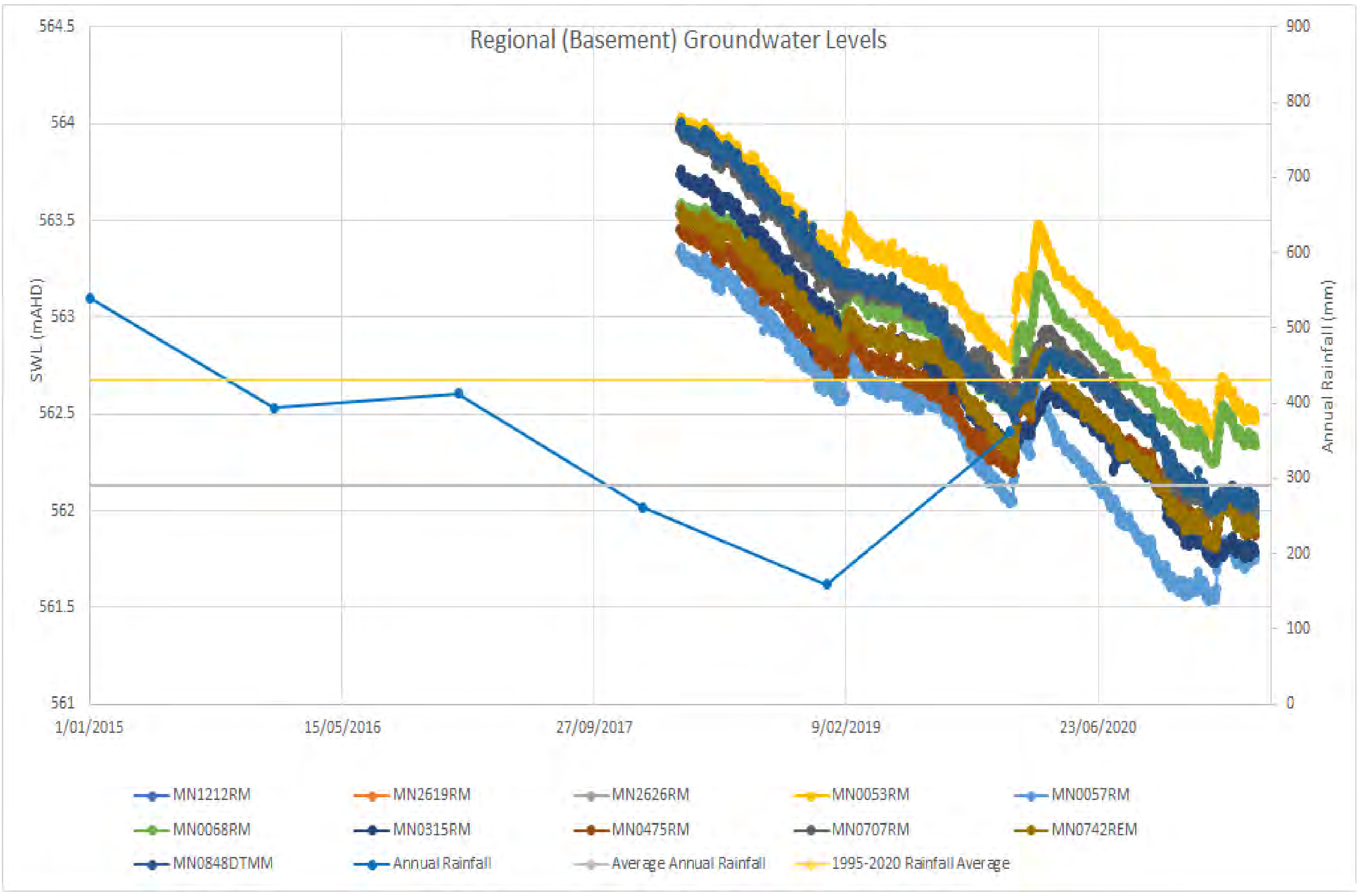

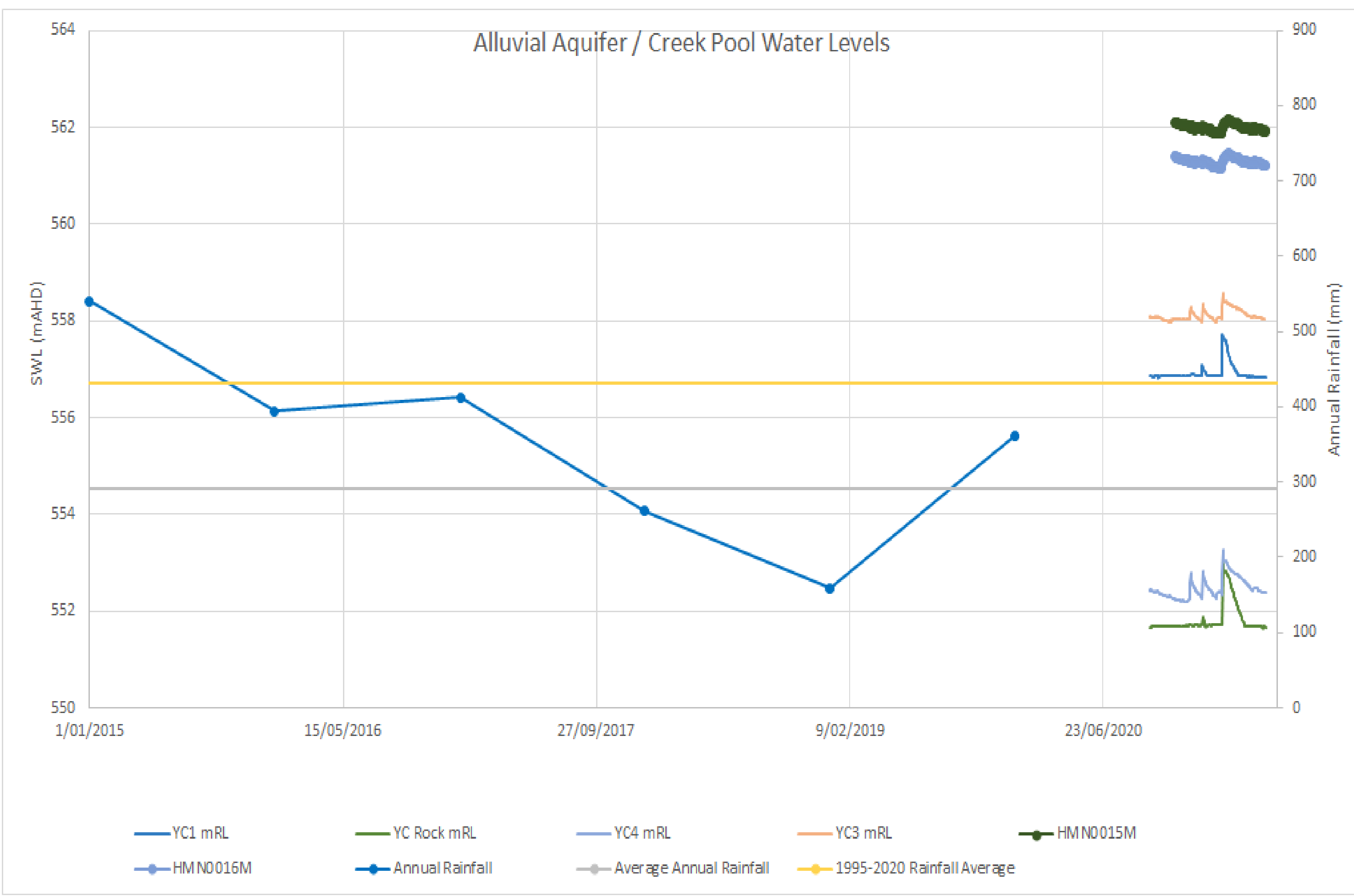

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Selected Groundwater Hydrographs FIGURE 3.4

