ECOHYDROLOGICAL CONCEPTUALISATION FOR THE EASTERN PILBARA REGION

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EXECUTIVE SUMMARY

Background and Approach

To support a Strategic Environmental Assessment of the Eastern Pilbara Region (EPR), an ecohydrological conceptualisation has been developed which incorporates the key ecohydrological processes and linkages occurring in the region. The key aims of the conceptualisation were to:

- Assess baseline ecohydrological conditions with a focus on ecohydrological receptors and orebodies.
- Develop an understanding of the ecohydrology through the identification of hydrological processes that sustain ecohydrological receptors.
- Develop conceptualisations for specific mining areas to assess the potential influences of mining on the hydrological processes that support the ecohydrological receptors.
- Provide a conceptual understanding to support future numerical groundwater modeling, which may be undertaken either at a regional scale or a local scale in support of specific orebody developments.

There are a number of existing and proposed mining operations located in the EPR including BHP Billiton Iron Ore's current operations at Orebody (OB) 18, OB24, OB25, Jimblebar, and Whaleback and exploration projects at Jimblebar, Shovelanna, Ophthalmia, Homestead, OB37, Prairie Downs and Western Ridge.

As part of the assessment, a number of Ecohydrological Landscape Units (EHUs) and their dependency on surface water and groundwater were identified. It also provided detailed understanding of Ethel Gorge being the only ecohydrological receptor in the region. The Ethel Gorge stygobiont community is listed as a Threatened Ecological Community (TEC) by the Department of Parks and Wildlife (2014).

Regional Overview

The EPR is within the Upper Fortescue River catchment. Four main creek channels converge into the Fortescue River upstream of Ethel Gorge which cuts through the Ophthalmia Range towards the Fortescue Marsh.

The ephemeral drainages flow in direct response to rainfall. Streamflow mainly occurs during the summer months of December through to March and is associated with the large and more intense rainfall events. Streamflow in the smaller flow channels is typically short in duration, and ceases soon after the rainfall passes. In the larger river channels that drain the larger catchments, runoff can persist for several weeks and possibly months following major rainfall events such as those resulting from tropical cyclones.

The EPR comprises a regional groundwater flow system hosted in Tertiary detritals and underlying dolomite of the Paraburdoo Member (Wittenoom Formation), which occurs within strike-oriented valleys between ridges of Brockman and Marra Mamba Iron Formations. There are also local aquifers associated with zones of high-permeability within the major orebodies. Some of these orebody aquifers are in direct or partial hydraulic connection with the regional groundwater system.

Nine EHUs have been identified across the EPR and are grouped into four broad landscape units:

- Upland Source Landscape Units comprising hills and plateaux and dissected slopes and plains.
- Upland Transitional Landscape Units comprising upland drainage channels.
- Lowland Transitional Landscape Units comprising sandplains, alluvial plains and calcrete plains.
- Lowland Receiving Landscape Units comprising major river channels and associated floodplains and claypans, flats and basins.

Upland Source and Transitional Landscape Units are characterised by a deep watertable (greater than 30 mbgl) and a steep topography that generates surface water runoff. In these areas, ecosystems have little dependency on regional groundwater and surface water systems.

In the lowland areas, the environment is closely integrated and connected with the hydrological system. Key ecohydrological characteristics of the lowland areas include:

- Surface water is present within the lowland areas for longer periods (than the upland and transitional areas) with greater flood magnitudes and durations.
- This surface water regime has led to enhanced riparian environments and greater subsurface water availability through infiltration, soil moisture replenishment and groundwater recharge.
- The environment has adapted to greater water availability.
- The watertable is often shallow (ranging from less than 1 m up to 30 mbgl) being accessible to phreatophytic vegetation and maintaining saturated habitat for stygofauna.

Regional Ecohydrological Conceptualisation

The regional ecohydrological conceptualisation can be summarised as follows:

- There are regional aquifers associated with Tertiary detritals and, in places, underlying Paraburdoo Member dolomite. Brockman and Marra Mamba orebodies also form localised aquifers.
- The regional aquifers are aligned with the main surface water system.
- On the Fortescue River floodplain, upstream and within Ethel Gorge, the Tertiary detritals form a dual aquifer system comprising shallow unconfined and deeper confined aquifers that are separated by an extensive sequence of clays.
- The orebody aquifers tend to be bound within less permeable lithologies. There may also be along-strike hydraulic connection between orebodies via faults and sub-grade mineralisation, as well as cross-strike connection to the regional aquifer system via faults.
- Some orebodies (and pit slopes) will be in direct hydraulic connection with the regional aquifer where saturated Tertiary detritals are adjacent to the orebody aquifers.
- The aquifers are naturally recharged by the infiltration of rainfall runoff. Discharge occurs as groundwater throughflow to downstream areas and as baseflow or evapotranspiration in low-lying areas.
- Most groundwater and surface water flows through Ethel Gorge.
- The majority of groundwater recharge occurs on the Fortescue River floodplain. Natural groundwater discharge is associated with evapotranspiration from dense vegetation on the Fortescue River floodplain.
- Since the commencement of mining, groundwater recharge on the Fortescue River floodplain has been enhanced near Ethel Gorge owing to leakage / seepage from Ophthalmia Dam.
- Since the commencement of mining, there has also been groundwater abstraction from the Ophthalmia borefield and more recently from the Homestead borefield, as well as for mine dewatering.
- Groundwater and surface water flow in the Jimblebar mining area discharges through a gorge in Wheelarra Hill to the north into the Jimblebar Creek floodplain, before moving into the Fortescue River to the downstream of Ethel Gorge.

Ecohydrological Conceptualisation – Ethel Gorge

Ethel Gorge occurs where tributaries of the Upper Fortescue River flow through the Ophthalmia Range. Downstream of Ethel Gorge, the Upper Fortescue River flows in a narrow channel to the north and then onto a broad floodplain that ultimately discharges towards the Fortescue Marsh. Surface water and groundwater flows are largely focused through Ethel Gorge.

From a landscape context, Ethel Gorge is characterised as a receiving environment comprising channels, floodplains and calcrete of the River and Calcrete Land Systems. There are shallow groundwater levels (less than 10 mbgl) resulting in connectivity and interaction between the groundwater and terrestrial environments. In these lowland areas, the ecosystems are more closely integrated.

Stygofauna are hosted in shallow alluvial aquifers (including calcrete) and their habitat is maintained by saturation of these aquifers. The vegetation community comprises both obligate and facultive (opportunistic) phreatophytes that also utilise the shallow groundwater.

The Ethel Gorge TEC comprises multiple species of stygofauna and uncommon communities of dense riparian and woodland vegetation within drainage lines and floodplains. The TEC is defined by the extent of calcrete outcrop between Ethel Gorge and a location about 15 km south, which is surrounded by a 6 km buffer zone in all directions.

The key features of the ecohydrological conceptualisation for Ethel Gorge are:

- The groundwater regime is recharged by a combination of groundwater throughflow from up-catchment, infiltration of rainfall runoff (via streamflow) beneath local drainage lines, and seepage from Ophthalmia Dam.
- The hydraulic behaviour of the groundwater system (and the maintenance of shallow groundwater levels which support the key ecological communities) is dominated by recharge from Ophthalmia Dam. The water balance suggests average inputs being:
  - Recharge from Ophthalmia Dam of approximately 50,000 kL/d.
  - Infiltration of runoff along stream channels of approximately 24,000 kL/d.
  - Groundwater throughflow of approximately 2,000 kL/d.
  - Discharge from the groundwater system is dominated by evapotranspiration being associated with extensive stands of vegetation (over 3,650 ha) within the Fortescue River floodplain. Recharge from Ophthalmia Dam of approximately 50,000 kL/d.
- The water balance suggests average outputs for pre-mine dewatering conditions of:
  - Evapotranspiration of approximately 63,000 kL/d.
  - Groundwater throughflow (through Ethel Gorge) of approximately 3,000 kL/d.
  - Water supply borefield abstraction of approximately 10,000 kL/d.
- Groundwater levels in the shallow alluvial aquifer that hosts the TEC have historically fluctuated across a large range being responsive to climatic cycles of wetter and drier periods, as well as variations in water supply abstraction from the existing borefields.
- Since 2007, dewatering in the Ethel Gorge area has resulted in groundwater drawdown in the deeper aquifer across a broad area. Groundwater drawdown in the shallow aquifer has been less than 10 m (apart from in the immediate pit areas) and the shallow aquifer has remained saturated.

In summary, the key hydrological processes that maintain the shallow groundwater conditions that support the TEC are infiltration of surface water flow through stream channels and recharge associated with leakage from Ophthalmia Dam. Groundwater throughflow from areas upstream of Ethel Gorge (including all mining areas) provides only a very small input (less than 3%) into the water balance.

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1. INTRODUCTION

1.1 Project Description

1.1.1 Location and Extent

The Eastern Pilbara Region (EPR) Study area spans four catchments that converge on four relatively narrow channels through the Ophthalmia Range and drain north along the Fortescue River to the Fortescue Marsh (Figure 1.1). Most of the Study area comprises the Upper Fortescue River catchment while the eastern portion of the area also comprises the Jimblebar Creek, Caramulla Creek and Davidson Creek catchments. There are a number of existing and proposed mining operations located in the EPR Study area including BHP Billiton Iron Ore’s current operations at, Orebody (OB) 18, OB24, OB25, Jimblebar, and Whaleback and exploration projects at Jimblebar, Shovelanna, Ophthalmia, Prairie Downs and Western Ridge.

1.1.2 Areas of Importance or Significance

1.1.2.1 Mining areas and orebodies

There are 38 designated orebodies in the EPR, which have been grouped into nine mining areas. These are shown on Figures 1.1 and 2.3 and they are summarised in Table 1.1. Details on each mining area and individual orebodies are presented in Section 5. It should be noted that estimates of percentage of ore below watertable are calculated from available internal data provided by BHP Billiton Iron Ore.

1.1.2.2 Receptors

The Ethel Gorge stygobiont community is listed as a Threatened Ecological Community (TEC) by the Department of parks and Wildlife (DPaW) and classed as "endangered" (EN B) ii) (DPaW, 2014). A detailed description of Ethel Gorge is presented in Section 4.2.

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Table 1.1: Below Watertable Orebodies in the Eastern Pilbara Region

Mining Area	Owner	Orebody	Host-Geology*	Operating Status**	% Below Watertable	Remarks
EASTERN RIDGE	BHP Billiton Iron Ore	OB23	BRK	CLOSED	N/A	
	BHP Billiton Iron Ore	OB24	BRK	M	4	
	BHP Billiton Iron Ore	OB25 PIT 1	BRK	M	83	AWT mining commenced
	BHP Billiton Iron Ore	OB25 PIT 3	BRK	M	67	BWT mining commenced, active dewatering
	BHP Billiton Iron Ore	OB25 PIT 4	BRK	M	1	BWT mining commenced, active dewatering
	BHP Billiton Iron Ore	OB37	MM	EXP	70	
EAST OPHTHALMIA	BHP Billiton Iron Ore	OB21	BRK	EXP	15	
	BHP Billiton Iron Ore	OB43 EAST	MM	EXP	70	
	BHP Billiton Iron Ore	OB43 WEST	MM	EXP	70	
HOMESTEAD	BHP Billiton Iron Ore	OB28	BRK	EXP	50	
	BHP Billiton Iron Ore	OB32	MM	EXP	70	
	BHP Billiton Iron Ore	OB32 WEST	MM	EXP	70	
	BHP Billiton Iron Ore	OB33	MM	EXP	70	
	BHP Billiton Iron Ore	OB36	MM	EXP	70	
JIMBLEBAR	BHP Billiton Iron Ore	EAST JIMBLEBAR	BRK	EXP	15	
	BHP Billiton Iron Ore	WEST JIMBLEBAR	MM	EXP	70	
	BHP Billiton Iron Ore	SOUTH JIMBLEBAR	MM	M	70	
	BHP Billiton Iron Ore	WHEELARRA 1,2 3	BRK	M	8	AWT mining commenced
	BHP Billiton Iron Ore	WHASHI	BRK	EXP	31	AWT mining commenced
	BHP Billiton Iron Ore	CARAMULLA EAST	BRK	EXP	15	WHASHI BWT mining schedule not confirmed
	BHP Billiton Iron Ore	CARAMULLA EAST	MM	EXP	70	
	BHP Billiton Iron Ore	CARAMULLA WEST	BRK	EXP	15	
	BHP Billiton Iron Ore	CARAMULLA WEST	MM	EXP	70	
OPHTHALMIA	BHP Billiton Iron Ore	CENTRAL BUTTES	MM	EXP	70	
	BHP Billiton Iron Ore	WESTERN BUTTES	CID	EXP	50	
PRAIRIE DOWNS	BHP Billiton Iron Ore	GRID A	MM	EXP	60	
SHOVELANNA	BHP Billiton Iron Ore	OB17	BRK	M	8	
	BHP Billiton Iron Ore	OB18	BRK	M	8	AWT mining commenced, BWT mining schedule not confirmed
	BHP Billiton Iron Ore	OB31	BRK	EXP	59	AWT mining commenced
	BHP Billiton Iron Ore	OB19	BRK	EXP	8	
	BHP Billiton Iron Ore	OB20	BRK	EXP	4	
	BHP Billiton Iron Ore	OB34	MM	EXP	70	
	BHP Billiton Iron Ore	OB39	MM	EXP	48	
WESTERN RIDGE	BHP Billiton Iron Ore	SILVER KNIGHT	MM	EXP	70	
	BHP Billiton Iron Ore	EASTERN SYNCLINE	MM	EXP	70	
	BHP Billiton Iron Ore	MT HELEN	BRK	EXP	15	
WHALEBACK	BHP Billiton Iron Ore	WHALEBACK	BRK	M	100	
	BHP Billiton Iron Ore	OB29	MM	EXP	39	BWT mining, active dewatering
	BHP Billiton Iron Ore	OB30	MM	EXP	43	

** Host Geology - MM = Marra Mamba, BRK = Brockman*

***Operating Status – M = Mining, EXP = Exploration, CLOSED = Mining Completed*

The content of the table is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This table has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development will actually proceed. As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from the contents of the table.

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1.2 Scope and Objectives

1.2.1 Study Objectives

RPS has been engaged by BHP Billtion Iron Ore to develop a conceptual hydrological model for the EPR. The principal aims of the study include:

- Provide an assessment of the current baseline hydrological conditions in the EPR to inform an impact assessment of the overall EPR catchment with a focus on ecohydrological receptors and orebodies.
- Develop an understanding of the ecohydrology of the EPR through the identification of hydrological processes that sustain the ecology.
- Provide a conceptual model to support future numerical modelling exercises that may be undertaken either at a regional scale or in support of specific orebody developments.
- Provide a conceptual hydrological model to support further development of the numerical groundwater model used to predict the long-term hydrological change resulting from groundwater abstraction in the Ethel Gorge catchment.
- Support the Strategic Environmental Assessment being undertaken by BHP Billtion Iron Ore by way of demonstrating an understanding of ecohydrological conditions and processes.

The overall approach to this study was to:

- Build a conceptual ecohydrological model that incorporates the key ecohydrological processes and linkages and describes the key role that water plays in the overall ecohydrological system. A description of ecohydrological principles and the approach to ecohydrological conceptualisation is presented in Section 1.3.
- Present conceptual hydrological models that describe the regional hydrological system including major aquifers, aquifer parameters, sources of recharge, and the primary groundwater and surface water flow regimes. The approach used to develop these conceptual follow the Australian National Groundwater Modelling Guidelines (NWC, 2012) and, to a lesser extent is influenced by the Hydrogeological Landscape Framework developed by Geoscience Australia (2010).

Section 2 presents a broad outline of the regional ecohydrological setting. Section 3 presents a description of the conceptual hydrological model at a regional scale. Section 4 presents the ecohydrological conceptualisation, as well as a description of ecohydrological functioning related to Ethel Gorge. This includes a conceptual hydrological/hydrogeological model for the receptor, key hydrological processes that support the receptor, and identification (through a quasi-catchment approach) of which orebodies could possibly change the key hydrological processes at Ethel Gorge.

Section 5 provides a summary of the hydrological setting and conceptual hydrological models for each mining area. Section 6 provides a summary of the current understanding of the hydrological system (i.e. conceptual hydrological model), the ecohydrological receptor (Ethel Gorge), and the potential risks of mining activities to Ethel Gorge.

All data used for the EPR report has been summarised in the data inventory and is presented in Appendix A.

1.3 Ecohydrology

1.3.1 What is Ecohydrology

Ecohydrology is the study of the interactions and interrelationships between hydrological processes and ecosystem patterns and dynamics.

Ecohydrology has traditionally focused on the role of vegetation in regulating various components of the water cycle, or the influence of hydrology on plant community composition (Westbrook et al. 2013). In a key publication in the Australian context, Eamus et al. (2006) define ecohydrology as "*the study of how the movement and storage of water in the environment and the structure and function of vegetation are linked in a reciprocal exchange*".

Broader definitions, which consider interactions between hydrology and a wider array of biological processes, have also been proposed, for example:

- Ecohydrology is the subdiscipline shared by the ecological and hydrological sciences that is concerned with the effects of hydrological processes on the distribution, structure and function of ecosystems, and on the effects of biotic processes on elements on the water cycle (Nuttle, 2002).
- Ecohydrology [is] the science of integrating hydrological and biological processes over varied spatial and temporal scales (Bonacci et al., 2008).
- Ecohydrology [is] the study of the interactions and interrelationships between hydrological processes and ecosystem patterns and dynamics (Neumann, 2013).

In all cases, ecohydrology seeks to provide an explanatory rather than descriptive understanding of landscapes. A practical impetus for gaining such understanding is the improved management, protection and/or restoration of landscape, water and ecological assets.

In this report, the term 'ecohydrology' is consistent with the broader definitions provided above.

1.3.2 Ecohydrological Concepts

Key concepts and principles underlying the development of an ecohydrological conceptualisation for the EPR Study area are summarised as follows:

1.3.2.1 Pathways and Connectivity

In consideration of the various water movement pathways through and beneath the landscape, it is important to understand factors that facilitate or impede water movement and how the pathways connect different landscape elements and ecosystem components.

Water is the primary medium of connectivity in dryland environments, because it controls physical and biological processes across different scales (Austin et al., 2004; Wang et al., 2009). Water not only connects and separates landscape elements, but is also the primary transporter of energy and matter within and across those elements.

Individual water movement pathways aggregate into networks of water transport. Pathways and networks of high relevance for environments of the central Pilbara region include:

- The soil–plant–atmosphere continuum (Figure 1.2). Note that soil properties such as infiltration and storage in the unsaturated profile influence surface water runoff behaviour and play an important role in making water available for uptake by vegetation. Subsoil characteristics may facilitate or impede the percolation of water into underlying groundwater systems.
- Surface flow along preferred pathways such as channels, rivers and floodplains as dictated by topography and geomorphology, but also influenced by vegetation (Figure 1.3).
- Groundwater flow driven by hydraulic gradients. Properties of basement rocks and the regolith affect groundwater transmissivity. Preferred flow pathways, for example associated with geological fault lines or palaeochannels, can be important for connecting landscape elements.

The term “connectivity” describes the nature of and the degree to which landscape elements are connected by water transport pathways. In a spatial context, connectivity operates in longitudinal, lateral and vertical dimensions; and also has a temporal dimension across each of these spatial dimensions (Jaeger and Olden, 2012).

Connectivity both influences and is influenced by landscape and ecosystem processes. For example, vegetation root systems can contribute to the development of preferred pathways for groundwater recharge along root channels (Wilcox et al., 2008), or hardpan layers which impede deep drainage (Verboom and Pate, 2006). The modification, loss or creation of connectivity has the potential to cause reversible or irreversible ecosystem change.

Water is delivered to the landscape via rainfall which is then redistributed three dimensionally. Surface runoff is a key redistribution process. At landscape and sub-landscape scales, preferential surface flow via preferred pathways (drainages) is a major lateral and longitudinal connectivity factor in the Pilbara.

Channel geomorphology can be categorised based on the magnitude and energy of transmitted flows (primarily a function of catchment size and topography):

- Type (a) - Minor drainages are associated with small catchment areas in upper landscape locations.
- Type (b) - High energy drainages are generally large and incised, and often exhibit regular bed load movement. They receive the combined flows and energy of minor drainages, reinforced by topographic gradients along their own length. They generally occur in upland landscapes associated with hills and ranges. Systems transmitting large flow volumes (e.g. Weeli Wolli Creek) can exhibit high energy drainage characteristics in zones of energy dissipation extending some distance from the base of the uplands across flatter country.
- Type (c) - Low energy drainages are commonly braided, meandering and/or anabranching. They are prevalent in areas of low relief (predominantly broad alluvial plains) where the energy of upstreamflows is dissipated. Low energy drainages often feature channel flow retardation structures related to avulsion, floodouts and splays.
- Type (d) - Drainage termini accumulate and store flows. Under typical conditions these areas represent the end point for surface water flow paths, however in some cases large magnitude flow events may overwhelm the terminal storage capacity and spill over into down-gradient systems. In such cases transient connectivity is provided between otherwise disjunct landscape elements. Where they occur, overtopping processes also provide a flushing mechanism.

Sheetflow can also be an important water redistribution process on some low gradient surface types (i.e. gentle slopes of approximately 1:50 to 1:500; Bromley et al., 1997). In practice it is difficult to distinguish between sheetflow and channel flow zones without high resolution surface elevation data. Some landscape surfaces are likely to exhibit both sheetflow and preferential flow characteristics under different wetting scenarios.

Soil properties influence the movement of water and nutrients in the landscape, which in turn affect patterns of vegetation. Soils in upland areas of the central Pilbara are generally shallow with relatively low water holding capacity. Deeper soils occur in association with drainage lines and depositional flats. Small rainfall pulses only recharge soil moisture in the top layers, whereas large pulses can penetrate to a greater depth where permitted by the soil profile. Subsoil hardpans, which may restrict vegetation root depth, are common on Pilbara washplains and alluvial flats.

Groundwater flow through regional-scale or linked aquifers is an important pathway for catchment scale water distribution in the Pilbara, transferring water from areas where rainfall recharges groundwater (e.g. in uplands and river channels) to lower lying terrain. In certain geomorphologic circumstances, groundwater may express at the surface or within the depth of vegetation root systems. Ecosystems in these areas may have varying levels of dependence on groundwater supply.

1.3.2.2 Spatial and Temporal Scales

Ecohydrological processes can be considered at different spatial and temporal scales. Four spatial scales relevant to ecohydrology processes in dryland environments are commonly recognised (Mueller et al., 2013):

- Plant-interspace scale – individual plants and their adjacent bare interspaces.
- Patch scale – multiple plant-interspaces, typically on the same soil or geomorphic unit.
- Landscape scale – a landscape unit characterised by internal connectedness. In dryland environments, landscape units are commonly represented by catchments.
- Regional scale – multiple landscape units, commonly within one or more contiguous biomes.

Temporal scales are important for water movement, storage, release and accessibility to biota. For example overland flow connectivity in the Pilbara is episodic and unidirectional. Consequently many Pilbara ecosystems are strongly influenced by, and are adapted to, erratic water inputs. Surface channels can transmit water long distances in a matter of hours. Conversely, stored soil water in deep, accessible profiles may sustain vegetation water use for many months or even years. Similarly vegetation may have access to transient or persistent groundwater.

Spatial and/or temporal processes can be important for overall system understanding. In the case of this assessment, the primary interest is the evaluation of potential impacts on ecological assets beyond areas of direct disturbance associated with mining and infrastructure developments (i.e. outside vegetation clearing footprints). In that context, the scales of highest relevance for ecohydrological conceptualisation are landscape and regional.

1.3.2.3 Vegetation Patterns

In arid and semi-arid regions, the interactions between climate, soils, vegetation and topography give rise to distinct patterns of vegetation and surface water re-distribution. These patterns in turn can be important determinants of many other ecosystem attributes. As such, patterns of vegetation can provide information about ecohydrological processes. For example, banded vegetation formations are generally considered to be associated with zones of sheetflow, which typically occur in broad inter-drainage areas on alluvial plains near the base of hills and ranges. Major channels often host *Eucalyptus* woodland communities, which are sustained by inflows combined with deep soils that can store large volumes of water.

Leaf area index (LAI) provides an indicator of water availability for vegetation, consistent with the principle of ecological optimality (O'Grady et al., 2011; Ellis and Hatton, 2008). This principle suggests that over long time scales, vegetation in dryland environments will equilibrate with climate and soils to optimally use the available soil water. As a consequence high LAI is correlated with high water availability, and often occurs in areas with:

- Deep soil profile with large water storage capacity, combined with surface or sub-surface lateral inflows; and/or
- Relatively fresh groundwater in vegetation root zones.

In the Pilbara, relationships between vegetation LAI and patterns of drainage are evident, with areas that persistently maintain very high LAI relative to surrounding vegetation being more likely to have access to (and potentially a dependency on) groundwater.

1.3.2.4 Plant Water Use Strategies

Plant species in dryland environments segregate along an eco-physiological spectrum of water use strategies. An understanding of these strategies is important in predicting vegetation responses to changes in surface or groundwater. Relevant traits that determine water use strategies are acquisition efficiency (root traits) and use efficiency (leaf and stem traits) as suggested by Moreno-Gutierrez (2012). There are four broad plant functional water use types (Figure 1.2) as follows:

- (1) Transient opportunistic – species with shallow root systems; respond rapidly to rainfall pulses; exhibit a range of drought avoidance strategies (e.g. ephemeral life history, dormancy, etc.).

- (2) Conservative shallow rooted – species with low but persistent water use; relatively low responsiveness to rainfall; exhibit a variety of adaptations for regulating root water uptake and transpiration (e.g. stomatal regulation, low hydraulic conductance of the root–stem–leaf pathway, succulence).
- (3) Deep rooted - species with persistent moderate water use; sustained through accessing stored water in the unsaturated soil profile. Relatively low responsiveness to rainfall. Restricted to zones of deeper soils, often in areas where rainfall inputs are augmented by run-on (e.g. drainage lines and floodplains).
- (4) Phreatophytic – species which use groundwater to meet some or all of their water use requirements. Access to groundwater may be permanent or temporary as dictated by site and species interactions. Groundwater in the Pilbara is generally deep and inaccessible to vegetation; hence phreatophytic species tend to have restricted distributions (e.g. *Melaleuca argentea*).

Different landscape elements can facilitate different water use strategies, although most vegetation communities include a mixture of species with different water use strategies. Indeed many observations of plant water use physiology in dryland environments are consistent with the two-layer hypothesis, which predicts that different plant species are able to coexist because they utilise water from different depths (Gwenzi et al., 2013; Ogle and Reynolds, 2004).

Many plant species have a level of adaptive capacity to the growing conditions that they experience, and may adopt multiple water use strategies across their range of occurrence. Even at the population level, water sources used by plants may vary considerably amongst individuals of the same species. Some tree and shrub species possess the ability to switch between deep and shallow water sources as dictated by seasonal water availability (Ogle and Reynolds, 2004). In the Pilbara, the riparian species *Eucalyptus camaldulensis* is considered to be a facultative phreatophyte; meaning it can persist on unsaturated storage derived from surface inputs as well as using groundwater where available. This is in contrast with obligate phreatophytes, which are dependent on access to groundwater. Global experience suggests that obligate phreotophytic behaviour seems to be more related to site-specific environmental conditions rather than the capabilities of a given plant species (Thomas, 2014).

1.3.2.5 Landscape Characteristics

The Pilbara landscape is ancient and shaped by a complex set of geomorphic and geological factors. In order to understand landscape function, it is necessary to consider landscape evolution processes and the effect these have had on the present day environment. As an example, palaeochannels are regionally significant hydrogeological features in the Pilbara that typically host a fully connected groundwater system and provide important habitats for stygofauna. Interactions between these palaeochannel features and drainages can be important for the persistence of surface and subterranean ecosystems.

The poor fertility of Pilbara soils, a legacy of millennia of weathering and leaching, accentuates the importance of run-off and run-on processes for the supply of water and nutrients to vegetation. Patterns of vegetation are often related to surface geology, as mediated by the effect of geology on soil properties. Although different vegetation types may occur on different geological substrates in similar landscape position, in many cases they are likely to exhibit similar water use strategies (for example floristically different spinifex communities).

Hardpans are commonly encountered within alluvial plains of the central Pilbara, comprising near surface indurated horizons which vary in thickness from centimetres to meters. Hardpans develop where there is a net moisture deficit and lack of seasonal flushing, facilitating the accumulation and precipitation of cementing agents such as oxides of iron, aluminium and manganese, carbonates and/or silica. The process of hardpan formation can be prolonged and therefore requires stable surfaces over geological timescales. Hardpans generally have low permeability and thus may restrict the percolation of water into the underlying regolith.

Major drainage systems of the central Pilbara commonly host groundwater derived calcrete. The calcrete has developed in riverine or lacustrine alluvium subject to strongly evaporitic conditions and fluctuating groundwater levels (Mann and Horwitz, 1979). These conditions facilitate the precipitation of calcium carbonate, where the solubility of calcite is exceeded. Varying degrees of silicification may also be exhibited, reflecting the influence of saline groundwater and silica precipitation/displacement of calcium carbonate. Some areas of calcrete occur higher in the landscape, in association with ancient drainage systems that are now dissected by more recent drainages. Carbonate precipitation remains active in spring discharge regions, such as at Millstream and Weeli Wolli Spring (Reeves et al., 2007).

The Pilbara has been subject to many decades of pastoral land use, with associated land degradation issues (O'Grady, 2004). The effects of livestock grazing, the introduction of weeds and feral animals, as well as modified fire regimes have all contributed to significant landscape changes affecting landscape ecohydrological connectivity. The spread of Buffel Grass (*Cenchrus ciliaris*) in riparian environments is a prime example. This species displaces native vegetation by increasing fuel loads, facilitating more frequent and intense fires and then regenerating/colonising rapidly after fire events. Such changes are expected likely to influence patterns of vegetation water use and infiltration/runoff processes. Post European settlement landscape effects are continuing with evolving rangelands management, and need to be considered when interpreting and conceptualising ecohydrological processes.

1.3.2.6 Ecological Water Requirements of Wetlands

Wetlands are areas that are permanently or persistently inundated or saturated by surface or groundwater. They may include subterranean habitats. Such areas require special attention owing to their potentially high level of connectivity with other landscape elements, restricted occurrence, and propensity to support unique or unusual ecosystems.

Water can converge and collect in wetlands from many different pathways. Transit times along these pathways can vary spatially and temporally in response to inputs and the physical structure of the catchment, resulting in dynamic and complex hydrological regimes (Neumann, 2013). In flat terrain where flow rates are lower, such as in lake chain systems, water is exposed for a longer time to climatic and biogeochemical processes which can alter its physicochemical properties. In steeper terrain where flow rates are greater, such as in rivers or headwater streams, there may be little modification of water properties owing to the shorter transit times. The properties of groundwater contributing to a wetland environment may similarly be modified based on residence times in aquifer systems.

The level of persistence of aquatic environments has an important effect on their biotic assemblages, and their functional importance as refuges (Davis et al., 2013). Longer hydroperiod allows more species to colonise and greater habitat complexity to develop (Boulton and Jenkins, 1998; Sheldon et al., 2002). In ephemeral wetlands the transition between wet and dry periods is important for driving biotic and abiotic exchanges, ecosystem succession processes, and maintaining ecosystem integrity (Boulton and Lloyd, 1992; Boulton and Jenkins, 1998; Junk et al., 1989).

Wetland ecosystems in the central Pilbara tend to be strongly influenced by episodic, intense, rainfall events and rapid surface water movement from source areas (Pinder et al., 2010). Many surface water features, such as river pools and clay pans, are intermittent or ephemeral. The persistence of waterbodies is dictated by flood frequency; the rate of water loss following flood events by drainage, evapotranspiration and infiltration/percolation into deep groundwater systems. Bank storage and/or perched groundwater may be important for prolonging waterbody persistence, where permitted by local area geomorphology. Different hydrological regimes associated with flooding and flow frequency, flood duration, salinity and source of water may support different species assemblages. Different stages of the hydrological regime may also be important for species life cycles, such as the utilisation of flooded wetlands by waterbirds for breeding.

Permanent pools usually occur where bedrock structures impede hyporheic groundwater flow, where springs discharge groundwater or where flow has scoured pools that are sufficiently deep to encounter the watertable (Pinder et al., 2010). These wetlands are uncommon, typically supporting unusual or unique flora and fauna assemblages and potentially functioning as refuges for a range of aquatic species.

Subterranean habitats in groundwater are defined by the types of voids and interstitial spaces within host rocks and groundwater chemistry (Halse et al., 2014). Both attributes are influenced by the geology of the aquifer, the amount of landscape weathering, and local chemical and hydrological processes (Reeves et al., 2007).

Connectivity with the surface influences the supply of oxygen and organic matter into subterranean ecosystems, highlighting the importance of recharge dynamics for these habitats as associated with cyclonic recharge events. Depth to groundwater is considered to constrain the complexity and abundance of stygofauna communities in the Pilbara (Halse et al., 2014). The response of stygofauna to fluctuations in the watertable is poorly understood; however, their persistence over geological time suggests they have capacity to adapt to dynamic habitat availability.

1.3.3 Ecohydrological Conceptualisation Approach

Taking into account the aforementioned ecohydrological concepts, a landscape ecohydrological conceptualisation was developed through the definition of ecohydrological units (EHUs) for the EPR Study area. Each EHU represents a landscape element with broadly consistent and distinctive ecohydrological attributes.

A detailed description of the methodology used to develop and spatially define the EHUs is provided in Appendix A of the main report. In summary the spatial definition of the EHUs is based on interpretation of land system mapping units developed by the Department of Agriculture (Van Vreeswyk et al., 2004), surface drainage networks, groundwater systems, inferred vegetation water use behaviour based on vegetation mapping (structure and dominant species) and Landsat NDVI (Normalized Difference Vegetation Index).

Nine EHUs are recognised within the Eastern Pilbara region as listed below.

- EHU 1 Upland source areas - hills, mountains, plateaux.
- EHU 2 Upland source areas – dissected slopes and plains.
- EHU 3 Upland transitional areas – drainage floors within EHUs 1 and 2 which tend to accumulate surface flows from up-gradient.
- EHU 4 Upland channel zones - channel systems of higher order streams which are typically flanked by EHU 3 and dissect EHUs 1 and 2.
- EHU 5 Lowland sandplains – level to gently undulating surfaces with occasional linear dunes. Little organised drainage but some tracts receive surface water flow from upland units.
- EHU 6 Lowland alluvial plains – typically of low relief and featuring low energy, dissipative drainage.
- EHU 7 Lowland calcrete plains – generally bordering major drainage tracts and termini, typically with shallow soils and frequent calcrete exposures.
- EHU 8 Lowland major channel systems and associated floodplains.
- EHU 9 Lowland receiving areas - drainage termini in the form of ephemeral lakes, claypans and flats.

The key attributes of each EHU are further described in Table 1.2. Factors considered in the definition of EHUs include:

- Landscape position and land surface types, including soil characteristics.
- Landscape water balance processes.
- Surface drainage/redistribution processes.
- Connectivity and interactions between surface water and groundwater systems.
- Major vegetation types and their water use strategies.

The EHUs transition from upland to lowland environments, in a spatial arrangement hierarchy depicted in Figure 1.4 and illustrated in a landscape context in Figure 1.5. The landscape distribution of aquatic habitats, such as pools, springs and ephemeral lakes, were also considered in the definition of EHUs. These habitats are typically confined to EHUs 8 and 9, where surface and groundwater flows accumulate and surface water/groundwater interactions may occur.

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Table 1.2: General attributes of landscape ecohydrological units (EHUs) in the central Pilbara region

Land-scape	Land-scape Unit	EHU	Landscape position, land surface and soils	Dominant landscape water balance processes	Dominant surface drainage/connectivity processes	Level of connectivity to groundwater systems	Major vegetation types
Upland Landscape	Upland Source Landscape Units	1	Upland source areas - hills, mountains, plateaux. Land surface is steep and rocky. Shallow or skeletal soils with frequent bedrock exposures.	Rainfall Infiltration Soil evaporation Runoff	Generally short distance overland flow into dendritic drainage networks (1st, 2nd and 3rd order streams).	Local and regional groundwater systems are deep and not accessible to vegetation. Preferential recharge can occur as dictated by local scale geology/regolith.	Hummock grasslands. Vegetation water demand met by direct rainfall and localised surface redistribution.
		2	Upland source areas – dissected slopes and plains, down-gradient from EHU 1. Land surface is sloping with shallow to moderately deep colluvial soils.	Rainfall Infiltration Soil evaporation Runoff	Overland flow short distance into channel drainage systems (mainly 1st to 4th order streams).	Local and regional groundwater systems are deep and not accessible to vegetation Preferential recharge can occur as dictated by local scale geology/regolith.	Hummock grasslands. Vegetation water demand met by direct rainfall and localised surface redistribution.
	Upland Transitional Landscape Units	3	Upland transitional areas – drainage floors within EHUs 1 and 2 which accumulate surface flows from up-gradient. Soils of variable depth derived from alluvium. Greater storage relative to soils in EHU 1 and 2.	Inflows Infiltration Storage Evapotranspiration	Surface accumulation and infiltration of flood flows (overland flows and channel breakouts). Excess volumes transferred to adjacent channels (EHU 4).	Local and regional groundwater systems are deep and not accessible to vegetation.	Smaller drainage floors support hummock grasslands; larger drainage floors support *Eucalyptus* and *Acacia* shrublands and woodlands. Vegetation water demand met by direct rainfall and stored soil water replenished by infrequent flood events.
		4	Upland channel zones - channel systems of higher order streams (generally ≥5th order) which dissect EHU 1 and EHU 2. Channels are high energy flow environments, subject to bed load movement and reworking. Soils of variable depth derived from alluvium including zones of deep soils. Generally high infiltration rates.	Inflows Infiltration Storage Evapotranspiration Channel throughflow	Channel beds and banks accept and store water during flow events. Large flows are transmitted down-gradient. Channels may support intermittent or persistent pools replenished by flood flows.	Regional groundwater systems are deep and not accessible to vegetation. Transient or less commonly persistent shallow groundwater systems may develop beneath channels in places, as dictated by local scale geology/regolith. In rare cases these may be connected with pools. In rare cases vegetation may access perched groundwater for periods of time.	Channels are typically lined with narrow woodlands of *E. victrix*, *A. citrinoviridis* and/or other *Eucalyptus* and *Acacia* species. These are sustained by soil water replenishment from flow events.
Lowland Landscape	Lowland Transitional Landscape Units	5	Lowland sandplains - landform characterised level or gently undulating plains up to 10 km in extent. Deep sandy soils of aeolian origin. Uncommonly features linear dunes up to approximately 15 m in height.	Infiltration Storage Evapotranspiration Groundwater recharge	Poorly organised drainage. High rainfall infiltration and recharge. Runoff is minimal and if it does occur is generally localised, with accumulation in swales or depressions. Sandplains may receive and infiltrate inflows from channels deriving from up-gradient areas.	Groundwater systems are generally deep and not accessed by vegetation. May include important zones of recharge, with associated groundwater mounding. Possibility of transient or more persistent perched groundwater at localised scales, depending on regolith characteristics.	Hummock grasslands, with *Acacia* sp. and other shrubs, occasional mallee Eucalypts. Distinctive grassland communities relative to other EHUs. Tracts receiving run-on include *Acacia* and *Eremophila* shrublands.
		6	Lowland alluvial plains – broad depositional plains of low relief. Soils typically loams, earths and shallow duplex types. Subsurface calcareous hardpans are frequently encountered.	Localised surface redistribution Infiltration Storage Evapotranspiration	Complex surface water drainage/redistribution patterns. Land surfaces are generally dissected by low energy channels of variable form and size. Areas of sheetflow can occur, which may be associated with banded vegetation formations. Some areas may be subject to infrequent flooding. Infiltration may be significant at local scales in association with drainage foci, These areas are likely to be correlated with relatively higher leaf area index.	Groundwater systems are generally moderately deep (>10 m) to deep (>20 m) and not accessed by vegetation.	*Acacia* shrublands; less commonly Hummock grasslands, Tussock grasslands or low shrublands of Bluebush/Saltbush.
		7	Lowland calcrete plains –plains of low relief generally bordering major drainage tracts and termini. Shallow soils underlain by calcrete of variable thickness, which occasionally outcrops.	Localised surface redistribution Infiltration Soil evaporation Groundwater recharge	Complex surface water drainage/redistribution patterns. Calcrete platforms may have varying permeability. Land surfaces are generally dissected by low energy channels of variable form and size. Generally characterised by numerous localised drainage termini.	Depth to groundwater can vary from shallow (<5 m) to deep (>20 m). Preferred pathways may facilitate rapid recharge at local scale. Groundwater systems are generally not accessed by vegetation. Groundwater systems in calcrete can provide important stygofauna habitat.	Hummock grasslands and *Acacia* scrublands with occasional Eucalypts. Distinctive vegetation communities relative to other EHUs.

Land-scape	Land-scape Unit	EHU	Landscape position, land surface and soils	Dominant landscape water balance processes	Dominant surface drainage/connectivity processes	Level of connectivity to groundwater systems	Major vegetation types
Lowland Landscape	Lowand Receiving Landscape Units	8	Lowland major channel systems and associated floodplains - supporting large flow volumes in flood events. Channels are high energy flow environments, subject to bed load movement and reworking. They may be physically altered by cyclonic floods.	Inflows Ponding Infiltration Storage Evapotranspiration Channel throughflow Groundwater recharge Groundwater discharge (localised)	Channel beds and banks accept and store water during flow events. Large flows are transmitted down-gradient. Soil water in the floodplains is replenished during flooding breakouts. Channels support transient, persistent and permanent pools.	Depth to groundwater is commonly shallow. Channels are significant recharge zones. Transient, persistent or permanent shallow groundwater systems may develop beneath channels in places, as dictated by local scale geology/regolith. These may be connected with pools in some situations. Groundwater is generally fresh. Groundwater systems can be accessible to vegetation in some situations. Evaporative discharge of shallow groundwater may occur.	Inflows from up-gradient sources sustain *Eucalyptus* and *Acacia* forest and woodland vegetation communities or Tussock grasslands. Supports most of the recognised groundwater dependant vegetation communities in the central Pilbara (with the key indicator species being *Eucalyptus camaldulensis*, *E. victrix* and *Melaleuca argentea*).
		9	Lowland receiving areas - drainage termini in the form of ephemeral lakes, claypans and flats. Deep silty and clay textured soils. Variable surface salinity (resulting from evaporites). Soils may be underlain by calcrete/ silcrete hardpans of variable depth.	Inflows Ponding Infiltration Storage Soil evaporation Evapotranspiration Groundwater recharge Groundwater discharge (localised)	Drainage termini receive inflows from up-gradient drainage systems. Transient to persistent ponding may occur as dictated by flooding regimes, with spillovers possible in large flooding events. Sediment accumulation and evaporative concentration of salts.	Depth to groundwater can vary from shallow (<5 m) to deep (>20 m). Groundwater may be fresh, brackish or saline. Groundwater systems can be accessible to vegetation in some situations. Evaporative discharge of shallow groundwater may occur.	Fringed or occupied by distinctive vegetation communities such as Samphire. Regularly inundated areas may be largely devoid of vegetation. Vegetation adapted to waterlogging, flooding and salinity stressors. Potential to support groundwater dependant ecosystems (GDEs), depending on the level of surface and groundwater connectivity. However this is likely to be uncommon.

2. REGIONAL SETTING

2.1 Climate

The Pilbara region is characterised by an arid-tropical climate influenced by tropical maritime and tropical continental air masses, receiving summer rainfall. Cyclones tend to occur during the summer, bringing heavy rain and strong winds that often cause destruction to coastal and inland towns.

2.1.1 Temperature

The Pilbara region has an extreme temperature range, rising up to 50 degrees Celsius (°C) during the summer, and dropping to around 0°C in winter (Bureau of Meteorology [BOM]). The long term BOM climatic station in the EPR is that at Newman Airport (Newman Aero - Site Number 007176). Mean monthly maximum temperatures at Newman Aero range from 39°C in January to 23°C in July, while mean monthly minimum temperatures range from 25°C in January to 6°C in July (BOM, 2013). The average monthly temperatures at Newman Aero are given in Table 2.1. High summer temperatures and humidity seldom occur together, giving the Pilbara its very dry climate. Light frosts occasionally occur during the winter season.

Table 2.1: Newman - Average Monthly Temperatures (1996 – 2013)

Average Temperature	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Max [°C]	39.4	36.9	34.7	31.7	27.2	23.1	23.0	26.0	30.3	34.8	37.3	38.9
Min [°C]	24.9	23.9	21.4	17.3	11.6	6.8	6.1	7.7	11.9	17.4	20.8	23.8

2.1.2 Rainfall

The Pilbara region has highly variable rainfall, which is dominated by the occurrence of tropical cyclones mainly from January to March. Moist tropical low pressure systems that develop in the north bring substantial rainfall over wide areas. With the exception of these large events, rainfall is highly variable, and localised, and dominated by short duration high intensity thunderstorm activity. As such, rainfall from a single site is not considered representative of the spatial variability of rainfall over a wider area.

Between May and October, low pressure cold fronts move in an easterly direction across South Western Australia and can reach the Pilbara region producing light winter rains.

The Newman Aero BOM station (Station No 7176) has recorded long term rainfall data for the inland Pilbara region where the annual average rainfall is 318 mm (BOM, 2013). Annual variability is high with recorded rainfall at Newman varying between 37 mm (1996) and 619 mm (1999).

Average monthly rainfall rates for Newman Aero are shown in Table 2.2 (BOM 2013). On average the driest period for Newman Aero is July to November, with September and October historically being the driest months. On average, January and February are the wettest months.

Table 2.2: Newman Aero - Average Monthly Rainfall and Evaporation (1996 – 2013)

Average Rainfall/Evap	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Rainfall [mm]	62.7	76.3	40.1	19.4	17.1	15.2	14.8	7.5	4.4	5.6	12.3	38.0
Evaporation [mm]	461	369	343	290	174	173	199	193	264	377	424	466

The mean annual pan evaporation rate at Newman is estimated at 3,733 mm (Department of Agriculture, 1987), which exceeds mean annual rainfall by approximately 3,400 mm. Average monthly pan evaporation rates for Newman vary between a minimum of 173 mm in June and a maximum of 466 mm in December (Table 2.2).

As annual average potential is far in excess of the annual average rainfall, there is commonly a large moisture deficit in the environment. Rainfall events below a threshold of approximately 20 mm tend to be insufficient to overcome this deficit and do not generate runoff. Consequently:

- Creek flow is ephemeral.
- Diffuse recharge to the regional groundwater system occurs at very low rates.
- Groundwater recharge occurs preferentially during rainfall-runoff events along the major creeks and other areas of surface water concentration/inundation.

2.2 Climate Change

The future climate of the Pilbara has been considered in detail in the CSIRO report entitled Hydroclimate of the Pilbara: past, present and future (Charles et al., 2013). The CSIRO report explains that the fundamental scientific tool used to evaluate how the future climate will evolve in response to enhanced concentrations of atmospheric greenhouse gases is the Global Climate Model (GCM). As the name implies these simulate the Earth's climate on a global scale. The CSIRO report used GCM projections from 13 GCMs for two different emissions. A scaling approach was then applied to modify historical daily rainfall and potential evaporation data to produce data sets of how the historical data would have looked under future atmospheric conditions. The baseline period was 1961 to 2011. The climate was based on 2030 and 2050 atmospheric conditions for both low and high emission scenarios.

2.2.1 Rainfall

The climate models produced a large range of results with some models suggesting a decrease in rainfall and others an increase in rainfall. In general the high emission scenario resulted in a dryer climate when compared to the existing and lower emission scenarios. The median (between models) results showed that future climate rainfall projections do not vary by more than 5% from current levels.

2.2.1.1 Extreme Events

The CSIRO report concludes that is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged owing to greenhouse warming. Modelling which has been undertaken on Australian tropical cyclones showed an approximate 100 km southward shift in genesis and decay regions of cyclones together with an increase in the wind speed, rainfall intensity and integrated kinetic energy (a measure of TC size and wind speed). These conclusions suggest that intensity of cyclonic rainfall in the Pilbara is likely to increase. The change to thunderstorm intensity which is important for regular runoff events in smaller catchments was not assessed. The change of Intensity Frequency Duration curves under future climate scenarios is currently being studied by Bureau of Meteorology.

2.2.1.2 Potential Evaporation

The calculated changes in potential evaporation are more consistent than those obtained for rainfall as they are a function of the trend in increasing temperature projected by the GCMs, rather than the regional trend in rainfall that varies across a large range between the different GCMs. This is expected given Potential Evaporation (PE) is calculated as a function of temperature, solar radiation and relative humidity.

As would be expected, the increase in potential evaporation is higher under the higher emissions scenario. The median (between models) increase in PE is 3% and 4% for the two emissions scenario at 2030 and 5% and 6% by 2050.

2.3 Topography

The regional topography is marked by a series of east-west trending valleys and alluvial plains bounded by hills (Figure 1.1).and low lying ridges. The topography is influenced by geology and geological structure and the bounding hills tend to be low-lying and rounded where they are formed by outcrops of the Marra Mamba Iron Formation (Marra Mamba) and higher with scarp slopes where they are formed of Brockman Iron Formation (Brockman) (see Section 2.5). The highest peaks are in excess of 1000 mAHD (Mount Newman and highs of the Ophthalmia Range), while the valley floors range between 700 mAHD down to 475 mAHD.

The main drainage catchment relates to the Fortescue River covering the majority of the western and southern parts of the EPR. There are also the smaller Warrawanda, Jimblebar, Caramulla, Davidson, Homestead and Whaleback Creek catchments making up the remaining area.

2.4 Regional Drainage

The regional catchments and main river systems in the Pilbara region are shown in Figure 2.1. The EPR study catchments together with the main iron ore mine sites are also highlighted. These study catchments (Ethel Gorge, Jimblebar, Caramulla and Davidson) are located within 100 km to the east and west of Newman. A more detailed plan showing the EPR study catchments is presented in Figure 2.2.

The EPR study catchments are located within the regional Fortescue River Basin. The Ashburton River Basin and the Lake Disappointment Basin are adjacent and to the south of the EPR study catchments. The Fortescue River Basin is discussed below and hydrological details for the Upper Fortescue, Jimblebar, Caramulla and Davidson catchments are provided in Section 3.1.

2.4.1 Fortescue River Basin

The Fortescue River Basin drains west to northwest towards the Indian Ocean and has a total catchment area of approximately 50,000 km^2. The Goodiadarrie Hills located within the Fortescue Valley and on the downstream (western) end of the Fortescue Marsh, effectively separates the Fortescue River into two river systems. The Upper Fortescue River system comprises the upper portion of the Fortescue River and several large creeks including the Weeli Wolli Creek and the EPR study catchments. Ophthalmia Dam is located on the Upper Fortescue River approximately 100 km upstream from the Fortescue Marsh and 12 km east from the Newman Townsite. The lower portion of the Fortescue River, downstream from the Fortescue Marsh, drains in a general north-westerly direction to the coast.

2.4.2 Streamflow

Streamflow in the Pilbara region is directly correlated to rainfall, with the majority of streamflow occurring during the summer months of December through to March associated with the large and more intense rainfall events. Streamflow in the smaller flow channels is typically short in duration, and ceases soon after the rainfall passes. In the larger river channels which drain the larger catchments, runoff can persist for several weeks and possibly months following major rainfall events such as those resulting from tropical cyclones.

Streamflow gauging stations are widely spaced in the Pilbara region, with only two Department of Water (DoW) gauges in the EPR area, namely Newman (gauge S708011) and Ophthalmia Dam (gauge S708012). The Newman gauging station is located on the Upper Fortescue River approximately 9 km upstream (south) from the Ophthalmia Dam embankment (and gauging station) and 8 km southeast from the Newman Townsite. It records streamflow from the Upper Fortescue River catchment for the 2,822 km^2 area above the gauging station. While, the Ophthalmia Dam embankment is located 4 km upstream (south) from the upstream end of Ethel Gorge and records water levels in Ophthalmia Dam.

2.5 Geology

2.5.1 Tectonic Setting and Structure

The geology of the EPR originates in the Hamersley Basin, a late Archaean to Palaeoproterozoic platformal cover sequence of weakly metamorphosed sedimentary and volcanic rocks (spanning approximately 2,770 Ma to 2,450 Ma), unconformably overlying the mid Archaean granite - greenstone terrain of the Pilbara Craton. The Hamersley Basin sequence comprises the regionally conformable Fortescue, Hamersley and Turee Creek Groups (Kepert 2001). Within the Central Pilbara area, outcrop geology is dominated by rocks of the Hamersley Group and (to a lesser extent) the uppermost Fortescue Group that underlies the Hamersley Group.

The Hamersley Basin has been subject to a complex tectonic history. Two major orogens affected the area (the Ophthalmian Orogeny and the Ashburton Orogeny) both of which contributed, in the EPR area, to the predominant ESE-WNW striking regional synclines and anticlines and a series of more intense tighter folds and faults. These structures have influenced, that control both the outcrop geology and the topography. Re-activation of older tectonic features in the underlying Pilbara Craton caused these major folds to rise and plunge and super-imposed a dome and basin effect.

The EPR is cross cut by a series of major transverse faults (orientated noretheast-southwest) such as the Whaleback, Fortescue River and Wheelara Faults. Available water level data suggests these faults are low-permeability barriers to groundwater flow with substantial water level differences occurring either side of them over a short distance.

A series of major faults also parallel the regional strike. At the regional scale, uplift on the north-eastern side of strike parallel faults such as the Homestead Fault and Ophthalmia Fault results in repetition of the geological sequence between the Marra Mamba and Brockman on the southern flank of the Ophthalmia Syncline. This has resulted in the regional aquifer formed in the Paraburdoo Member of the Wittenoon Formation being repeated in adjacent parallel valleys.

Local thrust faulting occurred during the Ophthalmian Orogeny associated with the more intense tighter folds in the Marra Mamba in particular along its contact with the overlying Wittenoom Formation in an "older over younger" pattern. This pattern of thrusting is commonly associated with mineralisation in the Marra Mamba and movement along the thrust planes can be in the order of 200 m. Members of the Wittenoom Formation can be a major regional aquifer and the thrusting movement has bought some orebodies into direct hydraulic connection with the regional groundwater system.

2.5.2 Lithology

The outcrop geology of the EPR is shown on Figure 2.3 and is summarised in Table 2.3 along with a brief commentary on groundwater potential. Detail on the regional hydrostratigraphy is provided in Section 3.

The stratigraphic column described below has been constrained to reflect only those formations that occur within the EPR.

2.5.2.1 Basement

The formations of the Hamersley Group comprise a series of siliceous and carbonate-rich moderate-to deep-water sediments (i.e. chert and shale) that have been chemically altered and iron-enriched to form banded iron formation (BIF) and dolomite. A key occurrence of dolomite is in the Paraburdoo Member of the Wittenoom Formation which forms part of the regional aquifer where it is weathered and karstic.

Subsequent additional iron-enrichment of the BIF has formed orebodies. The Brockman and the Marra Mamba have notable occurrences of iron-enrichment and these two formations host most orebodies. There is a marked increase in both porosity and permeability associated with the mineralisation process, as such the orebodies form important aquifers.

In the south of the EPR, the Hamersley Group is absent exposing members of the Jeerinah Formation of the Fortescue Group and Archaean granite that underlies the Hamersley Group.

2.5.2.2 Tertiary Landscape

The Wittenoom Formation is less resistant to weathering than the surrounding formations and has been eroded to form the subcrop in most of the low lying areas, such as valley floors and alluvial plains. Bedrock relief has been reduced since the Tertiary by infilling with erosional detritus from the surrounding outcrop (such that the subcropping Wittenoom Formation rarely occurs in outcrop). On the margins of hills, there are colluvial deposits (scree) that fine into alluvial deposits (sand and silt) further into the valley. In places, secondary cementation and chemical alteration of these sediments has occurred forming calcrete, silcrete and pisolite. These valley fill sediments (collectively referred to as Tertiary detritals) can be in excess of 100 m thick in some places.

Weathering is often present at the contact between the Tertiary detritals and underlying basement, possibly representing a paleo-lateritic horizon and marked by a vuggy hardcap zone with interspersed pisolite or manganese deposits. This zone can be permeable and often forms part of a regional aquifer in combination with permeable units in the overlying sediments and underlying karstic Paraburdoo Member dolomite (where present).

2.5.2.3 Quaternary - Recent

Active creek channels and floodplains are infilled with recent alluvium. This ranges from silt and clay to coarse gravel and is often poorly sorted - a characteristic of the ephemeral flow regime.

In places where groundwater levels are shallow and calcrete occurs as extensive outcrops and it is possible that calcrete is still actively forming (based on the morphology of groundwater calcrete in Australia (Horwitz and Mann, 1979). In such settings, calcrete formation occurs just below the groundwater table and occurs typically over a wide area where groundwater is at shallow depth. Active calcrete formation at the watertable the overlying calcrete upwards. Ultimately, a plateau or dome of calcrete emerges, with the youngest units at its base (around the watertable). As the plateau emerges, it is dissected by streams flowing across it - as is the case with the extensive calcrete outcrop upstream of Weeli Wolli Spring. In such environments, there will be a saturated zone (of approximately 5 m to 10 m) of high permeability calcrete at the watertable forming a potential aquifer stygobiont community.

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Table 2.3: Stratigraphy of the Regional Geology

Age	Group	Formation	Member	Approx. Thickness (m)	Lithological Description	Hydrogeological Description
Cainozoic	Recent Alluvium			20	Recent sands and gravels.	Generally unsaturated but can be aquifer where occurs below watertable
	Tertiary Detritals (TD)	TD3		Less than 40	Red haematitic silt and clay, scree on valley sides.	Some aquifer potential depends on clast-size
		TD2		Less than 200	Bleached and mottled clay / channel iron deposits (CID) / calcrete / silcrete.	Aquifers in CID/Calcrete/Silcrete
		TD1		Less than 40	Magnetite and haematite dominated pisolites, red ochre detrital / scree on valley sides.	Some aquifer potential depends on clast-size
Archaean to Early-Proterozoic	Hamersley Group	Boolgeeda Iron		to 450	Fine-grained, finely laminated, dark grey-brown to black flaggy iron-formation, minor chert, jaspilite, shale	Low permeability
		Woongarra Rhyolite		to 800	Acid lavas and tuffs with interbedded iron formation.	Low permeability
		Weeli Wolli		Less than 450	Banded iron formation (BIF), shaly BIF / shale / jaspilite.	Low permeability
		Brockman Iron	Yandicoogina	60 to 70	Interbedded chert and shale locally intruded by dolerite sills.	Low permeability
			Joffre	70 to 100	BIF with minor shale bands. Major ore-host.	Aquifer potential limited to mineralised zones
			Whaleback Shale	40 to 60	Interbedded shale, chert and BIF.	Low permeability
			Dales Gorge	90 to 190	Interbedded BIF and shale. Major ore-host.	Aquifer potential limited to mineralised zones
		Mount McRae Shale		45 to 50	Graphitic and chloritic shale interbedded with BIF. (Notably Colonial Chert unit.*)	Low permeability with localised aquifers associated with Colonial Chert Member
		Mount Sylvia		15 to 20	Shale, dolomite and BIF bands. (Notably 'Bruno's Band')	Low permeability with localised aquifers associated with Bruno's Band (chert)
		Wittenoom Formation	Bee Gorge	50 to 140	Calcareous shale and dolomite.	Low permeability
			Paraburdoo	Less than 480	Dolomite – locally with karstic characteristics.	Regional aquifer in karstic zone
			West Angela	20 to 40	Shale-BIF-chert-dolomite. Locally manganiferous.	Aquifer potential in some zones assoc with manganese/dolomite
		Marra Mamba Iron	Mount Newman	65	BIF with interbedded carbonate and shale. Major ore-host.	Aquifer potential limited to mineralised zones
			MacLeod	75	BIF, chert and shale.	Low permeability
			Nammuldi	90	BIF, chert and shale.	Aquifer potential limited to mineralised zones
	Fortescue Group	Jeerinah Formation	Roy Hill Shale	to 900	Shale with some dolomitic shale. Carbonaceous and pyritic.	Low permeability, localised aquifers assoc with structure
			Warrie		Chert, quartzite, shale and jaspilite. Pyrite cubes.	Low permeability, localised aquifers assoc with structure
			Woodiana		Silicified mudstone, shale, siltstone, chert, quartzite and tuff.	Low permeability, localised aquifers assoc with structure
		Granitoid Complex			Various tonalite-trondjhemite-granodiorite-granite plutons and gneisses	Low permeability

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2.6 Landscape and Environment

2.6.1 Bioregion

The EPR Study area straddles the boundary of the Pilbara and Gascoyne bioregions as defined under the Interim Biogeographic Regionalisation for Australia (IBRA) (Figure 2.4).

Four geographically distinct biogeographic sub-regions have been recognised in the Pilbara taking into account information on geology, landform, climate, vegetation and animal communities (Pepper et al., 2013):

- Chichester sub-region encompasses the granite/greenstone terrains of the northern Pilbara Craton but also includes the Chichester Plateau of the Hamersley Basin. While the broader Chichester sub-region is characterised by deeply weathered regolith and is dominated by spinifex (Triodia spp.) grassland with irregularly scattered shrubs (shrub steppe), the Chichester Plateau (bordering the northern side of the Fortescue Valley) more closely reflects the soil landscape and vegetation of the Hamersley Plateau.
- Fortescue sub-region is delineated by the Fortescue River valley dissects. It consists of salt marshes, mulga-bunch and short grass communities, with eucalyptus (*Eucalyptus spp*.) woodlands associated with permanent springs.
- Hamersley sub-region is the most mountainous area in Western Australia, comprising of a series of topographical features (ranges, ridges, hills and plateaux) encompassing isolated and continuous chains of uplands that rise above a plateau surface (McKenzie et al., 2009). Skeletal soils have developed on the iron-rich sedimentary rocks, and generally support spinifex grassland with mulga and snappy gum (tree steppe).
- Roebourne sub-region encompasses the mudflats and low dunes of the coastal plain. It comprises alluvial and aeolian sediments, often with a cover of grasses and soft spinifex.

The northwest portion of the Study area is within the Hamersley sub-region, and the northeast portion occurs in the Fortescue sub-region.

The southern half of the Study area is within the Augustus sub-region of the Gascoyne bioregion. This is characterised by rugged, Proterozoic sedimentary and granite ranges that support mulga (*Acacia aneura* and its close relatives) woodlands and spinifex (*Triodia* spp). Broad flat valleys separate the ranges and support mulga parklands (Desmond et al., 2001).

2.6.2 Land Systems

The Pilbara has been surveyed by the Western Australian Department of Agriculture and Food (DAFWA), for the purposes of land classification, mapping and resource evaluation. The region consists of 102 land systems; distinguished on the basis of topography, geology, soils and vegetation (Van Vreeswyk et al., 2004).

The Study area has 35 land systems (Figure 2.4) with the defining characteristics being described in Table 2.4.

Van Vreeswyk et al. (2004) grouped the land systems into 20 land surface types according to a combination of more generic landforms, soils, vegetation and drainage patterns (Table 2.4). This grouping provides information more suitable for regional scale assessments and has contributed to the delineation of landscape EHUs (refer to Section 1.3 and Appendix F of the main report).

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Table 2.4: Description of Land Systems in the EPR Study area

Land system	Land surface type	Percent of Project Area	Description	Geomorphology and soils
Adrian	6	0.9%	Stony plains and low silcrete hills supporting hard spinifex grasslands.	Erosional surfaces typified by rounded hills and rises. Short drainage lines with radial patterns away from rises. Soils are stony and shallow.
Augustus	2	0.1%	Rugged ranges, hills, ridges and plateaux supporting mulga shrublands and hard spinifex grasslands.	Erosional surfaces typified by steep escarpments and upper slopes. Lower slopes and valley floors are restricted and contain tributary drainage systems. Soils are shallow and stony.
Boolgeeda	8	3.0%	Stony lower slopes and plains below hill systems supporting hard and soft spinifex grasslands and Mulga shrublands. Widespread across the Pilbara region.	Quaternary colluvium parent materials. Closely spaced dendritic and sub-parallel drainage lines. Predominantly depositional surfaces characterised by red loamy soils of variable depth.
Balfour	14	0.3%	Shale, gravel and clay plains supporting *Eremophila*/*Senna* shrublands, tussock grasslands and halophytic shrublands	Mostly depositional surfaces; level to very gently inclined stony plains on shale, level plains with gilgaied clay soils, plains with saline alluvium and sluggish drainage tracts with minor channels. A mixture of clay, loam and duplex soil types.
Cadgie	12	1.6%	Hardpan plains with thin sand cover and sandy banks supporting mulga shrublands with soft and hard spinifex.	Depositional surfaces of low relief, including washplains exhibiting sheetflow behaviour and minor drainage tracts subject to more concentrated throughflow. Soils include shallow sands and loams over hardpan, with areas of deeper sand associated with wash banks.
Calcrete	18	0.03%	Low calcrete platforms and plains supporting shrubby hard spinifex grasslands.	Tertiary calcrete formed in valley fill deposits, with minor Quaternary alluvium. Drainage is generally indistinct. Soils are mainly shallow calcareous loams (<50 cm overlying calcrete), with minor calcareous loamy earths and red shallow loams.
Charley	2	0.4%	Dolerite hills and ridges and restricted plains supporting mulga and cassia shrublands or spinifex grasslands.	Erosional surfaces including steep hills and ridges with more gently inclined footslopes, restricted areas of gently undulating lower plains and nearly flat plains. Moderately spaced tributary drainage lines. Shallow loamy soils in upper landscape areas, with loams and earths (often calcareous) on the footslopes and plains.
Collier	7	0.8%	Undulating stony uplands, low hills and ridges and stony plains supporting mulga shrublands.	Erosional surfaces including undulating stony uplands, low hills and ridges with stony lower slopes and lower plains. Generally widely spaced tributary drainage floors and channels. Shallow loamy soils in upper landscape areas, with clays and earths in lower landscape positions.
Divide	11	13.1%	Sandplains and occasional dunes supporting shrubby hard spinifex grasslands.	Depositional surfaces reworked by Aeolian processes. Drainage is generally indistinct. Soils are mainly red deep sands and red sandy earths, with occasional shallower soils overlying gravel or rock.
Egerton	5	5.1%	Dissected hardpan plains supporting Mulga shrublands and hard spinifex hummock grasslands.	Erosional surfaces, formed on Tertiary colluvium. Minor residual hardpan plains with extensive marginal dissection zones. Numerous dendritic drainage lines. Dissected slopes adjacent to major drainage lines are often calcreted. Soils are mainly red shallow loams and sands.
Elimunna	10	2.3%	Stony plains on basalt supporting sparse Acacia and Senna shrublands and patchy tussock grasses.	Mainly depositional surfaces including level to gently undulating plains with a mosaic of surface types (e.g. stony, gilgai microrelief), Wide to very wide spaced tributary drainage floors, with sluggish internal drainage patterns on gilgai plains. Mostly heavy soil types (cracking and non-cracking clays).
Fortescue	17	1.2%	Alluvial plains and flood plains supporting patchy grassy woodlands and shrublands and tussock grasslands.	Depositional surfaces associated with river channels and commonly subject to fairly regular flooding. Soils are mainly deep red/brown non-cracking clays and self-mulching cracking clays.
Jamindie	12	4.7%	Stony hardpan plains and rises supporting groved mulga shrublands, occasionally with spinifex understorey.	Depositional surfaces including non-saline plains with hardpan at shallow depth, stony upper plains and low rises on hardpan or rock. Very widely spaced tributary drainage tracts and channels. Minor stony gilgai plains, sandy banks and low rides and hills. Shallow loamy soils (often stony/gravelly) are predominant.
Jigalong	17	0.6%	Alluvial plains and flood plains supporting grassy shrublands and woodlands and halophytic shrublands.	Depositional surfaces including flood plains and alluvial plains subject to fairly regular flooding from central anastomosing channels and creeklines. Also includes slightly more elevated, less frequently flooded gravelly plains and minor gilgai plains. A mixture of clay, loam and duplex soil types.
Kunderong	not classified	0.001%	Sandstone hills and outcrop plains covered in dwarf scrub, minor hardpan plains.	Erosional surfaces including rugged sandstone hills, undulating stony plains and minor peripheral hardpan plains.
Laterite	4	0.2%	Laterite mesas and gravelly rises supporting mulga shrublands.	Erosional surfaces formed by dissected parts of the old Tertiary plateaux. Mesas and breakaways, gravelly footslopes and lower plains. Drainage tracts and floors with sluggisg drainage or sub-parallel braided creeks (frequently saline). Soils are generally shallow sands and gravels; with red/brown cracking and non cracking clays in low lying areas.
McKay	1	0.8%	Hills, ridges, plateau remnants and breakaways of meta-sedimentary and sedimentary rocks supporting hard spinifex grasslands.	Erosional surfaces with moderately spaced tributary drainage patterns incised in narrow valleys in upper parts, becoming broader and more widely spaced downstream. Soils are mainly shallow and stony.
Newman	1	7.1%	Rugged jaspilite plateaux, ridges and mountains supporting hard spinifex grasslands. Widespread across the Pilbara region.	Erosional surfaces, characterised by skeletal soils (with abundant pebbles, cobbles and stones) and frequent rock outcropping. Soils are shallow and stony.
Nirran	6	0.6%	Undulating stony plains and hills supporting hard spinifex grasslands and mulga shrublands with soft spinifex.	Erosional surfaces including low ridges and hills and undulating stony plains and interfluves. Moderately to widely spaced tributary drainage patterns are incised between interfluves and low hills, with narrow drainage floors and channels. Soils are predominantly red loamy earths.
Nooingnin	12	1.8%	Hardpan plains with very large groves and sandy banks supporting mulga shrublands and wanderrie grasses.	Depositional surfaces of low relief, including hardpan washplains subject to sheetflow with very large groves and low sandy banks. Inter-dispersed with narrow drainage zones. Shallow loamy soils occur on the hardpan plains, with deeper earths and sands in groves and banks.
Platform	5	1.1%	Dissected slopes and raised plains supporting hard spinifex grasslands.	Erosional surfaces formed by partial dissection of the old Tertiary surface. Stony upper plains are separated by closely spaced dendritic or sub-parallel drainage lines, incised up to 30 m below the surrounding land surface. Soils are mainly red shallow loams and stony types, with red loamy earths in dissection zones.

Land system	Land surface type	Percent of Project Area	Description	Geomorphology and soils
Prairie	7	17.4%	Gently undulating stony plains and granite hills supporting *Acacia*/*Eremophila*/*Senna* shrublands and minor soft spinifex grasslands.	Erosional surfaces including: low hills with rounded, boulder strewn crests and steep benched upper slopes, short gentle lower slopes, extensive gently undulating lower plains and interfluves. Moderately dense patterns of finely branching tributary drainage with narrow sandy floors and braided channels becoming sub-parallel with major channels in lower parts. Shallow sandy and loamy soils.
Robertson	1	1.9%	Hills and ranges of sedimentary rocks supporting hard spinifex grasslands.	Erosional surfaces including hills, ranges, ridges and plateaux with rounded or gently inclined boulder strewn crests, steep rocky upper slopes, more gently inclined very stony lower slopes and restricted stony plains. Widely spaced tributary drainage patterns as narrow creeklines in valleys in upper parts becoming broader drainage floors with larger channels further downslope. Shallow sandy and loamy soils.
River	17	2.2%	Active flood plains and major rivers supporting grassy eucalypt woodlands, tussock grasslands and soft spinifex grasslands.	Riverine environments subject to flooding, with generally deep soils of various texture classes.
Robe	3	0.04%	Low limonite mesa and buttes supporting soft spinifex (and occasionally hard spinifex) grasslands.	Erosional surfaces formed by partial dissection of old Tertiary surfaces. Closely to moderately spaced narrow tributary drainage floors. Soils are generally shallow and gravelly.
Rocklea	1	6.0%	Basalt hills, plateaux, lower slopes and minor stony plains supporting hard spinifex (and occasionally soft spinifex) grasslands.	Erosional surfaces including hills, ridges and plateaux remnants. Tributary drainage patterns grade into broader floors and channels downslope. Soils are generally shallow with abundant basalt cobbles.
Spearhole	12	8.2%	Gently undulating hardpan plains supporting groved mulga shrublands and hard spinifex.	Depositional surfaces including level to gently undulating plains on hardpan. Sparse patterns of tributary drainage with restricted areas of shallow valleys and finely dissected slopes. Soils are generally red brown shallow loams with hardpans, and red loamy earths.
Sylvania	10	11.3%	Gritty surfaced plains and low rises on granite supporting *Acacia*/*Eremophila*/*Senna* shrublands	Mainly erosional surfaces including level to gently undulating gritty surfaced and stony plains, low rises and occasional granitic tor heaps, sandy plains, hardpan wash plains and minor stony plains with saline soils. Widely spaced tributary drainage floors with or without channels. Mainly shallow sandy soils, with loams and duplex soils in lower landscape positions.
Table	4	0.5%	Low calcrete plateaux, mesas and lower plains supporting mulga and *Senna* shrublands and minor spinifex grasslands.	Erosional surfaces formed by dissection of the old Tertiary surface. Includes low dissected plateaux with tops up to several kilometres in extent and with numerous small drainage foci, isolated mesas, buttes and low hills with vertical breakaway faces and short lower slopes, and restricted lower calcareous plains. Moderately to widely spaced tributary and non tributary drainage floors and channels. Soils are mainly shallow loams (often calcareous).
Talga	1	1.2%	Hills and ridges of greenstone and chert and stony plains supporting hard and soft spinifex grasslands.	Erosional surfaces inlcuding hill tracts and ridges on basalt, greenstones, schist, other metamorphics and chert with rocky rounded crests and ridge tops extending for many kilometres. Very steep upper slopes, more gently inclined lower footslopes, restricted lower stony plains and interfluves. Moderately spaced tributary and strike aligned drainage floors and channels. Soils are predominantly calcareous shallow loams.
Turee	14	0.2%	Stony alluvial plains with gilgaied and non-gilgaied surfaces supporting tussock grasslands and grassy shrublands.	Mosaic depositional surfaces of low relief (hardpan, stony and gilgai plains) inter-dispersed with few drainage channels. Localised sheet flow can occur. Soils include various earths, loams and clays often with abundant surface cobbles.
Warri	18	0.6%	Low calcrete platforms and plains supporting Mulga and Senna shrublands	Depositional surfaces of low relief. Calcreted valley fills and mosaics of calcrete tables, with narrow inter-table areas. Soil types mainly include calcareous shallow loams and loamy earths. Surface mantles commonly include calcrete pebbles and fragments.
Wannamunna	12	0.4%	Hardpan plains and internal drainage tracts supporting mulga shrublands and woodlands (and occasionally Eucalypt woodlands).	Depositional surfaces including level hardpan washplains. Broad internal drainage flats with some localised, arcuate drainage foci. Soils are generally by shallow loams often with red-brown hardpans. Heavier soil types occur on drainage plains.
Washplain	12	4.0%	Hardpan plains supporting groved mulga shrublands.	Depositional surfaces including alluvial level hardpan plains. Discrete drainage foci associated with groved vegetation, with some drainage tracts receiving more concentrated flow. Soils are generally deep duplex types, and red loamy earths; commonly with hardpans at depth.
Zebra	12	0.4%	Hardpan plains with large linear gravelly sand banks supporting acacia shrublands with soft and hard spinifex.	Depositional surfaces including level alluvial hardpan plains subject to overland sheet flow, linear sandy banks extending up to several kilometres and arranged with long axes at right angles to direction of sheet flow, and minor gravelly plains and occasional groves. No channelised drainage. Generally red loamy soils with some read loamy earths.

2.6.3 Vegetation and Flora

The EPR Study area is situated within the Fortescue Botanical District of the Eremaean Botanical Province, as described by Beard (1975; 1990). The vegetation of the Fortescue Botanical District is typically open and dominated by spinifex, *Acacia* small trees and shrubs, and occasional Eucalypts. Major plant families represented include Fabaceae (Acacia spp.), Myrtaceae (*Eucalyptus* spp.), Scrophulariaceae (*Eremophila* spp.), Chenopodiaceae (Samphires, Bluebushes, and Saltbushes), Asteraceae (Daisies) and Poaceae (Grasses).