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4 RIPARIAN ECOLOGY

4.1 Riparian Community

For the current study, three key ecotypes have been defined (Figure 4.1) from vegetation mapping and from the site reconnaissance:

- *Eucalyptus victrix* ecotype (Ev-type). Section 2 Plate 1 illustrates this ecotype. This ecotype comprises *Eucalyptus victrix* at low to moderate basal area; these areas are inferred to experience the greatest range in water availability. These areas are characterised by a grass understorey.
- *Eucalyptus camaldulensis* ecotype (Ec-type). Section 2 Plate 2 illustrates this ecotype. In this ecotype, *Eucalyptus camaldulensis* is the primary species. *Eucalyptus victrix* forms a subordinate species at its upstream margins while *Melaleuca argentea* is a subordinate species at its downstream margins. This ecotype includes *Acacia tumida* and *A. coriacea* as mid storey species. There is evidence of transient pools in areas where this ecotype occurs which implies at least periodic shallow water levels in the alluvium.
- *Melaleuca argentea* ecotype (Ma-type). Section 2 Plate 3 illustrates this ecotype. In this ecotype, *Melaleuca argentea* is dominant with subordinate *Eucalyptus camaldulensis.* This ecotype includes *Acacia tumida* and *A. coriacea* as mid storey species and extensive *Typha domingensis* in areas of both permanent and transient pools. The presence of permanent or semi-permanent pools implies stable shallow groundwater levels in these areas.

It should be noted that the transition between ecotypes is not discrete. Rather, it is marked by progressive changes in dominance of the representative species. The ecotypes occur in the Northern and Southern areas (Areas 1 and 3 respectively).

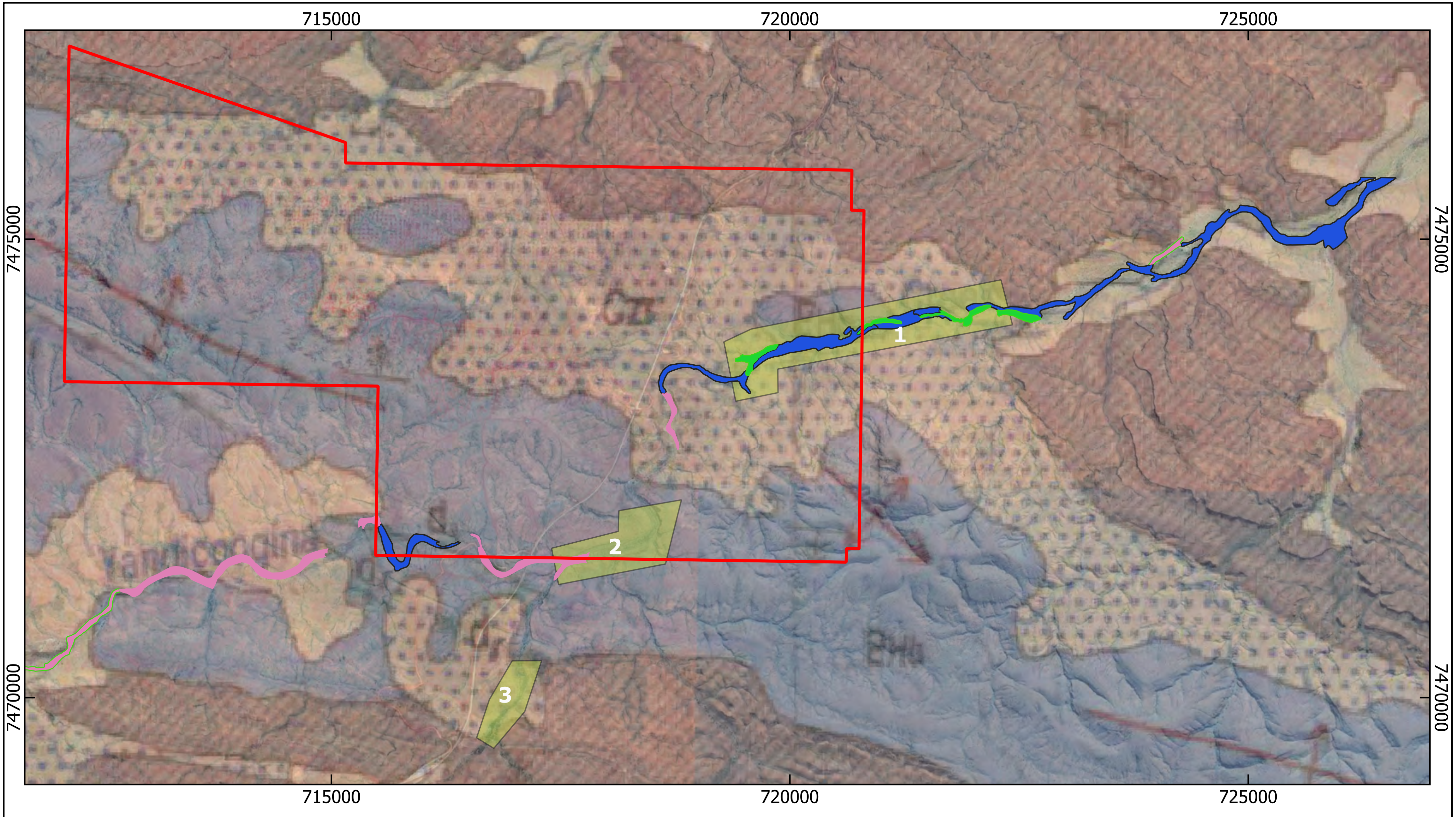
4.2 Riparian Community Dynamics

4.2.1 Long Term Trends

Normalised Difference Vegetation Index (NDVI) for the period 1995 to 2021, for selected locations through the project area is shown in Figure 4.2. The location of each measurement point is shown on Figure 2.1. The NDVI provides a remote-sensing measure of "greenness"; a high NDVI implies more vegetation. NDVI commonly shows a seasonal variation between winter / summer or wet season / dry season conditions. A relatively stable (and high) NDVI can imply vegetation that has consistent access to water (through both wet and dry seasons), as would be the case where groundwater is available.

Also shown in Figure 4.2 is a "Drought Index". The drought index is a cumulative plot of successive years with annual rainfall totals above or below the average annual rainfall. A larger positive number indicates an increasing number of years above the annual average whereas an increasing negative number indicates a series of years below the long-term average rainfall.

Summary statistics from these data are presented in Table 4.1.