The broad scale vegetation associations mapped by Beard (1975) within the Study area are summarised in Table 2.5 and spatially depicted in Figure 2.5.

Table 2.5: Description of vegetation association in the EPR Study area mapped by Beard (1975)

Vegetation Association Reference	Percent of Study area	Description
18	12.9%	Low woodland; mulga (*Acacia aneura* and its close relatives).
28	0.4%	Open low woodland; mulga.
29	26.9%	Sparse low woodland; mulga, discontinuous in scattered groups.
39	0.1%	Shrublands; mulga scrub
82	15.7%	Hummock grasslands, low tree steppe; snappy gum over *Triodia wiseana.*
111	9.2%	Hummock grasslands, shrub steppe; *Eucalyptus gamophylla* over hard spinifex.
117	0.2%	Hummock grasslands, grass steppe; soft spinifex
157	0.7%	Hummock grasslands, grass steppe; hard spinifex, *Triodia wiseana*.
166	0.1%	Low woodland; mulga and *Acacia victoriae.*
175	1.4%	Short bunch grassland - savannah/grass plain (Pilbara).
178	0.3%	Hummock grasslands, grass steppe; hard spinifex, *Triodia basedowii.*
199	1.5%	Hummock grasslands, shrub steppe; mulga over soft spinifex on rises.
216	30.6%	Low woodland; mulga with spinifex on rises.

McKenzie et al. (2009) more recently synthesised the broad patterns of vegetation in the IBRA Hamersley and Fortescue sub-regions of the Pilbara bioregion. Their findings relevant for the Study area are summarised as follows:

Hamersley

- On mountain summits, the vegetation is characteristically shrub mallee (*E. kingsmillii, E. ewartiana, E. lucasii*) with emergent snappy gum or iron bloodwood (*Corymbia ferriticola*) over shrubs (*Acacia arida, Gastrolobium grandiflorum, Hibbertia glaberrima, Daviesia eremaea*) and hard spinifex (*Triodia brizoides*).
- The rolling hills and stony plains support an open woodland of snappy gum (*Eucalyptus leucophloia*) over low shrubs (*Acacia bivenosa*, *A. ancistrocarpa*, *A. maitlandii*, *Keraudrenia* spp.) and hard spinifex (*T. wiseana, T. basedowii, T. lanigera*), with upland drainage features supporting slightly denser vegetation mostly comprising wattle shrubs with some Pilbara bloodwood (*Corymbia hamersleyana*). Shrub mallee (*Eucalyptus gamophylla*, *E. trivalva, E. socialis* subsp. *eucentrica, E. striaticalyx*) over tea tree (*Melaleuca eleuterostachya*) and hard hummock grasses (*T. basedowii, T. longiceps, T. angusta*) are also a common community on stony plains and rolling hills, particularly on calcareous pediments.
- The ironstone and basalt ridges, ranges and hills of the sub-region are dominated by snappy gum woodlands over shrubs (*Acacia hilliana, A. adoxa, Gompholobium karijini, Mirbelia viminalis*), tussock grasses (*Amphipogon carinatus, Cymbopogon* spp.) and hard spinifex (*T. wiseana, T. basedowii*). Various eucalypt mallee species (*E. gamophylla, E. pilbarensis, E. trivalva*) may also be common on the slopes.

- Run-on, water-gaining slopes and bajadas (coalescing alluvial fans) above detrital banded ironstone deposits and valley-fills support a cover of Acacia woodland and shrubland dominated by mulga (*A. aneura* s.l., *A. ayersiana, A. minyura*) over an understorey of open shrubs (*Ptilotus obovatus*, *Rhagodia eremaea*, *Senna glutinosa*) and tussock grasses (*Chrysopogon fallax*, *Eragrostis* spp., *Eriachne* spp).
- The small drainages are dominated by emergent Pilbara bloodwoods, Pilbara box (*Eucalyptus xerothermica*), western coolibah (*Eucalyptus victrix*) with Acacia (*A. maitlandii, A. monticola, A. tumida var. pilbarensis, A. ancistrocarpa*) shrubland over hard and soft hummock grasses (*T. wiseana, T. pungens*) and occasional tussock grasses (*Themeda* spp.) depending on landscape position.
- The large channels contain extensive alluvium and fine depositional deposits and support a fringing riparian open tall woodland of river red gums (*Eucalyptus camaldulensis*) and western coolibahs over woodlands or tall shrublands of Pilbara jam (*Acacia citrinoviridis*), slender petalostylis (*Petalostylis labicheoides*) and weeping wire wood over soft hummock grasses (*T. pungens, T. epactia*) and tussock grasses such as Buffel Grass, Kangaroo Grass and Silky Browntop (*Eulalia aurea*).
- In sites where the drainage is interrupted and the watertable is shallow, extensive silver cadjeput (*Melaleuca argentea*) forests with red river gums and western coolibah woodlands over native cotton (*Gossypium* spp.) and sedgelands of stiffleaf sedge (*Cyperus vaginatus*) may exist.
- Internal drainage basins (e.g. Lake Robinson, Munjina Claypan and the Mt Bruce, Coondewanna and Wanna Munna Flats) generally support extensive tall to low mulga woodland with scattered emergent Pilbara box over bunch grasses (*Aristida* spp., *Eriachne* spp) on fine textured soils. The basement sump of such internal drainage basins is usually dominated by woodlands of western coolibah over tussock grasses (*Themeda triandra*, *Eulalia aurea, Eragrostis* spp., *Eriachne* spp., *Chrysopogon fallax*) or lignum and swamp grass.
- On very flat pediments, well-developed grove-intergrove mulga woodlands may exist with emergent western gidgee (*Acacia pruinocarpa*) and a suite of mulga allies (*A. paraneura, A. ayersiana, A. aneura* var. intermedia, *A. aneura* var. *macrocarpa*, *A. aneura* var. *ilbarana*). These are also termed banded mulga formations.

Fortescue

- Aeolian sandplains occasionally with small dunes support open mulga, Pilbara box (*Eucalyptus xerothermica*), northwest box (*E. tephrodes*) or desert bloodwood (*Corymbia deserticola*) woodlands with some blue-leafed mallee (E. gamophylla) over soft hummock grasses (*Triodia pungens*, *T. melvillei*). Low scrub and heath comprising conspicuous sandy desert floral elements (*Grevillea juncifolia*, *G. eriostachya, Kennedia prorepens*, *Leptosema chambersii*, *Diplopeltis stuartii*) persist in the dune areas.
- Bajadas and hardpan plains in the east of the sub-region are typically covered by low woodlands of mulga (*Acacia aneura* and its close relatives) over open shrubs (*Eremophila forrestii, E. cuneifolia, E. lanceolata*) and scattered hummock grasses. Herbs (e.g. *Ptilotus exaltatus, P. auriculifolius, P. helipteroides*) are abundant in season.
- Bajadas and hardpan plains in the south of the sub-region include open mulga woodlands (*Acacia aneura* and its close relatives, *A. pruinocarpa*) and snakewood shrublands over tussock grasses (*Eragrostis* spp.) or open hummock grasslands (*Triodia wiseana*, *T. melvillei*).
- Flood-out zones associated with the sluggish dendritic drainage lines and foci of the upper branches of the Fortescue River and its tributaries (e.g. Jigalong and Jimblebar Creeks) support woodlands of Western Coolibah, Western Ghost Gum (*Corymbia candida*), Whitewood (*Atalaya hemiglauca*), mulga, weeping wire wood (*Acacia coriacea* subsp. *pendens*) and *A. distans* over tussock grasses (**Cenchrus ciliaris, Eragrostis benthamii, Eulalia aurea*) and herbs (*Calotis multicaulis, Ptilotus helipteroides, P. gomphrenoides*).

Over the past decade BHP Billiton Iron Ore has completed more detailed vegetation surveys, mostly in mountainous areas proximal to the Ophthalmia Range and in the vicinity of Ethel Gorge (Figure 2.5). In addition to providing greater detail on vegetation floristic and species distributions more generally, this mapping has spatially delineated vegetation units including the potentially groundwater dependent species *Eucalyptus camaldulensis* and *E. victrix*. These species are associated with the River Land System and also some of the major drainage lines feeding into the River Land System.

Populations of the declared rare species *Lepidium catapycnon*, which is listed under State and Commonwealth legislation, have been recorded in upland areas west of Newman. Several priority listed flora as recognised by the Department of Parks and Wildlife have also been recorded in various environmental settings within the Study area.

A number of invasive introduced species occur in the Study area. Of these the perennial grass Buffel is notable due to its propensity to rapidly colonise alluvial surfaces via river systems and displace indigenous shrub and grass cover.

2.6.4 Terrestrial Fauna

The fauna of the Pilbara region is typified by arid-adapted vertebrates, with generally extensive regional distributions. Many species tend to have affinities with land surface substrates and vegetation structure. Climatic variables tend to have a weaker influence on species distributions. Informed by land system mapping and previously completed fauna surveys in sections of the Study area, the major habitat types can be characterised as follows:

- Mountainous rugged terrain associated with the major peaks and ranges (e.g. Ophthalmia Range, Western Ridge, Robertson Range, hills and ridges south of Jimblebar).
- Rolling hills and foothills around the peripheries of the major peaks and ranges.
- Aeolian sandplains supporting spinifex grasslands principally associated with the Divide Land System.
- Stony plains and granite hills supporting *Acacia*/*Eremophila*/*Senna* shrublands, principally associated with the Prairie Land System.
- Broad valleys and plains supporting mulga woodlands and scrublands, mainly west of the Upper Fortescue River.
- The major drainage systems and floodplains, featuring riparian Eucalypt woodlands. These are principally associated with Upper Fortescue River and lower sections of its tributaries (Western Creek, Spearhole Creek, Warrawanda Creek/Sylvania Creek, Shovelanna Creek), and also the major creek systems further east (Jimblebar Creek, Caramulla Creek, Thirteen Creek and Jigalong Creek).

The existing conservation reserve system in the Pilbara includes examples of a wide variety of the sandy, clayey and rocky substrates and geomorphic units that characterise the Pilbara (McKenzie et al., 2003). With respect to the habitats of the Study area, these reserves provide suitable habitat for many of the Pilbara's recorded vertebrate species and are generally considered provide adequate habitat to ensure species persistence with appropriate management (e.g. Gibson and McKenzie 2009, Burbidge et al 2010, Doughty et al., 2011). However, riparian vegetation has been noted to support distinctive bird assemblages and may require special conservation attention (Burbidge et al. 2010). The richest microbat assemblages are associated with well-developed riparian environments including complex vegetation structures and permanent pools set in cavernous landscapes (McKenzie and Bullen, 2009). Two microbat species (*Nyctophilus bifax* and *Chalinolobus morio*) are considered to be restricted to productive riparian environments.

A number of fauna of elevated conservation significance, including those listed under State and Commonwealth legislation, are known from the Study area. Several species have an association with wetland habitats including:

- Pilbara Olive Python (*Liasis olivaceus barroni)* - occurs in rocky areas, showing a preference for habitats near water in particular rock pools.

- Orange Leaf-nosed Bat (Pilbara form) (*Rhinonicteris aurantius*) - utilises deep caves offering suitable humidity and a stable temperature. In the Pilbara, this species is thought to be restricted to caves where at least semi-permanent water occurs nearby.

Migratory wetland birds – utilise significant water bodies associated with major drainage systems and lakes. Examples include the Great Egret (*Ardea modesta*), Cattle Egret (*Ardea ibis*) and Eastern Osprey (*Pandion cristatus*).

2.6.5 Subterranean Fauna

The Pilbara is a global "hotspot" for stygofauna diversity (Halse et al., 2014). There is evidence that the aridification of Australia during the late Miocene contributed to the descent of terrestrial invertebrates into subterranean environments, based on affinities that many Pilbara stygofauna species have with tropical fauna lineages (Humphreys, 2001; Guzik et al., 2010). Subsequent erosion and other landscape formation processes have separated and/or isolated some aquifer environments resulting in promoted speciation. This can predispose some species to restricted geographic distributions. Owing to their requirement for permanent groundwater and their ancient origins, the presence of stygofauna may indicate the long term presence of groundwater (Humphreys, 2006).

Stygobitic species are obligate groundwater inhabitants and have the potential for restricted geographical distributions, depending on the extent and connectivity of groundwater systems in which they occur. They may be classified as Short Range Endemic species (SREs), where confined to a particular aquifer system that can act as a subterranean island. In the Pilbara ostracods are the dominant stygofaunal group in terms of both species richness and animal abundance. Other major groups include copepods, amphipods and oligochaetes.

A variety of factors influencing the diversity and distribution of stygofauna at a range of habitat and temporal scales have been identified (Hancock et al., 2005; Boulton, 2000). Some of the more influential factors at the microhabitat (sediment) scale include interstitial pore size, inflow rates of energy resources (e.g. organic carbon, biofilm growth, prey), and water quality parameters such as water temperature, pH, salinity, dissolved oxygen, and organic carbon levels.

At the mesohabitat (catchment) scale, factors include flow patterns along a water course influencing zones of upwelling and downwelling of energy resources or dissolved oxygen according to geomorphological features, as well as interactions with riparian and parafluvial sediments (Boulton et al., 1998).

A feature of the Pilbara is that stygofauna occur across most landscapes and lithologies, often where the depth to groundwater is considerable, although, typically, lower capture rates are associated with depth to groundwater of more than 30 m.

Porous and karstic aquifers (alluvium and calcrete in the Pilbara) often have greater species diversity and abundance (Maurice and Bloomfield, 2012). Heterogeneity of habitat and water chemistry within groundwater systems may give rise to distinct stygofauna assemblages, reflecting different habitat and water chemistry conditions (Hahn and Fuchs, 2009; Maurice and Bloomfield, 2012).

Nine areas of high stygofauna richness have been identified in the Pilbara, where some protection of stygofauna values may be warranted if not already in place, (Halse et al., 2014). One of these, the Ethel Gorge TEC, occurs within the Study area.

2.6.6 Ecological Assets

The Study area does not include any areas with conservation management tenure. Karijini National Park is the nearest conservation area, located approximately 33 km to the west of the Study area.

The Study area contains the Ethel Gorge Aquifer Stygobiont Community TEC. Further information on the TEC is provided in Section 4.2.

2.7 Water Use

There are no permanent surface water resources sufficient to meet mine water requirements and all water use is supported by groundwater abstraction. Ophthalmia Dam forms a semi-permanent surface water body and has resulted in an increase in the duration and frequency of surface water presence. However, the dam is used to enhance recharge to the groundwater system to indirectly support water supply and is not used directly for water supply itself.

Originally, groundwater abstraction was solely used in mining operations (dust suppression and ore processing) and for the Newman town water supply scheme. Such abstraction is demand driven. More recently, deposits have been mined below the watertable and abstraction has occurred to dewater the ore. Abstraction volumes are driven by dewatering requirements, regardless of whether there is a subsequent use for the abstracted water.

Figure 2.6 illustrates water supply abstractions. Abstraction has occurred from the following key borefields:

- Ophthalmia Borefield (E/K/H Line Bores). These bores targeted the alluvial aquifer on the floodplains of the Fortescue River and Homestead Creek. Abstraction from this borefield formed the original water supply for the Study area. Abstraction peaked around 1980 at approximately 18,000 kL/d. At this level of abstraction, groundwater levels were in decline and questions over sustainability prompted the construction of Ophthalmia Dam to augment recharge to the aquifer. Abstraction from this borefield has declined since as other water sources have been developed. Notwithstanding, the borefield is still the primary water source for Newman.
- Whaleback Water Supply and Dewatering Borefields. Water supply to Whaleback mine is augmented by local bores. However, from the early 1980s dewatering investigations were underway. Dewatering commenced in 1985 and increased to approximately 10,000 kL/d by 2000.
- OB18 and Jimblebar water supply borefields. Mining progressed eastwards from Whaleback, initially to the Shovelanna area where operations were supported by abstraction from the OB18 borefield. This borefield targets a combination of the Tertiary detrital/dolomite and Marra Mamba aquifers. More recently mining has started in the Jimblebar area and water supply abstraction started again from Tertiary detrital/dolomite and orebody aquifers. Abstraction from both borefields has been in the order of 2,000 kL/d to 3,000 kL/d. However, several deposits in this area will go be mined below the watertable and abstraction will increase once dewatering starts; this increase has been observed at Jimblebar since 2010.
- OB23 and OB25 Borefields. Dewatering started at OB23 and OB25 in 2006 with abstraction from a combination of the orebody and adjacent alluvial aquifer. Dewatering requirements have been large at over 30,000 kL/d in combination.

The large dewatering requirements at OB23 and OB25 resulted in a water surplus from 2010. Excess water was returned to the alluvial aquifers of the Fortescue River floodplain by infiltration through Ophthalmia Dam and associated downstream infiltration ponds.

3. REGIONAL HYDROLOGY

3.1 Surface Water

3.1.1 Setting and Key Features

3.1.1.1 General

The EPR orebodies are located within the Upper Fortescue River Upper catchment which drains into the eastern end of the Fortescue Marsh, as shown in Figure 2.1. The Fortescue River is the main drainage outlet with its main tributaries including the Whaleback, Homestead, Warrawanda, Shovelanna, Jimblebar, Caramulla and Davidson Creeks. These creek systems are discussed in subsequent sections.

In common with most natural drainage systems in the Pilbara region, the Upper Fortescue River catchment contains ephemeral drainages that flow in direct response to rainfall. Streamflow mainly occurs during the summer months of December through to March being associated with the large and more intense rainfall events. Streamflow in the smaller flow channels is typically short in duration, and ceases soon after the rainfall passes. In the larger river channels which drain the larger catchments, runoff can persist for several weeks and possibly months following major rainfall events such as those resulting from tropical cyclones.

In arid and semi-arid zones, such as the Pilbara, surface runoff is typically generated when the rate of rainfall exceeds the infiltration capacity of the ground causing overland flow. This is termed "infiltration excess" runoff. Surface runoff can also be generated from soils already saturated to the surface where additional rainfall becomes overland flow. This is termed "saturation excess" runoff. Although not known to be present in the EPR Study area, another mechanism for surface runoff generation is by groundwater flowing to the surface (e.g. Weeli Wolli Spring). Similarly surface runoff could be lost from a catchment by interception, infiltration and evaporation.

All of these runoff generation and loss processes could be active at the same time within the one catchment depending on rainfall intensity/duration, as well as the variable catchment conditions including surface topography, areal extent, hydrogeology, soil type, soil depth, antecedent soil moisture status and vegetation conditions.

Four broad types of landscape units that influence surface runoff can be defined (refer Table 1.2) and all four may be present in the larger catchments:

- Upland Source Landscape Units where runoff is generated.
- Upland Transitional Landscape Units where runoff is both generated and concentrated into drainage channels.
- Lowland Transitional Landscape Units where the drainage is poorly organised or comprises complex redistribution patterns.
- Lowland Receiving Landscape Units where runoff is directed into major surface water features and dissipated.

Upland Landscape Units are characterised as rocky upland areas with shallow stony soils and steep slopes. In these low infiltration areas, runoff will be generated following a relatively low rainfall event and drainage is typically characterised by short-distance overland flow towards many small gullies.

The Upland and Lowland Transitional Landscape Units are characterised by several land-systems including stony slopes lying below the steeper upland landscape units; stony plains comprising gently sloping colluvial and alluvial plains extending across the valley; and ephemeral drainage channels through the stony slopes and plains. Drainage occurs as sheetflow and channel flow into larger drainage channels.

Receiving Landscape Units comprise a variety of land-systems and may include clay pans characteristic of internally draining playas; river channels and floodplains; and expansive areas of calcrete. Drainage is also as varied as the land-systems with overland sheetflow and inundation in the playas, and well defined channels and floodplains along the river systems with runoff dissipated by infiltration, evapotranspiration and flow downstream.

3.1.1.2 Fortescue River System Upstream from Ethel Gorge

Introduction

Ethel Gorge is located on the Fortescue River where it cuts through the Ophthalmia Range, approximately 15 km northeast from Newman and approximately 100 km upstream from where it enters the Fortescue Marsh. Several creek systems drain into the Fortescue River upstream from Ethel Gorge with the main creek systems comprising Homestead Creek, Whaleback Creek, Shovelanna Creek and Warrawanda Creek, as shown in Figure 2.2.

Prior to passing through Ethel Gorge, the main Fortescue River together with the Whaleback and Warrawanda Creeks discharge into Ophthalmia Dam and only when full would surface runoff overflow the dam and discharge downstream through Ethel Gorge. Immediately upstream from Ethel Gorge but downstream from Ophthalmia Dam, Homestead Creek and Shovelanna Creek enter the Fortescue River. The Jimblebar, Caramulla and Davidson Creeks drain into the Fortescue River downstream from Ethel Gorge (upstream from Fortescue March). These three creek systems are discussed separately.

Upstream from its entry into Ethel Gorge, the Fortescue River has a total catchment area of almost 4,900 km^2 as detailed in Table 3.1. Catchment areas for the main contributing creek systems entering the river are also provided in Table 3.1. In comparison, the catchment area upstream from Ophthalmia Dam is 4,319 km^2 which represents 89% of the total catchment upstream from The Gorge.

Table 3.1: Catchment Areas

Catchment	Area (km^2)
Fortescue River Upstream from Ophthalmia Dam	2,889
Warrawanda Creek Upstream from Ophthalmia Dam	1,225
Whaleback Creek Upstream from Ophthalmia Dam	205
Total Catchment Area Upstream from Ophthalmia Dam	4,319
Shovelanna Creek Upstream from Ethel Gorge	248
Homestead Creek Upstream from Ethel Gorge	305
Total Catchment Area Upstream from Ethel Gorge	**4,872**

The EPR orebodies and existing mine areas located in the Upper Fortescue River catchment are shown with respect to a topography plan in Figures 3.1 and 3.2. These show the catchment and sub-catchment boundaries and the main drainage corridors with respect to the orebody outlines. The existing flood control diversions on Whaleback Creek have also been shown upstream of the railway loop adjacent to the stockpile area.

Fortescue River

Within Ethel Gorge, the Fortescue River has a wide; semi braided sandy gravel bed of variable width, typically approximately 100 to 200 m wide though maybe wider in places, and has variable bank heights, typically approximately 1 to 2 m. This river section has an average bed slope of approximately 0.2%, however both upstream and downstream from The Gorge the Fortescue River has a slightly lesser gradient. The upstream average gradient is approximately 0.15% and downstream the average gradient reduces to approximately 0.1% as the river channel approaches the Fortescue Marsh.

With its natural flow regime, the Fortescue River main channel carries low to medium flows, and large flood flows tend to overtop the banks into the adjacent floodplains, which is typical for the Pilbara river systems. Within Ethel Gorge, the river bed comprises sandy gravels, as shown in Plate 3.1, indicative of moderate flow velocities, whereas the floodplains comprise sands and silts indicative of slower flow velocities. Bands of eucalypt trees are supported within the river bed (Plate 3.1) as well as along its banks and floodplain zones.

The BHP Billiton Iron Ore Jimblebar railway crosses the Fortescue River just upstream from Ethel Gorge and a bank of culverts carries the railway over the main river channel. These culverts appear to have a limited discharge capacity and major floods can overtop the railway embankment as evident by the debris along the railway corridor.

Ophthalmia Dam, constructed on the Fortescue River approximately 4 km upstream from its entry to Ethel Gorge, captures runoff from the main Fortescue River and from its tributaries Warrawanda and Whaleback Creeks. Only when full will surface runoff overtop the dam and discharge downstream through The Gorge.

Upstream from Ethel Gorge, the main Fortescue River channel extends southwards approximately 60 km to its catchment divide with the Ashburton River Basin. Average gradients along the upstream river sections are still rather modest at approximately 0.2%. Aerial photography indicates that the upstream river channel is well-defined, has a slightly braided alluvial bed typically approximately 100 m wide and supports eucalypt trees along its braided sections and over bank zones.

The Western and Spearhole Creeks are major tributaries which enter the Fortescue River approximately 25 km upstream from Ethel Gorge. These creeks drain an area extending approximately 50 to 100 km to the west and form a significant portion of the Fortescue River catchment. In a similar manner as the Fortescue River main channel, the average main channel gradients along the middle river sections are still rather modest at approximately 0.2%, and aerial photography indicates that the main channels are well defined and have slightly braided and meandering alluvial beds. The Spearhole Creek has the larger catchment and larger main channel width with a typical main bed width approximately 50 m as compared with 20 m for Western Creek. The creeks support eucalypt trees along their braided sections and over bank zones, which become sparse with distance upstream. The upstream ends of the Western Creek branches become rather steep and incised where they drain a part of the Ophthalmia Range.

Warrawanda Creek

The Warrawanda Creek has a catchment area of 1,225 km^2 and naturally merges into the Fortescue River just upstream from Ethel Gorge. With the construction of Ophthalmia Dam, runoff from these two drainage systems now combines within the dam storage area. The Warrawanda Creek catchment has very similar topographic features as the main Fortescue River. Upstream from The Gorge, the Warrawanda Creek extends southwards approximately 55 km to its catchment divide and has an average bed gradient approximately 0.2%. Aerial photography indicates that the main creek channel is well defined, has a slightly braided alluvial bed typically approximately 200 m wide in its downstream reaches and approximately 50 to 100 m wide in its upstream reaches. Southeast from Ophthalmia Dam, in places the divide between the Warrawanda Creek and Shovelanna Creek catchments is relatively flat and not well defined. The Warrawanda Creek supports eucalypt trees along its braided sections and over bank zones. Sylvania Creek is a tributary which enters Warrawanda Creek from the east.

Whaleback Creek

The Whaleback mining area and Newman townsite are located within the Whaleback Creek catchment which drains into the Fortescue River near the upstream edge of the Ophthalmia Dam storage area. Whaleback Creek has a main channel length of approximately 30 km and a catchment area of 205 km^2. For the initial approximately 20 km upstream from its confluence with the Fortescue River (through the Whaleback mining zone), Whaleback Creek's main channel has an average gradient of approximately 0.3%, typical bed widths of 10 to 20 m and typical bank heights of 1 to 2 m. Further upstream, the main creek channel gradually becomes steeper and bed width narrows.

Whaleback Creek has been partially impacted by developments associated with the Whaleback mining zone and Newman townsite. Several railway and road bridges have been constructed over the creek and flood control diversions have been installed through the Newman Hub stockyard area, upstream from the railway loop to confine the creek.

Two main tributaries drain into Whaleback Creek. The northern tributary drains the area north from the main Whaleback mining zone and is often referred to as Power Station Creek. The southern tributary drains the Western Ridge area and is often referred to as Southern Creek. Both these tributaries have similar channel characteristics as the corresponding sections of Whaleback Creek.

Within the Whaleback Creek main channel, bed materials are dominated by cobbles around the OB35 Project area decreasing to sand and gravel as the creek approaches Ophthalmia Dam. A photograph of the Whaleback Creek channel bed near OB30 is shown in Plate 3.2. Within Southern Creek, the main channel bed materials vary between sand to cobbles in the downstream reach changing to silt and sand with distance upstream.

Due to climatic conditions, the creek is ephemeral with typically one to three flow events per year. These events are usually short, with little post-rainfall flow persistence.

Ophthalmia Dam

Ophthalmia Dam located on the Fortescue River 4 km upstream from Ethel Gorge was installed in 1981 to capture surface water runoff for subsequent slow release to replenish the downstream alluvial and calcrete aquifers. These aquifers support the Ophthalmia Borefield that previously supplied potable and process water to Newman. The main dam embankments and spillways extend for approximately 5 km across the Fortescue River valley but only hold a peak effective water storage depth of approximately 4.5 m. Hence these embankments create a wide but shallow water storage. Leakage through the valley storage floor has been sufficient to maintain the downstream aquifers without the need to manually release water from the dam to directly recharge the aquifers via purpose built recharge basins located downstream within the original Fortescue River main channel.

When at full storage level, Ophthalmia Dam has a capacity of 31 gigalitres (GL) and a surface area of 16 km^2. Large areas of eucalypts are supported in the floodplains upstream from the dam and along the original river channels and floodplains downstream from the dam. A photograph of Ophthalmia Dam overflowing is given in Plate 3.3.

The dam receives streamflow from the Fortescue River, Warrawanda Creek and Whaleback Creek which have a combined catchment area of 4,319 km^2 (based on updated catchment mapping). Large flood events fill the storage and when full, runoff overtops the service spillway and discharges via the original Warrawanda Creek main channel towards Ethel Gorge. Ophthalmia Dam also has an auxiliary and a fuse plug spillway to cater for extreme flood events. DoW gauging stations have been installed to record the Fortescue River discharges just upstream from the dam since 1980 and water levels in the dam storage since 1981.

In recent years, surplus dewatering from OB25 has been discharged to the dam, the dam forms part of an integrated surplus water management option for EPR.

Shovelanna Creek

Immediately upstream from Ethel Gorge but downstream from Ophthalmia Dam, the Shovelanna Creek enters Fortescue River from the southeast. Shovelanna Creek has a main channel length of approximately 35 km and a catchment area of 248 km^2. For the first 10 km upstream from its confluence with the Fortescue River, Shovelanna Creek typically has an average gradient of approximately 0.15%, a bed width of 10 to 20 m and bank heights of 1 to 2 m. Further upstream, the creek becomes slightly steeper with average gradients 0.2% to 0.25% and the bed widths increase to 50 to 100 m. The main channel of Shovelanna Creek mostly comprises sands and supports eucalypt trees on its bed and banks which gradually become more scattered with distance upstream. A creek bed photograph taken approximately 15 km southeast from Ophthalmia Dam is shown in Plate 3.4.

Homestead Creek

Homestead Creek drains a catchment area of 305 km^2 and enters the Fortescue River just upstream from Ethel Gorge and downstream from Ophthalmia Dam. Drainage from the existing OB25 and OB23 mining areas discharges into the creek's downstream section. The creek crosses the main Newman railway via a bridge and the new OB24 railway via a bank of culverts.

The creek has a well-defined main channel with a length of approximately 45 km to the western catchment boundary. For the first 10 km upstream from its confluence with the Fortescue River, Homestead Creek has an average gradient approximately 0.2%, a bed width of approximately 10 m and bank heights of 1 to 2 m. Further upstream, the creek becomes slightly steeper with average gradients of 0.3% to 0.4% and bed widths increase to typically approximately 20 m though wider in places. The upstream creek branches become rather steep and incised where they drain a section of the Ophthalmia Range.

The main channel and its main branches have gravelly sand beds with some areas of cobblestones, and support scattered eucalypt trees on their banks, as shown in Plate 3.5. These trees become sparser with distance from the downstream confluence. In common with all Pilbara creek systems, during major flood events floodwaters will overflow the main creek and tributary channels into the surrounding floodplains.

3.1.1.3 Jimblebar Creek Catchment

Several EPR orebodies are located within the Jimblebar Creek catchment including the existing active mining areas at OB18 and Wheelarra Hill.

Jimblebar Creek is located within the Fortescue River Upper catchment and is a major ephemeral tributary. It merges into the Fortescue River approximately 50 km southeast from where the Fortescue River discharges into the eastern end of the Fortescue Marsh. In the merger zone between Jimblebar Creek and Fortescue River (Figure 2.2), natural ground levels are extremely flat (less than 0.1%) and the main flow channels become braided and less defined. The Caramulla and Jigalong Creeks also merge in this same general area. Flood discharges from these main river/creek systems tend to disperse into a wide floodplain and travel via smaller flow channels and as overland flow. Mapping indicates that this floodplain is potentially 10 to 20 km wide.

Upstream (south) from the creek confluence and through the EPR area, Jimblebar Creek has a more defined main channel as shown in Figure 3.2. Jimblebar Creek and its main branches have gravelly sand beds and support scattered eucalypt trees on their banks. Through the Hashimoto ridgeline, Jimblebar Creek has cut a gorge and is confined within an alluvial bed width of approximately 30 m with relatively narrow floodplains. Flood discharges through the gorge zone would have a locally higher velocity and a natural large erosion pool (Innawally Pool) has formed downstream of the gorge.

Upstream from Innawally Pool, Jimblebar Creek has a catchment area of approximately 348 km^2 which is approximately equally split between two main branches unofficially known as Jimblebar Creek West Branch and Jimblebar Creek East Branch. These branches join just upstream from the gorge, and prior to joining, these two branches both have a partially braided main channel over 50 m wide with typically 1.0 to 1.5 m bank heights and average gradients of approximately 0.2%. A typical view of the Jimblebar Creek West Branch upstream of the junction is shown in Plate 3.6.

The existing Wheelarra Hill and the planned Jimblebar South orebodies are predominantly located in the Jimblebar Creek West Branch catchment. Copper Creek, a tributary to the Jimblebar Creek West Branch passes through this orebody area. Although Copper Creek has a similar bed gradient to Jimblebar Creek West Branch, it has a less defined main channel, as shown in Plate 3.7.

The northern side of Wheelarra Hill and general OB18 mining area drains into a catchment unofficially named OB18 catchment. This catchment discharges into Jimblebar Creek approximately 4 km downstream of Innawally Pool and drains an area of approximately 78 km^2. Within the OB18 catchment, drainage flows eastwards along the valley floor which is relatively wide and without a defined main flow channel, except towards its downstream end near Jimblebar Creek where the main channel becomes better defined.

Innawally Pool

Innawally Pool is located in the Jimblebar Creek main channel and receives runoff from the upstream creek system and from some minor local drainage lines. Following the March 2009 flood event on Jimblebar Creek, Innawally Pool was observed at its maximum capacity, as shown in Plate 3.8. When full, the pool is approximately 1 km long and of variable width, although approximately 40 m in the central zone. The maximum pool depth is believed to be approximately 2 to 3 m and eucalypt trees line its banks. Anecdotal information indicates that the pool is semi-permanent and holds water for many months following a runoff event. Regional groundwater levels under the Hashimoto ridgeline are at a depth of approximately 50 m below the base of Innawally Pool. This suggests that Innawally Pool is a perched water feature and not connected with the regional watertable.

During 2012, monitoring of the pool water level and conductivity was undertaken. Monitoring started after a flood event in March 2012 and found that the pool water level fell from being full to a relatively stable lower level (approximately 0.8 m lower) over three months giving an initial average water level decline of approximately 9 mm/d (RPS Aquaterra 2013). This decline is around twice the May to June average evaporation rate for an open storage in the Newman area indicating that stored water must initially also be dissipating by seepage. Conductivity monitoring shows that the stored water is fresh with a TDS between 50 to 640 mg/L.

3.1.1.4 Caramulla Creek Catchment

Caramulla Creek is located within the Upper Fortescue River catchment and is a major ephemeral tributary which merges into the main Fortescue River approximately 40 km downstream from the EPR (Caramulla West and East) orebody areas. The Jimblebar and Jigalong Creeks also merge in this same general area which is approximately 50 km southeast from where the Fortescue River discharges into the eastern end of the Fortescue Marsh. In this merger zone (Figure 2.2), the natural ground levels are extremely flat (less than 0.1%) and the main flow channels become braided and less defined. Discharges from these main river/creek systems tend to disperse into a wide floodplain and travel via smaller flow channels and as overland flow. Mapping indicates that this floodplain is potentially 10 to 20 km wide.

Through the EPR (Caramulla West and East) orebody areas, the Caramulla Creek catchment discharges via the Caramulla Creek main channel and via a smaller unnamed tributary to the east, as shown in Figure 3.2. Collectively these two flowpaths have a 747 km^2 catchment area upstream from the orebody northern boundary. Through the orebody area, these flowpaths drain northwards with gradients of approximately 0.2%. Approximately 5 km downstream from the EPR orebody areas, where the unnamed tributary merges into the main Caramulla Creek flowpath, Caramulla Creek becomes very braided; however a defined main channel is maintained downstream to the Fortescue River merger zone.

Within the Caramulla West and East orebody areas, Caramulla Creek typically has a sandy bed with scatter zones of fine to medium gravel and supports scattered eucalypt trees, as shown in Plate 3.9. The main creek channel typically has a 100 to 200 m bed width with banks 1 to 2 m high.

3.1.1.5 Davidson Creek Catchment

Similar to Caramulla Creek, Davidson Creek is located within the Upper Fortescue River catchment and is a major ephemeral tributary which merges into the Fortescue River approximately 50 km southeast from where the Fortescue River discharges into the eastern end of the Fortescue Marsh. In the confluence between Davidson Creek and the Fortescue River (Figure 2.2), the natural ground levels are extremely flat (less than 0.1%) and the main flow channels become braided and less defined. Discharges from these main river/creek systems tend to disperse into a wide floodplain and travel via smaller flow channels and as overland flow. Mapping indicates that this floodplain is 10 to 20 km wide.

Through the EPR (Caramulla East) orebody area, the Davidson Creek catchment discharges via three main flowpaths namely Davidson Creek, Thirteen Creek and an unnamed tributary to the west, as shown in Figure 3.2. Collectively these three flowpaths have a 639 km^2 catchment area upstream from the orebody northern boundary. Through the orebody area, these flowpaths drain northwards with gradients of approximately 0.2%. Downstream the flowpaths generally become less defined dispersing into wide shallow flow zones where peak flows and runoff volumes would tend to be attenuated.

Within the Caramulla East orebody area, Davidson Creek and Thirteen Creek have gravelly sand beds that support scattered eucalypt trees, as shown in Plates 3.10 and 3.11. Thirteen Creek has a wider main channel than Davidson Creek that suggests that it carries a larger runoff volume. Based on aerial photography, the unnamed western tributary creek appears to discharge via a wide dispersed flowpath without a defined low flow channel. Relative runoff from this tributary would be expected to be less than the other creek systems.

3.1.2 Catchment Response to Rainfall

3.1.2.1 EPR Rainfall Data

Streamflow in the Pilbara directly correlates to rainfall, and where streamflow data are not available rainfall data can assist with streamflow predictions. Locations of the existing and historical BOM, and DoW rainfall monitoring stations in the Study area are shown in Figure 3.3 and listed in Table 3.2. Locations of the BHP Billtion Iron Ore rainfall monitoring stations, which typically have a more recent data record, are also shown in Figure 3.3. Additional rainfall monitoring stations are likely to be operating at the Rio Tinto Iron Ore mine sites, though no public data are available.