Location Map

Path: F:\XXX\4.GIS\Workspaces\XXX

Legend

Ministers North Project Area

Vegetation Mapping

- Ec-type
- Ev-type
- Ma-type

0 1 2 km

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AUTHOR: DGS

DRAWN: LDS

DATE: 04/03/2022

Report No: 006a

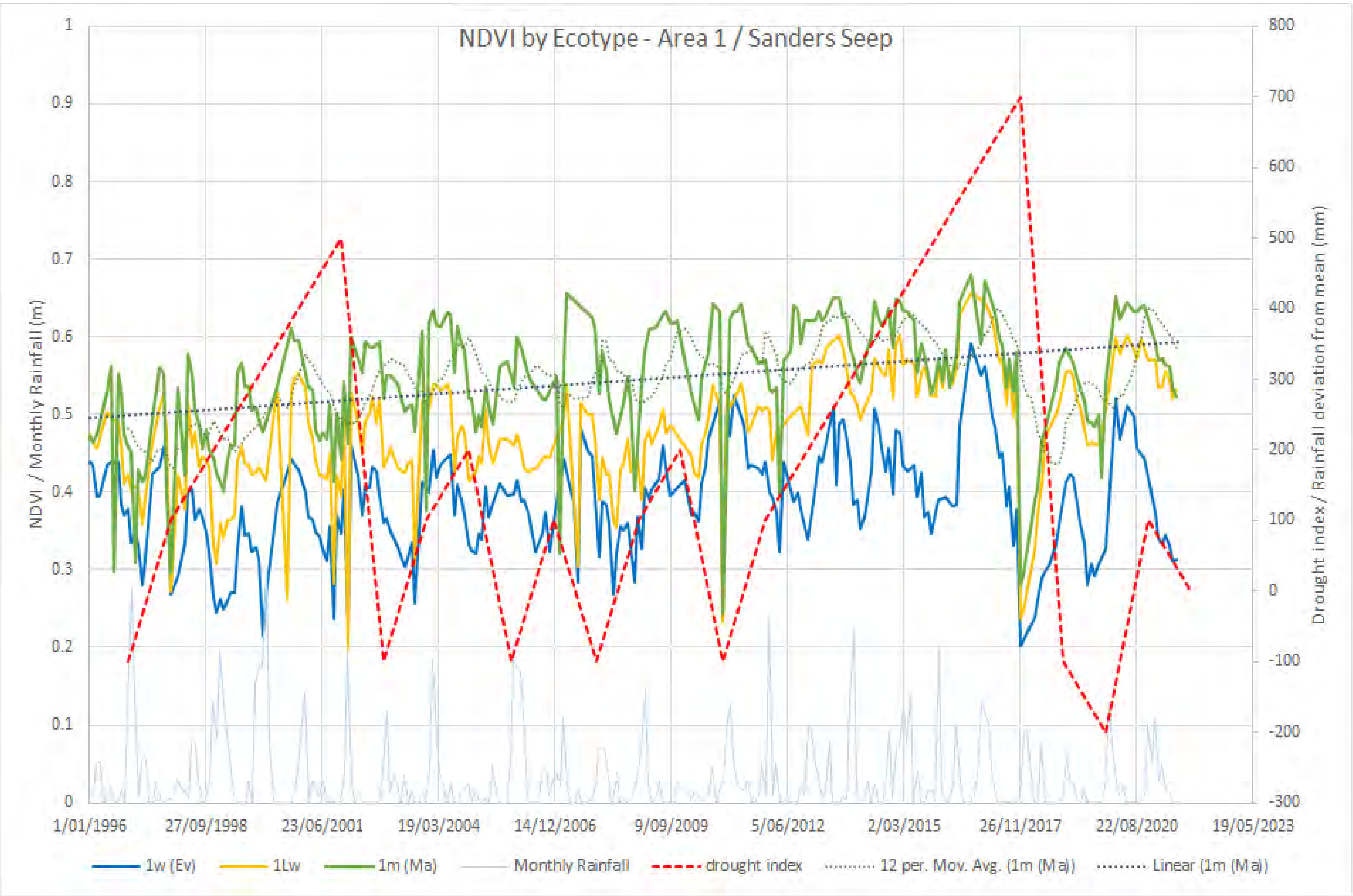
Revision: A

JOB No: 408

NOTES & DATA SOURCES:

Aerial image from Bing, Microsoft.

FIGURE 4.1:
Major Ecotypes


NDVI by Ecotype - Area 1 / Sanders Seep
NDVI / Monthly Rainfall (m)
Drought index / Rainfall deviation from mean (mm)
1/01/1996
27/09/1998
23/06/2001
19/03/2004
14/12/2006
9/09/2009
5/06/2012
2/03/2015
26/11/2017
22/08/2020
19/05/2023
1w (Ev)
1Lw
1m (Ma)
Monthly Rainfall
drought index
12 per. Mov. Avg. (1m (Ma))
Linear (1m (Ma))

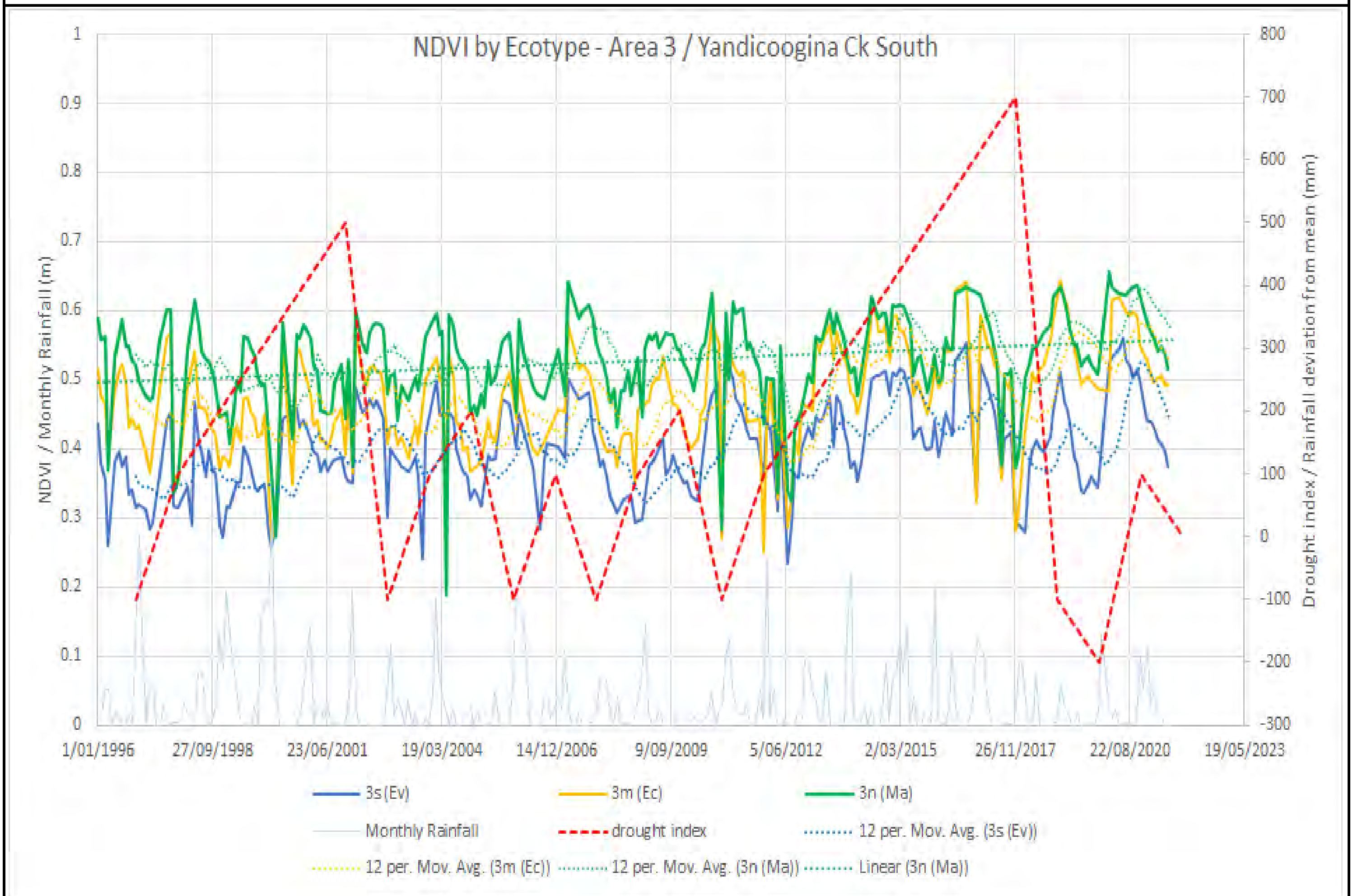

NDVI by Ecotype - Area 3 / Yandicoogina Ck South
NDVI / Monthly Rainfall (m)
Drought index / Rainfall deviation from mean (mm)
1/01/1996
27/09/1998
23/06/2001
19/03/2004
14/12/2006
9/09/2009
5/06/2012
2/03/2015
26/11/2017
22/08/2020
19/05/2023
3s (Ev)
3m (Ec)
3n (Ma)
Monthly Rainfall
drought index
12 per. Mov. Avg. (3s (Ev))
12 per. Mov. Avg. (3m (Ec))
12 per. Mov. Avg. (3n (Ma))
Linear (3n (Ma))

Table 4.1: NDVI Summary

Start	End	Site	Ecotype	Avg Rainfall (mm)	NDVI			
					Average	Max	Min	Variance
1/01/96	31/12/00	3S	Ev-type	581	0.35	0.47	0.26	45%
1/01/01	31/12/11	3S	Ev-type	354	0.40	0.53	0.24	55%
1/01/12	31/12/16	3S	Ev-type	428	0.43	0.55	0.23	57%
1/01/17	31/07/21	3S	Ev-type	305	0.43	0.56	0.28	50%
1/01/96	31/12/00	3M	Ec-type	581	0.44	0.57	0.27	53%
1/01/01	31/12/11	3M	Ec-type	354	0.45	0.58	0.25	57%
1/01/12	31/12/16	3M	Ec-type	428	0.51	0.64	0.29	56%
1/01/17	31/07/21	3M	Ec-type	305	0.52	0.64	0.28	56%
1/01/96	31/12/00	3N	Ma- type	581	0.51	0.61	0.27	55%
1/01/01	31/12/11	3N	Ma- type	354	0.52	0.64	0.19	70%
1/01/12	31/12/16	3N	Ma- type	428	0.53	0.63	0.32	49%
1/01/17	31/07/21	3N	Ma- type	305	0.56	0.66	0.37	43%
1/01/96	31/12/00	1W	Ev-type	581	0.35	0.46	0.22	53%
1/01/01	31/12/11	1W	Ev-type	354	0.38	0.53	0.23	56%
1/01/12	31/12/16	1W	Ev-type	428	0.42	0.59	0.32	45%
1/01/17	31/07/21	1W	Ev-type	305	0.37	0.56	0.20	64%
1/01/96	31/12/00	1LW	Ec-type	581	0.43	0.55	0.26	53%
1/01/01	31/12/11	1LW	Ec-type	354	0.46	0.54	0.20	63%
1/01/12	31/12/16	1LW	Ec-type	428	0.55	0.66	0.44	33%
1/01/17	31/07/21	1LW	Ec-type	305	0.52	0.64	0.24	63%
1/01/96	31/12/00	1M	Ma-type	581	0.48	0.61	0.30	52%
1/01/01	31/12/11	1M	Ma-type	354	0.55	0.66	0.24	63%
1/01/12	31/12/16	1M	Ma-type	428	0.59	0.68	0.40	42%
1/01/17	31/07/21	1M	Ma-type	305	0.54	0.67	0.28	58%
Average values for Ecotype since 1996								
1/01/96	31/07/21	n/a	Ev-type	431	0.39	0.53	0.25	53%
1/01/96	31/07/21	n/a	Ec-type	431	0.48	0.60	0.28	54%
1/01/96	31/07/21	n/a	Ma- type	432	0.54	0.65	0.30	54%

Figure 4.2 shows that at all locations, NDVI follows a seasonal trend. Seasonal minima are in the range 0.2 to 0.4. The average value for seasonal minima (Table 4.1) varies between 0.25 and 0.3 (increasing from the Ev-type to the Ma-type). Higher average minimum values for the Ma-type result from higher "greenness" levels during the dry-season which implies more persistent PAW.

Over the past 15-years, there are some marked low points in NDVI at Sites 1 and 3: 2010, 2012 and 2017 / 2018; NDVI minima values for 2019 were also relatively low. These low values could represent historical vegetation stress events, as implied during the site reconnaissance. Low values in 2017/2018 and 2019 also coincide with below average rainfall and the accumulating moisture deficit described in Section 3.

Seasonal maxima range between 0.3 and 0.6 with an increase as the wetness of the eco type increases (i.e., from Ev-type to Ma-type).

The following inferences are made:

- The average values for NDVI show the increasing moisture availability and wetness from the Ev-type to the Ma-type:
    - Ev-type average values are less than 0.4
    - Ec-type average values are less than 0.5
    - Ma-type average values are greater than 0.5
- At all locations and types, the inter-seasonal variance is high (averaging over 50%). This implies that a large component of the vegetation at all locations varies with seasonal water availability and is therefore likely to rely on vadose-water or transient groundwater (i.e., some of the vegetation is likely to be vadophytic or facultatively phreatophytic). Variance may be driven by understorey species such as the extensive stands of *Acacia tumida*, *Gossypium robinsonii* and *Typha domingenisis* (as observed during the site reconnaissance) around transient pools. However, the presence of obligate phreatophytes, at least in the Ma-type, is also noted.
- Long-term trends in NDVI, since 1995, across the project area are modest and predominantly represented in the seasonal maxima. This implies the increases in rainfall since 1995 may have resulted in an increase in seasonal vegetation or seasonal productivity, but less so, the vegetation that is sustained perennially (such as riparian tress). This trend is consistent with the alluvial aquifer acting as a drainage invert level (or fulcrum); groundwater levels in the alluvium are relatively stable.
- All three defined ecotypes are present at Site 1 (the main gorge) and Site 3 (the riparian area south of Ministers North). The NDVI characteristics of Sites 1 and Site 3 are comparable which implies Site 3 may be a suitable analogue for Site 1 to compare potential mining-related impacts.

4.2.2 Vegetation Stress

Vegetation stress was observed at several locations during the reconnaissance (refer Section 2). Tree deaths and vegetation stress has not been specifically monitored. Tree deaths appeared to span several historical stress events. Low seasonal NDVI values can be seen in 2010, 2012, 2017/2018 and 2019. The stress events from 2017 correspond to a decline in rainfall (compared to the average since 1995) and to small but consistent declines in regional groundwater levels.

4.3 Vegetation Characteristics and Metrics

4.3.1 Direct Measurements

Vegetation mapping has been completed (as previously described) and three riparian ecotypes can be defined in the study area. However, specific metrics that allow quantification of this riparian community are not available. Key metrics for the riparian trees would include:

- Stand basal area, sapwood area and the relationship between basal area and sapwood area. In combination, these data underpin estimates of community level transpiration.
- Size class distribution which provides insights into growth rates and recruitment trends.

- Leaf water potential data (both pre-dawn and midday). In combination, these data provide a direct indication of tree water status. Pre-dawn leaf water potential data alone can provide an indication of tree water source and, whether a tree is in hydraulic connection with groundwater at the time of measurement. Time-series leaf water potential data can provide insights to seasonal trends in tree water use and water source.

4.3.2 Inferred Measurements

Access to a consistent source of water would be expected to result in less seasonal variation in NDVI when compared to the NDVI from a community with seasonally varying water availability. Figure 4.3 (a) provides a plot of average, minimum and maximum NDVI against intra-period NDVI variability. It is inferred that there is no relationship between intra-period variation and maximum NDVI or annual average NDVI. However, there is an inverse relationship between minimum NDVI and intra-period variation. Systems that are using groundwater would be expected to exhibit low levels of variance. Conservatively, a threshold of 50% variability in NDVI has been adopted to identify areas of risk (i.e., where inter-seasonal variability in NDVI is less than 50%, then the degree of consistent greenness maybe indicative of groundwater use).

It should be noted that based on experience at other locations, this is a high degree of variability for a phreatophytic system (<40% being common from other Pilbara projects) and as such, should be considered conservative.