Table 3.2: BOM & DoW Rainfall Monitoring Stations

SiteNo.	Site Name	Owner	Type	Date Commenced	Date Closed
505040	Tarina	DoW	Continuous	08/05/1985	-
7169	Rhodes Ridge	BOM	Daily	30/01/1971	Intermittent after 2003
507012	Wonmunna	DoW	Continuous	28/11/1984	-
507007	South Giles	DoW	Continuous	12/01/1980	19/05/2002
507008	East Giles	DoW	Continuous	13/01/1980	19/05/2002
507014	Spearhole Creek	DoW	Continuous	27/11/1980	29/12/1988
507013	Western Creek	DoW	Continuous	27/11/1980	29/12/1988
7151	Newman	BOM	Daily	29/11/1965	15/08/2003
507005	Newman	DoW	Continuous	06/02/1980	-
7172	Minderoo	BOM	Daily	01/01/1913	31/12/1931
7176	Newman Aero	BOM	Continuous	01/01/1971	-
7191	Capricorn Roadhouse	BOM	Daily Continuous	27/02/1975 16/07/1984	01/12/2008 20/11/2006
505038	Poonda	DoW	Continuous	29/11/1984	-
7153	Prairie Downs	BOM	Daily	29/04/1968	-
507009	Southern Fortescue	DoW	Continuous	29/01/1980	19/05/2002
7079	Sylvania	BOM	Daily	1950	Intermittent after 2001
7102	Murramunda	BOM	Daily	29/04/1915	29/12/1949
5003	Ethel Creek	BOM	Daily Continuous	01/01/1907 30/01/1963	- 17/05/1984

Of the 18 BOM/DoW rainfall monitoring stations in the study area, nine are still operating but two of these have intermittent records. Although many of the rainfall monitoring stations are now closed, the historical data records are still useful. Several of the DoW rainfall (and streamflow) monitoring stations are supported by BHP Billtion Iron Ore.

BHP Billtion Iron Ore has installed full weather stations (recording rainfall, temperature, evaporation, humidity, etc.) at most operating mine sites and in the EPR area these sites include Whaleback, Ophthalmia and Wheelarra.

Representative long-term rainfall data for the Ethel Gorge catchment can be obtained by averaging between the rainfall data at Newman, Newman Aero, Sylvania and Prairie Downs (just outside catchment), as well as BHP Billtion Iron Ore weather stations at Whaleback and Ophthalmia. Rainfall data for the Jimblebar catchment can be obtained from the BHP Billtion Iron Ore weather station at Wheelarra. However there are no current BOM/DoW/ BHP Billtion Iron Ore rainfall stations within the Caramulla Creek and Davidson Creek catchments.

Average annual rainfall recorded for the longer term rainfall monitoring stations in the EPR catchments are provided in Table 3.3. For comparison purposes and to provide a more definitive representation of wet season rainfall volumes, these annual data are taken for the July to June water year for the period July 1980 to June 2013, except for Sylvania where rainfall data after 2001 is unavailable or unverified. Although outside the catchment area, the average annual Prairie Downs rainfall is also given in Table 3.3, as it is close to the Ethel Gorge catchment boundary. However this station data was calculated using just the July 1980 to June 2012 data as 2013 data is not available.

Table 3.3: Average and Maximum Annual Rainfall (1980 – 2013)

Catchment	Station Name	Average Annual (mm)	Maximum Annual (mm)	Year of Maximum
Ethel Gorge	Newman (507005)	326	909	1999 – 2000
	Newman Aero (7176)	328	691	1999 – 2000
	Sylvania (7079) [1]	275	1,030	1998 – 1999
	Prairie Downs (7153) [2]	294	735	1999 – 2000
	SILO Database (119.60°E, 23.50°S)	319	735	1998 – 1999
Jimblebar Creek (Innawally Pool)	SILO Database (120.20E, 23.40S)	294	866	1998 – 1999
Caramulla Creek	SILO Database (120.30°E, 23.55°S)	291	812	1998 – 1999
Davidson Creek	SILO Database (120.55°E, 23.50°S)	297	722	1998 – 1999

1 Sylvania data from July 1980 – June 2001

2 Prairie Downs data from July 1980 – June 2012

Generated rainfall data for the study area are also available from the SILO database where SILO is a meteorological dataset managed by the (Queensland) Science Delivery Division of the Department of Science, Information Technology, Innovation and the Arts (DSITIA). SILO is able to generate a daily historical rainfall record from 1889 to present, for any location in Australia to the closest 0.05° latitude/longitude. It should be noted however that these data sets are generated from long term rainfall data available in the same general area. Hence rainfall data accuracy in the general Pilbara area is expected to be low away from the rainfall monitoring stations (Figure 3.3).

SILO data for the centroids of the Ethel Gorge, Jimblebar Creek (Innawally Pool), Caramulla Creek and Davidson Creek catchments for the 33 year period (1980 – 2013) have also been included in Table 3.3. For the Ethel Gorge catchment, the SILO average annual rainfall of 319 mm appears representative of the recorded rainfall station observations.

Average annual SILO rainfall isohyets across the Pilbara are shown in Figure 3.4, for the period 1961 to 2012. On average the highest annual rainfall occurs over the more elevated Hamersley Ranges (north of Tom Price) and then decreases to the east and south towards the study area. Average annual rainfalls over the study catchments are shown approximately 300 mm (1961–2012) which are slightly lower than the averages given in Table 3.3 (1980–2013), due to increased annual rainfall in recent years.

An assessment of the long-term annual rainfall for the Ethel Gorge catchment has been undertaken using the SILO annual rainfall data which are available for the period 1885 to 2013, and using the July to June water year. These annual data are shown in Figure 3.5, together with average annual rainfall and the five year moving average annual rainfall for the period starting in July 1900. An examination of the annual data plot shows that since 1994, more years have recorded rainfall totals above average than below average and that many years had rainfall totals significantly in excess of the long-term average. This long-term apparent change in annual rainfall can be seen in the five year moving average annual rainfall with average annual rainfall increasing since the 1960s.

This increasing trend can also be seen when comparing the long-term SILO average annual rainfall of 258 mm for the period 1900 to 2013 with the SILO average annual rainfall of 319 mm for the period 1980 to 2013 (Table 3.3). The SILO data indicate that annual rainfall over the past approximately 20 years has been noticeably higher resulting in the catchments experiencing a wetter period, compared with the longer term average rainfall. This higher rainfall would be expected to provide higher aquifer recharge and catchment runoff, as compared with the longer term average.

CSIRO in partnership with the Western Australian Departments of Water and Regional Development, BHP Billiton Iron Ore and the Water Corporation are conducting an assessment of water resources in the Pilbara. This assessment will provide an overview of the effect of future climates and proposed developments on the region’s surface water and groundwater resources. In August 2013, the Pilbara Water Resource Assessment released its interim report on the past, present and future climate of the region. The latest climatic models indicate there is large uncertainty as to whether the recent wetting trend in most of the Pilbara will continue. Most projections indicate that future rainfall is likely to be close to the long term average and not increase – as has been experienced in the central and east Pilbara since the 1960s.

3.1.2.2 EPR Runoff Data

Streamflow gauging stations are limited with just two operating DoW gauging stations in the study area. These are both located in the Ethel Gorge catchment as shown in Figure 3.6 and station details given in Table 3.4. No DoW streamflow gauging stations are located within the Jimblebar Creek (Innawally Pool), Caramulla or Davidson Creek catchments.

Table 3.4: DoW Streamflow Gauging Stations in EPR Region

Station Number	Station Name	Location (MGA Z50)	Status	Station Opened	Station Closed
708011	Fortescue River - Newman	785,590E, 7,409,280N	Open	09/01/1980	-
708012	Ophthalmia Dam	791,640E, 7,415,905N	Open	01/11/1981	-

The Fortescue River (Newman) gauging station is located approximately 10 km upstream from the Ophthalmia Dam embankment and monitors streamflow from the 2,889 km^2 catchment. Note that this area is slightly larger than the quoted DoW area of 2,822 km^2, based on more recent topographic data providing an adjustment for the catchment boundary. Some water quality data is also collected at this station.

Ophthalmia Dam is located on the Fortescue River approximately 4 km upstream of Ethel Gorge. The dam was completed in 1981 to capture surface water runoff from the Fortescue River as well as Whaleback and Warrawanda Creeks. Together, these waterways have a combined catchment area of 4,319 km^2 upstream of the dam. The DoW Ophthalmia Dam gauging station records daily storage levels, overflow volumes and some water quality data. Except for the Fortescue River (Newman) gauging station, the other waterways discharging to Ophthalmia Dam are ungauged by the DoW.

To supplement the DoW streamflow monitoring system, BHP Billtion Iron Ore has installed two water level monitoring stations on Whaleback Creek and one on Homestead Creek. These sites have been measuring water levels for approximately 10 years, although data quality and quantity is generally poor. The locations of these monitoring sites are shown in Figure 3.6 and the station details are listed in Table 3.5. Since 2011, records from Whaleback and Homestead Creeks have not been able to be collected due to working at height restrictions to download the data. Assessment of DoW/ BHP Billtion Iron Ore runoff data is discussed below.

Table 3.5: BHP Billtion Iron Ore Water Levels Position Stations

Location	Location	Location (MGA Z50)
Whaleback Creek	Near site road bridge upstream of Power Station Creek junction	776,731E ; 7,414,152N
	Downstream of Nullagine Road	784,787E ; 7,413,176N
Homestead Creek	Upstream of Nullagine Road	790,829E ; 7,417,435N

BHP Billtion Iron Ore also conducts surface water sampling when there is streamflow. Sampling occurs at several locations (Figure 3.6), including the Fortescue River, Homestead Creek, Whaleback Creek, Jimblebar Creek, several locations around OB18 and also Ophthalmia Dam. A comprehensive suite of water quality parameters are sampled, including pH, total suspended and dissolved solids, metals and hydrocarbons.

Based on the water quality sampling conducted by the DoW and BHP Billtion Iron Ore, the pH at Fortescue River, Homestead and Whaleback Creeks is neutral and typically between 6 and 8. Total Dissolved Solids (TDS) can be highly variable depending on volume of streamflow and how much flow preceded the water sample date. Salinity at the Fortescue River (Newman) gauging station typically varies between 20 and 100 mg/L TDS after a major flow event, with an average approximately 40 mg/L. Salinities at Homestead and Whaleback Creeks show higher levels, at around an average of 100 to 150 mg/L TDS, potentially due to lower streamflow volumes or less frequent flushing events.

3.1.2.3 Fortescue River Catchment Runoff

An assessment of the Upper Fortescue River runoff characteristics has been undertaken by comparing the recorded streamflow volumes at the Fortescue River (Newman) DoW gauging station with SILO rainfall for the catchment. Monthly data for these variables between January 1980 and April 2013 are presented in Figure 3.7. The SILO rainfall data is taken from the centroid of the Fortescue River catchment area upstream of the gauging station. As most rainfall typically occurs during the December to April period, most runoff also occurs during this period.

To assess the annual correlation between rainfall depths and runoff volumes for the Fortescue River catchment, the catchment SILO annual rainfall was compared to the annual discharge volumes for the 33 year period of data availability at the Fortescue River (Newman) gauge, using the July to June water year. These annual data are given in Table 3.6 together with the calculated annual runoff percentages, which vary between annual runoffs of 0.03% (1988/1989) to 18.2% (1999/2000) of annual rainfall. The total catchment runoff over the 33 year period is estimated at 5.4% of the total rainfall (i.e. average 17.0 mm/year).

The median annual rainfall and runoff totals (Table 3.6) are the mid-point values in the data set and represent the 50% AEP (annual exceedance probability) event. These median values are always lower than the average values, because the average values get distorted by the more extreme rainfall and flood events, particularly for the runoff volumes. The median catchment runoff of 2.5% of annual median rainfall (6.6 mm/year) could be considered a more typical runoff characteristic for the catchment and is significantly less than the long term average runoff of 5.4% (17.0 mm/year).

Table 3.6: Fortescue River (Newman) Catchment - Annual Rainfall and Runoff (1980 – 2013)

Year	Fortescue River Catchment Annual SILO Rainfall (mm)	Fortescue River Annual Runoff Volume (ML)	Annual Runoff (%)
1980 – 1981	246.4	9481	1.3
1981 – 1982	247.7	30,256	4.2
1982 – 1983	234.6	3,445	0.5
1983 – 1984	236	2,581	0.4
1984 – 1985	293.3	31,402	3.7
1985 – 1986	169.4	35,567	7.3
1986 – 1987	247.1	18,884	2.6
1987 – 1988	282.8	21,144	2.6
1988 – 1989	232.1	192	0.03
1989 – 1990	172.3	12,710	2.6
1990 – 1991	169.7	10,490	2.1
1991 – 1992	315	23,346	2.6
1992 – 1993	230.6	2,394	0.4
1993 – 1994	156.9	6,458	1.4
1994 – 1995	432.9	98,214	7.9
1995 – 1996	192.1	2,277	0.4%
1996 – 1997	600.3	219,270	12.6
1997 – 1998	198.2	3,707	0.6
1998 – 1999	717.5	83,471	4.0
1999 – 2000	745.5	391,186	18.2
2000 – 2001	442.9	87,838	6.9
2001 – 2002	261.3	19,102	2.5
2002 – 2003	390.2	126,464	11.2
2003 – 2004	352.6	51,226	5.0
2004 – 2005	84.4	560	0.2
2005 – 2006	491.4	57,616	4.1
2006 – 2007	285.2	3,378	0.4
2007 – 2008	264.4	16,927	2.2
2008 – 2009	318.7	83,297	9.0%
2009 – 2010	114.9	7,108	2.1
2010 – 2011	410.9	83,037	7.0
2011 – 2012	430.1	64,559	5.2
2012 - 2013	367.8	12,542	1.2
Average	**313**	**49,095**	**5.4** [1]
Median Value	**264**	**19,102**	**2.5**

1. Volume weighed average for 33 year record

Plots of the annual runoff percentage versus annual SILO rainfall data (Table 3.6) and the monthly runoff percentage versus monthly SILO rainfall for the Fortescue River catchment are shown in Figure 3.8. As expected, these data generally show that the runoff increases with rainfall. Although relationship trend lines have been plotted, the trend lines lack any confidence, and do not reliably represent the recorded data. When assessing the monthly data, in several instances, runoff in one month was due to rainfall late in the previous month, hence giving false plot points (i.e. effectively zero rainfall with high runoff). These data points have been ommitted.

The Fortescue River (Newman) streamflow gauging station (DoW Station 708011) is the only streamflow station installed on the tributaries discharging to Ethel Gorge (Warrawanda, Whaleback, Shovelanna and Homestead Creeks). Based on the available historical record from this station (1980 to 2013), the Fortescue River typically has one to three flow events per year. Each flow event typically persists for several days to several weeks/months, depending on rainfall volume and duration. Typically monthly rainfalls of at least 50 to 100 mm are required for initial runoff. The longest recorded period of continuous flow was in 1999/2000 when the Fortescue River had significant flow for over four months followed by progressively lower river flows for around another two to three months as water slowly drained from natural storages within the catchment (e.g. alluvium). These flows resulted from Tropical Cyclone John (December 1999) and consistently high rainfall in January to March 2000. During low rainfall years, the river flow persists for just a few days after the rainfall event.

When a runoff event occurs in the Fortescue River, runoff would also likely occur in the surrounding Warrawanda, Whaleback, Shovelanna and Homestead Creeks, although it is expected that these smaller creeks may flow for a shorter duration for the same storm event. A comparison of flow durations in the Fortescue River and Whaleback Creek (using water level position data) was undertaken for the 2010/2011 wet season (only period when useable Whaleback Creek data is available). The data shows that the Fortescue River flowed for approximately 83 consecutive days during January – March 2011, while Whaleback Creek recorded elevated water levels for a few hours before they subsided. However, the water level data collected from Whaleback Creek is inconclusive and it is possible flow events are falsely indicated by elevated water levels due to a pool of water at the monitoring station. After events showing elevated water levels, the data shows a steady and slow decline in water levels suggesting dissipation of pooled water by seepage and evaporation.

Runoff volumes as a percentage of rainfall recorded on the Fortescue River at Newman (DoW Station 708011) are relatively high compared to those recorded in the central Pilbara on Weeli Wolli Creek at Tarina (DoW Station 708014) and Marillana Creek at Flat Rocks (DoW Station 708001). Plots of the annual and monthly runoff percentages versus corresponding annual and monthly SILO rainfall for these three gauging stations are shown in Figure 3.9. Relationship trend lines clearly show that relative runoff volumes on the Fortescue River are over double those recorded on the Weeli Wolli Creek at Tarina and over four times greater than those recorded on the Marillana Creek at Flat Rocks.

The Flat Rocks gauging station records runoff from the upper Marillana Creek catchment which contains large flat storage areas, in particular the Munjina Claypan, which attenuates catchment runoff. Hence relative runoff volumes from this catchment could be expected to be below those experienced in catchments without large flat storage areas such as the Weeli Wolli Creek and Fortescue River. Physical characteristics within the Fortescue River catchment which possibly increased the relative runoff include the extensive areas of granite outcrop and subcrop, resultant vegetation communities on these granite derived soils (different interception/storage characteristics) and a general shallower depth to groundwater which reduces the water volume required to satisfy the soil moisture deficit.

3.1.2.4 EPR Catchment – Runoff Volumes

Runoff volumes for the ungauged EPR catchments have been estimated using catchment areas and rainfall-runoff relationships derived from the Fortescue River (Newman) gauging station.

Within the Ethel Gorge catchment, the Fortescue River, Warrawanda Creek and Whaleback Creek discharge into Ophthalmia Dam. Whaleback and Shovelanna Creeks discharge into the Fortescue River downstream of Ophthalmia Dam prior to flowing through Ethel Gorge. Jimblebar, Caramulla and Davidson Creeks also form part of the Upper Fortescue River catchment and discharge into the Fortescue River downstream from Ethel Gorge. Apart from the Fortescue River at Newman, all these catchments are ungauged.

Estimated annual runoff volumes for the EPR catchments are shown in Table 3.7. Volumes have been estimated based on the 17.0 mm/year average runoff (5.4%) and 6.6 mm/year median annual runoff (2.5%) for the Fortescue River catchment. These estimates are based on the 33 years (1980 – 2013) of annual runoff data for the Fortescue River (Newman) gauging station and assume similar rainfall and catchment characteristics.

Table 3.7: Estimated Annual Runoff from EPR Catchment Areas

Catchment	Catchment Area (km^2)	Average Annual Runoff Volume (GL)[1]	Median Annual Runoff Volume (GL)[2]
Fortescue River	2,889	49.1	19.1
Warrawanda Creek	1,225	20.8	8.1
Whaleback Creek	205	3.5	1.4
Ophthalmia Dam	4,319	73.4	28.6
Homestead Creek	305	5.2	2.0
Shovelanna Creek	248	4.2	1.6
Ethel Gorge without Ophthalmia Dam	4,872	82.8	32.2
Jimblebar Creek	348	5.9	2.3
Caramulla Creek	747	12.7	4.9
Thirteen Creek	639	10.9	4.2

1 Based on average annual rainfall of 17.0 mm

2 Based on median annual rainfall of 6.6 mm

3.1.3 Ophthalmia Dam Water Balance

Ophthalmia Dam interrupts natural surface water flow in the Ethel Gorge catchment by capturing surface water runoff from Fortescue River, Whaleback Creek and Warrawanda Creek. The dam has a top storage level of 513.5 mRL (level of service spillway) and is essentially empty at 509 mRL, giving an effective maximum storage water depth of 4.5 m and storage capacity of 31 GL. When full, runoff overtops the service spillway and discharges via the former Warrawanda Creek towards Ethel Gorge. Since its construction, storage water levels in Ophthalmia Dam have been monitored by a DoW gauging station (708012) with the gauging record starting in December 1981. Daily water levels are shown in Figure 3.10.

The estimated historical total monthly runoff volumes discharged to Ophthalmia Dam from the Fortescue River, Whaleback Creek and Warrawanda Creek for the period since 1981 are also shown in Figure 3.10. These volumes have been estimated based on the Fortescue River (Newman) streamflow gauging data (site 708011). Ophthalmia Dam receives catchment runoff over most years with runoff completely filling or overtopping the dam in 14 of the past 31 years (July 1981 – June 2013), as seen in Figure 3.10. However the data also shows that from July 1994, the dam overflowed in 11 out of 18 years, and prior to July 1994 the dam overflowed in three out of 13 years. Additionally the dam did not overflow during eight consecutive years (wet seasons) from July 1986 to June 1994 (effectively nine years without overflowing). The more frequent overtopping since July 1994 coincides with the longer term increase in annual rainfall as shown in Figure 3.5.

The estimated median annual inflow volume into Ophthalmia Dam from Fortescue River, Warrawanda Creek and Whaleback Creek is approximately 28.6 GL as given in Table 3.7. This represents a 50% AER (2 year ARI) event and is almost equal to the storage capacity of the dam (31 GL). Hence the storage could be expected to almost completely fill (from empty) on average every two years which is typically what the storage water level data shows (overtopped in 14 of the past 31 years). Based on these data, the estimated median annual overflow volume from the storage would be zero.

From the storage water level plot (Figure 3.10), if no additional runoff occurs, the storage typically is depleted from full in approximately 12 months. This suggests that the combined losses from the storage by seepage and evaporation (no water is released) is approximately 4.5 m/year water depth or 31 GL/year water volume. The average Class A pan evaporation for the Newman area is 3,733 mm/year and for open storages this is predicted to reduce to 2,346 mm/year (Department of Agriculture 1987), which allows a pan factor of 0.63. Recent assessments indicate that a pan factor of 0.54 is more applicable for the Newman area (Parsons Brinkerhoff, 2013) which gives a revised open water evaporation loss of 2,016 mm/year. Assuming minimal additional rainfall over the 12 months while the storage was fully depleted, then the loss due to evaporation would be approximately 2.0 m/year (average 5.5 mm/day) and the loss due to seepage would be approximately 2.5 m/year (average 6.8 mm/day). Assuming that evaporation and seepage relate to the same surface area, then proportionally evaporation would be approximately 14 GL/year (average 38 ML/d) and seepage would be approximately 17 GL/year (average 47 ML/d).

Recent water balance modelling of Ophthalmia Dam (Parsons Brinkerhoff, 2012) estimates seepage at 5.5 to 7.7 mm/day which is similar to the above estimated 6.8 mm/day seepage. During previous water balance modelling by Aquaterra, (2010), for the 27 year modelling period, estimated an average seepage of 16 GL/year (44 ML/d) which essentially agrees with the new estimate of 17 GL/year (47 ML/day).

During large runoff events, a large proportion of the runoff volume overflows the dam. Runoff is estimated at an average of 76.3 GL/year entering the storage with an estimated average of 50.6 GL/year overflowing the spillway. This equates to an average 66% of the total annual inflow overflowing to Ethel Gorge. However this percentage varies markedly with 17 of the past 31 years (July 1981 – June 2013) without overflow, and one very wet year (1999/2000) where over 90% of the total annual inflow overflowed toward Ethel Gorge.

Average annual runoff volumes to Ethel Gorge after the construction of Ophthalmia Dam can be estimated assuming 66% of inflow to the dam overflows downstream to Ethel Gorge. Based on the average annual inflow into Ophthalmia Dam of 73.4 GL (Table 3.7), the average annual overflow from the dam is estimated at 48.4 GL and the resulting average annual volume discharged to Ethel Gorge is estimated at 57.8 GL. With the median annual overflow volume from Ophthalmia Dam of zero, the median annual runoff to Ethel Gorge would now be 3.6 GL. These annual runoff volume estimates at Ethel Gorge after construction of Ophthalmia Dam are given in Table 3.8.

Table 3.8: Estimated Annual Runoff Volumes at Ethel Gorge with Ophthalmia Dam

Catchment	Catchment Area (km^2)	Average Annual Runoff Volume (GL)	Median Annual Runoff Volume (GL)
Ophthalmia Dam Overflow [1]	4,319	48.4	0
Homestead Creek	305	5.2	2.0
Shovelanna Creek	248	4.2	1.6
Ethel Gorge with Ophthalmia Dam [1]	4,872	57.8	3.6

1. Average 66% overflow from Ophthalmia Dam

Comparing the annual runoff data provided in Tables 3.7 and 3.8, the estimated annual volume of surface water runoff discharging to Ethel Gorge has reduced by an average of approximately 25 GL due to Ophthalmia Dam.

Since 2007, the Ophthalmia Dam storage has been receiving dewatering discharge from OB25, and excess discharges from additional orebodies are also planned. In the storage, these dewatering discharges would be expected to increase average water levels and increase the average seepage volumes. Based on previous scenario modelling (Aquaterra, 2010), storage seepage typically increases by an amount equal to approximately 50% of the dewatering discharge volume. These increases would be temporary for the duration of dewatering discharge.

3.1.4 Ophthalmia Dam Salt Balance

Within the Ophthalmia Dam storage, relative fresh streamflow would be captured by the dam and with evaporation this stored water would gradually become more saline over time. During the next major runoff event, the relative fresh streamflow would mix with and dilute the more saline stored water, and if overflow from the dam occurred, the overflow would discharge at a slightly higher salinity than the inflow.

A daily combined water and salt balance model was developed for the storage to better define this process (Aquaterra, 2010). The salt balance model was calibrated using an average streamflow salinity of 40 mg/L recorded at the Fortescue River – Newman gauging station (DoW 708011) and the limited Ophthalmia Dam storage salinity data available for the period (January 1985 to March 1989).

The storage data shows the cyclical salinity pattern with salinity varying between approximately 40 mg/L when the storage was full, increasing to approximately 250 mg/L as the storage empties (DoW, 2009). The salinity of the stored water, seepage and overflow water from the dam was estimated in the salt balance model and the storage salinity modelling results are shown in Figure 3.11 for the 27 year study period (February 1982 to April 2009). The modelled salinity results replicated those used for model calibration. Over the modelling period, the predicted weighted average salinity was 60 mg/L in the storage and 65 mg/L in the seepage water. Overflow from the dam had a predicted weighted average salinity of 40 mg/L, the same as the adopted streamflow salinity.

With the Ophthalmia Dam storage receiving excess dewatering discharges from OB25 and planned excess dewatering discharges from additional orebodies, these discharges typically have a salinity of approximately 1,000 mg/L TDS and potentially increase storage salinity to an extent dependent on the dewatering volumes discharged. Based on the previous scenario modelling using dewatering discharges of 8.9 ML/d and 20.7 ML/d (Aquaterra, 2010), these discharges were predicted to increase the average storage salinity from an estimated 60 mg/L to 155 mg/L and 270 mg/L respectively, and increase the peak storage salinity from 270 mg/L to 1,660 mg/L and 2,300 mg/L respectively. Seepage salinities were also predicted to increase from an average of 65 mg/L to 225 mg/L and 390 mg/L respectively and overflow salinities slightly increase from 40 mg/L to 47 mg/L and 58 mg/L respectively. These salinity increases would be temporary for the duration of the dewatering discharges.

3.1.5 Catchment Peak Discharges

Based on the streamflow record available for the Fortescue River gauging station at Newman (DoW Station 708011), a partial series flood frequency analysis of the available monthly peak streamflow data was completed to estimate peak discharges for a range of design AEP (annual exceedance probability) flood events. The assessment found that the Log Normal Distribution showed a better fit to the data and the design peak discharges estimated by this distribution are given in Table 3.9. These discharges range between 400 m^3/s for the 50% AEP event to 2,500 m^3/s for the 1% AEP event. The peak discharge recorded during the data record was 1,730 m^3/s which resulted from Tropical Cyclone Dean (Feb. 1980) and corresponds to between a 5% and 2% AEP event.

Table 3.9: Design Peak Discharges at Fortescue River (Newman) Gauging Station

Flood Event (% AEP) [1]	Estimated Peak Discharge (m^3/s)
50	400
20	780
10	1,100
5	1,500
2	2,000
1	2,500

1. For comparison: ARI (Year) = 100 / AEP (%)

Assuming that the peak discharges for the Jimblebar Creek (Innawally Pool), Caramulla Creek and Davidson Creek catchments are a direct proportion to those recorded at Fortescue River at Newman (2,889 km^2) based on an area ratio to the power 0.7 (i.e. $[A_1/A_2]^{0.7}$), then the predicted corresponding peak catchment discharges are shown in Table 3.10. Due to flood attenuation within the Ophthalmia Dam storage, peak discharge for the Ethel Creek catchment could not be estimated by this method.

Table 3.10: Indicative Peak Discharges for EPR Catchment Areas

Flood Event	Jimblebar Creek (Innawally Pool) Catchment (m^3/s) [1]	Caramulla Creek Catchment (m^3/s) [2]	Davidson Creek Catchment (m^3/s) [3]
50% AEP	91	155	139
20% AEP	177	303	271
10% AEP	250	427	383
5% AEP	341	582	522
2% AEP	455	776	696
1% AEP	568	970	869

1 Jimblebar Creek catchment area of 348 km2

2 Caramulla Creek catchment area of 747 km2

3 Davidson Creek catchment area of 639 km2

3.2 Groundwater

3.2.1 Setting

Broadly, the EPR comprises a regional groundwater flow system hosted in aquifers associated with the Tertiary detritals and underlying Paraburdoo Member dolomite, which are surrounded by low-permeability lithologies. The regional aquifer is present beneath most of the present day strike oriented valleys between ridges of Brockman and Marra Mamba Iron Formations, where there are deep sequences of Tertiary detritals overlying Paraburdoo Member dolomite. The regional aquifer is also present where major drainages have eroded valleys across strike and there are deep sequences of Tertiary detritals. In places the regional aquifer may only comprise either the Tertiary detritals or the dolomite, and in other places the regional aquifer comprises both units.

There are also zones of high-permeability material associated with orebodies that form local aquifers within the low-permeability surrounds (orebody aquifers); the extent to which they are in hydraulic connection with the broader regional groundwater system varies with site-specific geology. Site-specific detail is provided in the following chapters on individual mining areas and environmental receptors.

A summary of the groundwater aquifer potential in the EPR area was included in Table 2.3. Example hydro-stratigraphical type-sections are provided in Figures 3.12a to 3.12d to illustrate the hydrogeology of the EPR area; the section locations were shown in Figure 2.3.

3.2.2 Hydrostratigraphy

3.2.2.1 Jeerinah Formation

The Jeerinah Formation comprises low-permeability mudstone, basalt and shale. Anecdotal evidence from the West Angelas mine suggests that local fault zones can act as aquifers; although these are generally discontinuous, of limited areal extent and isolated from the main regional aquifer. The formation is generally considered an aquitard.

3.2.2.2 Marra Mamba Iron Formation

The Marra Mamba comprises generally low-permeability BIF and shale. However, where mineralised (typically in the Mt Newman Member), the Marra Mamba has enhanced permeability and storage, and is considered an aquifer. Aquifer potential is limited to zones of mineralisation forming localised aquifers that are limited below and along strike by low permeability unmineralised BIF and above by the West Angela Member.

In certain settings, hydraulic isolation of Marra Mamba orebody aquifers may be compromised where the geometry of the valley and the orebody are such that the orebody is juxtaposed to Tertiary detritals and not just West Angela Member. Hydraulic connection may also occur when the permeability of the West Angela Member is increased (refer Wittenoom Formation section below) or when thrust faulting causes a permeable conduit between the Marra Mamba and the Wittenoom Formation. Recent test pumping at Jimblebar (refer Chapter 5.8) has indicated hydraulic connection between the orebody and the regional aquifer. It is likely that the Marra Mamba orebodies in both the Eastern Ridge and Western Ridge mining areas will be in some hydraulic connection with the regional aquifer (in this case alluvial aquifers of the Fortescue River floodplain) and that many of the Marra Mamba orebodies elsewhere in the EPR will be in hydraulic connection with the regional aquifer (being Tertiary detritals and dolomite)

Overall, the Marra Mamba is generally an aquitard but can be an important local aquifer where mineralised with a varying degree of connection to the regional aquifer.

3.2.2.3 Wittenoom Formation

The Wittenoom Formation comprises shale and dolomite and subordinate BIF in three members - the West Angela Member, Paraburdoo Member and Bee Gorge Member.

On a regional scale, the West Angela Member is a generally low permeability unit and acts as an aquitard overlying the Marra Mamba. However, in places it can be permeable: where there is a larger proportion of BIF that has been mineralised; where the unit is rich in secondary manganese (which forms a very permeable "honeycomb" horizon); and where the unit is affected by thrust faulting.

The Paraburdoo Member comprises dolomite with extensive karstification resulting in localised zones of high permeability. As the Wittenoom Formation is prone to weathering and erosion, the Paraburdoo Member usually occurs in subcrop under valley floors and often acts in hydraulic connection with overlying Tertiary detritals to form an important, integrated aquifer (regional aquifer). The Bee Gorge Member is a generally low permeability unit of crystalline dolomite, BIF and shale, however, increased permeability can occur when weathered or altered. It can generally be considered an aquitard along with the overlying Mt Sylvia and Mt McRae Formations.

3.2.2.4 Mount Sylvia Formation and Mount McRae Shale

Mount Sylvia Formation (Mt Sylvia) and overlying Mount McRae Shale (Mt McRae) comprise low permeability shale and regionally can be considered aquitards.

However, they include prominent chert bands known as the Triplets, Brunos Band and Colonial Chert. In tightly folded and faulted settings, these chert bands can be highly fractured/broken, permeable, and act as a local aquifer. This structural setting often occurs in conjunction with mineralisation in the overlying Brockman and this local chert aquifer can influence pit hydrogeology.

3.2.2.5 Brockman Iron Formation

The Brockman comprises generally low-permeability BIF and shale. However, where mineralised (typically in the Dales Gorge and Joffre Members), the Brockman has enhanced permeability and storage forming an important localised aquifer. Aquifer potential is limited to zones of mineralisation being restricted at depth and along strike by low permeability unmineralised BIF, and above and below by the Yandicoogina and Whaleback Shale Members.

In certain settings, hydraulic isolation of Brockman orebody aquifers may be compromised where the adjacent valley has eroded sufficiently into the Mt McRae the footwall of the orebody is in direct connection with the Tertiary detritals (and the regional aquifer).

At OB23 and OB25 deposits, the Brockman orebody aquifer is in direct hydraulic connection with the Tertiary detritals of the Fortescue River Valley. Dewatering requirements have ranged between 10 ML/d to 20 ML/d at these pits.

Overall, the Brockman is generally an aquitard but can be an important local aquifer where mineralised. Orebody aquifers are generally isolated from the regional aquifer. This is highlighted at Mt Whaleback, the largest pit in the area, where dewatering has occurred for over 20 years and water level drawdown at the pit has been substantial; however drawdown remains concentrated around pit and has limited lateral extent. Despite this, Brockman orebody aquifers maybe in connection where pit geometry is such that Tertiary detritals are also intersected and/or where the orebody is affected by permeable faults.

3.2.2.6 Weeli Wolli Formation

The Weeli Wolli Formation comprises low permeability BIF, chert and jaspilite. It is a regional aquitard.

3.2.2.7 Tertiary Detritals 1 (TD1)

The oldest valley fill sediment in the overall Tertiary detritals sequence is the TD1 unit, where present in the upper valleys and tributaries of the Fortescue River (and in the Copper Creek valley at Jimblebar and other parts of the Jimblebar-Caramulla-Davidson Creek systems where there are deep valley fill sediments). The TD1 comprises sand, silt and pisolith of low to moderate permeability. The TD1 unit is generally considered a low permeability aquifer rather than an aquitard.

On the margins of the valley, ancient scree deposits may be preserved representing a TD1 colluvial environment. These can be variably permeable depending on the extent of secondary hematite cementation and the degree of mineralisation in the original clasts. They can be considered a moderate permeability aquifer flanking the valleys.

The lower-most sediments of the Fortescue River floodplain comprise alluvial sand and gravel. These sediments occur at up to 100 mbgl and are generally approximately 30 m thick; under Ophthalmia Dam, they attain a thickness of almost 100 m. Thus, they represent a significant aquifer at the base of a thick alluvial sequence. They are overlain by an extensive clay (refer Tertiary Detritals 2 below). While the lower alluvial unit comprises less hematite than TD1 elsewhere in the Pilbara, geomorphologically, it is a similar setting (a TD1 alluvial environment overlain by a TD2 low-energy fluvial environment in which extensive clay was deposited). The reduced hematite content may result from the extensive granite outcrop in the headwaters of the Fortescue River.

3.2.2.8 Tertiary Detritals 2 (TD2)

TD2 occurs in most of the Tertiary detritals sequences over the project area. It is generally a low permeability clay that may be considered an aquitard. However, in places it comprises calcrete/silcrete and vitreous goethite (occurring both within the sequence and as a hardcap where the sequence overlies basement) which are very permeable. While these units do not always occur through the entire thickness of TD2, they do occur over a great lateral extent and may be continuous over many kilometres in the overall Tertiary detritals sequences. They act as a regional aquifer.

Over the Fortescue floodplain, the TD2 sequence comprises an extensive clay that acts as a confining unit over the underlying TD1 gravels. The top of this clay is generally 30 to 40 m below ground level and the clay is typically 30 to 40 m thick. This clay sequence is also present in the Copper Creek valley at Jimblebar.

3.2.2.9 Tertiary Detritals 3 (TD3)

TD3 and recent alluvium occur at outcrop valleys and creeks-beds throughout the project area. The permeability of TD3 varies considerably with the proportion of sand and silt in its matrix and it can be considered a low to highly permeable aquifer. Moreover, in places, TD3 comprises calcrete and silcrete which are a high permeability aquifer.

On the Fortescue River floodplain and along Homestead Creek, the TD3 deposits comprise both coarse alluvium and substantial thicknesses of calcrete. In these areas, the TD3 alluvial sequence forms a high-permeability, high storage regional aquifer. On the Fortescue floodplain, this formation hosts the ecological asset for the EPR (the Ethel Gorge stygofauna community). Calcretes are also present in some of the tributary valleys and form local aquifers, although the overall TD3 is less of an extensive aquifer in these regions.

3.2.3 Hydrostratigraphic Connectivity

There are nine designated mining areas in the EPR, of which all are BHP Billtion Iron Ore projects. In each case, the mining area comprises a number of deposits hosted in either mineralised Brockman or Marra Mamba and they form local aquifers where they occur below the regional watertable.