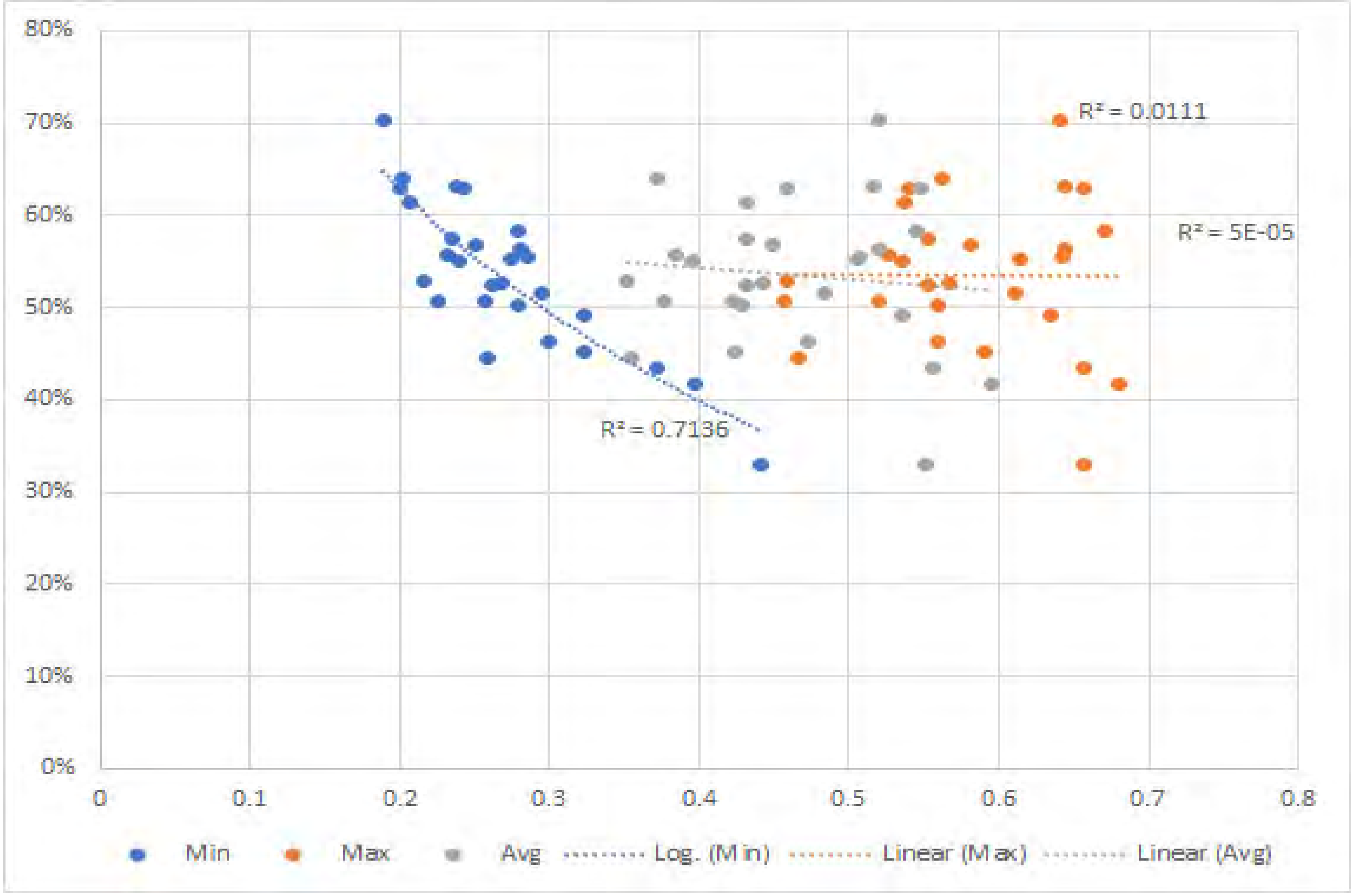
Figure 4.3(b) provides a time-series plot of minimum and maximum NDVI for the hydrological trends described in Section 3. The "threshold" line on Figure 4.3(b) represents the zone within which data points will fall when intra-period variability is less than 50%. Comments follow:

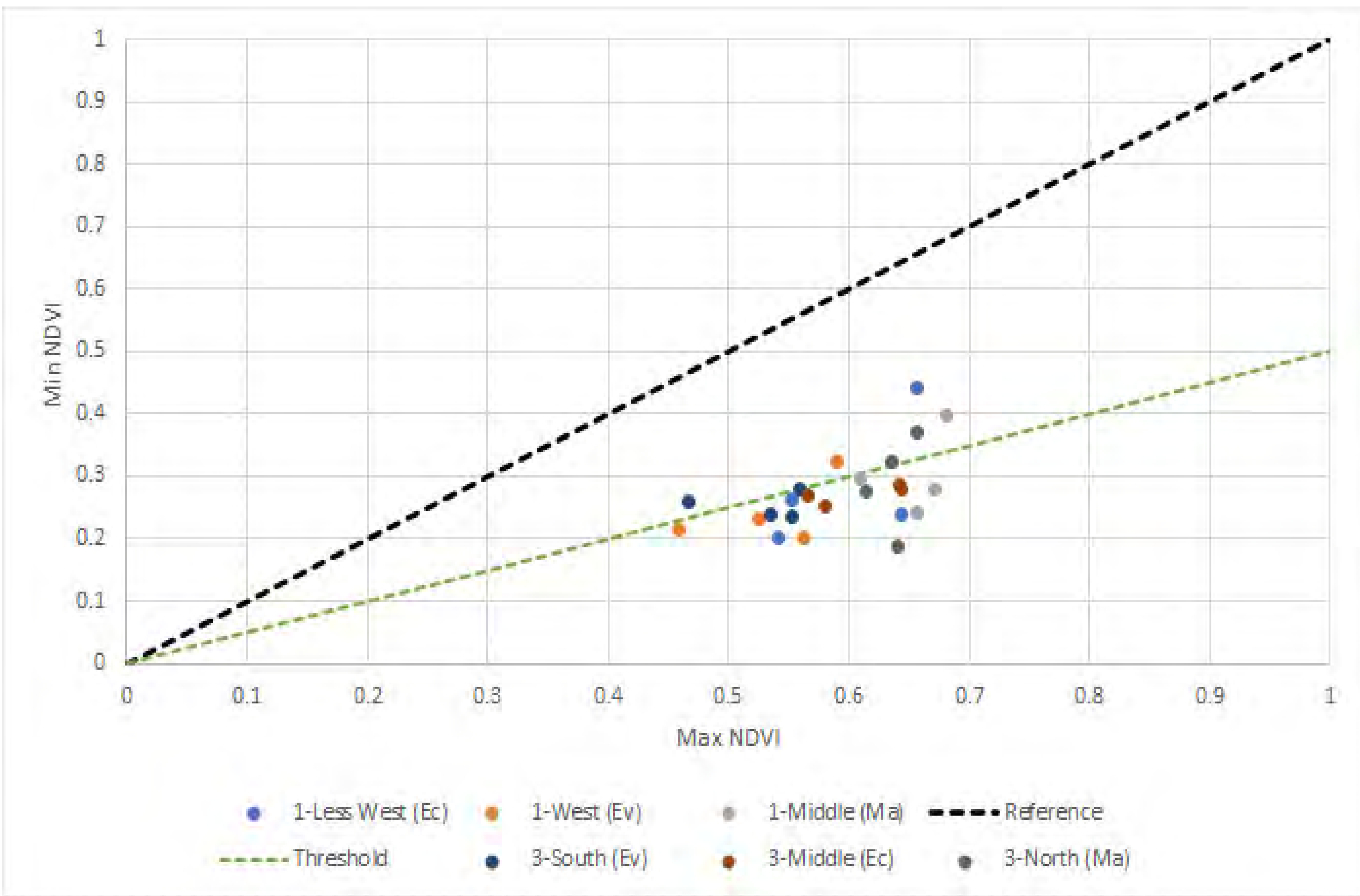
- The data are equivocal, and all locations have data that demonstrate a higher degree of inter-seasonal variability than may be expected for a system with constant access to shallow groundwater.
- 50% of the data points for Ma-type fall on or inside the threshold line.
- For the Ev-type and Ec-type, more of the data fall outside the threshold than within.

It is cautioned that the analysis is preliminary, data are limited, and no firm conclusions can be drawn. The data have not been corrected for the impacts of fire or the potential recruitment events that were inferred during the site reconnaissance visit.

Notwithstanding, it appears there is a significant variation between seasonal minimum and maximum NDVI values within the study area which may indicate much the system does not have access to consistent PAW; this would imply the system does not (consistently) use groundwater. This conclusion is especially relevant to the Ev and Ec ecotypes.