In some cases, the deposits are surrounded by low-permeability unmineralised basement and will behave as "bath-tub" aquifers (that is, aquifers completely surrounded by low permeability rocks). Abstraction from this type of aquifer will deplete groundwater stored within the deposit. However, the effects of this will be generally contained by the low permeability surrounding geology and abstraction volumes will be limited by the volume of water held in storage (i.e. the specific yield of the ore). For example, dewatering at Mt Whaleback has little impact on the wider groundwater system.

In other cases, the deposits are in hydraulic connection with Tertiary detritals and abstraction this type of aquifer will draw water from the regional aquifer. Operating experience from OB23 and OB25 shows the impact of this can be wide ranging and abstraction volumes will be large.

The hydrogeology of each mining area is discussed in following chapters.

3.2.4 Hydraulic Parameters

3.2.4.1 Hydraulic Conductivity

Table 3.9 summarises the range in hydraulic conductivities that have been determined for the major hydrogeological units of the EPR. These estimates comprise both the results of field tests (falling/rising head, airlift and pumping tests) and parameters determined through the process of calibrating numerical models.

There is a considerable range in hydraulic conductivity estimates which reflects both the range in methods of determination and also natural variation within the formations. Considerable variation will occur on a local scale where the permeability is secondary and reliant on the development of either solution or structural features. For example, while the Paraburdoo Member is part of a major regional aquifer, the derived hydraulic conductivity varies with the degree of karst-development encountered in a specific bore. As such, the estimates that are determined from calibration of regional scale numerical modelling exercises may provide the best estimates of average hydraulic conductivity for the aquifer on a regional scale. Conversely, when considering local detail, for example inflow to a specific section of a pit, then the actual hydraulic conductivity around that location will be more relevant.

For numerical modelling at the regional scale, it may be appropriate to adopt an average value to simulate bulk aquifer behaviour. Whereas, for more local modelling, such as for operational dewatering predictions at the pit-scale, a wider range in parameters for each hydrostratigraphic unit may be required to appropriately simulate the behaviour of the groundwater system. As such, it is not possible to recommend a single value that should be adopted for each formation.

3.2.4.2 Major Aquifers

The major regional aquifer occurring over a wide area and providing continuity within the regional groundwater system are the Paraburdoo Member dolomite and the overlying Tertiary detritals; notably the calcrete/silcrete and CID/geothitic hardcap of TD2 in the upper valleys and the entire TD1 and TD2 sequence on the Fortescue River floodplain.

Estimates of the hydraulic conductivity of the dolomite range between 0.1 m/d to 101 m/d with a median value of 10 m/d determined from both pumping tests and calibrated numerical models.

Estimates of hydraulic conductivity for the Tertiary detritals range between 2.5 m/d and 41 m/d with median values of 11 m/d and 29 m/d determined from pumping tests and calibrated models respectively.

In practice, the Tertiary detritals are commonly grouped into a single hydraulic unit during modelling, masking any difference in hydraulic conductivity between calcrete/silcrete and CID/geothitic hardcap. The higher median value from calibrated models largely occurs due to the inclusion in models of very high permeability calcrete to facilitate groundwater discharge in key areas such as Weeli Wolli Spring and Ethel Gorge, affecting previous groundwater models developed for CPR and EPR respectively. As such, values at the higher end of the range of hydraulic conductivity are likely to occur locally and where the calcrete aquifer occurs in abundance. The value of 11 m/d is more representative of the Tertiary detritals on a regional scale where the aquifer is a mix of calcrete and underlying CID/geothitic hardcap.

Mineralised zones of both the Brockman and the Marra Mamba form important but often disconnected orebody aquifers across the area. Estimates of hydraulic conductivity for mineralised Brockman range between 0.2 m/d and 24 m/d. The median value determined from both pumping tests and modelling is 3 m/d.

The mineralised Marra Mamba is generally more permeable than the mineralised Brockman. Estimates of hydraulic conductivity for mineralised Marra Mamba range between 0.3 and 85 m/d. The median value determined from both pumping tests and modelling is between 2 and 5 m/d.

Table 3.11: Estimates of Aquifer Permeability

Aquifer	Field testing k (m/d)					model kh (m/d)					Integrated Range k (m/d)				
	min	max	average	median	count	min	max	average	median	count	min	max	average	median	count
Detritals - Undiff	0.03	100	11.63934	0.9	32	0.2	30	6.2	2.5	14	0.03	100	10.0	1.7	46
Calcrete/CID	2.5	41.4	16.6	11.2	7	20.0	50.0	33.0	29.0	3	2.5	50	21.5	20	10
Fault						0.0001	0.0030	0.0008	0.0001	4	0.0001	0.003	0.0008	0.0001	4
Boolgeeda Formation *1						0.001	2.0	1.0	1.0	2	0.001	2	1	1	2
Brockman ore	0.2	24.0	8.3	3.3	6	0.2	5.0	3.2	3	13	0.15	24	4.8	3.2	19
Brockman sub ore						0.040	0.500	0.208	0.100	5	0.04	0.5000	0.21	0.1	5
Brockman BIF	0.04	0.4	0.3	0.34	3	0.001	0.050	0.011	0.002	7	0.001	0.4	0.1	0.2	10
Brunos Band	12.2	12.2	12.2	12.2	1	14	14	14	14	1	12.0	14.0	13.1	13.1	2
Whaleback Shale	0.004	0.3	0.2	0.2	2	0.02	0.02	0.02	0.02	2	0.004	0.3	0.1	0.1	4
Mc Rae	0.00001	0.8	0.1	0.006	13	0.0001	0.1000	0.0344	0.0121	5	0.00001	0.8	0.1	0.01	18
Mt Sylvia	0.00002	0.1	0.029	0.01	9	0.01	1.00	0.25	0.10	5	0.00002	1	0.1	0.1	14
Bee Gorge	1.8	1.8	1.8	1.8	1	0.002	1.000	0.367	0.501	3	0.002	1.8	0.7	1.2	4
Weeli Wolli						0.001	0.100	0.043	0.010	5	0.001	0.1	0.043	0.01	5
Dolomite	0.1	105.0	18.5	10.4	41	0.00002	39.0	10.1	11.0	21	0.00002	105	15.7	10.7	62
Dolomite non aquifer						0.00002	0.0020	0.0010	0.0010	3	0.00002	0.002	0.001	0.001	3
West Angela Shale	0.027	0.027	0.027	0.027	1	0.008	11.300	1.986	0.800	9	0.008	11.3	1.8	0.4	10
West Angela ore						0.010	1.000	0.505	0.505	2	0.01	1	0.5	0.5	2
Woongarra Formation *1						0.001	2.000	1.001	1.001	2	0.001	2	1	1	2
MM ore	0.3	85.1	6.8	2.3	28	0.001	14.500	5.769	5.000	13	0.001	85	6.4	3.6	41
MM Sub Ore						0.100	8.000	2.020	0.500	5	0.1	8	2.0	0.5	5
MM BIF	4.4	137.0	40.3	9.8	4	0.000020	0.004	0.00168	0.001	9	0.00002	137	12.4	4.9	13
Jeerinah	0.0001	7.2	1.6	0.7	19	0.00001	0.03000	0.016665	0.03000	11	0.00001	7.2	1.0	0.3	30
Dolerite	0.003	0.5	0.3	0.3	2	0.0010	0.0010	0.0010	0.0010	1	0.001	0.5	0.2	0.1	3
Igneous *1	0.000019	2.4	0.8	0.4	9	0.00010	0.00010	0.00010	0.00010	1	0.00002	2.4	0.7	0.2	10

3.2.4.3 Aquifers Associated with Geological Structure

Some local aquifers occur associated with specific faults and/or folds; as such their hydraulic conductivity is site-specific. Bruno's Band and Colonial Chert are prominent chert bands within the Mt Sylvia and the Mt McRae respectively. In tightly folded settings (e.g. in the footwall of the Brockman), these cherts have been broken/brecciated to form local aquifers such as within the Whaleback mine. Hydraulic conductivities in the order of 10 m/d are common. In an orebody setting, they can offer good targets to the footwall; whereas, they contribute to water supplies in the heavily-faulted Homestead Creek valley.

Similarly, discontinuous local aquifers caused by fault zones have been reported from the Jeerinah Formation. This has been observed in the West Angelas mine area where the outcrop of Jeerinah Formation is contiguous with the outcrop of Jeerinah Formation on Wanna Munna Flats to the west of the EPR. In this area, discontinuous zones of enhanced permeability are associated with local faults, broadly trending north-south and often aligned with drainage channels.

Faulting in orebodies can also produce local zones of structurally-enhanced permeability. In particular, thrust faulting associated with mineralisation in the Marra Mamba. Commonly these thrusts occur through Marra Mamba and the overlying Wittenoom Formation resulting in higher permeability than the surrounding geology (particularly the West Angela Member). In particular, these faults may be important in connecting orebody aquifers (formed in mineralised zones on the valley margins) with the regional aquifer. Such faulting is believed to contribute to inflows into the Marra Mamba orebody aquifer at Jimblebar.

Available data suggest strike-parallel faults, often of considerable length, may also act as local aquifers. For example, there is some degree of hydraulic connection along strike between OB25 Pit 1 and Pit 3; and there is possibly hydraulic connection between OB23 and OB24.

The study area is structurally complex and future investigations and mining experience will likely reveal that additional local faults also contribute to hydraulic connection within the system.

However, other than these local features, groundwater level data suggest that the major regional faults (Whaleback, Wheelara and Homestead Faults) can also be barriers to groundwater flow (refer Aquitards).

3.2.4.4 Aquitards

The BIFs of the Weeli Wolli Formation and unmineralised Marra Mamba and Brockman behave as aquitards with hydraulic conductivity ranging between 0.001 m/d and 0.01 m/d. The estimates of hydraulic conductivity from field tests are two or more orders of magnitude higher for these units; there are however relatively few tests. Most tests will have taken place during an orebody-investigation. The difference could be due to the field tests occurring on bores close to mineralised zones where the material tested may be either sub-grade ore, or have enhanced hydraulic conductivity due to structure within the orebody. At the regional scale, estimates derived from model calibration are considered more representative.

The shales of the Mt Sylvia and Mt McRae and the West Angela Member of the Wittenoom Formation behave as aquitards. Estimates of hydraulic conductivity range between 0.02 m/d and 0.1 m/d based on field tests, and 0.01 m/d and 0.1 m/d from calibrated models (the latter range excluding the model-derived estimates for the West Angela Member).

The model-derived hydraulic conductivity for the West Angela Member is higher at 0.8 m/d. However, this probably occurs because it is only in proximity to an orebody where the West Angela Member would be differentiated as a specific hydraulic unit (as opposed to being lumped with other adjacent aquitards such as unmineralised Marra Mamba). In such areas, experience from the adjacent CPR study area suggests permeability can be enhanced in the West Angela Member due to a combination of thrust faulting (e.g. Marra Mamba orebodies of the North Flank), manganiferous deposits resulting in a high permeability honeycomb (e.g. Hope Downs and C Deposit) and mineralisation in subordinate BIF units within the West Angela Member. Recent testing at Jimblebar has suggested conditions could be similar. Thus, the higher estimates of hydraulic conductivity are likely to reflect the specific structural setting associated with mineralisation.

A key principle from the Australian Groundwater Modelling Guidelines (2012) is the process of simplification of the groundwater system. As such, on a regional scale, the hydrogeology can be simplified with the aquitards being lumped together. For example, unmineralised Brockman, Mt McRae and Mt Sylvia and the underlying Bee Gorge of the Wittenoom Formation could be considered a single aquitard; as could the low permeability West Angela Member and unmineralised Marra Mamba. In general, hydraulic conductivity of the aquitards is in the order 0.01 m/d.

3.2.4.5 Aquitards Associated with Geological Structure

The EPR area is structurally complex and is crossed by several major faults with a northeast/southwest orientation perpendicular to the regional strike. Available water level data suggest these structures act as hydraulic barriers with large falls in water level across them. The Wheelarra Fault, Whaleback and Homestead Faults are key examples. It is possible the Fortescue Fault (which occurs in subcrop beneath alluvium) acts in a similar manner.

3.2.4.6 Storage Coefficients

Unconfined and confined storage coefficients for the region are difficult to determine from field tests in the EPR. An aquifer unit at the weathered contact between basement and the overlying Tertiary detritals will typically be confined (i.e. "pressured") by the overlying lower-permeability Tertiary detritals. The response in a bore to abstraction is affected by leakage from these lower permeability units that overlie the abstraction horizon making the storage component difficult to isolate during analysis. As such, the storage coefficients derived through model calibration are likely to be more representative, especially where the model is being calibrated against a large stress on the system such as on-going groundwater abstraction (Table 3.12). Such estimates are available for CPR and EPR through on-going work at the North Flank Valley and Hope Downs (CPR), Jimblebar, Homestead Creek and Ethel Gorge (EPR).

The model-derived parameters should be adopted for hydrogeological conceptualisation.

Table 3.12: Estimates of Aquifer Storage Coefficients

Aquifer	Estimates of Specific Yield (Sy - %)					Estimates of Confined Storage (S - unitless)				
	min	max	average	median	count	min	max	average	median	count
Detritals - Undiff	0.001	0.1	0.065857	0.06	14	0.000005	0.0001	8.64E-05	0.0001	7
Calcrete/CID	0.06	0.08	0.066667	0.06	3	0.000005	0.000005	0.000005	0.000005	3
Fault	0.001	0.01	0.00325	0.001	4	0.0002	0.0002	0.0002	0.0002	1
Boolgeeda Formation [*1]	0.001	0.05	0.0255	0.0255	2	n/a	n/a	n/a	0.00001	0
Brockman ore	0.05	0.1	0.062692	0.06	13	0.0001	0.0002	0.000154545	0.0002	11
Brockman sub ore	0.001	0.05	0.0134	0.005	5	0.000005	0.00001	6.66667E-06	0.000005	3
Brockman BIF	0.001	0.005	0.002714	0.001	7	0.000005	0.0002	0.00005625	0.00001	4
Brunos Band	0.015	0.015	0.015	0.015	1	0.0002	0.0002	0.0002	0.0002	1
Whaleback Shale	0.01	0.01	0.01	0.01	2	0.0002	0.0002	0.0002	0.0002	2
Mc Rae	0.001	0.005	0.0026	0.001	5	0.000005	0.0002	0.0001025	0.000103	2
Mt Sylvia	0.001	0.005	0.0018	0.001	5	0.0001	0.0001	0.0001	0.0001	2
Bee Gorge	0.001	0.001	0.001	0.001	3	0.0001	0.0001	0.0001	0.0001	2
Weeli Wolli	0.001	0.005	0.0034	0.005	5	0.0002	0.0002	0.0002	0.0002	3
Dolomite	0.001	0.25	0.023619	0.0075	21	0.0001	0.0002	0.000157143	0.00015	14
Dolomite non aquifer	0.001	0.01	0.007	0.01	3	0.0002	0.0002	0.0002	0.0002	2
West Angela Shale	0.001	0.02	0.004111	0.001	9	0.00009	0.00015	0.000102857	0.0001	7
West Angela ore	0.001	0.001	0.001	0.001	2	0.000018	0.000018	0.000018	0.000018	2
Woongarra Formation [*1]	0.001	0.05	0.0255	0.0255	2	n/a	n/a	n/a	0.00001	0
MM ore	0.001	0.2	0.072462	0.075	13	0.000005	0.00027	0.000203333	0.00027	6
MM Sub Ore	0.001	0.1	0.0324	0.01	5	0.0001	0.00027	0.000156667	0.0001	3
MM BIF	0.001	0.01	0.004889	0.005	9	0.00005	0.0002	0.000175	0.0002	6
Jeerinah	0.001	0.03	0.0095	0.0075	8	0.000005	0.0002	0.000161	0.0002	5
Dolerite	0.001	0.001	0.001	0.001	1	0.00001	0.00001	0.00001	0.00001	1
Igneous [*1]	0.001	0.001	0.001	0.001	1	n/a	n/a	n/a	0.00001	0

*1 No estimates available from previous work - suggested value only

3.2.5 Groundwater Recharge

Groundwater recharge in the Pilbara occurs both as diffuse recharge and as concentrated recharge along creeks and areas of water impoundment (e.g. internal draining alluvial basins such as Wonnamunna and Coondewanna Flats and artificial features such as Ophthalmia Dam).

Generally, large soil moisture deficits prevent recharge in areas where depth to water is greater than around 30 mbgl. In areas where surface water volumes are concentrated and depth to water is particularly shallow (<15 mbgl), recharge occurs on an annual basis generally associated with the summer wet season. Elsewhere recharge may occur less frequently and is only associated with larger rainfall events.

The process of groundwater recharge can be observed in the response of groundwater levels. Hydrographs of groundwater levels spanning the EPR area are shown in Figures 3.13a to 3.13c. The following observations are important for discussion:

- Between 1970 and 1981, there was a general trend of declining groundwater levels caused by depletion of aquifer storage related to abstraction from Ophthalmia Borefield. Water levels declined by up to 10 m in some bores, as groundwater levels were at the lowest recorded.
- In 1981, Ophthalmia Dam was commissioned and groundwater levels started to recover as increased recharge caused by the dam replenished aquifer storage. Groundwater levels continued to rise through until 2000 (by up to 15 m) when, regionally, groundwater reached the highest levels on record. This demonstrates the dam has had a significant effect on increasing recharge to the alluvial aquifers of the Fortescue River floodplain, which is consistent with the large leakage volumes from the dam discussed in Section 3.1.2.5).
- Over most of the area, between 2000 and 2006, groundwater levels were essentially stable at this very high level. Through this period, seasonal fluctuations were generally smaller than when groundwater levels were lower and it is believed, in many areas where recharge may occur, the alluvial aquifer was fully saturated with no capacity to receive additional recharge.
- Groundwater levels have declined in several areas across the region as a result of dewatering: since 1986 at Whaleback and since 2006 at OB23 and OB25. The extent of decline varies with distance from the dewatering operations and degree of connection between the mine and the regional groundwater system. However, since 2006, groundwater level declines have been observed over a wide area on the Fortescue River floodplain suggesting good hydraulic connection and a general, relatively even decrease in aquifer storage across the aquifer. Notwithstanding, groundwater levels remain high in comparison with the lowest levels recorded prior to the commissioning of Ophthalmia Dam.
- Superimposed on these broad trends, there are seasonal responses to rainfall. Over alluvial channels and plains in the lower catchment (lower Homestead Creek and the Fortescue River floodplain), groundwater levels on an annual basis rise by 1 m to 3 m in response to recharge generated by rainfall runoff. The mid and lower catchment areas represent receiving areas of river channel and floodplain areas where surface water runoff is concentrated and attenuated.
- Elsewhere in the Upland and Transitional environments of hills, slopes and dissected drainage channels, catchment areas are smaller and runoff moves through the environment much more quickly affording less opportunity for large volumes to infiltrate. Infiltration is usually only sufficient to contribute to soil moisture and little groundwater recharge occurs. In these areas, hydrographs show muted long-term trends and responses to groundwater abstraction.

Groundwater recharge occurs preferentially on the Fortescue River floodplain between Ophthalmia Dam and Ethel Gorge. Based on a combination of hydrograph responses and the estimated water balance for the dam, total recharge in the EPR catchments is 100,000 kL/d and of this, it is estimated that 74,000 kL/d occurs between Ophthalmia Dam and Ethel Gorge. However, notwithstanding the daily average recharge rate, recharge actually occurs seasonally or periodically resulting from high magnitude low frequency rainfall events.

Of the estimated 74,000 kL/d recharge, approximately 50,000 kL/d is enhanced recharge from Ophthalmia Dam. The annual average recharge prior to the dam was estimated, by applying recharge rates more typical of creek channels to the area currently affected by impoundment from the dam. On this basis, it is estimate that total recharge prior to construction of the dam was in the order of 30,000 kL/d.

Chemical evolution of the groundwater suggests most recharge occurs as direct infiltration through the Tertiary detritals; correlation of recharge areas with depth to water suggests this takes place where the depth to water is less than 30 mbgl and where the catchment is large enough to generate substantial runoff volumes. However, it appears infiltration volumes in other areas are insufficient to result in significant recharge to the groundwater system, but rather replenish soil moisture.

The total EPR water balance suggests total recharge is approximately 100,000 kL/d. The remaining 26,000 kL/d of recharge that does not recharge on the Fortescue River floodplain probably occurs as seepage along the other major creek channels and as diffuse recharge across the catchment in response to subtle changes in soil moisture between wetter and drier periods. It is likely that this diffuse recharge occurs at low rates:

- At the valley margins, coarser sediments and colluvium (Steep Slope and Stony Slope landscape units) will capture runoff from the hills occurring both as sheetflow and channelised flow.
- Over the orebodies (Mountain and Steep Slope landscape units), the permeable geology at outcrop will allow infiltration of rainfall and of runoff occurring both as sheetflow and channelised flow.
- As seepage from alluvial gravels after flood events in the main creeks (Drainage Channel landscape unit).

Summarily, recharge is concentrated in receiving environments that comprise floodplains and river channels notably on the Fortescue River. Recharge is particularly enhanced by the attenuation of flow by Ophthalmia Dam.

3.2.6 Groundwater levels and flow

Contours of groundwater levels across the EPR are presented in Figure 3.14. The specific elevations of the watertable may vary seasonally and between longer periods of above or below average rainfall. Groundwater flow is generally in a north-easterly direction, converging on Ethel Gorge. Immediately south of Ethel Gorge, the water levels are approximately 505 mAHD and gradually rise in a southerly and westerly direction to the catchment boundary, reaching:

- 660 mAHD in the headwaters of Western and Spearhole Creeks (western tributaries of the Fortescue River).
- 640 mAHD in the headwaters of Homestead Creek.
- 600 mAHD in the far south of the project area in the headwaters of the Fortescue River and some Shovelanna Creek.
- 600 mAHD in the headwaters of Jimblebar and Caramulla Creek (the eastern most creeks draining the EPR area).

Most groundwater flow converges on the Fortescue River floodplain and Ethel Gorge with a shallow hydraulic gradient of approximately 0.001. The relatively low gradient indicates high permeability in the alluvial aquifers of the floodplain. Groundwater levels fall from 505 mAHD to 500 mAHD northwards through the gorge. The hydraulic gradient through the gorge is approximately 0.002. Hydraulic gradients steepen through the gorge where groundwater flow is constrained by the narrowing aquifer. However, the increase in gradient is not as great as would be expected were all the throughflow from the Fortescue River floodplain to discharge through the gorge. This indicates additional groundwater discharge from the aquifers of the floodplain other than throughflow into the gorge (cf Water Balance - Groundwater Discharge).

Groundwater levels are high on the plateau of Jeerinah Formation at Wonnamunna in the west. This marks an indistinct groundwater catchment boundary between the headwaters of Weeli Wolli Creek and the adjacent Coondiner Creek to the northwest of the EPR, Turee Creek to the south west and tributaries of the Fortescue River within the EPR. Hydraulic gradients indicate a component of flow across the strike of the Jeerinah Formation to the southeast, draining into tributaries of the Fortescue River flow systems. Groundwater gradients are steep which demonstrate the generally low-permeability across strike and the generally low permeability nature of the Jeerinah Formation.

In several areas, low-permeability faults cross the regional flow system and act as barriers to groundwater flow, causing significant changes in groundwater levels and restricting flow across the faults:

- In the Whaleback area, the Whaleback Fault (northeast/southwest orientation) results in a water level difference of 40 m (560 mAHD to 520 mAHD across the fault on the north side of the Whaleback pit) over a distance of only a few hundred metres.
- A northeast/southwest fault across Homestead Creek in the Homestead mining area results in a water level difference of 10 m (530 mAHD to 520 mAHD) over a very short distance and restricts groundwater flow to the southeast along the alluvial/dolomite aquifer in the Homestead valley.
- The Wheelarra Fault (northeast/southwest orientation) and a series of fault splays result in a water level difference of approximately 50 m (480 to 430 mAHD) over a relatively short distance between the Shovelanna and Jimblebar mining areas. This overall fault system (and lateral displacement of aquifers/aquitards along the faults system) effectively compartmentalises, along strike, and separates the groundwater system into two distinct areas.
- Historically, groundwater resources on the Fortescue Flood Plain were subject to over-abstraction for water supply. However, the construction of Ophthalmia Dam and the use of dewatering abstraction for water supply has ameliorated the impact of previous water supply abstraction from the Ophthalmia Borefield. The effects of dewatering at OB23 and OB25, and Whaleback can still be seen.

3.2.7 Groundwater Discharge

3.2.7.1 Natural Discharge

Natural groundwater discharge occurs primarily through the extensive vegetation stands in the receiving environments comprising river channels and alluvial plains along the lower reaches of Homestead and Shovelanna Creek and in particular the Fortescue River. It is estimated that total groundwater discharge through evapotranspiration is in the order of 75,000 kL/d and this occurs from approximately 4,500 ha of vegetation.

Under natural conditions, there is a small component of groundwater throughflow to the north towards the Fortescue Marsh. This occurs as diffuse flow through the Jimblebar mining area and as more concentrated throughflow in the Ethel Gorge alluvial aquifer. It is estimated that under natural conditions, total groundwater outflow is in the order of approximately 12,000 kL/d. However, much of this outflow through Ethel Gorge has been more recently captured by dewatering at OB23; mine developments in the Jimblebar area may similarly decrease outflow from the eastern EPR catchments.

3.2.7.2 Existing Users - Additional Groundwater Discharge

Another important loss of groundwater from the natural hydrological system is through abstraction to support mining operations and the town of Newman. The main sources of abstraction within the EPR area are associated with the Whaleback, OB23 and OB25 operations, the OB18 and Jimblebar Borefields, and potable water abstraction from the Ophthalmia Borefield which will be augmented by the newly commissioned Homestead Borefield.

3.2.8 Connectivity with the Environment

The depth to water across the study area varies between 0 mbgl and over 100 mbgl (Figure 3.15). Depth to water is greatest in the upland and transitional landscape units where runoff is generated and initially flows. Whereas, depth to water is shallowest in receiving receiving landscape units where surface and groundwater flow concentrates.

Depth to water is of key importance in influencing vegetation communities; as the depth to water exceeds 20 mbgl, so the vegetation becomes increasingly xerophytic. Additionally, where depth to water is greater than 20 mbgl, there is a thicker unsaturated soil column which must be wetted before recharge can occur. Thus, depth to water is also an important control on groundwater recharge.

The upland and transitional landscape units, where the depth to water is well below the root-zone of the riparian vegetation, are characterised by xerophytic species such as Snappy Gums, Acacia and hummock grasses; such environments cover much of the EPR. Walvoord et al. (2002) suggested that the soil moisture deficit created by such arid-zone riparian vegetation, in the upper 10 m or so of the soil profile, is sufficient to prevent significant groundwater recharge However, while not contributing substantially to recharge, the infiltration of surface water remains an important contributor to the soil moisture budget and support for the xerophytic environment.

Depth to water ranges between 0 and 10 mbgl at Ethel Gorge and over the Fortescue River floodplain, depending on both local topography and seasonal factors. Over all of this range in depth to water, groundwater will be readily accessible by opportunistic phreatophytic vegetation such as *E.victrix* (Coolibah) and *E. camaldulensis* (River Red Gum). At the shallower end of this range (0-5 mbgl), likely in proximity to creek channels, groundwater will be readily accessed by obligate phreatophytic vegetation such as *M. glomerata* (Paperbark). The distribution of these vegetation types is marked on Figure 2.3 as a evapotranspiration discharge zone .

Moreover, such a range in groundwater levels maintains a substantial saturated thickness in the upper alluvial aquifer (including the calcrete) and provides a consistent habitat for stygofauna. The area of the TEC is also marked on Figure 2.3 and coincides with both areas of shallow groundwater and deposits of calcrete and alluvium.

The shallow depth to water will result in relatively small soil moisture deficits to overcome and recharge from runoff events will occur readily increasing groundwater-surface water connectivity in areas with shallow groundwater levels.

3.2.9 Hydrochemistry

Figure 3.16 and shows water types ranging between:

- Calcium/magnesium and bicarbonate type water - characteristic of recharge water in the Pilbara.
- Water with no dominant anion or cation - characteristic of an intermediate groundwater that has been subject to some mixing, dissolution and evapotranspiration.
- Sodium/chloride type water - characteristic of a mature groundwater that has undergone both evolution through mixing and evapotranspiration.
- TDS ranged from 500 mg/L to 2,000 mg/L, generally increasing as the groundwater becomes more mature. The increase in salinity occurs as groundwater flows towards Ethel Gorge and results from evapotranspirative concentration of salts as water flows through the shallow alluvial aquifer.

Overall, the chemistry suggests an environment where groundwater quality evolves during recharge and aquifer residence - notably through the adsorption of carbonate and magnesium, and ion-exchange related increases in sodium. Groundwater in the alluvial aquifer evolves to a sodium-chloride type suggesting evapotranspiration plays a major role in its evolution and the influence of groundwater-surface water-vegetation interaction, particularly on the alluvial aquifer of the Fortescue River floodplain

3.3 Water Balance

The overall water balance for EPR accounts for surface water flow, groundwater recharge, natural groundwater discharge, groundwater abstraction, and changes in groundwater storage.

The groundwater balance for the EPR area (prior to dewatering at OB23, OB25 and Jimblebar) has been developed using both a chloride mass balance and also an assessment of recharge and discharge as outlined in sections 3.2.5 and 3.2.7. The water balance is summarised in Table 3.13.

3.3.1 Chloride Balance - Groundwater Outflow

Chloride is considered a conservative element in the natural environment. In the EPR area, groundwater is generally fresh and there are no salt pans or salinas; there are no obvious areas of active salt accumulation. As such, it can be assumed that the chloride delivered to the catchment (as a solute in rainfall) will equal chloride leaving the catchment (as a solute in water outflow). Groundwater outflow from the Fortescue catchment can be estimated using the Chloride balance approach due to good available data and the concetration of flow into the relatively narrow channel (Ethel Gorge). However, no such detailed controls on water quality (chloride) are available for the catchments in the Jimblebar area. As significant abstraction has not occurred in these catchments to date, it is simply assumed that recharge and discharge in these catchments are in balance.

The key components of the chloride balance for the Fortescue catchment are summarised below:

1. Chloride inflow to the groundwater system as solutes in rainfall over the entire catchment area at an annual average rate of 320 mm/yr (based on the Newman rain gauge). The concentration of chloride in rainwater is estimated at 0.5 mg/L (PB, 2013).
2. Chloride outflow as solutes in surface water through Ethel Gorge (representing the combined surface water discharge from Homestead, Shovelanna and Warrawanda Creeks and overflow from Ophthalmia Dam representing the non-regulated discharge from the Fortescue River). The combined surface water outflow through Ethel Gorge has been estimated from a combination of gauged flows at the dam and derived flows for the tributary creeks. This approach provides an annual average outflow of 41,400 ML/yr. The measured chloride concentration in flood flows through Ethel Gorge ranges between 5 and 7 mg/L; as a result, 6 mg/L has been used to estimate the chloride flux.
3. Chloride outflow as solutes in groundwater abstracted for water supply purposes from the Ophthalmia Borefield. Over the period for which the water balance was assessed (2000-2006), water supply abstraction was approximately 10,000 kL/d with a typical chloride concentration of 120 mg/L. However, most of the water supplied will ultimately return to the groundwater system as leakage from the distribution network, irrigation return flows from domestic gardens and seepage of treated sewage effluent. Permanent consumptive use has been estimated at only 50% of total water supplied (i.e. 50% water return).
4. Chloride outflow as solutes in groundwater throughflow along Ethel Gorge. Water chemistry data are available from abstractions from the Ophthalmia Borefield and more recently from OB23. The concentration of chloride in the groundwater of Ethel Gorge is approximately 500 mg/L. The groundwater flow volume has not been measured. However, assuming that chloride is in balance, then the volume is estimated as that required to remove the required volume of chloride to maintain balance (given the other components of chloride input and output outlined above). It is estimated that groundwater outflow is approximately 3,000 kL/d. This number is comparable with an estimate of throughflow based on hydraulic gradients and aquifer properties made by PB (2013).

3.3.2 Water Balance - Summary of Groundwater Fluxes

Total recharge and discharge under steady-state conditions with Ophthalmia Dam operational are estimated to be approximately 100,000 kL/d and of this, 75,000 kL/d occurs in the Fotescue River catchment. The overall water balance for the Fortescue catchment is summarised in Figure 3.18. Ophthalmia Dam is a major contributor to groundwater recharge.

The major discharge from the EPR area is evapotranspiration. For the period considered, it is estimated that evapotranspiration losses account for 75,000 kL/d and of this, 60,000 kL/d occurs on the Fortescue River flood plain in the area around Ethel Gorge.

Table 3.13: EPR Water Balance (Steady State / Pre-Mining)

Chloride Balance

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	
2	GW throughflow conc		500	mg/L	measured AAR
3	Surface Water Flood Concentration		6	mg/L	measured Ethel Groge
4	Water Supply concentration		100	mg/L	measured AAR
	Measured Parameters				
5	Catchment Area	5030		km^2	
6	rainfall	320		mm/yr	Newman rain gauge
7	Rainfall Volume	1,609,600,000		m^3/year	5*6
8	Surface Water Outflow	41,401,000		m^3/year	Calculated
9	Water Supply Pumping	3650000		m^3/year	measured AAR
	Chloride Movement				
10	Chloride inflow from rain		8.0480E+11	mg/year	1*7
11	Cl outflow - surface water flood		2.4841E+11	mg/year	8*3
12	Cl in consumptive water supply		1.8250E+11	mg/year	9*4*consumption factor
	Unaccounted for Chloride - groundwater outflow				
13	(Cl rain) - (Cl out through surface flow)		3.7389E+11	mg/year	Balance of Cl flux
	Water Balance				
14	**calculated GW outflow**	**2,047**		**m^3/d**	13/2; Volume required to remove (13)Cl at 500mg/L

Current Groundwater Balance

Feature	kL/d	Remarks
Groundwater Recharge - Fortescue		
Direct Recharge along Fortescue	13700	hydrograph analysis - ~annual
Direct recharge along Homestead/below Dam	10500	hydrograph analysis - ~annual
Seepage from Dam	50000	water balance calculation based on dam water levels (RPS and PB ~5-6mm/day)
Additional recharge (below dam)	4000	additional aquifer capacity due to drawdown
Discharge to Infiltration Ponds	10000	excess dewatering not put in dam
Diffuse Recharge over remainder of catchment	2000	inflow from upstream catchment area
Groundwater Recharge - Jimblebar Area		
Reharge over Jimblebar Creek	2002	estimated at 0.7% annual rainfall
Reharge over Caramulla Creek	4298	estimated at 0.7% annual rainfall
Reharge over Davidson Creek	3676	estimated at 0.7% annual rainfall
Total Groundwater Recharge	**100176**	
Groundwater Discharge		
Groundwater Outflow (Ethel Gorge)	2047	calculated from Cl balance
Groundwater Outflow (Jimblebar area)	9976	assume no reduced outflow
Water Supply Pumping	12300	measured data (Ophthalmia and OB18)
Evapotranspiration	75853	calculated by difference for whole catchment
Total Groundwater Discharge	**100176**	

3.4 Hydrological Landscape Conceptual Framework

The conceptual hydrological system is outlined in Figure 3.17 and salient features of the integrated surface water, groundwater and landscape system in the EPR area are shown in Figure 3.18 and summarised below:

3.4.1 Geomorphology

- The EPR area comprises alluvial valleys and plains bounded by steep hills formed of basement outcrop. It includes EHUs 1 to 9 described in Table 1.2 and Figures 1.4 and 1.5.
- The hills constitute Upland Source Landscape Units (EHUs 1 and 2).
- The lower slopes and upstream alluvial areas include drainage floors and dissected drainage channels corresponding with Upland Transitional Landscape Units (EHUs 3 and 4).
- The valley flats and plains include Lowland Transitional Landscape Units (EHUs 5 and 6, and restricted occurrences of EHU 7 in the upper reaches of Spearhole Creek).
- The lower reaches of the catchments support a Lowland Receiving Landscape Unit of river channels and alluvial plains (clay-pan and hard-pan) corresponding with EHUs 8 and 9. These areas are extensively represented on the Fortescue River and Warrawanda Creeks.

3.4.2 Hydrology

- Annual average rainfall across the area is 258 mm (since 1900); the average since 1985 is 319 mm indicating a general wetting trend.
- The median annual runoff is approximately 2.5% of annual rainfall for the EPR area. Average annual runoff is higher at approximately 5.4%indicating the disproportionate influence of high magnitude low-frequency events.
- Runoff in the Ethel Gorge catchment is attenuated by Ophthalmia Dam. The dam has a maximum capacity of 31 GL and estimated average annual inflow to the dam is 28.6 GL.
- Water impounded in the dam is lost to evaporation and seepage into the underlying alluvial aquifer.
- Runoff is generated in the Upland Landscapes. The brevity of runoff-duration and limited volume afford little opportunity for groundwater recharge.
- When combined with topographic elevation and poor soils of the Upland Source Landscape Unit, this suggests the watertable is predominantly deep (>40 mbgl) and vegetation is xerophytic - runoff only plays an important role in replenishing shallow soil moisture.
- A key hydrologic process in the Upland Source Landscape Unit is the generation of overland flow and direct infiltration to replenish shallow soil moisture periodically.
- In the Upland and Lowland Transitional Landscape Units, surface water flow volumes increase as runoff is progressively concentrated in drainage channels; larger volumes infiltrate and some recharge occurs. In the drainage channels crossing the Transitional Landscapes Units, the watertable remains relatively deep (>30 mbgl) but due to the accumulation of alluvial sediments, soil moisture is more abundant supporting vadophytic trees such as Coolibahs in addition to xerophytic species.
- Key hydrological processes in the Transitional Landscape Units are sheet flow and direct infiltration to support the xerophytic vegetation of the stony plains and infiltration from channel flows to replenish deeper soil moisture in the vadose zone along the drainage lines.

3.4.3 Groundwater Recharge

- Groundwater recharge occurs preferentially in the Lowland Receiving Landscape Unit along the river channels and alluvial plains of Homestead and Warrawanda Creeks and the Fortescue River. Here, water levels are relatively shallow with vadophytes and phreatophytes relying on both abundant soil moisture and shallow groundwater.
- Recharge is enhanced by seepage from Ophthalmia Dam.
- The key hydrological processes in the Receiving Landscape are the concentration of surface

and groundwater flow from upstream and local recharge and also seepage from Ophthalmia dam, to support shallow groundwater levels.