It is also possible that the high inter-seasonal range and the changes between hydrological periods are driven by changes in the productivity of the mid and understorey vegetation i.e., periods of higher rainfall may cause rapid changes in the productivity (greenness) of the *Acacia tumida* and *Gossypium robinsonii* communities around a more stable riparian tree community.





NDVI Variability FIGURE 4.3

5 ECOHYDROLOGICAL CONCEPTUAL MODEL

5.1 Structure of the Conceptual Ecohydrological Model

A conceptual model of the ecohydrological system for potentially groundwater using riparian areas of Yandicoogina Creek near Ministers North comprises a series of discrete elements. These elements are critically linked to each other and the broader environment through a series of key processes that serve to add or remove water from within the system or transfer water between elements.

5.2 Key Elements

Elements comprise:

Vegetation Community

- Riparian vegetation community, with the following characteristics:
  - o *Eucalyptus victrix* ecotype (Ev-type). This ecotype comprises a low woodland of *Eucalyptus victrix* at low to moderate basal area. These areas are characterised by a grass understorey.
  - o *Eucalyptus camaldulensis* ecotype (Ec-type). This ecotype comprises a mid-woodland with *Eucalyptus camaldulensis* as the primary species. *Eucalyptus victrix* forms a subordinate species at its upstream margins while *Melaleuca argentea* is a subordinate species at its downstream margins. This ecotype includes *Acacia tumida* and *A. coriacea* as mid storey species. Extensive *Gossypium robinsonii* occurs in slightly elevated areas on the margin of the creek.
  - o *Melaleuca argentea* ecotype (Ma-type). This ecotype comprises a high woodland to open-forest of *Melaleuca argentea* with subordinate *Eucalyptus camaldulensis.* This ecotype includes *Acacia tumida* and *A. coriacea* as mid storey species and extensive *Typha domingensis* in areas of both permanent and transient pools. Extensive *Gossypium robinsonii* occurs in slightly elevated areas on the margin of the creek.
- The root depth of the riparian trees has not been determined. However, the lowest seasonal groundwater level will provide a lower limit and root depth; roots are likely to range up to 5 m.
- Periodic water stress has affected the riparian community (notably in the Ev-type and Ec-type communities) as shown by historical limb-failures, epicormic growth and stress cracks on the trunks. This is consistent with the preliminary NDVI analysis which suggests access to groundwater in these communities maybe transient.

These riparian elements occur in two locations within the study area:

- In the Yandicoogina Creek gorge close to the Ministers North Deposit, around the area known as Sanders Seep (Area 1 in this study). This is the riparian community that maybe subject to the influence of mining at Ministers North.
- A smaller area with similar characteristics about 5km to the south within the Yandicoogina Creek channel; Area 3 from this study. This area is less likely to be subject to impacts from mining. Given the similar characteristics, this area may be suitable as analogue or baseline location.

Vadose Zone / Soil Substrate

Vadose Zone – hosted in alluvium (soil) substrate that has two functions:

- Growing medium for vegetation.
- Soil Water Reservoir – comprising PAW contained in unsaturated alluvium of the channel and flood plain environments.

The alluvium is likely to comprise coarse gravel lenses within a low-permeability silty-clay alluvial matrix. The high silt and clay fraction of the fine-grained alluvium will result in high potential moisture retention (i.e., the fine-grained alluvium will provide high levels of PAW from unsaturated storage following replenishment events). The vadose zone is estimated to be between 0 and 5 m thick; thickness will vary seasonal with groundwater rise and fall.

Aquifer System

Groundwater Reservoir – comprising water resources contained in the saturated zone (both in the alluvium and in adjacent basement which will "support" water levels in the alluvium). Regional groundwater levels have been in decline since 2017 in the surrounding basement aquifer. However, levels in the alluvial aquifer are at lower elevations than the surrounding basement; the alluvial aquifer appears to function as a drain for the surrounding basement massif and groundwater levels do not show the continuous declining trend. The depth to groundwater ranges between 0 mbgl where there are permanent pools to around 5 mbgl in the upstream Ev-type areas.

5.3 Linking Processes

Salient linking processes comprise:

- Hydrological processes that result in episodic rainfall and flow events in the Creek. Based on BHP's pool monitoring, these appear to occur 2 – 3 times per year.
- Infiltration of water from the surface into the subsurface; infiltrating water replenishes the soil water reservoir and when volumes are sufficient, recharges groundwater. Continuous infiltration due to the perennial presence of discharge water results in consistently high levels of soil water and groundwater recharge. Flood modelling indicates that most of the creek channel is activated in floods and so infiltration will occur over much of the surface area of the channel.
- Groundwater flow from the surrounding basement massif into the alluvium. The creek channel is incised into the basement and functions as a natural drain. Groundwater monitoring suggests there is up to a ~10 m head driving seepage from the basement into the alluvium.
- Tree water uptake by roots in the unsaturated zone and capillary fringe. Tree water uptake can deplete both soil water storage, and groundwater; the latter where capillary rise, and the capillary fringe contribute to tree water use. Root dynamics (i.e., their distribution within the soil profile) are an important mediator on tree water uptake.
- Evapotranspiration from trees, understorey vegetation and bare soil to the atmosphere.
- Evapotranspiration from pools and open water bodies.
- Groundwater outflow as natural throughflow in the alluvial aquifer.

5.4 Change Risk

The primary change risks relate to disruption or alteration of the “linking processes” that have a consequential change on the key elements. Discussion of key risks follows:

- Dewatering at the Ministers North deposits will reduce groundwater levels in the Brockman Iron Formation into which the creek is incised. The extent to which water level drawdown will propagate will depend on the distribution of hydraulic conductivity:
  - If water level decline in the Brockman occurs close to the Yandicoogina Creek gorge, then the gradients that drive groundwater flow into the alluvial aquifer will decline and water availability may reduce.
  - If groundwater levels fall below the invert level of the creek channel, then groundwater levels in the alluvial aquifer will decline and pools will become permanently or seasonally dry.
  - Recent pumping tests suggest there is hydraulic connection between the southern orebody and the creek-alluvium aquifer and direct impact may occur while dewatering Ministers North South deposit.
- It appears that the riparian vegetation in the study area may have a varying degree of groundwater use: the Ev-type maybe highly facultative or transient in its groundwater use (or not use groundwater at all); whereas the Ma-type is likely to require groundwater most of the time (despite the equivocal NDVI data). As such, the risks of vegetation impact related to mining-drawdown will be variable spatially and between species or eco-type. However, available data are qualitative and there is also a risk the current interpretation is not correct.
- Notwithstanding shallow groundwater levels, it is inferred that periodic flooding replenishes vadose zone water and that vadose-zone water storage is high due to the fine-grained nature of the alluvial sediments. If mining requires diversion of tributaries, then there is a risk of downstream “shadow” impacts if flood frequency is materially reduced. Hydrological modelling to date implies this change risk is small.

6 KEY DATA GAPS AND LIMITATIONS

6.1 Limitations and Data Gaps

The work to date is based on a review of available data and the development of a qualitative ecohydrological conceptual model. The model has been developed to include the key elements and processes, at scales that are typical for Pilbara riparian ecosystems. The following key metrics and data would be required for quantification of the conceptual model:

- Stand basal area, sapwood area and the relationship between basal area and sapwood area.
- Size class distribution of the riparian trees.
- Leaf water potential data (both pre-dawn and midday).
- Root depths and root distribution for the key riparian species in each ecotype (which may be inferred from groundwater level changes).
- Groundwater monitoring data for the alluvial aquifer over a wider area to confirm depth to water and the range in seasonal groundwater level change.

These data should be used to estimate evapotranspiration demands from the existing system (which will be required as inputs to groundwater modelling and future impact assessment).

Natural dynamics in the vegetation system have been implied from site observations and are consistent with NDVI analysis that suggests high variability in the water availability for the Ev and Ec types. However, the NDVI analysis is preliminary and has not taken account of fire or recruitment history, both of which were also implied from the site visit.

The work to date has not included a quantitative risk assessment (i.e., modelled change-predictions). Rather, the qualitative conceptual model has been used to define potential change pathways. Primarily, these relate to water reduction risks (drawdown resulting from depressurisation and drawdown in the basement rocks into which the creek is incised). The following data would be required to undertake quantified change risk assessment:

- Predicted changes to the groundwater regime; this will come from BHP's groundwater assessment and modelling work. Recent pumping tests demonstrate hydraulic connection between the southern orebody and the creek alluvium. Long-term drawdown is likely to have a material impact on groundwater levels and a time series prediction for the rate and extent of change would be required.
- Predicted changes to the surface water regime that may result from creek diversions. The key outcome is areas of increased or reduced flood frequency / volume (especially of the magnitude that are currently associated with 1:2 to 1:5 ARI frequencies). This will come from BHP's hydrological modelling. Hydrological modelling to dates indicates these are not likely to be significant.
- Quantification of change risk to the riparian vegetation will also require development of an Integrated Ecohydrological Water Balance Model (for example in Hydrus) and this would be based on all the data outlined above.

6.2 Uncertainties

Within the study area, it is likely that the Ma-type community has obligate groundwater use and the Ec-type community has facultative or transient groundwater use. Visible signs of water stress and lower vegetation density imply the Ev-type community may not use groundwater. In the absence of quantitative data, the distribution of groundwater use and groundwater dependence across the Ev and Ec ecotypes, remains uncertain.

Baseline ecohydrological metrics (basal area, estimated evapotranspiration and tree-water-status) remain key uncertainties. This will allow baseline conditions in Area 1 to be confirmed and allow the suitability of Area 3 as an analogue to be confirmed.

7 SUMMARY AND RECOMMENDATIONS

7.1 Summary

Available data have been reviewed on the ecohydrology of Yandicoogina Creek near the Ministers North Deposit. The data include BHP drilling, testing, and monitoring, technical studies and investigations and vegetation mapping. The data review was complimented by a 3-day site reconnaissance visit, review of other relevant literature and anecdotal comparison and professional experience from other AQ2 studies undertaken within the broader Weeli Wolli Creek catchment.

In the study area, the hydrological regime is ephemeral, with flow events occurring 2-3 times per year. Regional groundwater levels in the basement massif into which the creek is incised, decreased over the period of the monitoring record (from 2017 to present), which is believed to relate to rainfall trends. Notwithstanding, limited monitoring suggests groundwater levels in the creek alluvium have been stable, (other than for seasonal variation) over the same period; the depth to groundwater in the alluvial aquifer ranges between 0 mbgl and 5 mbgl. Transient and permanent pools are consistent with shallow groundwater levels.

Riparian vegetation occurs along the creek channel. In two areas, (Areas 1 and Area 3), this is characterised by a mesic progression of riparian vegetation from:

- *Eucalyptus victrix* ecotype (Ev-type). This ecotype comprises a low woodland of *Eucalyptus victrix* at low to moderate basal area. These areas are characterised by a grass understorey.
- *Eucalyptus camaldulensis* ecotype (Ec-type). This ecotype comprises a mid-woodland with *Eucalyptus camaldulensis* as the primary species. *Eucalyptus victrix* forms a subordinate species at its upstream margins while *Melaleuca argentea* is a subordinate species at its downstream margins. This ecotype includes *Acacia tumida* and *A. coriacea* as mid storey species. Extensive *Gossypium robinsonii* occurs in slightly elevated areas on the margins of the creek.
- *Melaleuca argentea* ecotype (Ma-type). This ecotype comprises a high woodland to open-forest of *Melaleuca argentea* with subordinate *Eucalyptus camaldulensis.* This ecotype includes *Acacia tumida* and *A. coriacea* as mid storey species and extensive *Typha domingensis* in areas of both permanent and transient pools. Extensive *Gossypium robinsonii* occurs in slightly elevated areas on the margin of the creek.

A conceptual ecohydrological model of the system has been developed. It is inferred that the Ev ecotype does not rely on consistent access to groundwater and is not groundwater dependent, based on relatively low observed basal area and clear indications of historical water stress. The Ec ecotype may facultatively use groundwater although periods of water stress are also inferred. The Ma ecotype is likely to have an obligate groundwater dependence.

Specific metrics to allow quantified description of the ecotypes are not currently available (such as measured basal area or leaf water potential). Consequently, the water-demand of each ecotype has not been determined. It is likely that the mesic progression mirrors a progression in higher water demands for the Ma type compared to the Ev type and less tolerance for dry (i.e., low-matric pressure) conditions.

It is believed the key approval and operational risks relate to:

- Limited quantification and modelling in for the ecohydrological systems. Specifically:
    - Quantified metrics to describe the systems and allow determination of evapotranspiration demands.
    - Determination of baseline conditions taking account of evidence for historical water stress and recruitment.
- Confirmation (through quantification) of the suitability of Area 3 to provide an analogue for Area 1.
- Predicted impacts from reduced groundwater levels related to future mine-dewatering.
- A wider potential impact footprint than anticipated because uncertainties and limitations mean there is in fact a stronger link between vegetation and groundwater, over wider area, than inferred during this initial study.

7.2 Recommendations

Recommendations are summarised in Table 7.1. The following recommendations are made:

1. Field Ecohydrological surveys to collect data on:
    a. Stand basal area and sapwood area. Sapwood should be collected through cores of the same trees that contribute to the basal area calculations. The survey would be undertaken in a series of representative transects for each ecotype.
    b. Leaf water potential (pre-dawn and midday) or continuous data if a psychrometer can be successfully deployed.
    c. Assessment of the characteristics of dead trees within the survey transects should also be undertaken (basal area, frequency, condition).

    The field surveys should include transects in the Ev, Ec and Ma ecotypes in the Northern and Southern areas (Areas 1 and 2). The field surveys should be used to derive estimates of stand-level evapotranspiration.

2. The ecohydrological model should be refined as required to incorporate the results from the field investigations, including root depths and hydrological boundary conditions. The conceptual model should be used to develop a numerical water balance model (e.g., in Hydrus). The numerical model should then be calibrated taking account of observed data on:
    a. Basal area and sapwood area (using this to estimate transpiration flux).
    b. Interpreted recruitment events to recreate the range in potential baseline conditions.

3. Once the numerical ecohydrological model is calibrated, the time-series of predicted hydrological change (from BHP's groundwater modelling) should be used as an input to the model to quantify the magnitude of vegetation change that may occur during mining. The modelled change in groundwater level and surface water regime should be added to the ecohydrological model as imposed surface and sub-surface boundary conditions. Variations in transpiration can then be used to assess potential changes in basal area. In this regard,

the correlation of sapwood area and basal area is important confirming estimates of stand-level tree water use and associated basal area.

4. The calibrated model can be used to consider mitigation strategies (should this be required). Strategies will likely involve supporting transitional environmental adaptions to less water; irrigation to supplement PAW for example, while root zones adapt.
5. The calibrated ecohydrological model should also be used to determine theoretical baseline conditions for alternative (drier) climate cycles.
6. A vegetation monitoring programme should be developed to provide baseline conditions. On-going monitoring recommendations would be an outcome (and on-going extension) of the proposed ecohydrological field work.
7. Additional monitoring bores should be installed in the alluvial aquifer to:
    a. Confirm the alluvial thickness in Area 1 and Area 3.
    b. Confirm the depth to water and water table surface for the shallow alluvium (in Area 1 and Area 3).
    c. To expand the spatial coverage of on-going groundwater monitoring:
        i. 1 – 2 extra bores are suggested for Area 1 (depending on access constraints).
        ii. 2 bores are recommended for area 3.