- Over much of receiving environments of river channels and floodplains, recharge occurs on an almost annual basis. The annual average recharge rate is 74,000 kL/d; up to 50,000 kL/d originates as seepage from the dam.
- Recharge occurs at diffuse low volumes across the remainder of the catchment at an annual average rate of 2,000 kL/d.

3.4.4 Aquifer System

- Flow within the regional aquifer system is hosted in valley aquifers of Tertiary detritals, and underlying dolomite. Groundwater flow occurs from the south west to northeast, converging predominantly on Ethel Gorge and to a lesser extent on flow through Jimblebar and Caramulla Creeks.
- Calcrete and coarse alluvium within the detrital profile and karstic zones within the dolomite are the primary aquifers. The median value for permeability for these aquifers is 20 m/d and 10 m/d respectively.
- The aquifer system is surrounded by low permeability geology of shales and unmineralised BIF. Overall, these aquitards have permeability ranging between 0.001 and 0.01 m/d.
- There are zones of higher permeability associated with orebodies that form local aquifers within the low-permeability valley-surrounds. The median permeability of Brockman and Marra Mamba ore is 3.2 m/d and 3.6 m/d respectively.
- The extent to which the orebody aquifers are in hydraulic connection with the broader regional aquifer varies with site-specific geology - notably the presence of thrust faults through the orebodies and the juxtaposition of ore and Tertiary detritals.
- The region is crosscut by several faults that form low-permeability barriers to groundwater flow. The faults do not actually disrupt the overall flow direction but there are differences in groundwater levels of between 10 to 50 m across them.

3.4.5 Groundwater Discharge

- Groundwater discharge occurs predominantly on the floodplains and channels of the Fortescue River and Homestead Creeks as evapotranspiration from extensive vegetation at an estimated average rate of 63,000 kL/d from some 3,650 ha of vegetation.
- Groundwater throughflow is a relatively small component of discharge and is estimated to be 3,000 kL/d.
- Under natural conditions, the project area is characterised by large volumes of recharge to and evapotranspirative losses from the alluvial aquifer on the Fortescue River flood plain.

  There is active mining in EPR area with associated abstractions for both water supply and mine-dewatering. Groundwater abstractions for water and dewatering exceed the natural throughput resulting in the depletion of groundwater storage and groundwater levels in the area have declined as a result. However, much of this is offset by annual groundwater recharge, enhanced by Ophthalmia Dam.

4. ECOHYDROLOGICAL CONCEPTUALISATION

4.1 Regional Receptor Assessment

4.1.1 Landscape EHUs

Eight of the nine identified EHUs are represented in the landscapes of the EPR study area (Table 4.1; Figure 4.1). Upland areas (EHUs 1 and 2) are principally associated with the Ophthalmia Range and other peaks and ranges (e.g. Western Ridge, Robertson Range, hills and ridges south of Jimblebar). The span of EHU 2 also includes the extensive granitic, stony hills and plains south and east of Newman. EHU 1 typically includes dendritic networks of drainage floors and channels (EHUs 3 and 4). EHU 2 includes sloping country, in some cases immediately down-gradient from EHU 1, which is dissected by ephemeral creeks. Within EHU 2 these may further coalesce before feeding into lowland areas.

Lowland areas include alluvial plains (EHU 6) principally associated with valley systems of the major drainage lines. An area of calcrete plains (EHU 7) occurs in the upper reaches of Spearhole Creek. Major channel systems (EHU 8) are associated with the Upper Fortescue River and its major tributaries, in addition to the major river systems further east.

Groundwater flow tends to parallel the major valley systems at a regional scale. Ethel Gorge is an area of surface and groundwater coalescence associated with the Upper Fortescue River and its tributaries.

The key ecohydrological characteristics of each EHU are described in Table 1.2 (Section 1.3), with further detail provided in Appendix F (of the main report).

4.1.2 Identification of Ecohydrological Receptors

Ecological assets which display a high level of connectivity have been identified as hydroecological receptors. Within the study area, Ethel Gorge has been identified as an ecohydrological receptor that supports a shallow groundwater system, hosts the Ethel Gorge aquifer stygobiont community TEC, and extensive riparian vegetation communities (Figure 4.1).

No other ecohydrological receptors have been identified in the study area based on available knowledge and information. However, it is possible that other significant stygofauna and riparian vegetation communities could occur in association with poorly surveyed riparian environments (EHU 8), such as the creek systems east of Newman.

Ecological assets considered to have a low level of ecohydrological connectivity are summarised as follows:

- Flora species of conservation significance such as *Lepidium catapycnon* (Declared Rare Flora) and various priority flora taxa recognised by the Department of Parks and Wildlife (DPaW), which do not occur in EHU 8.
- Fauna species of conservation significance whose habitat requirements are not strongly dependent on, or otherwise intimately associated with, the Ethel Gorge aquifer stygobiont community TEC.

Table 4.1: Summary of EHUs within the EPR Study Area

EHU	Percent project area	Distribution in project area	Component land systems
1	16.6%	Mountainous rugged terrain associated with the major peaks and ranges (e.g. Ophthalmia Range, Western Ridge, Robertson Range, hills and ridges south of Jimblebar)	Newman; Rocklea (major) Augustus; Charley; Laterite; McKay; Robe; Robertson; Table; Talga (minor)
2	35.3%	Foot slopes of the Ophthalmia Range and other peaks and ranges (mainly west of Newman), and stony hills and plains associated with granite south and east of Newman.	Prairie; Sylvania (major) Adrian, Boolgeeda; Collier; Egerton; Elimunna; Nirran; Platform (minor)
3	5.8%[1]	Drainage floors within EHUs 1 and 2	Within EHUs 1 and 2
4	2.9%[1]	Major channels within EHUs 1 and 2	
5	13.2%	Sandplains and occasional dunes between the Fortescue River and Warrawanda Creek, and east of Jimblebar Creek.	Divide
6	21.5%	Alluvial plains associated with major valley systems and generally adjacent to major drainage lines.	Spearhole; Jamindie; Washplain (major) Balfour; Cadgie; Nooingin; Turee; Wannamunna; Zebra (minor)
7	0.7%	Low calcrete platforms and plains in the upper reaches of Spearhole Creek, in the south west portion of the Study Area.	Warri (major) Calcrete (minor)
8	4.0%	Associated with the river channels and floodplains of the major rivers and creek i.e. Upper Fortescue River and lower sections of its tributaries (Western Creek, Spearhole Creek, Warrawanda Creek/Sylvania Creek, Shovelanna Creek), and the major creek systems further east (Jimblebar Creek, Caramulla Creek, Thirteen Creek and Jigalong Creek).	River (major) Fortescue; Jigalong (minor)

[1] Estimated based on proportional frequency in mapped areas.

4.2 Ethel Gorge

4.2.1 Overview

Ethel Gorge (The Gorge) is on the Fortescue River some 15 km northeast of Newman (Figure 4.2). The Gorge is downstream (north) of the confluence of Homestead, Shovelanna and Warrawanda Creeks within the Fortescue River. It is formed where the Fortescue River flows through the Ophthalmia Range in a northerly direction. Downstream of The Gorge, the river flows in a narrow channel to the north, then onto a broad floodplain and ultimately into the Fortescue Marsh.

The Fortescue River and its surrounding floodplain in the vicinity of Ethel Gorge is a Lowland Receiving Landscape Unit classified as EHU 8 (refer to Section 1.3). Surface and groundwater flows from the entire upstream catchment area are focused into Ethel Gorge, resulting in relatively shallow groundwater levels typically less than 10 m below ground level (mbgl). This provides the basis for interactions between the groundwater system and the terrestrial environment.

The area hosts the Ethel Gorge Stygobiont TEC. The community was described by TEC Scientific Committee (2006) as inhabiting the “Ethel Gorge/Ophthalmia Basin alluvium calcrete aquifer”. The nomination stated “there is no evidence that the habitat of the community is not the whole Ophthalmia Basin aquifer, but it may be restricted to the most permeable alluvial and calcrete formations within that aquifer”. The official location of the TEC in 2006 was -23.31667° S, 119.85000° E with a buffer of radius 13 km around that site (Figure 1.1). The extent of surface calcrete at Ethel Gorge was determined to be the boundary of the TEC itself in November 2012, and a buffer of 6 km beyond the calcrete was added (Figure 4.2).

Aquifers in and around Ethel Gorge have been used for town and mine water supplies for Newman since the Ophthalmia Borefield (formerly the Ethel Gorge Borefield) was developed in 1969. Abstraction from the borefield steadily increased during the 1970s, leading to concerns regarding the long-term sustainability of the resource. A managed aquifer recharge (MAR) scheme - Ophthalmia Dam - was constructed on the Fortescue River and started operation in 1982. The dam is 5 km upstream of Ethel Gorge and was constructed to augment groundwater resources in the Ethel Gorge area. The dam impounds water much of the time and forms a largely permanent surface water body in close proximity to The Gorge. The dam has an important influence on the hydrological system of Ethel Gorge. The Ophthalmia Borefield currently comprises 10 bores (E, K and H-Line series).

Many of the mining areas and the town of Newman are located in the Ethel Gorge catchment, although most deposits are some distance from Ethel Gorge itself. However, the Eastern Ridge and East Ophthalmia mining areas occur in particularly close proximity to The Gorge. Since 2006, aquifers in the area around Ethel Gorge have been affected by dewatering at OB23 and OB25 in the Eastern Ridge mining area. Dewatering abstraction has been used to make up a significant proportion of mine water demand which has resulted in a reduced draw from the Ophthalmia borefield. Excess water from dewatering is discharged to Ophthalmia Dam and recharge ponds downstream of the dam.

4.2.2 Previous Work

The Ethel Gorge area has been the focus of numerous previous studies involving both drilling and testing, monitoring and groundwater modelling dating as far back as 1970. Synthesis of the resulting data gives a high degree of confidence in the conceptual understanding of the Ethel Gorge hydrological system.

Studies have occurred over many years and relate to the development of the Ophthalmia Borefield, Ophthalmia Dam and dewatering at OB23 and OB25. Additionally, operational monitoring has also been collected. Numerous monitoring bores have been installed, however the quality of data is variable with many bores having only sporadic or partial records. Geology/construction information is not available for all of the bores. Nevertheless, the resulting monitoring record is substantial, with some bores having long periods of continuous record extending as far back as 1970.

The monitoring record show the hydrological system responded to several major stresses: including medium term climatic variation with several periods of prolonged above and below average rainfall, artificial recharge induced by Ophthalmia Dam, a "distributed" stress from water supply abstraction in the Ophthalmia Borefield and a significant local stress due to dewatering-induced drawdown of up to 100 m in OB23 and OB25. The monitoring record also reveals the range through which water levels have historically fluctuated in the shallow aquifers that support the environmental assets around Ethel Gorge.

A groundwater model of the area was developed during the EIA for OB23 and OB25 dewatering and this has been subject to ongoing re-calibration against the effects of dewatering at both orebodies. Re-calibration efforts have provided updated aquifer parameters and distilled key elements of the groundwater system (RPS, 2013). The water balance of Ophthalmia Dam has been recently assessed as an option to receive excess dewatering discharge from Jimblebar (RPS Aquaterra, 2010); and as part of an assessment of the impact of the dam on groundwater resources (Parsons Brinckerhoff, 2013).

Previous modelling, along with studies of the water balance for Ophthalmia Dam, have helped refine many aspects of the catchment water balance including throughflow in Ethel Gorge and recharge to the groundwater system from the dam.

An environmental assessment of groundwater dependent vegetation was completed (Ecologia 1997), as part of the approval for OB23, when both the stygofauna and vegetation communities were mapped. Since then additional work has been undertaken, in particular relating the distribution and constraints on stygofauna (e.g. Aquaterra 2001, Env 2011, Bennelongia 2013 and Onshore Environmental 2013). There are no reports available on evapotranspirative water use by vegetation in the Ethel Gorge area. However, comparable estimates of tree water use are available from other areas in the Pilbara (e.g. Weeli Wolli Spring, Paraburdoo Creek (Rio Tinto 2010 and SKM 2012)).

4.2.3 Ecological description

The ecology of the Ethel Gorge area is defined by surface and subsurface inflows and the presence of a shallow groundwater system associated with the Fortescue River and its floodplain. This supports riparian vegetation communities, permanent and persistent pools and a unique stygofauna community associated with calcrete habitat.

The vegetation of the major channels includes some uncommon communities of dense riparian and woodland vegetation (Figure 4.2). Major vegetation types include (DEC 2013):

- Open Forest of and *Eucalyptus camaldulensis* (River Red Gum) over sedges of *Cyperus vaginatus* and *Typha domingensis* along major drainage lines.
- Open Woodland of *Eucalyptus victrix* over Low Open Woodland of *Acacia citrinoviridis* over Scattered Tussock Grasses of *Cenchrus ciliaris.*
- Open Mallee of *Eucalyptus socialis* subsp. *eucentrica* over Very Open Hummock Grassland of *Triodia pungens* on floodplains.

The vegetation includes facultative (*E. camaldulensis; E. victrix*) phreatophytes that use the shallow groundwater and hence contribute to groundwater discharge. The proportion of vegetation water use contributed by groundwater, in comparison with surface inputs to the unsaturated profile (i.e. rainfall and runoff), is unknown. It is possible that in some areas groundwater is only accessed transiently, during prolonged dry periods where the unsaturated profile dries out. In general terms a greater reliance on groundwater would be expected as the depth to watertable decreases. This is due in part to less storage in the unsaturated zone when the groundwater is close to the surface. Vegetation communities overlying stygofauna habitat may be an important source of carbon and nutrients for stygobiont communities. Phreatophytic roots are known to be a source of organic matter to aquifer invertebrates (Jasinska et al*.,* 1996).

The Ethel Gorge area hosts a number of permanent and persistent pools, for which little ecological information is available. These pools may be an important source of carbon and nutrients for stygobiont communities. This also applies to the Ophthalmia Dam, which leaks water into the Ethel Gorge shallow groundwater system (refer to Section 4.2.4.3).

A unique and diverse stygofauna assemblage was identified in the shallow alluvial and calcrete aquifers of Ethel Gorge in the late 1990s (Bradbury 2000; Boulton et al. 2003). This was subsequently classified as the Ethel Gorge Aquifer Stygobiont Community TEC. The shallow groundwater system host approximately 53 species of stygofauna including *Chydaekata* sp. amphipods, the presence of which formed the original basis for the identification of the TEC (DEC 2013). In the absence of definitive boundaries for the stygofauna distribution, the DEC demarcated a 6 km buffer zone around the TEC. Groundwater levels in this area can fluctuate in response to climatic drivers; however, habitat for stygofauna is considered to be maintained by zones of permanent saturation in the shallow alluvial groundwater system. At Ethel Gorge, stygofauna are uncommon in the deeper groundwater system being separated from the shallow groundwater system by low permeability clay layers.

Information on habitat requirements for stygofauna, including their distributions within heterogeneous groundwater environments and tolerances of differing water qualities, is very limited in the Pilbara and elsewhere (DoW, 2013). As a general rule, stygofauna are often most abundant and diverse near the watertable, with species richness and abundance decreasing with distance below the watertable in association with decreasing oxygen and nutrients (Stumpp & Hose, 2013). Areas with a shallow watertable typically have greater stygofauna diversity, where attenuation of organic matter and oxygen by the overlying unsaturated profile is minimised. Areas with watertable depth of less than 15 m from the surface have been found to favour high stygofauna diversity in alluvial aquifers in eastern Australia (Hancock & Boulton, 2008). However the depth at which stygofauna communities can persist is also influenced by different geologies, such as calcrete or karst. Where transfer of water from the surface to aquifer is rapid, the suitable depth to watertable is likely to be greater.

The quality of stygofauna habitat may be influenced by the level of connectivity between pores, cavities, and fractures which facilitate fauna movement and dispersal. The spatial heterogeneity of the calcrete habitat at Ethel Gorge is not well understood. The zone of watertable fluctuations (i.e. the boundary between unsaturated and saturated zone) may constitute a zone with different species assemblages in comparison with constantly saturated and unsaturated zones respectively; however this has not been confirmed at Ethel Gorge.

The ability of stygobitic species to recolonise areas that become re-saturated after a dewatering event is unknown. However in the Ethel Gorge area, the high watertable and seasonally variable influx of water from storm events are likely to aid in stygofauna fauna dispersal.

4.2.4 Hydrological Processes

4.2.4.1 Fortescue River at Ethel Gorge

Several creek systems drain into the Fortescue River upstream from Ethel Gorge with the main creek systems comprising Homestead Creek, Whaleback Creek, Shovelanna Creek and Warrawanda Creek (Figure 4.3). Prior to passing through Ethel Gorge, the main Fortescue River together with the Whaleback and Warrawanda Creeks discharge into Ophthalmia Dam and only when full would surface runoff overflow the dam and discharge downstream through Ethel Gorge.

Upstream from its entry into Ethel Gorge, the Fortescue River has a total catchment area of 4,872 km^2. In comparison, the catchment area upstream from Ophthalmia Dam is 4,319 km^2 which represents 89% of the total catchment upstream from The Gorge. Catchment areas for the main contributing creek systems draining to Ethel Gorge and Ophthalmia Dam are given in Table 4.2. The groundwater catchment is considered to broadly reflect the surface water catchment.

Table 4.2: Ethel Gorge Catchment Areas

Catchment	Area (km^2)
Fortescue River Upstream from Ophthalmia Dam	2,889
Warrawanda Creek Upstream from Ophthalmia Dam	1,225
Whaleback Creek Upstream from Ophthalmia Dam	205
Total Catchment Area Upstream from Ophthalmia Dam	4,319
Shovelanna Creek Upstream from Ethel Gorge	248
Homestead Creek Upstream from Ethel Gorge	305
Total Catchment Area Upstream from Ethel Gorge	4,872

Within Ethel Gorge, the Fortescue River has a wide, semi-braided, sandy gravel bed of variable width, typically around 100 to 200 m wide though wider in places, and has variable bank heights, typically around 1 to 2 m high. This river section has an average bed slope of approximately 0.2%. Local catchment and flowpath details approximately Ethel Gorge and Ophthalmia Dam are given in Figure 4.3. In addition to the main catchments defined above, the Fortescue River within Ethel Gorge also receives runoff from small local catchments located on the Ophthalmia Range.

In common with most natural drainages in the Pilbara, the Fortescue River catchment has ephemeral flow in direct response to rainfall. With its natural flow regime, the Fortescue River main channel carries low to medium flows, and large flood flows tend to overtop the banks into the adjacent floodplains. Within Ethel Gorge, the river bed comprises sandy gravels, indicative of moderate flow velocities, whereas the floodplains comprise sands and silts indicative of slower flow velocities. Bands of eucalypt trees are supported within the river bed (Plate 3.1) as well as along its banks.

4.2.4.2 Catchment Runoff Volumes

The Fortescue River (Newman) streamflow gauging station (DoW Station 708011) is the only streamflow station installed on the tributaries discharging to Ethel Gorge (Warrawanda, Whaleback, Shovelanna and Homestead Creeks). Based on the available historical record from this station (1980 – 2013), the Fortescue River has one to three flow events per year. Each flow event typically persists for several days to several months, although longer periods of flow have been recorded. For example, in 1999/2000 the Fortescue River flowed for over 12 months due to Tropical Cyclone John (December 1999) and consistently high rainfall in January – March 2000.

When a runoff event occurs in the Fortescue River, runoff would also likely occur in the surrounding Warrawanda, Whaleback, Shovelanna and Homestead Creeks, although it is predicted (and supported by anecdotal evidence) that these smaller creeks typically flow for a shorter duration for the same rainfall event.

An assessment of the Fortescue River runoff characteristics has been undertaken by comparing the recorded streamflow volumes at the Fortescue River (Newman) DoW gauging station with SILO rainfall for the catchment. Monthly data for these variables between January 1980 and April 2013 are presented in Figure 3.7. As most rainfall typically occurs during the December to April period, most runoff also occurs during this period.

Plots of the annual runoff percentage versus annual rainfall (using the July to June water year) and the monthly runoff percentage versus monthly rainfall for the Fortescue River catchment are shown in Figure 3.8. As expected, although these data points show a large scatter, they generally show that runoff increases with rainfall and relationship trend lines have been plotted.

The annual correlation between rainfall and runoff percentage, for the 33 year data period available at the Fortescue River (Newman) gauge, gave annual runoffs which varied between 0.03% and 18.2% of the corresponding annual rainfall. The total catchment runoff over the 33 year period is estimated at 5.4% of the total rainfall (i.e. average 17.0 mm/year) and median annual catchment runoff is estimated at 2.5% of median annual rainfall (i.e. 6.6 mm/year).

The median annual rainfall and runoff totals are the mid-point values in the data set and represent the 50% AEP (annual exceedance probability) event. These median values are always lower than the average values, because the average values get distorted by the more extreme rainfall and flood events, particularly for the runoff volumes. The median annual catchment runoff of 2.5% of median annual rainfall (6.6 mm/year) could be considered a more typical runoff characteristic for the catchment and is significantly less than the longer term average annual runoff of 5.4% (17.0 mm/year).

Annual runoff volumes for the ungauged catchments upstream from Ethel Gorge can be estimated using catchment areas and the rainfall-runoff relationships derived from the Fortescue River (Newman) gauging station, assuming similar rainfall and catchment characteristics. These estimates are given in Table 4.3 and for Ethel Gorge the annual runoff volume has been estimated assuming that Ophthalmia Dam had not been constructed.

Table 4.3: Estimated Annual Runoff Volumes from Ethel Gorge Catchment Areas

Catchment	Catchment Area (km^2)	Average Annual Runoff Volume (GL)[1]	Median Annual Runoff Volume (GL)[2]
Fortescue River	2,889	49.1	19.1
Warrawanda Creek	1,22	20.8	8.1
Whaleback Creek	205	3.5	1.4
Ophthalmia Dam Inflow	4,319	73.4	28.6
Homestead Creek	305	5.2	2.0
Shovelanna Creek	248	4.2	1.6
Ethel Gorge without Ophthalmia Dam	4,872	82.8	32.2

1 Based on average annual rainfall of 17.0 mm/yr

2 Based on median annual rainfall of 6.6 mm/yr

4.2.4.3 Inputs from Ophthalmia Dam

Ophthalmia Dam located on the Fortescue River 3 km upstream from Ethel Gorge was installed in 1981 to capture surface water runoff for subsequent slow release to replenish the downstream alluvial and calcrete aquifers. The main dam embankments and spillways extend for approximately 5 km across the Fortescue River valley but only hold a peak effective water storage depth of approximately 4.5 m. Hence these embankments create a wide but shallow water storage impoundment. Seepage through the valley storage floor has been sufficient to maintain the downstream aquifers without the need to manually release water from the dam to directly recharge the aquifers via purpose built recharge basins located downstream within the original Fortescue River main channel. When full, the dam has a storage capacity of 31 GL and a surface area of 16 km^2.

The dam receives streamflow from the Fortescue River, Warrawanda Creek and Whaleback Creek which have a combined catchment area of 4,319 km^2. Large flood events fill the storage and when full, runoff overtops the service spillway and discharges via the original Warrawanda Creek main channel towards Ethel Gorge. Since its construction, storage water levels in Ophthalmia Dam have been monitored by a DoW gauging station (708012) with the gauging record starting in December 1981. A plot of these daily maximum water levels is given in Figure 3.10.

The estimated historical total monthly runoff volumes discharged to Ophthalmia Dam from the Fortescue River, Whaleback Creek and Warrawanda Creek for the period since 1981 are also shown in Figure 3.10. These volumes have been estimated based on the Fortescue River (Newman) streamflow gauging record. Based on these data, the dam receives catchment runoff most years with runoff completely filling or overtopping the dam in 14 of the past 31 years (July 1981 – June 2013). However the data also shows that from July 1994, the dam overflowed in 11 out of 18 years, and prior to July 1994 the dam overflowed in three out of 13 years. Additionally the dam did not overflow during eight consecutive years (wet seasons) from July 1986 to June 1994 (effectively nine years without overflowing). The more frequent overtopping since July 1994 corresponds with higher annual rainfall totals.

The estimated median annual inflow volume into Ophthalmia Dam of 28.6 GL (Table 4.3) represents a 50% AER (2 year ARI) event and is also approximately equal to the storage capacity of the dam (31 GL). Hence the storage could be expected to almost fill on average every two years which is typically what the storage water level data shows (overtopped in 14 of the past 31 years). Based on these data, the estimated median annual overflow volume from the storage would be zero. However the average annual overflow volume from the storage has been estimated at 66% of the average inflow volume, based on the water balance assessment undertaken for the storage (discussed in report Section 3). This equates to an estimated average annual overflow volume from the storage of 48.4 GL.

With construction of Ophthalmia Dam, the volume of surface water runoff discharging through Ethel Gorge has been reduced and seepage into the downstream alluvial aquifer has been increased. The estimated annual runoff volumes through Ethel Gorge are now an average of 57.8 GL and a median of 3.6 GL, as shown in Table 4.4, compared with 82.6 GL (average) and 32.2 GL (median) from Table 4.3.

Of the estimated average annual 25 GL reduction in the surface water runoff to Ethel Gorge (due to the dam), an estimated average annual 16 GL (44 ML/d) seeps through the storage floor and augments the downstream aquifers.

Table 4.4: Estimated Annual Runoff Volumes at Ethel Gorge with Ophthalmia Dam

Catchment	Catchment Area (km^2)	Average Annual Runoff Volume (GL)	Median Annual Runoff Volume (GL)
Ophthalmia Dam Overflow [1]	4,319	48.4	0
Homestead Creek	305	5.2	2.0
Shovelanna Creek	248	4.2	1.6
Ethel Gorge with Ophthalmia Dam [1]	4,872	57.8	3.6

Average 66% overflow from Ophthalmia Dam

As stated above, based on the DoW Fortescue River (Newman) streamflow gauging station data, the Fortescue River has one to three flow events per year. The same flow event frequency should be experienced within Ethel Gorge, even though the flow event volumes would be reduced.

4.2.5 Hydrostratigraphy

The basement geology of the Ethel Gorge area is complex and much is covered by alluvium which is extensive and continuous but of variable thickness; the alluvium forms the primary regional aquifer. The basement geology comprises the southern limb of a regional syncline, striking northwest southeast and the core of which hosts erosion-resistant formations that crop out to form the Ophthalmia Range. The Fortescue River flows to the northeast (aligned with a fault that controls Ethel Gorge) across the geological strike and across progressively younger basement. The geology is illustrated on Figure 4.4 (which also illustrates the location of key bores used in this assessment). Figures 4.5 and 4.6 show hydrogeological cross sections through the area.

4.2.5.1 Basement Aquifers

The geology of the basement in the southern-most part of the floodplain comprises Archaean granite. It is concealed by an alluvial cover that is approximately 20 m thick with some granite outcrops in the floodplain forming flat rocky areas. Most of the bores drilled in the granite are shallow pastoral bores relying on leakage from overlying alluvial aquifer suggesting that the granite itself is of low permeability.

Further to the north around the area of Ophthalmia Dam, the floodplain is underlain by the Jeerinah, Marra Mamba and Wittenoom Formations. All formations are concealed beneath by a thick alluvial sequence varying between 30 m to over 100 m in thickness. The Marra Mamba and Jeerinah Formation can outcrop as discontinuous low-lying hills within the floodplain. The Wittenoom Formation is particularly low lying due to preferential weathering and only occurs as subcrop being covered by the thickest sequence of Tertiary detritals.

The Marra Mamba and Jeerinah Formations are aquitards. However, aquifers are developed in the Marra Mamba where it is mineralised. These orebody aquifers are not extensive and are bounded along and across strike by low permeability unmineralised material. Such aquifers may, however, be in hydraulic connection with the regional aquifer where the mineralised zone is in direct hydraulic connection with the Tertiary detritals. In the Ethel Gorge area, local aquifers occur in the Marra Mamba associated with: OB37 on the western side of the Fortescue River (at the confluence of the Fortescue River and Homestead Creek); and OB42 on the eastern side of the Fortescue River. In both cases, it is believed these orebody aquifers are in hydraulic connection with alluvial aquifers and dewatering will result in groundwater inflows from and reductions in groundwater storage and flow in the regional aquifer.

The Wittenoom Formation includes the Paraburdoo Member which is often karstic and can form a major aquifer. The Parauburdoo Member is prone to weathering and erosion, the dolomite usually occurs in subcrop under valley floors and often acts in hydraulic connection with overlying Tertiary detritals (for example along Homestead Creek and Shovelanna Creek).

Further north, the Fortescue River flows to the southern edge of the Ophthalmia Range, a series of prominent ridges formed by weathering resistant Brockman. The river cuts through the range in a narrow channel to form Ethel Gorge. The Gorge has been eroded through Brockman and overlying units of Weeli Wolli Formation and Boolgeeda Iron Formation (Boolgeeda) and these units subcrop the alluvium-filled channel in The Gorge.

The Brockman, Weeli Wolli and Boolgeeda Formations usually form aquitards. However, aquifers develop in the Brockman where mineralisation has occurred although typically such aquifers are not laterally extensive as they are hydraulically limited along and across strike by low permeability unmineralised material. Such aquifers may however be in hydraulic connection with the regional aquifer where the mineralised zone occurs on the side of a valley and is in direct contact with the Tertiary detritals. In the Ethel Gorge area, local aquifers occur in the Brockman associated with: OB23 and OB25 on the western side of the Fortescue River and OB21 on the east. Both OB23 and OB25 are in hydraulic connection with the alluvial aquifer and dewatering at these mines has resulted in drawdown in the Tertiary detrital aquifer.

Orebody aquifers in the Ethel Gorge area, and their likely connection with the regional aquifer, are illustrated on Figure 4.4.

4.2.5.2 Groundwater and Geological Structure

Geological structure in the area is complex. Key features of the geological structure that influence the hydrogeology of the area are illustrated on Figure 4.5. The topography of the basement subcrop reflects both lithology and structure. Both the Marra Mamba and Brockman are resistant to erosion in comparison with the surrounding lithology and there are two "ridges" of shallow basement under the alluvium, running parallel with the strike and that correspond with the subcrop of these units:

- A basement high associated with a subcrop of Marra Mamba runs across the area approximately 1 km downstream of Ophthalmia Dam and is contiguous with low ridges of Marra Mamba that crop out and form OB37 to the west of the Fortescue River and OB42 to the east; the alluvium thins to approximately 30 m over this area of shallow Marra Mamba.
- A basement high associated with a subcrop of Brockman runs across Ethel Gorge approximately 1.5 km downstream of OB23 and is contiguous with the prominent ridges of Brockman through which Ethel Gorge is cut. The alluvium thins to approximately 30 m over this area of shallow Brockman.

The basement highs are illustrated on the sections shown in Figure 4.5.

A major northeast orientated fault underlies the alignment of the Fortescue River and Ethel Gorge itself with the geological sequence on the eastern side of the fault offset to the north by approximately 2 km. It may result in enhanced permeability in the basement along the fault. Deep alluvium-filled troughs occur either side of the basement highs, as such a zone of enhanced permeability along the fault would allow the hydraulic response in the deeper alluvium to propagate between troughs (as is suggested by the available hydrograph data in Section 4.2.4.4).

There are several faults running parallel with the regional strike (i.e. southeast to northwest). Drilling results suggest that this results in a repeat of the Marra Mamba / Wittenoom Formation sequence in the downstream-most reaches of Shovelanna Creek adjacent to OB42 and OB43. A similar fault may afford hydraulic connection between OB23 and 24 (Section 5.1 - Eastern Ridge mining area), as well as between the various pits along the strike of OB25.

4.2.5.3 Alluvial Aquifers

The alluvial sediments that infill the floodplain and channels of the Fortescue River and its tributaries are predominantly of Cenzozic age. The sediments comprise an extensive alluvial sequence that can be differentiated into three hydrogeological units:

- TD3 - An upper aquifer unit comprising sand, gravel and calcrete. The upper aquifer occurs throughout the Ethel Gorge area (and over most of the Fortescue River flood plain) and varies between 10 m and 30 m in thickness, which forms the stygofauna habitat. Calcrete is well developed throughout the sequence. Calcrete occurs extensively at outcrop and in subcrop where it has been incised by river channels that are infilled with more recent alluvium. In the area from approximately 500 m south of OB23 to approximately 1 km downstream (north) of OB23, the calcrete is particularly well developed forming almost the entire 30 m thick upper aquifer sequence; this is also the area where stygofauna are most abundant. In the lower reaches of The Gorge, to the north, the calcrete thins and occurs at a generally greater depth. The sand, gravel and calcrete form a high permeability unconfined aquifer across which the major creek systems flow and on which Ophthalmia Dam captures water.
- The upper alluvial aquifer is underlain by an extensive deposit of clay (TD2) that forms an aquitard. The clay underlies the flood plain north of Ophthalmia Dam, being absent only where it onlaps basement highs. The clay attains a thickness of up to 80 m in a zone approximately 2 km downstream of Ophthalmia Dam (in one of the alluvium-filled troughs that flank the basement highs). More commonly, the clay is 20 m to 30 m thick. Upstream of Ophthalmia Dam, the clay starts to thin towards the granite outcrop in the south. Based on available geological information, there is a zone underlying the lake behind Ophthalmia Dam where the clay is absent and the upper and lower alluvial aquifers are in direct hydraulic contact. The clay forms an extensive aquitard.

- The clay aquitard is underlain by a lower aquifer unit comprising alluvium (TD1). This deep alluvial aquifer has accumulated in the troughs that occur between the basement highs and while it occurs extensively, its distribution is not continuous as it is interrupted by the basement highs. These deeper accumulations of alluvium form a high permeability aquifer that with confined conditions.

Figure 4.7 shows the interpolated thickness and extent of calcrete within the upper alluvial sequence, varying between less than 5 m thick to over 40 m thick. Calcrete thickness varies between outcrop to more than 20 mbgl. The thickest accumulation of calcrete occurs around the upstream entrance to and within Ethel Gorge, which coincide with the TEC.

4.2.6 Aquifer Parameters

Table 4.5 below compares the range of aquifer parameters estimated for Ethel Gorge with the regional values outlined in Chapter 3 of the main EPR report.

Table 4.5: Permeability in Ethel Gorge Area

Unit	Regional Values k (m/d)			Ethel Gorge		Remarks
	Min	Max	Med	Min	Max	
Alluvium	0.02	30	6.2	3	30	10 to 30 m/d predominant range around Ethel Gorge
TD3 Calcrete	20.0	50.0	29.0	40	40	
TD2 (Clay)				0.1	0.1	Formations not differentiated in regional hydrogeology; 30 m/d predominant range; higher values in Gorge
TD1 Alluvium (deep aquifer)				30	60	
Brockman Iron Formation	0.001	0.05	0.002	0.01	0.05	
Brockman Ore	0.2	5	3	2	5	
Mount McRae Shale	0.0001	0.1	0.0121	0.01	0.05	
Mount Sylvia Formation	0.01	1	0.1	0.01	0.05	
Wittenoom Dolomite	0.00002	39.0	11.0	-	-	No estimates from Ethel Gorge area - adopt regional values
West Angela Member/Bee Gorge	0.00001	0.002	1.8	-	-	
Marra Mamba Iron Formation	0.00002	0.004	0.001	-	-	
Marra Mamba Ore	0.001	14.50	5.00	-	-	
Jeerinah Formation / Granite	0.0001	7.2	0.03	-	-	

Available data from hydraulic tests in the Ethel Gorge area mainly originate from dewatering investigations at OB23 and OB25; only a limited number of hydraulic tests are available. Moreover, the pumping tests were undertaken in bores completed across the entire alluvial sequence and so it is difficult to determine specific aquifer parameters for each unit. Estimates of aquifer parameters for the area have also been determined from groundwater modelling at both OB23 and OB25 with calibration to dewatering operations and long term stresses such as Ophthalmia Dam and abstraction from the Ophthalmia Borefield.

In general, the aquifer parameters around Ethel Gorge are typical of the range of regional values. The estimates of permeability confirm the hydrostratigraphical interpretation that the main aquifers are within the alluvial sequence; that the clay within this sequence is low permeability; and that the basement is generally low permeability other than where the Marra Mamba and Brockman are mineralised and form orebody aquifers.

No specific estimates of confined or unconfined storage are available for Ethel Gorge. The adoption of the regional values (refer Table 3.11) is recommended.

4.2.7 Groundwater Levels and Flow

Groundwater levels in the Ethel Gorge area have varied considerably since monitoring started, related to wet and dry climatic periods, abstraction and enhanced recharge from Ophthalmia Dam (ref 2.5.2 below). Prior to the recharge enhancement resulting from the dam, over-abstraction had occurred to the extent that the direction of groundwater throughflow in Ethel Gorge had reversed. Thus, natural and/or steady state groundwater conditions cannot be determined. However, the hydrographs show that following a period of water level recovery (to some of the highest levels recorded) after the dam was constructed, groundwater levels were essentially stable from 2000 until 2006 prior to the start of dewatering at OB23 and OB25. Stable groundwater levels indicate that through 2000 to 2006, the aquifer system was in balance. This period has been used to determine pre-mining flow directions and the catchment water balance.

4.2.7.1 Water levels and flow

Contours of pre-mining groundwater levels in the Ethel Gorge area are presented in Figure 4.8. These contours represent “average" conditions between 2000 and 2006 when water levels were relatively high and essentially stable and subject to only seasonal variation. The specific elevations of the watertable may vary seasonally and between longer periods of above or below average rainfall. However, in the absence of large drawdown associated with abstraction, the overall trend and flow directions will remain the same.

Groundwater flow is generally in a north-easterly direction, converging on Ethel Gorge. Immediately south of Ethel Gorge the water levels are approximately 505 mAHD, and gradually rise in a southerly direction, reaching 515 mAHD some 8 km away upstream of Ophthalmia Dam. The hydraulic gradient across the Fortescue River floodplain into The Gorge is approximately 0.001.

Groundwater levels fall from 505 mAHD to 500 mAHD northwards through Ethel Gorge. The hydraulic gradient through The Gorge is approximately 0.002. Hydraulic gradients steepen through The Gorge where groundwater flow is constrained by the narrowing aquifer. However, the increase in gradient is not as great as would be expected were all the throughflow from the Fortescue floodplain to discharge through The Gorge. This indicates there maybe additional groundwater discharge from the aquifers of the floodplain other than throughflow into The Gorge (see Water Balance - Groundwater Discharge).

4.2.7.2 Depth to groundwater

Depth to water ranges between 0 and 10 mbgl at Ethel Gorge and over the Fortescue River floodplain, depending on both local topography and seasonal factors (Figure 4.8). This range in watertable suggests groundwater will be readily accessible by opportunistic phreatophytic vegetation such as Coolibahs and River Red Gums. The distribution of these vegetation types is shown on Figure 4.8 as a zone of potential discharge by evapotranspiration.

Moreover, such a range in groundwater levels maintains a substantial saturated thickness in the upper alluvial aquifer (including the calcrete) and provides a permanently saturated habitat for stygofauna. The area of the TEC is also marked on Figure 4.8 and coincides with areas of shallow groundwater and the presence of calcrete.

4.2.7.3 Groundwater Levels – Changes over Time

Available groundwater level monitoring data for the Ethel Gorge area are shown in Figure 4.9 with the data for some bores extending back to 1970. Groundwater hydrographs have been studies extensively by PB (2013) and key trends can be summarised as:

- Between 1970 and 1981, there was a general trend of declining groundwater levels, caused by abstractions from the Ophthalmia Borefield and overall depletion of aquifer storage. Water levels declined by up to 10 m in some bores as groundwater levels regionally fell to their lowest recorded levels.

- In 1981, Ophthalmia Dam was commissioned and groundwater levels started to recover as increased recharge caused by the dam replenished aquifer storage. Groundwater levels continued to rise through until 2000 (by up to 15 m) when, regionally, groundwater reached the highest levels on record.
- Between 2000 and 2006, groundwater levels were essentially stable at this very high level. Through this period, seasonal fluctuations are generally smaller than when groundwater levels were lower and it is believed, in many areas, the alluvial aquifer was fully saturated with no capacity to accept additional recharge.
- Since 2006, groundwater levels have declined as a result of dewatering at OB23 and OB25. While the extent of decline varies with distance from the dewatering operations, groundwater level declines are observed over a wide area suggesting a general decrease in aquifer storage. Notwithstanding, groundwater levels remain high in comparison with the lowest levels recorded prior to the commissioning of Ophthalmia Dam.
- Superimposed on these broad trends, there are seasonal responses to rainfall. Over most of the area, these occur on an annual basis with groundwater levels rising by 1 to 3 m in response to recharge generated by rainfall runoff events.

Shallow and Deep Aquifers

Many of the monitoring bores are constructed against the entire alluvial sequence and present a "composite picture" of general groundwater flow direction and overall trends in water levels as aquifer storage is depleted or recharged. However, around OB23 there are some nested piezometers (discreetly completed against the shallow and deep alluvial aquifers) and elsewhere some individual bores can be identified that are in proximity to each other and are screened against either the shallow or deep aquifer. Examples of paired hydrographs (shallow and deep alluvial aquifers) are shown on Figure 4.10. The following is interpreted from these hydrographs:

- Under pre-mining conditions, over much of the Fortescue River floodplain, the deep aquifer has a higher piezometric head than water levels in the shallow aquifer; the head difference is approximately 2 m. This indicates the lower alluvial aquifer is hydraulically confined and that there is potential for upwards flow of groundwater.
- The piezometric head in the lower aquifer close to Ophthalmia Dam is approximately 510 to 512 mAHD. This approximates the dam water level and suggests the lower aquifer is subject to hydraulic loading from the dam (that is the water levels in the lower aquifer reflect dam water levels due to the transmission of hydraulic pressure from the dam).
- Water levels in the shallow aquifer close to the dam are generally less than 510 mAHD. This level is likely to be controlled by topography with water levels higher than 510 mAHD resulting in baseflow in the river.
- Water levels in the shallow and deep aquifers equilibrate immediately upstream of Ethel Gorge and are likely to be equal along The Gorge.

Figure 4.10 also shows dewatering rates at OB23 and water levels in Ophthalmia Dam since dewatering started. Additional information on the hydrogeology can be interpreted from the response of the aquifer system to the stress imposed by dewatering:

- In the area affected by dewatering, much larger effects are observed in the lower aquifer (e.g. in P20, the piezometric head reduction in the deep alluvial aquifer has been up to 40 m whereas water levels in the shallow aquifer at the same location have only fallen by approximately 10 m). Over most of the area, there remains a substantial saturated thickness in the shallow aquifer (maintaining saturated conditions in the calcrete - the stygofauna habitat) even when "apparent" drawdown (i.e. piezometric head reduction in deep bores) are in excess of 40 m (refer also Figure 4.11).
- Despite the large drawdown in the deep aquifer, water levels remain above the base of the intervening clay over most of the area (i.e. the deep alluvial aquifer remains under confined conditions) and there has been a depressurisation response.

- Piezometric head in the deep alluvial aquifer responds rapidly to water levels in Ophthalmia Dam (even when the dam levels are insufficient to result in overflow and a downstream flood event). This suggests the piezometric response is caused by hydraulic loading from the dam.
- Water levels in the shallow aquifer close to Ethel Gorge respond to rainfall runoff events that result in a spill from the dam. There is no change in water levels in the shallow aquifer when the dam water level rises in response to rainfall runoff but there is no actual overflow event. This suggests the short term rise and fall in water levels in the shallow aquifer is a result of local infiltration from creek flow.
- Total dewatering abstraction at OB23 varies with piezometric head in the lower aquifer.
- The period 2009 to 2012 coincided with three large rainfall events and a general increase in water levels in Ophthalmia Dam. Over this same period, both the shallow and deep alluvial aquifers show a general rising trend in addition to the annual variation caused by either hydraulic loading or the local infiltration of creek flow for the deep and shallow aquifers respectively. This is believed to result from seepage and the slow movement downstream of water from the dam. The majority of the water seeping from the dam will recharge the shallow aquifer. Based on a confined storage coefficient of 0.0005, the observed water level rises in the deep alluvial aquifer can be generated with a recharge rate of less than 1,000 kL/d (compared the total estimated seepage from the dam of 50,000 kL/d).

Groundwater Levels in the TEC

Figure 4.11a illustrates the pre and post dewatering water levels in the shallow aquifer and piezometric head in the deep alluvial aquifer around Ethel Gorge in association with OB23. Despite a large reduction in pressure in the deep aquifer, much of the stygofauna habitat in the shallow aquifer remained saturated.

Figure 4.11b shows the natural range through which groundwater levels have fluctuated (and degree of saturation) in the shallow aquifer. Additional drawdown, in excess of this natural range, as a result of dewatering is also shown. The natural range in water levels is substantial which suggests a degree of robustness in the TEC. Moreover, the portion of the TEC subject to fluctuations in water level that exceed this natural range is small.

4.2.8 Groundwater Recharge

4.2.8.1 Current Recharge Regime

Ethel Gorge is a receiving environment characterised by the accumulation and attenuation of surface water runoff from the entire upstream catchment; runoff is especially attenuated by Ophthalmia Dam. The depth to groundwater across the area is less than 10 m, soil moisture deficits will be small and recharge to the groundwater system will readily occur.

Groundwater recharge occurs predominantly as seepage from Ophthalmia Dam. Water balance studies for the dam suggest water seeps from the dam into the shallow alluvial aquifer at 5 mm to 6 mm per day over the impounded area (RPS Aquaterra 2010 and PB 2013). The surface area of the lake behind the dam will vary with dam stage; the annual average seepage rate is 50,000 kL/d.

Additional recharge occurs from surface water flows that infiltrate along the creeks running into The Gorge. A simple storage accretion model based on seasonal rises in groundwater level over specific areas can be used to estimate recharge. Based on hydrograph data, the following recharge areas have been defined:

1. Recharge along the Fortescue River channel in the area upstream of Ophthalmia Dam. Seasonal rises in this area are in the range 1 to 2 m and occur over a zone approximately 1 km wide centered along the Fortescue River channel. The average recharge rate to this area is estimated at 14,000 kL/d.
2. Recharge along Homestead Creek in the reach of the valley that hosts OB25 and OB37 (downstream of the H-line bores). Seasonal water level rises in this area are in the range 2 to 3 m and occur annually. Average recharge to this area is estimated at 7,500 kL/d.

3. Recharge on the Fortescue River floodplain below Ophthalmia Dam where creek flows from Homestead, Shovelanna and Warrawanda Creeks coalesce with overflows from the dam and flow through The Gorge. Notwithstanding seasonal variations, throughout the period of record, water levels in this area generally do not exceed approximately 505 mRL (the topographic elevation over much of the area and above which groundwater would discharge as base flow into the creek system).. Over the period 2000 to 2006, seasonal water level rises in this area are approximately 1 m and recharge is estimated at 3,000 kL/d. However, water levels were lower through much of the 1990s (associated with less annual rainfall) but seasonal fluctuations were larger reflecting the greater available aquifer capacity to accept recharge (ie less “rejected recharge”).

These recharge zones are illustrated on Figure 4.12.

Elsewhere in the catchment, infiltration will occur and will be an important contributor to soil moisture. However, it appears recharge volumes in other areas of the Ethel Gorge catchment are relatively small. Groundwater throughflow into the Fortescue River floodplain upstream of the dam (representing recharge to the upper catchment) is estimated to be 1,500 kL/d from the upper Fortescue and Warrawanda Creeks. Groundwater throughflow into Homestead Creek upstream of OB25 (representing recharge in the upper Homestead catchment) is estimated to be 300 kL/d.

Total recharge to the Ethel Gorge catchment is estimated to be approximately 75,000 kL/d.

4.2.8.2 Pre-development Groundwater Recharge (without Ophthalmia Dam)

Ophthalmia Dam was designed to augment natural groundwater recharge by attenuating surface water flows that would otherwise quickly dissipate, allowing more time for infiltration. Seepage from Ophthalmia Dam accounts for two thirds of current recharge.

In the case of recharge to the Fortescue River alluvial aquifer upstream of Ophthalmia Dam, the 14,000 kL/d recharge occurs over 8.5 km of river reach; recharge can therefore be estimated at approximately 1,500 kL/d/km of river channel. Under natural conditions without Ophthalmia Dam in place, there would be 50,000 kL/d less seepage to the groundwater system. However, infiltration from flood flows from the Fortescue River would occur over an additional 3 km of river reach (which currently forms the dam reservoir) resulting in an additional 4,500 kL/d of natural recharge. Additionally, groundwater levels would be generally lower (without the dam in place) and the shallow alluvial aquifer would have additional capacity to accept more recharge during a flood event. Overall, recharge during a flood event on the Fortescue flood plain may increase by between 50% and 100% due to additional aquifer capacity.

It is estimated that without Ophthalmia Dam, total recharge to the system would be 30,000 kL/d.

4.2.9 Groundwater Discharge

4.2.9.1 Groundwater Outflow

Natural groundwater discharge occurs as throughflow in Ethel Gorge. There is no other groundwater outflow from the catchment. Total groundwater flow is estimated to be approximately 2,000 kL/d (based on previous numerical modelling for OB23, simple Darcy estimates of flow (PB, 2013) and a catchment chloride balance outlined below and summarised in Table 4.6.

Evapotranspiration

Additional groundwater discharge occurs as evapotranspiration from extensive vegetation on the Fortescue River floodplain and within Ethel Gorge. Woodlands comprising Coolibah, River Red Gums and Paperbark are characteristic of over 80% of the River Land system (cf Chapter 3 Coolibahs and River Red Gums are facultative (opportunistic) phreatophytic species and can utilise groundwater at depths in excess of 10 mbgl. Based on the observed depths to water on the Fortescue River flood plain, these species could cause evapotranspiration over large areas. There are 3,650 ha of such vegetation communities within the Ethel gorge area, based on Department of Agriculture landscape mapping (e.g. Department of Agriculture 2013). This zone of evapotranspiration is illustrated on Figure 4.12.

No specific estimates of evapotranspiration are available for the woodlands in the Ethel Gorge area. Estimates of evapotranspiration by mixed phreatophytic/vadophytic woodlands elsewhere in the Pilbara range between 120 mm/yr and 600 mm/yr (e.g. Hope Downs 2000 and Rio Tinto 2010). This range probably reflects variations in the density of respective species between woodlands and variations in water abundance; Eucalypts have the capacity to regulate transpiration in response to water availability. Based on this range, groundwater losses by evapotranspiration around Ethel Gorge could range between 12,000 kL/d and 60,000 kL/d. Given that the watertable is very shallow over much of the area and water should be readily available for the woodland, evapotranspiration towards the higher end of this range could be anticipated.

4.2.9.2 Existing Users

The other important discharge of groundwater from the natural hydrological system is through abstraction to support mining operations. The main sources of abstraction are associated with the Ophthalmia Borefield and more recently from dewatering operations at OB23 and OB25. Only the former are considered in the base-case water balance as it was based on observations for the pre-dewatering period of 2000 to 2006. Average abstraction from the Ophthalmia borefield during this period was approximately 10,000 kL/d.

4.2.10 Water Balance

The overall water balance for Ethel Gorge must account for surface water flow, groundwater recharge and natural groundwater discharge, other groundwater abstractions and changes in groundwater storage.

The groundwater balance for the Ethel Gorge catchment (prior to dewatering at OB23 and OB25) has been developed using both a chloride mass balance and also an assessment of recharge and discharge as outlined above (refer section 4.2.4.5 and 4.2.4.6). The water balance is summarised in Table 4.6. The water balance is developed using a simple analytical model based on annual averages and some key components are derived by difference. As such, it should only be considered an estimate; it is not precise and simply provides an estimate of the scale and relativity of key parameters.

Table 4.6: Ethel Gorge Catchment Water Balance

Chloride Balance

Ref	Item	No.	Chloride Conc	Units	Remarks/Formula
	Concentrations				
1	Rainfall		0.5	mg/L	
2	GW throughflow conc		500	mg/L	measured AAR
3	Surface Water Flood Concentration		6	mg/L	measured Ethel Groge
4	Water Supply concentration		100	mg/L	measured AAR
	Measured Parameters				
5	Catchment Area	5030		km^2	
6	rainfall	320		mm/yr	Newman rain gauge
7	Rainfall Volume	1,609,600,000		m^3/year	5*6
8	Surface Water Outflow	41,401,000		m^3/year	Calculated
9	Water Supply Pumping	3650000		m^3/year	measured AAR
	Chloride Movement				
10	Chloride inflow from rain		8.0480E+11	mg/year	1*7
11	Cl outflow - surface water flood		2.4841E+11	mg/year	8*3
12	Cl in consumptive water supply		1.8250E+11	mg/year	9*4*consumption factor
	Unaccounted for Chloride - groundwater outflow				
13	(Cl rain) - (Cl out through surface flow)		3.7389E+11	mg/year	Balance of Cl flux
	Water Balance				
14	**calculated GW outflow**	**2,047**		**m^3/d**	13/2; Volume required to remove (13)Cl at 500mg/L

Steady State Groundwater Balance

Feature	kL/d	Remarks
Groundwater Recharge		
Direct Recharge along Fortescue	13700	hydrograph analysis - ~annual
Direct recharge along Homestead/below Dam	10500	hydrograph analysis - ~annual
Seepage from Dam	50000	water balance calculation based on dam water levels (RPS and PB ~5-6mm/day)
Diffuse Recharge over remainder of catchment	2000	inflow from upstream catchment area
Total Groundwater Recharge	**76200**	recharge~0.8% of catchment rainfall
Groundwater Discharge		
Groundwater Outflow	2047	calculated from Cl balance
Water Supply Pumping	10300	measured data
Evapotranspiration	63853	calculated by difference (equates to 600mm/yr over 3650ha)
Total Groundwater Discharge	**76200**	
Comments		
Recharge as % of annual average rainfall	*1.7%*	*Dam increases recharge (cf CPH ~0.8%)*
Est Pre-Dam Recharge % annual average rainfall	*0.7%*	*Without Dam, comparable with CPH*

Cl-based calculation of groundwater outflow

4.2.10.1 Chloride Balance

Chloride is generally considered a conservative element in the natural environment. In the EPR area, groundwater is generally fresh and there are no salt pans or salinas; there are no obvious areas of active salt accumulation. As such, it can be assumed that the chloride delivered to the catchment (as a solute in rainfall) will equal chloride leaving the catchment (as a solute in water outflow).

The key components of the chloride balance are summarised below:

1. Chloride inflow to the groundwater system as solutes in rainfall over the entire catchment area at an annual average rate of 320 mm/yr (based on the Newman rain gauge). The concentration of chloride in rainwater is estimated at 0.5 mg/L (PB, 2013).
2. Chloride outflow as solutes in surface water flood flow through Ethel Gorge (representing the combined surface water discharge from Homestead, Shovelanna and Warrawanda Creeks and overflow from Ophthalmia Dam representing the non-regulated discharge from the Fortescue River). The combined surface water flow through Ethel Gorge has been estimated from a combination of gauged flows at the dam and derived flows for the tributary creeks. This approach provides an annual average outflow of 41,400 ML/yr. The measured chloride concentration in flood flows through Ethel Gorge ranges between 5 mg/L and 7 mg/L; 6 mg/L has been used to estimate the chloride flux.
3. Chloride outflow as solutes in groundwater abstracted for water supply purposes from the Ophthalmia Borefield. Over the period for which the water balance was assessed (2000 to 2006), water supply abstraction was approximately 10,000 kL/d with a typical chloride concentration of 120 mg/L. However, most of the water supplied will ultimately return to the groundwater system as leakage from the distribution network, irrigation return flows from domestic gardens and seepage of treated sewage effluent. Permanent consumptive use has been estimated at only 10% of total water supplied (i.e. 90% water return).
4. Chloride outflow as solutes in groundwater throughflow along Ethel Gorge. Water chemistry data are available from abstractions from the Ophthalmia Borefield and more recently from OB23 and OB25. The concentration of chloride in the groundwater of Ethel Gorge is approximately 500 mg/L. The groundwater flow volume has not been measured. However, assuming that chloride is in balance, then the volume is estimated as that required to remove the required volume of chloride to maintain balance (given the other components of chloride input and output outlined above). It is estimated that groundwater outflow is approximately 2,000 kL/d. This number is comparable with an estimate of throughflow based on hydraulic gradients and aquifer properties made by PB (2013).

4.2.10.2 Estimates of Total Recharge and Discharge

Total recharge and discharge under steady-state conditions with Ophthalmia Dam operational are estimated to be approximately 75,000 kL/d. The overall water balance for the Ethel Gorge catchment in summarised in Table 4.6. Ophthalmia Dam is a major contributor to groundwater recharge. The major discharge from the catchment is evapotranspiration. For the period considered, it is estimated that evapotranspiration losses account for 60,000 kL/d.

4.2.11 Groundwater Quality

Figure 4.13 illustrates groundwater quality for the Ethel Gorge catchment. The majority of samples are from bores that penetrate both the shallow and deep aquifer. However, in most cases, samples are taken from abstraction bores that have been slotted against both aquifers to simply maximise yield. It is not to possible to discern water quality differences between the shallow and deep aquifers and only broad trends can be gleaned from the available data.

The expanded durov plot shows water types range between:

- Calcium/magnesium and bicarbonate type water characteristic of recharge water in the Pilbara.

- Waters with no dominant anion or cation characteristic of an intermediate groundwater that has been subject to some mixing, dissolution and evapotranspiration.
- Sodium/chloride type waters characteristic of a mature groundwater that has undergone both evolution through mixing and evapotranspiration.
- TDS ranged from 500 mg/L to 2,000 mg/L, generally increasing as the groundwater becomes more mature. The increase in salinity occurs as groundwater flows towards The Gorge and this is largely due to evapotranspirative concentration of salts as water flows through the shallow alluvial aquifer.

4.2.11.1 Orebodies

Figure 4.14 summarises the orebodies that extend below the watertable and fall within an area that could affect the water balance of Ethel Gorge. The actual influence on the groundwater system at Ethel Gorge by any of these orebodies will depend on:

- The degree of hydraulic connection between the orebody aquifer and the regional aquifer (refer to Section 5 for individual mining areas/orebodies).
- Cumulative effects if dewatering is occurring at multiple mining operations concurrently.
- On-going mitigation measures such as the irrigation of trees in The Gorge and the operation of Ophthalmia Dam both to augment recharge from natural flood flows in the Fortescue River and also to dispose of dewatering excess.
- Finally, the distance from the orebody to Ethel Gorge. The assessment of recharge and discharge above shows that most recharge to the groundwater system occurs on the Fortescue River floodplain below Ophthalmia Dam and that groundwater throughflow to this area (from the Homestead Creek valley for example) is a very small component of the water balance. This means as long as the dam operates to maintain recharge on the Fortescue floodplain, the storage depletion as a result of reduced throughflow caused by upstream mining operations, is likely to be modest.

On this basis, the orebodies that could result in the largest change to the groundwater system at Ethel Gorge are those on or in proximity to the Fortescue River floodplain including OB23, OB25 (Pit 3 and West), OB37 and OB42. Dewatering has already occurred at OB23 and OB25 where large volumes of groundwater have been abstracted and piezometric head in the deep alluvial aquifer has been lowered by up to 80 m in localised areas. The potential effects on the shallow alluvial aquifer close to Ethel Gorge (the TEC habitat) are minimised due to groundwater replenishment from the dam, as well as hydrologic separation of the shallow and deep alluvial aquifers by a low permeability clay layer.

4.2.12 Ecohydrological Conceptual Model

The key features of the ecohydrological conceptualisation of the Ethel Gorge environment are depicted in Figure 4.15 and summarised as follows:.

4.2.12.1 Surface and Groundwater Systems

- The Ethel Gorge groundwater system occurs in valley sediments bounded by low permeability basement rocks. It consists of a highly permeable alluvial aquifer comprising an upper unit of sandy-alluvium and calcrete (upper alluvial aquifer) and a lower unit of gravelly-alluvium (deep aquifer). The two units are separated by an extensive low permeability clay sequence. Orebody aquifers, hosted in the Brockman, may have varying levels of hydraulic connection with the upper alluvial and deep aquifers respectively where the mineralised zone occurs on the side of a valley and is in direct contact with the Tertiary detritals.
- Hydraulic behaviour of the Ethel Gorge groundwater system is dominated by Ophthalmia Dam – a MAR structure that has been constructed on the Fortescue River floodplain. The dam serves to substantially increase groundwater recharge and hydraulic loading to the upper alluvial aquifer.

- The upper alluvial aquifer is unconfined and receives recharge from direct infiltration associated with river flow events. In addition to seasonal recharge along the river channels, the upper aquifer also receives most of the water seeping from Ophthalmia Dam and this supports long-term trends in the volume of water stored in the aquifer and water levels.
- Groundwater levels in the upper alluvial aquifer range between 0 and 10 mbgl across the entire area. This provides a substantial saturated thickness in the upper alluvium and calcrete, which constitutes the main stygofauna habitat and root-zone of obligate phreatophytic vegetation.
- The lower aquifer is confined by the overlying clay and is predominantly subject to hydraulic loading from Ophthalmia Dam. Bore data indicates that the lower aquifer has piezometric heads which commonly equal or exceed water levels in the upper alluvial aquifer, particularly close to the Dam.
- Aquifer parameters are within the range of regional estimates and the system is driven by recharge to the shallow aquifer from floods and notably from the dam, the high permeability in the calcrete and alluvium and low permeability in the basement.
- Recharge to the groundwater systems in the Ethel Gorge area occurs predominantly as seepage from Ophthalmia Dam at an average rate of approximately 50,000 kL/d. Other sources of recharge include direct infiltration from channel flow events (along the Fortescue River channel when the dam overflows and above the area of impoundment) and also along Homestead Creek and Shovelanna Creek which are unregulated. Total recharge from infiltration along creek channels is approximately 24,000 kL/d (average) on an almost annual basis. There is also a small component of throughflow into the Ethel Gorge area from the upstream catchments; estimated to be approximately 2,000 kL/d in total.
- Recharge volumes mainly replenish the shallow alluvial aquifer. Percolation into the lower aquifer is restricted by the low permeability clay layer and the hydraulic loading (pressurisation) of the deep aquifer.
- Groundwater discharge occurs as throughflow along Ethel Gorge (approximately 3,000 kL/d), evapotranspiration from riparian vegetation communities (approximately 63,000 kL/d) and abstraction (approximately 10,000 kL/d) for pre-dewatering steady state conditions.

4.2.12.2 Ecosystem Components

- The area in the vicinity of Ethel Gorge hosts approximately 3,650 ha of Eucalypt woodland communities including the facultative phreatophytes *E. camaldulensis* and *E. victrix*. These access shallow groundwater and contribute to groundwater discharge via evapotranspiration of up to 60,000 kL/day. Woodland transpiration is likely to occur from areas where the watertable is less than 10 to 20 mbgl. The proportion of groundwater used by the woodland vegetation (as a component of total water use) would be expected to be greatest where the depth to watertable is shallow (i.e. where soil moisture storage in the unsaturated profile is limited by depth).
- A TEC of stygofauna exists in the shallow alluvial aquifer, within an area on the Fortescue River flood plain from approximately 2 km upstream of The Gorge to 4 km downstream of the entrance to The Gorge. This coincides with a thick accumulation of calcrete (in excess of 20 to 40 m in thickness) occurring at less than 20 mbgl and often at outcrop. The zone of watertable fluctuations (i.e. the boundary between unsaturated and saturated zone) may be a distinct ecotone in comparison with the underlying permanently saturated profile.
- Groundwater levels in the alluvial aquifer that hosts the TEC have historically fluctuated; mostly related to climatic cycles of wetter and drier periods.
- Since its commissioning in 1982, Ophthalmia Dam has also changed the groundwater regime of the area and contributed to elevated groundwater levels. The dam now plays an important role in sustaining the present day groundwater system and hence stygofauna habitat.

4.2.12.3 Existing and Potential Stressors

- Abstraction related to dewatering of BHP Billtion Iron Ore mining areas (OB23 and OB25) has resulted in reductions in water level across the area. The largest reductions are noted from the deep alluvial aquifer and represent a depressurisation response. Water levels in the shallow alluvial aquifer have generally declined by less than 10 m (other than in very close proximity to the pits). Thus to date the calcrete of the TEC has remained substantially saturated.
- More extensive depressurisation of this deep aquifer, as a result of future orebody dewatering activities, has the potential to accentuate leakage into the underlying deep aquifer where the piezometric head falls below the water levels in the upper alluvial aquifer. This has the potential to reduce groundwater levels in the upper alluvial aquifer. The ability of stygobitic species to recolonise areas that become re-saturated after a dewatering event is unknown. However in the Ethel Gorge area the high watertable and seasonally variable influx of water from storm events are likely to aid in stygofauna fauna dispersal.

4.2.12.4 Potential Indicators

The potential indicators for the preservation of ecological values of the Ethel Gorge Groundwater Dependent Ecosystem are:

1. Average depth to watertable.
2. Mean annual watertable fluctuation.
3. Flood recharge event frequency.
4. Groundwater quality.
5. Rate of watertable decline (in response to dewatering stressors).
6. Extent of permanently saturated calcrete habitat for stygofauna.

Current knowledge with respect to the natural/existing range for each of these indicators and the tolerance of groundwater dependent ecosystem components is summarised in Table 4.7.

Table 4.7: Ethel Gorge Groundwater Dependent Ecosystem - potential indicators for the preservation of ecological values

Variable	Groundwater Dependent Vegetation		Ethel Gorge Aquifer Stygobiont Community TEC	
	Tolerance	**Observed/modelled range**	**Tolerance**	**Observed/modelled range**
Average depth to watertable (mbgl)	*No data*	0 to 20 m	*No data*	0 to 10 m
Mean annual watertable fluctuation (m)	*No data*	5	*No data*	5
Flood recharge event frequency (per year)	*No data*	1	*No data*	1
Groundwater quality (TDS)	*No data*	<2,000 mg/L	*No data*	<2,000 mg/L
Rate of watertable decline (adaptability and natural recession)	*No data*	0.2 to 0.5 m per month	*No data*	0.2 m to 0.5 m per month
Maximum observed drawdown	Not applicable		*No data*	12 to 17 m
Extent of permanently saturated calcrete habitat for stygofauna	Not applicable		*No data*	Approx. 285,000,000 m^3

5. STRESSORS

5.1 Introduction

As outlined in Chapter 1.1.2, there are thirty eight designated orebodies in the EPR, which have been grouped into nine mining areas. Water management activities in each effectively provide varying degrees of hydraulic stress on the overall ecohydrology of the EPR and the mining areas have been termed stressors.

Each of the following sections covers the nine mining areas and provides:

- A broad overview of the setting, the mining history and the level of previous hydrological investigations undertaken.
- A summary of the conceptual hydrological / hydrogeological models for the overall mining area.
- An orebody overview table.

The orebody overview tables (Tables 5.1 to 5.10) include a summary of the hydrogeological investigations completed to date, the key hydrogeological interactions that will influence mine dewatering and control the influence that mine water management practices (including at mine closure) will have on Ethel Gorge and an outline of key data gaps in relation to the conceptual hydrogeology.

The contents of Tables 5.1 to 5.10 are conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. These tables have been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and are not intended for use for any other purpose. No representation or warranty is given that project development will actually proceed. As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from the contents of these tables.

The orebody overview table also includes characterisation of each orebody based on a generic orebody type. The generic orebody types reflect the ore type and the degree to which the orebody aquifers are below the watertable and in hydraulic connection with the regional aquifer which will influence the need for and magnitude of dewatering (as outlined in Chapter 3). In the EPR the orebody types include Banded Iron Formation (BIF) and Tertiary detritals (DET) which include Channel Iron Deposits (CID). Five generic sub-types based on hydrological features have been identified, which are illustrated in Figure 5.1 and are as follows:

5.1.1 Above the Watertable

Orebodies located above the regional watertable will not encounter groundwater during mining and require dewatering. There is limited potential for direct impact on groundwater resources; however, there may need to be diversion of surface drainages and possible sourcing of water resources (either surface water or groundwater) to meet water requirements. It is considered that mines above the watertable pose no potential impact risk on the regional aquifer and associated receptors.

5.1.2 Isolated or Disconnected

These mine types are typically located in upland areas (EHU 1 and 2). The orebody is bound within impermeable aquicludes to very low permeability aquitards associated with shale-dominated lithologies that are often un-mineralised. Brockman orebodies are more commonly associated with this mine type being bound or confined by Mt Sylvia and Mt McRae Formations; whereas, the Marra Mamba orebodies may be bound in the hanging wall by thick sequences of unminerliased West Angela Member. Dewatering will be required for the removal of stored groundwater within the orebody aquifer. Inflows to the pit will be low being less than 2 ML/d and may decline over time. Drawdown will be localised being largely confined within and along the orebody aquifer.

The propagation of drawdown will be restricted by the marginal shale units; as a result, there is little to no groundwater flow and connectivity between these orebodies and the regional aquifer. It is considered that isolated / disconnected mine types pose minimal to very low potential impact risk on the regional aquifer and associated receptors.

5.1.3 Partially Connected

Lower in the landscape, typically within valley margins, there is potential for orebodies to extend below the watertable. The pit geometry suggests that the valley-side pit wall may intersect either saturated Tertiary detritals or fault structures that may be in connection with the regional aquifer.

Dewatering requirements are likely to be moderate between 2 and 10 ML/d; although, groundwater inflows from localised basement aquifers would be low. Drawdown would be limited within the basement aquifer; however, there is potential for some watertable decline to extend outwards into the regional aquifer. The propagation of drawdown is most likely to develop as an elongate cone of depression along the strike of the regional aquifer and in the same alignment as the valley.

Despite connectivity between the orebody and regional aquifer, the low permeability of the detrital aquifer suggests that watertable decline would be localised and be highly marginal with respect to the proposed mine. It is considered that partially mine types pose low potential impact risk on the regional aquifer and associated receptors; however, monitoring is recommended to demonstrate water level response.

OB25 Pit 3 in Eastern Ridge is a current mining operation that is representative of this orebody type. As many of the proposed mines in the SEA will be below the watertable with marginally connectivity with the regional aquifer, it will necessary to demonstrate the extent and nature of the hydraulic connectivity.

5.1.4 Connected

The orebody extends a considerable depth below the watertable on the margins of a valley. The geometry of the pit is such that much of at least one of the pit walls intersects an exposure of saturated Tertiary detritals or faults in the wall which affords connection between the pit and regional aquifer.

Pit inflows will be high (10 to 20 ML/day) although inflow through the pit wall formed in basement would be low. The effects of drawdown would be limited beyond the basement wall but would extend some distance through the detrital wall and along the strike of the regional aquifer. Typically, the propagation of drawdown through the detrital wall maybe constrained by low-permeability basement forming a barrier on the opposite side of the wall; thereafter drawdown will propagate as an elongate cone of depression along the strike of the regional aquifer aligned with the valley.

Many of the future Marra Mamba pits in the EPR could fall into this category.

5.1.5 Fully Connected

The orebody extends a considerable depth below the watertable on the margins of a wide alluvial plain. The geometry of the pit is such that much of at least one of the pit walls intersects a large exposure of the saturated and permeable Tertiary detritals, which could also be in connection with the dolomite aquifer.

Inflows to the pit would be very high (>20 ML/d) although inflow through the pit wall formed in basement would be low. The effects of drawdown would be limited beyond the basement wall but would extend a considerable distance across the alluvial plain and along the strike of the regional aquifer.

OB23 is the only example of such an orebody mined to date by BHP Billtion Iron Ore. Rio Tinto's Hope Downs in the CPR would be similar. In the future, OB37 and OB42 in the EPR among others, could be similar.

5.2 Eastern Ridge

The Eastern Ridge mining area is located 8 km northeast of Newman and 7 km southwest of Ethel Gorge. The mining area is bound topographically to the north by the Ophthalmia Range, to the west and southwest by the Homestead and Whaleback mining areas respectively and to the south and east by the Fortescue River valley. Ophthalmia Dam is in close proximity to the eastern boundary of the mining area. The Eastern Ridge mining area is shown on Figure 5.2.

There are eight orebodies in the mining area, six Brockman orebodies and two Marra Mamba orebodies. Mining has been completed at one of the Brockman orebodies (OB23) and one of the Marra Mamba orebodies (OB38) is above the watertable and will not require dewatering.

BHP Billtion Iron Ore have extensive hydrogeological experience of the Eastern Ridge mining area dating back to the 1970's when the original Newman water supply borefields were installed in Homestead and Ethel Creeks. The investigations completed since this time, at Eastern Ridge and elsewhere in the EPR region, have provided a high level of confidence in the local hydrogeology. An overview of the key hydrogeological features of each orebody is listed in Table 5.1.

5.2.1 Eastern Ridge Conceptual Model

The main surface water drainages in the Eastern Ridge mining area are Whaleback and Homestead Creeks (Figure 3.1). These creeks are ephemeral and flow generally eastwards through the mining area before discharging into Ophthalmia Dam (Whaleback Creek) and Fortescue River downstream of Ophthalmia Dam (Homestead Creek). The creeks have gravelly sand beds and support scattered eucalyptus trees, with channel gradients of approximately 0.2 to 0.3% through the mining area.

Regional groundwater throughflow is generally from west to east through the mining area and then northwards to Ethel Gorge, enhanced by seepage from Ophthalmia Dam.

There are six orebodies to be mined below watertable, five Brockman orebodies and one Marra Mamba orebody.

Two of the Brockman orebodies (OB24 and OB25 Pit 4) are mostly surrounded by low permeability unmineralised BIF or shales/siltstones and dewatering will simply require desaturation of the orebodies, followed by some maintenance pumping to accommodate low rate residual inflows from the surrounding aquitards. At OB25 Pit 1, there is interpreted to be some along strike hydraulic connection to OB25 Pit 3 (which is in connection with the regional aquifer – refer below) and longer term inflows and dewatering requirements are expected to be higher than at OB24 and OB25 Pit 4. At OB24, it is suspected that there might be some along strike connection with the now mined out OB23 pit. If present, this may result in some, if only minor, increased longer term inflows.

At three of the Brockman orebodies (OB23, OB25 Pit 3 and OB25 West), the hanging walls of the pits will intersect part of the regional aquifer system (Tertiary detritals) and dewatering requirements will be higher than for the other Brockman pits. As was the case at the now completed OB23, dewatering will require both desaturation of the orebody aquifers and sustained high abstraction rates to intercept inflows from the regional aquifer, with longer term dewatering rates being dependent on the degree of hydraulic connection with the regional aquifer.

The Marra Mamba orebody (OB37) will be bound along strike and in the footwall by low permeability unmineralised BIF, but the hanging wall will be exposed to a significant thickness of the regional aquifer (saturated Tertiary detritals and possibly also dolomite). Similarly to the connected Brockman pits, dewatering will require both desaturation of the orebody aquifers and sustained high abstraction rates to intercept inflows from the regional aquifer, with longer term dewatering rates being dependent on the degree of hydraulic connection with the regional aquifer. However, at OB37, dewatering rates are expected to be even higher as active recharge of the regional aquifer by seepage from Ophthalmia Dam will maintain groundwater levels in the regional aquifer adjacent to OB37 and hydraulic gradients towards the pit.

The conceptual hydrogeological model is shown schematically in Figures 5.3a, 5.3b and 5.3c.