Table 7.1: Recommendations

Recommendation	Risk Addressed	Outcome	Activity
Ecohydrological field surveys	Qualitative conceptual model No ability to quantify and predict impacts.	Quantified vegetation metrics to support estimates of evapotranspiration and modelling. Data to support determination of tree-water sources.	Field surveys covering: - vegetation density (by species) measured as Stand Basal Area - Predawn and midday leaf water potential measurements in representative transects
Ecohydrological quantified conceptual model and water balance model	Unanticipated impacts because vegetation uses groundwater. Impacts from other operations inseparable from Fortescue impacts. Baseline inappropriately defined due to historical time-variance.	Assessment of impacts and long-term baselines to support approvals and on-going compliance.	Quantify conceptual model with field data. Develop numerical ecohydrological model to predict: - historical baselines - confirm water sources required by the riparian system and predict impacts related to Fortescue operations.
Specific comparison of modelling of Area 1 and Area 3 to confirm Area 3 is an analogue location	Natural changes in Area 1 related to climate are assigned to mining-induced change Limited time-series baseline.	Confirmation Area 3 can be used as a non-impact analogue location	Comparison of ecohydrological characteristics from field work and modelling between Area 1 and Area 3.
BHP Groundwater modelling to predict groundwater level change in the Yandicoogina alluvial aquifer	Changes to groundwater levels in the alluvial aquifer and implications for vegetation / management / mitigation strategies	Time series of groundwater level changes as an input to predictive ecohydrological modelling	BHP internal groundwater modelling programme
Expansion of groundwater monitoring network	Uncertainty over spatial / temporal depth to water in riparian area and spatial thickness of alluvium	Geometry of alluvial aquifer and range groundwater levels (that influence both root depth and PAW)	BHP monitoring bore drilling and installation of loggers
Ecohydrological monitoring	No baseline conditions against which to measure Fortescue impacts. Impacts related to Iron Valley are confused with Fortescue operations.	Establish baseline conditions Monitoring on-going changes related Iron Valley operations (prior to Fortescue start).	Regular (seasonal) monitoring of: - vegetation condition - LWP to provide a measure of tree water status

8 REFERENCES

Argus RE, Page GFM and Grierson PF 2015, 'Impacts of artificial inundation of ephemeral creek beds on mature riparian eucalypts in semi-arid northwest Australia', *Geophysical Research Abstracts*, GU General Assembly held 27 April - 2 May 2014, Vienna.

Argus RE, 2018, 'Flooding responses of riparian eucalypts in the Pilbara region of Western Australia', PhD Thesis, University of Western Australia.

AQ2, 2015. Ecohydrological Assessment of Coondewanna Flats. Unpublished report for BHP.

AQ2, 2019. Solomon ecohydrological Assessment. Unpublished report for FMG (Doc Ref: 137C_013a), April 2019.

Biologic (2020), Ministers North Misc. Licence Area Amendment Yandi Creek Detailed Flora and Vegetation Assessment, unpublished report to BHP.

BHP (2021) Ministers North Monitoring Review (unpublished power point summary).

BHP (2019) RED NPH Ministers North Conceptual Hydrogeological Model Rev 3, unpublished internal memo.

Budyko, M.I. 1974, Climate and Life. Academic Press, London.

David TS, Pinto CA, Nadezhdina N and David JS 2016, 'Water and forests in the Mediterranean hot climate zone: a review based on a hydraulic interpretation of tree functioning', *Forest Systems*, vol. 25, doi: http://dx.doi.org/10.5424/fs/2016252-08899

Dogramaci S, Firmani G, Hedley P, Skrzypek G and Grierson PF 2015, 'Evaluating recharge to an ephemeral dryland stream using a hydraulic model and water, chloride and isotope mass balance', *Journal of Hydrology*, vol. 521, pp: 520-532.

Eastham J 2015, Understanding Riparian Vegetation Responses to Groundwater Drawdown and Discharge from Below Water Table Mining in the Pilbara, Unpublished report for Rio Tinto Iron Ore, July 2015.

Gou, S. and Miller, G. (2014), *A groundwater–soil–plant–atmosphere continuum approach for modelling water stress, uptake, and hydraulic redistribution in phreatophytic vegetation. Ecohydrol., 7: 1029-1041. https://doi.org/10.1002/eco.1427.*

KREUZWIESER, J. and RENNENBERG, H. (2014), Responses of tree to waterlogging. Plant Cell Environ, 37: 2245-2259. https://doi.org/10.1111/pce.12310.

Maeght J, Rewald B and Pierret A 2013, 'How to study deep roots and why its matters', *Frontiers in Plant Science*, vol. 4, pp: 1 - 14.

McLean EH, Iles J, Siebers A, Pettit N, Skrzypek G, Brand M, Dogramci S and Grierson PF, in press, 'Transpiration by a semi-arid riparian eucalypt in an extreme vapour pressure deficit environment', Journal of the Total Environment.

McFarlane DJ (ed.) 2015, *Pilbara Water Resource Assessment: past, present and future hydroclimate*, A report to the Government of Western Australia and industry partners from the CSIRO Pilbara Water Resource Assessment, CSIRO Land and Water, Australia.

Naumburg E, Mata-Gonzalez R, Hunter RG, McLendon L and Martin DW 2005, 'Phreatophytic vegetation and groundwater fluctuations: a review of current research and application of ecosystem response modeling with an emphasis on great basin vegetation', *Environmental Management*, vol. 35, pp: 726-740.

Onshore Environmental (2018), Ministers North to Yandi Corridor Flora and Vegetation Survey, unpublished report to BHP.

Orellana F, Verma P, Loheide SP and Daly E, 'Monitoring and modelling water-vegetation interactions in groundwater dependent ecosystems', Reviews of Geophysics, 50, RG3003.

Pate J, Bell T and Verboom B, "Unravelling the secret lives of plant root systems", pub UWA Press.

Pfautsch S, Dodson W, Madden S and Adams MA 2014, 'Assessing the impact of large-scale water table modifications on riparian trees: a case study from Australia', *Ecohydrology*, DOI: 10.1002/eco.1531.

Phukan UJ, Jeena GS, Shukla RK. WRKY Transcription Factors: Molecular Regulation and Stress Responses in Plants. Front Plant Sci. 2016 Jun 3; 7:760. doi: 10.3389/fpls.2016.00760. PMID: 27375634; PMCID: PMC4891567.

Schenk HJ 2008, 'The Shallowest Possible Water Extraction Profile: A Null Model for Global Root Distributions', *Vadose Zone Journal*, vol. 7, pp 1119 – 1124.

Schenk HJ and Jackson RB 2005, 'Mapping the global distribution of deep roots in relation to climate and soil characteristics', *Geoderma*, vol. 126, pp:129–140.

Schenk HJ and Jackson RB 2002, 'Rooting depths, lateral root spreads and belowground/ above‐ground allometries of plants in water‐limited ecosystems', *J. Ecol.*, vol. 90, pp: 480–494.

Schymanski SJ, Sivapalan M, Roderick ML, Beringer J and Hutley LB, 2008, 'An optimality-based model of the coupled soil moisture and root dynamics', Hydrological Earth Systems Science, 12, pp 913-932.

Schilling O, Cook PG, Grierson PF, Dogramaci S and Simmons CT, in press, 'Controls on intersections between surface water, groundwater and riverine vegetation along intermittent and ephemeral streams in arid regions', Water Resources Research.

Stantec (2018), Ministers North Surface Water Environmental Impact Assessment, Final Report for BHP Billiton Iron Ore; BHP Ref 83504610.

Storkey A, Doecke A and Whaanga A 2010, 'Stratigraphy of the Western channel iron deposits of the Marillana Creek Operations, Western Australia', *Applied Earth Science*, vol. 119, pp: 2-11.

Trancoso R, Larsen J R, McAlpine C, McVicar T R, Phinn S, 2016 "Linking the Budyko framework and the Dunne diagram", Journal of Hydrology, vol 535, 2016, pp: 581-597, doi.org/10.1016/j.jhydrol.2016.02.017.

Wang, P., Niu, G.Y., Fang, Y.H., Wu, R.J., Yu, J.J., Yuan, G.F., et al. (2018). Implementing dynamic root optimization in Noah MP for simulating phreatophytic root water uptake. Water Resources Research, 54, 1560–1575.