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Table 5.1: Eastern Ridge - Orebody Overview

Orebody	Orebody 24	Orebody 25 Pit3	Orebody 25 West	Orebody 25 Pit 4	Orebody25 Pit 1	Orebody 37	Orebody38	Orebody23
Ore Type	Brockman	Brockman	Brockman	Brockman	Brockman	Marra Mamba	Marra Mamba	Brockman
Current Status[1]	- Mining current AWT - Potential BWT mining - Limited drilling	- Current Mining - Active dewatering for approximately 7 yrs	- Proposed Mining - Limited drilling	- Proposed mining - Limited drilling	- Current Mining - Active dewatering for approximately 7 yrs	- Proposed Mining - Limited drilling	- Proposed mining - Limited drilling	- Mining complete - Dewatering history of 7 yrs - On-going abstraction
Previous Hydrogeological Studies[2]	Desktop: - DW - SW	Drilling and testing: - DW, WS, EIA Modelling: - DW, WS, EIA Performance review: - DW (7yrs), WS (since 1970s) - SW	Desktop: - DW	Desktop: - DW	Desktop: - DW Drilling and testing: - DW Performance review: - DW	Desktop: - DW - SW	Nil	Drilling and testing: - DW, WS and EIA Modelling: - DW, WS and EIA Performance review: - DW (7yrs) and WS (since 1970s) Detailed review of dewatering on Ethel Gorge
Ore Below Watertable (BWT)[3]	4%	67%	NA	1%	83%	70%	NA	Mined-out
Max Saturated Thickness[4] (m)	21	128	–	*20*	*20*	110	–	84
Strike Length (m)	7,500	2,000	–	1,000	1,500	6,000	4,000	500
Generic Type[5]	BIF - Isolated or Disconnected	BIF - Connected	BIF - Partially Connected	BIF - Isolated or Disconnected	BIF - Partially Connected	BIF- Fully Connected	BIF - Above Watertable	BIF - Fully Connected
Dewatering Requirements (and basis[6])	LOW (<2 ML/d) analytical model Analogous to OB25 Pit 4	HIGH (14 ML/d) (numerical model and performance data) Analogous to OB23	MOD (5 ML/d) (analytical model)	LOW (<2 ML/d) (generic model) Analogous to OB25 Pit 4	MOD (3 ML/d) (analytical model and performance data)	VERY HIGH (15 to 37 ML/d) (analytical model) Hydrogeological setting similar to OB23/25 with enhanced recharge	Nil (all above WT)	VERY HIGH (20 to 30 ML/d) (numerical modeling and performance data). mining complete
Key Dewatering Drivers[7]	- Storage - Possible hydraulic connection with OB23	- Storage - TD connection	Storage	Storage	Storage - Some hydraulic connection with OB25 Pit 3	Storage - TD connection - Recharge from Ophthalmia	Nil (all above WT)	- Storage - TD connection - Recharge from Ophthalmia
Interaction with Ethel Gorge	- Distant - Hydraulically isolated - < 0.1% reduction in runoff	- Distant - Interception of throughflow to receptor - Possible reversal of GW flow from receptor - dewatering lowers regional water levels - ameliorated by recharge from Ophthalmia - < 0.1% reduction in runoff	- Distant - Hydraulically isolated - < 0.1% reduction in runoff	- Distant - Hydraulically isolated - < 0.1% reduction in runoff	- Distant - Hydraulically isolated - < 0.1% reduction in runoff	- Distant ? - Interception of throughflow to receptor - Possible reversal of GW flow from receptor - dewatering lowers regional water levels - ameliorated by recharge from Ophthalmia - Potential 0.1% reduction in runoff	- Potential 0.1% reduction in runoff	- Proximal - Interception of throughflow to receptor - Reversal of GW flow from receptor - dewatering lowers regional water levels - ameliorated by recharge from Ophthalmia - < 0.1% reduction in runoff

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in *italics* indicates saturated thickness is estimated from drillhole section data only

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

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5.3 East Ophthalmia

The East Ophthalmia mining area is located 15 km northeast of Newman and extends from Ethel Gorge 5 km to the south. The mining area is bound topographically to the north by the Ophthalmia Range, to the east by the Ninga orebodies of the Shovelanna mining area, and to the south and east by the Fortescue River valley. Ophthalmia Dam is in close proximity to the southern margin of the mining area, and the Eastern Ridge mining area is immediately across the Fortescue River valley to the west. The East Ophthalmia mining area is shown on Figure 5.4.

There are four orebodies in the mining area, two Brockman orebodies and two Marra Mamba orebodies. One of the Marra Mamba orebodies (OB42) is above the watertable and will not require dewatering. In addition, it has been assumed that one of the Brockman orebodies (OB22, for which there is little information) is also above the watertable.

BHP Billtion Iron Ore have extensive hydrogeological experience of the general area dating back to the 1970's when the original Newman water supply borefields were installed in the Ethel Gorge area and later in the 1980s with the development of Ophthalmia Dam and the aquifer recharge schemes. More recently, detailed investigations of dewatering requirements (and the influences of dewatering on the overall groundwater system) and the implementation of dewatering at OB23 and OB25 (Eastern Ridge mining area) have been completed. While there have been little to no direct investigations completed at East Ophthalmia, work completed in the general area allows for a moderate level of confidence in the local hydrogeology. An overview of the key hydrogeological features of each orebody is listed in Table 5.2.

5.3.1 East Ophthalmia Conceptual Model

The main surface water drainages within the East Ophthalmia mining area are the Fortescue River, Warrawanda Creek and Shovelanna Creek (Figure 3.2). Upstream of the mining area, the Fortescue River and Warrawanda Creek flow into Ophthalmia Dam. Within the mining area both drainages form overflow channels for Ophthalmia Dam and have semi-permanent flow as a result of seepage from the dam. They form semi-braided sandy gravel beds which support eculypts and melelucas, with channel gradients of around 0.2% through the mining area.

Shovelanna Creek, flows from southeast to northwest through the mining area to a confluence with Warrawanda Creek just downstream of Ophthalmia Dam. The creek is ephemeral with a channel gradient of around 0.15% and a sandy bed which supports eucalypt trees which gradually become lower density with distance upstream.

Regional groundwater throughflow is generally from the south and southeast through the mining area and then northwards towards Ethel Gorge, enhanced by seepage from Ophthalmia Dam.

There are two orebodies to be mined below watertable: OB21 (Brockman) and OB43 (Marra Mamba).

The Brockman orebody (OB21) will be mostly surrounded by low permeability unmineralised BIF or shales/siltstones and dewatering will simply require desaturation of the orebodies, followed by some maintenance pumping to accommodate low rate residual inflows from the surrounding aquitards. There is the possibility of some along strike hydraulic connection via fractures or subgrade mineralisation, and this might result in some increased longer term inflows. However, any such increases in inflows are expected to be only minor.

The Marra Mamba orebody (OB43) will be bound along stike and in the footwall by low permeability unmineralised BIF, but the hanging wall will be exposed to a significant thickness of the regional aquifer (saturated Tertiary detritals and possibly also dolomite). Dewatering will require both desaturation of the orebody aquifers and sustained high abstraction rates to intercept inflows from the regional aquifer, with longer term dewatering rates being dependent on the degree of hydraulic connection with the regional aquifer. Similar to OB37 (in the Eastern Ridge mining area), dewatering rates are expected to be very high as active recharge of the regional aquifer by seepage from Ophthalmia Dam will maintain groundwater levels in the regional aquifer adjacent to OB43 and hydraulic gradients towards the pit.

The conceptual hydrogeological model is shown schematically in Figures 5.5a, 5.5b and 5.5c.

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Table 5.2: Orebody Overview – East Ophthalmia

Orebody	Orebody 21	Orebody 22	Orebody42	Orebody 43
Ore Type	Brockman	Brockman	Marra Mamba	Marra Mamba
Current Status[1]	Proposed Mining No drilling	Proposed Mining Limited drilling	Proposed Mining Limited drilling	Proposed Mining Extensive drilling
Previous Hydrogeological Studies[2]	Nil	Nil	Nil	Nil
Ore Below Watertable (BWT)[3]	15%	NA	All above WT	70%
Max Saturated Thickness[4] **(m)**	20	–	–	85
Strike Length (m)	6,000	2,500	6,500	2,000
Generic Type[5]	BIF - Isolated or Disconnected	BIF - NA	BIF - Above Watertable	BIF - Fully Connected
Dewatering Requirements (and basis[6]**)**	LOW (<2ML/d) (empirical model)	NA	Nil (all above WT)	VERY HIGH (>20ML) (generic model)
Key Dewatering Drivers[7]	Storage	NA	Nil (all above WT)	- Storage - TD connection
Interaction with Ethel Gorge	- Proximal - Possible interception of GW throughflow to receptor - Possible reversal of GW flow from receptor	NA	Nil	- Proximal - Possible interception of GW throughflow to receptor - Possible reversal of GW flow from receptor

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in *italics* indicates saturated thickness is estimated from drillhole section data only

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

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5.4 Shovelanna

The Shovelanna – Ninga - Mesa Gap mining area (referred to collectively as Shovelanna) extends along the Shovelanna Creek valley from approximately 20 to 40 km east of Newman (Figure 5.6). The mining area is bound to the north by the Ophthalmia Range and to the south by Shovelanna Creek. It extends from the East Ophthalmia mining area and Ethel Gorge westwards to the Jimblebar mining area. The Jimblebar access road and rail link traverse the mining area, and there is active mining (within the Shovelanna mining area) at OB17 and OB18.

There are seven orebodies in the mining area, four Brockman orebodies and three Marra Mamba orebodies, all of which will be mined below watertable.

There have been numerous groundwater investigations in the Shovelanna mining area since the mid 1990s. These investigations have provided a high level of confidence in the local hydrogeology throughout the mining area; although further work will improve understanding of hydraulic connection with Ethel Gorge to the west, Shovelanna Creek to the south and Jimblebar Creek to the east. An overview of the status and key hydrogeological features of each orebody is listed in Table 5.3.

5.4.1 Shovelanna Conceptual Model

Shovelanna and Jimblebar Creeks are the main drainage features in the mining area. Runoff from OB20, OB19 and the west side of OB39 drains to the south and west into Shovelanna Creek before discharging through Ethel Gorge. There is also some surface water flow from the western end of OB21 westwards towards Ethel Gorge. Runoff from OB17, OB18, OB31, OB34 and the east side of OB39 flows generally eastwards and discharges into Jimblebar Creek approximately 4 km downstream of Innawally Pool.

Groundwater outflow from the mining area mostly occurs to the northeast towards Jimblebar Creek via the regional aquifer and creek alluvium. There is an interpreted hydraulic barrier aligned along Wheelarra Fault which restricts groundwater flow to the east and southeast. Groundwater flow from the western end of the mining area (western end of OB20) is towards Ethel Gorge. There is also interpreted to be some northwards groundwater inflow from the Shovelanna Creek valley into the mining area via a fault zone through subcropping Marra Mamba at the western end of OB39 which forms the southern margin of the mining area.

Three of the Brockman orebodies (OB17, OB18 and OB20) are surrounded by low permeability unmineralised BIF and or siltstone/shale. In these pits, dewatering will simply require the initial desaturation of the orebody aquifers and then minor maintenance abstraction to accommodate low rate ongoing inflows from the surrounding aquitards. If there is any enhanced connection to other aquifers via local faults, then longer term pit inflows might be higher but they are unlikely to be as high as the initial dewatering rates required to desaturate the orebody aquifers.

In one Brockman orebody (OB31), there appears to be significant faulting through the footwall sequence which is interpreted to provide hydraulic connection with regional aquifer system. If such connection is present, dewatering may not only require desaturation of the orebody aquifers, but may also require sustained high rate abstraction to intercept any inflows from the regional aquifer.

At the two Marra Mamba orebodies (OB34 and OB39), the hanging walls of the pits will likely intersect significant thicknesses of Tertiary detritals and possibly also the underlying dolomite and the pits will be in good hydraulic connection with the regional aquifer. As such, dewatering will not only require desaturation of the orebody aquifers, but also sustained high rate abstraction to intercept inflows from the regional aquifer.

Figures 5.7a, 5.7b and 5.7c show the influence of the conceptual hydrogeology on dewatering requirements.

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Table 5.3: Orebody Overview – Shovelanna

Orebody	Orebody 17 (Ninga)	Orebody 18 (Ninga)	Orebody 19 (Ninga)	Orebody 20 (Ninga)	Orebody 31 (Shovelanna)	Orebody 34 (Mesa Gap)	Orebody 39 (Mesa Gap)
Ore Type	Brockman	Brockman	Brockman	Brockman	Brockman	Marra Mamba	Marra Mamba
Current Status[1]	Extensive drilling	Approved BWT mining Current AWT mining Extensive drilling	Proposed mining Limited drilling	Proposed mining Limited drilling	Proposed mining Extensive drilling	Proposed mining Moderate drilling	Proposed mining Moderate drilling
Previous Hydrogeological Studies[2]	Desk-top: - DW Drilling and testing: - DW	Desk-top: - SW Drilling and testing: - DW, WS, EIA Modelling: - DW (analytical)	Desk-top: - DW Modelling: - DW (analytical)	Desk-top: - DW Modelling: - DW (analytical)	Desk-top: - DW - SW Modelling: - DW (analytical and numerical) Drilling and testing: - DW (	Desk-top: - DW Modelling: - DW (analytical)	Desk-top: - DW Modelling: - DW (analytical)
Ore Below Watertable (BWT)[3]	8% (Swan pit)	8%	8%	4%	59%	70%	48%
Max Saturated Thickness[4] (m)	57	57	53	93	132	126	177
Strike Length (m)	2,000	4,000	8,500	4,000	5,000	5,000	2,000
Generic Type[5]	BIF - Partially Connected	BIF - Partially Connected	BIF - Isolated or Disconnected		BIF - Connected	BIF - Connected	BIF - Connected
Dewatering Requirements (and basis[6])	MOD (2 to 10 ML/d) (empirical model)	MOD (2 to 10 ML/d) (analytical model)	LOW to MOD (1 to 3 ML/d) (analytical model)		VERY HIGH (35 ML/d) (analytical/numerical model)	VERY HIGH (11 to 28 ML/d) (analytical model)	VERY HIGH(13 to 35 ML/d) (analytical model)
Key Dewatering Drivers[7]	Storage	Storage	Storage	Storage	Storage TD connection	Storage TD connection	Storage TD connection
Interaction with Ethel Gorge	Distant Hydraulically isolated	Distant Hydraulically isolated	Distant Hydraulically isolated < 0.1% reduction in runoff	Distant Hydraulically isolated < 0.1% reduction in runoff	Distant Possible interception of throughflow to receptor- Possible reversal of GW flow from receptor	Distant Possible interception of throughflow to receptor- Possible reversal of GW flow from receptor	Distant Possible interception of throughflow to receptor- Possible reversal of GW flow from receptor < 0.1% reduction in runoff

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in *italics* indicates saturated thickness is estimated from drillhole section data only

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

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5.5 Homestead

The Homestead mining area is located 10 km north of Newman and 8 km west of Ethel Gorge being the nearest ecohydrolgical receptor (discussed in Chapter 4.2). The mining area is bound topographically to the north by the Ophthalmia Range, east by the Eastern Ridge mining area and south by the Whaleback mining area (Figure 5.8). Homestead Creek, and its tributary Homestead South Creek, flow in an approximately west to east direction through the mining area. Homestead South Creek meets the Homestead Creek to the west of OB28 and OB32, and south of OB26 (Figure 5.8).

There are six orebodies in the mining area, two Brockman orebodies and four Marra Mamba orebodies. Apart from one of the Brockman orebodies (OB26), which is unlikely to be mined below watertable, all pits will require dewatering.

There have been extensive hydrogeological investigations within the Homestead mining area, dating back to the 1970’s associated with initial investigations to develop a water supply borefield for Newman and more recently (since 2012) as part of developing a 7.5 ML/day potable supply borefield to augment existing supplies from the Ophthalmia Dam Borefield. A preliminary assessment of dewatering risks at one orebody was also carried out in 2013. Overall, there is little specific information on each of the orebodies and while there is a reasonable level of confidence in the overall groundwater throughflow and water supply potential in the area.

An overview of the status and key hydrogeological features of each orebody is listed in Table 5.4.

5.5.1 Homestead Conceptual Model

The main surface water drainage in the Homestead mining area is Homestead Creek (Figure 3.1), which flows generally eastwards through the mining area before discharging into the Fortescue River downstream of Ophthalmia Dam. One of the orebodies (OB33) is on the catchment divide between Homestead Creek and a tributary of Whaleback Creek, which flows eastwards and discharges into Ophthalmia Dam.

Within the mining area, Homestead Creek is ephemeral with a channel gradient approximately 0.3% with a gravelly sand bed supporting scattered eucalypt trees. The Whaleback Creek tributary has a poorly-defined channel with an average gradient of approximately 0.3%.

The one below watertable Brockman orebody (OB28) is surrounded on most sides by low permeability BIF. Ordinarily, dewatering a Brockman orebody in such a location would simply require desaturation of the orebody aquifer followed by minor maintenance pumping to accommodate longer term low rate inflows from the surrounding aquitards. However, part of OB28 is juxtaposed against OB32 West by vertical displacement along the Homestead Fault. OB32 West is interpreted to be in partial hydraulic connection with the regional aquifer (refer below) and longer term abstraction from OB28 might be higher if there is good hydraulic connection across the fault and there are inflows from OB32 West and/or the regional aquifer.

The Marra Mamba orebodies (OB32, OB32 West, OB33 and OB36) are all surrounded by low permeability BIF and siltstones/shales along strike and in their footwalls, except for parts of OB32 West which may be in connection with the OB28 orebody aquifer. The hanging walls of all of the pits appear to be in either Tertiary detritals or shale of the West Angela Member, and there may be some hydraulic connection with the regional aquifer depending on the saturated thickness and / or permeability of these units. Depending on the degree of hydraulic connection to the regional aquifer, longer term dewatering (following desaturation of the orebody aquifers) may require moderate to high rates of abstraction.

The conceptual hydrogeological model is illustrated in Figures 5.9a, 5.9b and 5.9c.

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Table 5.4: Orebody Overview - Homestead

Orebody	Orebody 26	Orebody 28	Orebody 32	Orebody 32 West	Orebody 33	Orebody 36
Ore Type	Brockman	Brockman	Marra Mamba	Marra Mamba	Marra Mamba	Marra Mamba
Current Status[1]	Proposed Mining Limited recent drilling BWT mining unlikely	Proposed Mining Limited recent drilling Potential BWT mining	Potential Mining Limited recent drilling Likely BWT mining	Potential Mining Limited recent drilling Likely BWT mining	Proposed Mining Limited recent drilling Likely BWT mining	Proposed Mining Limited recent drilling Likely BWT mining
Previous Hydrogeological Studies[2]	None	Drilling & testing - WS Modelling - WS	Drilling & testing - WS Modelling - WS, DW SW	Drilling & Testing -WS Modelling - WS, DW	Modelling - WS	Modelling - WS
Ore Below Watertable (BWT)[3]	TBC	50%	70%	70%	70%	70%
Max Saturated Thickness[4] (m)	–	*122*	*150*	*72*	*128*	*45*
Strike Length (m)	Unknown	Unknown	4,000	2,500	12,000	3,000
Generic Type[5]	BIF – Above Watertable	BIF - Partially Connected	BIF - Fully Connected	BIF - Partially Connected	BIF - Fully Connected	BIF - Fully Connected
Dewatering Requirements (and basis[6])	N/A	MOD (4 ML/d) BHP Billtion Iron Ore Generic Model	VERY HIGH (26 ML/d) BHP Billtion Iron Ore Generic Model 5-19 ML/d ID Phase water risk (incorporating Orebody 32 West)	MOD (9 ML/d) BHP Billtion Iron Ore Generic Model	VERY HIGH (26 ML/d) BHP Billtion Iron Ore Generic Model	VERY HIGH (21 ML/d) BHP Billtion Iron Ore Generic Model
Key Dewatering Drivers[7]	N/A	- Storage - TD connection at eastern end of the orebody - Connection with OB32	- Storage - TD connection - Connection with OB28	- Storage - TD connection - Connection with OB28	- Storage - TD (calcrete) / Wittenoom Formation connection	- Storage - TD connection
Interaction with Ethel Gorge	- <0.1% reduction in runoff	- Distant - Interception of throughflow to receptor - ameliorated by recharge from Ophthalmia Dam - <0.1% reduction in runoff	- Distant - Interception of throughflow to receptor - ameliorated by recharge from Ophthalmia Dam - <0.1% reduction in runoff	- Distant - Interception of throughflow to receptor - ameliorated by recharge from Ophthalmia Dam - <0.1% reduction in runoff	- Distant - Interception of throughflow to receptor - lowering of water levels in nearby calcrete (potential stygofauna habitat) - <0.1% reduction in runoff	- Distant - Interception of throughflow to receptor - dewatering lowers regional groundwater levels - lowering of water levels in nearby calcrete (potential stygofauna habitat) - <0.1% reduction in runoff

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in *italics* indicates saturated thickness is estimated from drillhole section data only.

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

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5.6 Whaleback

The Whaleback mining area is located 5 km west of Newman, immediately to the south of the Homestead mining area and north-east of the Western Ridge mining area (Figure 5.10). The northern part of the mining area comprises the largest, single, continuous, iron orebody in Australia (Mt Whaleback – also one of the largest in the world), which is hosted in the Brockman and which has already been mined some 150 m below the pre-mining watertable. The southern part of the mining area comprises three orebodies (OB29, OB30 and OB35) hosted in the Marra Mamba, all of which are to be mined below watertable.

There have been extensive groundwater investigations in the Whaleback mining area commencing with the initial development of the Mt Whaleback mine in the 1960s and 1970s and more particularly the period leading up to below watertable mining in the early 1980s. Preliminary hydrogeological investigations were conducted at OB29 in the late 1990s, with comprehensive investigations at OB29, OB30 and OB35 in 2012.

The completed investigations and operational experience at Mt Whaleback (and other nearby mines) have provided a high level of confidence in the local hydrogeology and its interaction with the ecohydrological receptor.

An overview of the status and key hydrogeological features of each orebody is listed in Table 5.5.

5.6.1 Whaleback Conceptual Model

The main surface water drainage within the Whaleback mining area is Whaleback Creek (Figure 3.1.) which flows north-eastwards through the mining area before discharging into the east side of Ophthalmia Dam. The downstream section of Whaleback Creek has an average gradient approximately 0.3% with a channel bed dominated by cobbles around the OB35 area, decreasing to sand and gravel closer towards Ophthalmia Dam.

Groundwater outflow from the mining area occurs through a narrow zone to the northeast of Whaleback through the alluvium of Whaleback Creek (where it is saturated) and through underlying permeable basement rocks (either Paraburdoo Member dolomite or sub-mineralised or fractured / faulted Marra Mamba / West Angela Member).

The Mt Whaleback (Brockman) orebody is mostly surrounded by low permeability unmineralised BIF, shale, dolerite and mafic units and dewatering mostly only required desaturation of the orebody aquifer. This is confirmed by measured groundwater levels which indicate that dewatering induced drawdown has been generally confined to the orebody area. However, the dewatering / depressurisation of the Whaleback Fault system within the pit has resulted in some drawdown extending to the west of the pit and there may be potential connection between the orebody and dolomite aquifers in this area. This may result in some inflows from the dolomite.

As a result of the overall structure and folding, the Marra Mamba orebodies (OB29, OB30 and OB35) are generally surrounded by a low permeability footwall sequence of unminerised BIF and siltstones/shales. However, recent drilling at OB29 indicates that there may be a zone of sub-mineralised / fractured BIF within the Nammuldi Member, directly underlying the orebody, which increases the area requiring dewatering (desaturation) and may also provide some hydraulic connection between OB29 and OB30.

There is also the potential for hydraulic connection between the orebody aquifers and the regional Paraburdoo Member dolomite aquifer. At OB29 and OB30 the degree of connection will depend upon the permeability of the intervening West Angela Member, which may be mineralised and/or fractured. At OB35, the orebody and regional aquifer may be juxtaposed against each other along the OB35 thrust fault. If there is hydraulic connection, dewatering of the OB29, OB30 and OB35 pits will not only require desaturation of the orebody aquifers, but also sustained high rate abstraction to intercept inflows from the regional aquifer. Figures 5.11a, 5.11b and 5.11c show the influence of the conceptual hydrogeology on dewatering requirements.

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Table 5.5: Orebody Overview – Whaleback

Orebody	Whaleback	Orebody 29	Orebody 30	Orebody 35
Ore Type	Brockman	Marra Mamba	Marra Mamba	Marra Mamba
Current Status[1]	Current BWT mining Extensive drilling	Proposed BWT mining Current AWT mining Extensive drilling	Approved BWT mining Current AWT mining Extensive drilling	Proposed BWT mining Planned AWT mining Moderate drilling
Previous Hydrogeological Studies[2]	Drilling and testing: - WS, DW Modelling: - WS, DW (numerical) EIA: - DW - SW	Drilling and testing: - DW Modelling: - DW (analytical)	EIA: - DW - SW Modelling: - DW (analytical)	EIA: - DW - SW Modelling: - DW (analytical) Nil
Ore Below Watertable (BWT)[3]	100%	39%	43%	NA
Max Saturated Thickness[4] (m)	306	86	66	*82*
Strike Length (m)	5,000	2,000	1,000	2,500
Generic Type[5]	BIF - Partially Connected	BIF - Partially Connected	BIF - Partially Connected	BIF - Partially Connected
Dewatering Requirements (and basis[6])	MOD (10 ML/d) (numerical model and direct measurement)	MOD (2 to 10 ML/d) (analytical modeling)	MOD (2 to 10 ML/d) (analytical modeling)	MOD (2 to 10 ML/d) (analytical modelling)
Key Dewatering Drivers[7]	Storage Connection via WB fault (possible)	Storage Dolomite connection (possible) Along strike connection (possible)	Storage Dolomite connection (possible) Along strike connection (possible)	Storage Connection via thrust fault (possible)
Interaction with Ethel Gorge	Distant Little to no GW interaction Potential 0.3% reduction in runoff	Distant Little to no GW interaction <0.1% reduction in runoff	Distant Little to no GW interaction <0.1% reduction in runoff	Distant Little to no GW interaction <0.1% reduction in runoff

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in *italics* indicates saturated thickness is estimated from drillhole section data only.

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

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5.7 Western Ridge

The Western Ridge mining area is located approximately 15 km southwest of Newman and 8 km southwest of BHP Billiton Iron Ore's Mt Whaleback mine (Figure 5.12).

There are a number of identified orebodies within the Western Ridge mining area, at an early stage of mine planning, which have been combined into three broad orebodies: Silver Knight (Marra Mamba), Eastern Syncline (also known as Western Ridge Marra Mamba) and Mt Helen (also known as Western Ridge Brockman).

Hydrogeological investigations to date have been limited to groundwater supply studies which included investigation drilling for a camp water supply in 2011 and a desk top assessment as part of the Newman potable water supply augmentation study in 2012. While there are no site specific data on aquifer properties, experience gained in the overall EPR and Whaleback mining area specifically allows for a low to moderate level of confidence in the conceptual hydrogeological model. An overview of the status and key hydrogeological features of each orebody is listed in Table 5.6.

5.7.1 Western Ridge Conceptual Model

The main surface water drainage in the Western Ridge mining area is a tributary of Whaleback Creek known as Southern Creek (Figure 3.1). Southern Creek flows west to east through the mining area and then northwards to its confluence with Whaleback Creek near OB35 (in the Whaleback mining area). Whaleback Creek eventually discharges into Ophthalmia Dam. The upstream (western) end of Southern Creek is dominated by silt and sand with an average main channel gradient approximately 0.6%. Downstream of the Western Ridge mining area, the Southern Creek bed changes to sand and cobbles.

Regional groundwater throughflow in the mining area is interpreted to be towards the northeast towards the Whaleback mining area, through the regional aquifer system (Tertiary detritals and underlying dolomite) and following the course of Southern Creek.

The Brockman orebodies (Mt Helen) are likely to be completely surrounded by low permeability unmineralised BIF and siltstones/shales and pit dewatering should simply require desaturation of the orebody aquifers and then minor maintenance abstraction to accommodate low rate ongoing inflows from the surrounding aquitards. However, should there be some along strike hydraulic connection between individual orebodies then the volume of ore to be desaturated could be large and high rate inflows to individual pits could be sustained for some time. This would, however, result in the advanced dewatering of along strike orebodies and the dewatering rates for subsequent pits could be lower than expected.

The Marra Mamba orebodies (Silver Knight and Eastern Syncline) appear to be surrounded on all sides by low permeability unmineralised BIF and siltstones/shales and pit dewatering should also simply require desaturation of the orebody aquifers and then minor maintenance abstraction to accommodate low rate ongoing inflows from the surrounding aquitards. However, there is the potential for pits in the northern part of Eastern Syncline to intersect Tertiary detritals and underlying dolomite, providing hydraulic connection with the regional aquifer. If this is the case, then higher rate longer term dewatering may be required to accommodate inflows from the regional aquifer.

Figures 5.13a, 5.13b and 5.13c show the influence of the conceptual hydrogeology on dewatering requirements.

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Table 5.6: Orebody Overview – Western Ridge

Orebody	Silver Knight	W Ridge M (Eastern Syncline)	W Ridge B (Mt Helen)
Ore Type	Marra Mamba	Marra Mamba	Brockman
Current Status [1]	Proposed Mining High mineral drilling density	Proposed Mining Low mineral drilling density	Proposed Mining Moderate mineral drilling density
Previous Hydrogeological Studies[2]	None	WS	None
Ore Below Watertable (BWT)[3]	70%	70%	15%
Max Saturated Thickness[4] (m)	*33*	*45*	*57*
Strike Length (m)	5,000	4,000	3,500
Generic Type[5]	BIF - Isolated or Disconnected	BIF - Partially Connected	BIF - Isolated or Disconnected
Dewatering Requirements (and basis[6])	HIGH (>10 ML/d) (generic model – high inflows as a result of large strike length)	HIGH (>10 ML/d) (generic model – high inflows as a result of large strike length))	HIGH (>10 ML/d) (generic model – high inflows as a result of large strike length)
Key Dewatering Drivers[7]	Storage	Storage TD connection	Storage
Interaction with Ethel Gorge	Not expected	Not expected	Not expected

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in italics indicates saturated thickness is estimated from drillhole section data only.

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

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5.8 Jimblebar

The Jimblebar–Wheelarra–Hashimoto-Caramulla mining area (hereafter referred to collectively as Jimblebar) extends from the West Jimblebar orebodies, located immediately to the south of the active OB18 mine (in the Shovelanna mining area) along a strike length of 50 km to the east. It is approximately 30 km east of Newman (Figure 5.14).

There are eleven orebodies in the mining area, seven Brockman orebodies and four Marra Mamba.

There have been extensive groundwater investigations in the Jimblebar mining area since its initial development in the late 1980s and early 1990s. The completed investigations and operational experience gained to date have provided a high level of confidence in the local hydrogeology in and around the South Jimblebar orebody. The level of confidence in the hydrogeology of the Wheelarra and WHASHI orebodies lower than at South Jimblebar, but is expected to improve when current investigations are completed. There are little to no hydrogeological data for the West and East Jimblebar, and Caramulla orebodies.

An overview of the status and key hydrogeological features of each orebody is listed in Tables 5.7 and 5.8.

5.8.1 Jimblebar Conceptual Model

The Jimblebar, Caramulla and Davidson Creeks are the main drainage features (Figure 3.2). These creeks are major ephemeral tributaries which discharge northwards through the mining area. The creeks have gravelly sand beds, support scattered eucalypt trees and typically have a channel gradient of approximately 0.2% through the orebody areas. Downstream of the orebody areas, the flows disperse into a wide, flat floodplain and travel via smaller flow channels and overland flow before merging with the Fortescue River.

Regional groundwater outflow occurs to the north towards the Fortescue River floodplain, mostly via fault zones through Wheelarra Hill and the extended low ridge of Brockman to the east.

The most sensitive feature in the mining area is Innawally Pool, a surface water feature in Jimblebar Creek that is maintained by surface water flow and intermittent perched groundwater flow in the creek alluvium. It is not considered to be groundwater dependent, as the depth to the regional watertable below the pool is almost 50 m. There might, however, be some infiltration of water from the pool to the unsaturated zone which might eventually make its way to the watertable.

The Brockman orebodies are mostly surrounded by low permeability unmineralised BIF and shales/siltstones and, in most cases, dewatering will simply require desaturation of the orebody aquifers followed by minor maintenance abstraction to handle low rate ongoing inflows from the surrounding aquitards. However, there appear to be permeable faults zones at two pits (in the WH1,2,3 and WHASHI orebodies) which could provide direct hydraulic connection to the regional aquifer (Tertiary detritals and underlying dolomite). Depending on the degree of hydraulic connection, longer term pit inflows and dewatering requirements could be similar to initial dewatering requirements.

The Marra Mamba orebodies will also be bound along strike and in the footwall by low permeability unmineralised BIF. Some of the orebodies (e.g. South Jimblebar) are extensive along strike and comprise a number of individual deposits and planned pits. In some case there will be good hydraulic connection between these individual deposits/pits while others will be hydraulically isolated. The hanging walls of most, if not all, pits are likely to intersect Tertiary detritals (and possibly also the dolomite) of the regional aquifer. The degree of hydraulic connection can also be enhanced if the West Angela Member, which will be intersected in the lower sections of most footwalls, is mineralised, fractured or manganiferous. As such, dewatering of these pits will not only require desaturation of the orebody aquifers, but also sustained high rate abstractions to intercept inflows from the regional aquifer.

The eastern orebodies are in topographically low areas and, in some cases, covered by recent alluvium. However, other than the deep intersections of the Tertiary detritals by Marra Mamba pits as outlined above, the intersection of the recent alluvium and other sediments will all be above the regional watertable.

Figures 5.15a, 5.15b and 5.15c show the influence of the conceptual hydrogeology on dewatering requirements.

Table 5.7: Orebody Overview – Wheelarra – Hashimoto - Jimblebar

Orebody	Wheelarra WH1,2.3	Wheelarra WH4	WHASHI (WH5/6 and Hashi 1)	Hashimoto H2,3,4	East Jimblebar 1,2,3	South Jimblebar	West Jimblebar
Ore Type	Brockman	Brockman	Brockman	Brockman	Brockman	Marra Mamba	Marra Mamba
Current Status[1]	Approved BWT mining Current AWT mining Extensive drilling	Approved BWT mining Current AWT mining Extensive drilling	Approved BWT mining Extensive drilling	Proposed mining Moderate drilling	Proposed mining Moderate drilling	Approved BWT mining AWT mining commenced Extensive drilling	Proposed mining Limited drilling
Previous Hydrogeological Studies[2]	Drilling and testing: - DW Modelling: - DW (numerical) SW	SW	Drilling and testing: - DW Modelling: - DW (numerical)	Drilling and testing: - DW	Nil	Drilling and testing: - DW, WS, ASR, EIA Modelling: - DW, WS, ASR, EIA (numerical) SW	Nil
Ore Below Watertable (BWT)[3]	8%	–	31%	–	15%	70%	70%
Max Saturated Thickness[4] (m)	105	–	158	–	*45*	136	*110*
Strike Length (m)	5,000	2,500	4,000	3,500	4,000	9,000	3,000
Generic Type[5]	BIF Partially Connected	BIF Above Watertable	BIF Isolated or Disconnected	BIF AWT	BIF Partially Connected	BIF Fully Connected	BIF Fully Connected
Dewatering Requirements (and basis[6])	MOD (2 ML/d) (numerical model – but recent drilling suggests much higher)	NA	LOW (1 to 2 ML/d) (numerical model – but recent drilling suggests might be higher)	NA	MOD (2 to 10 ML/d) (experience)	VERY HIGH (30 to 70 ML/d) (numerical model for 2009 mine plan)	HIGH (>10 ML/d) (generic model)
Key Dewatering Drivers[7]	Storage	NA	Storage	NA	Storage TD connection	Storage TD connection	Storage TD connection
Interaction with Innawally Pool, or Ethel Gorge for West Jimblebar	No GW interaction Potential 1.7% reduction in runoff to Innawally Pool	No GW interaction Potential 0.8% reduction in runoff to Innawally Pool	No GW interaction Potential 1.1% reduction in runoff to Innawally Pool	Potential 1.0% reduction in runoff to Innawally Pool	No GW interaction Potential 0.6% reduction in runoff to Innawally Pool	No GW interaction Potential 3.3% reduction in runoff to Innawally Pool	Distant (from Ethel Gorge) Possible increase in interception of GW throughflow to Ethel Gorge Potential 0.2% reduction in runoff to Ethel Gorge

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in *italics* indicates saturated thickness is estimated from drillhole section data only.

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

Table 5.8: Orebody Overview – Caramulla

Orebody	**Caramulla West (BRK)**	**Caramulla West (MM)**	**Caramulla East (BRK)**	**Caramulla East (MM)**
Ore Type	Brockman	Marra Mamba	Brockman	Marra Mamba
Current Status[1]	Proposed mining Limited drilling	Proposed mining Limited drilling	Proposed mining Limited drilling	Proposed mining Limited drilling
Previous Hydrogeological Studies[2]	Nil	Nil	Nil	Nil
Ore Below Watertable (BWT)[3]	15%	70%	15%	70%
Max Saturated Thickness[4] (m)	*10*	*47*	*10*	*47*
Strike Length (m)	3,000	5,000	3,000	5,500
Generic Type[5]	BIF - Partially Connected	BIF - Connected	BIF - Partially Connected	BIF - Connected
Dewatering Requirements (and basis[6])	MOD (2 to 10 ML/d) (generic model)	HIGH (>10 ML/d) (generic model)	MOD - (2 to 10 ML/d) (experience)	HIGH (>10 ML/d) (generic model)
Key Dewatering Drivers[7]	Storage Potential TD connection	Storage Potential TD connection	Storage Potential TD connection	Storage Potential TD connection
Interaction with Innawally Pool	No GW interaction No surface water impact on Innawally Pool	No GW interaction No surface water impact on Innawally Pool	No GW interaction No surface water impact on Innawally Pool	No GW interaction No surface water impact on Innawally Pool

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in italics indicates saturated thickness is estimated from drillhole section data only.

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

5.9 Ophthalmia

The Ophthalmia mining area is located approximately 40 km west of Newman (Figure 5.16). It is bound to the north by the western end of the Ophthalmia Range. The Homestead mining area is approximately 40 km to the east and the Prairie Downs mining area is some 10 km to the south of Ophthalmia. Rio Tinto's Giles Point prospect is approximately 10 km to the west of Ophthalmia.

There are three orebodies in the Ophthalmia mining area, two of which will be mined below watertable and will require dewatering. One of these (Central) is a Marra Mamba orebody and the other (Western Buttes) is mostly Tertiary detritals (and/or CID) ore but which could also include some Marra Mamba ore at depth.

The only hydrogeological investigation completed to date is a camp/drilling water supply investigation in early 2013. However, coupled with the experience gained in other mining areas in the region, the available data allow for a low to moderate level of confidence in the conceptual hydrogeological model.

An overview of the status and key hydrogeological features of each orebody is listed in Table 5.9.

5.9.1 Ophthalmia Conceptual Model

The main surface water drainage within the Ophthalmia mining area is Western Creek (Figure 3.1), a tributary of the Fortescue River. Western Creek flows south-eastward through the mining area before merging with the Fortescue River some 50 km downstream, prior to discharging into Ophthalmia Dam. The orebodies are located in the upstream reach of Western Creek where the main channel has a bed gradient of approximately 0.4%, although the side channels which drain the Ophthalmia Range are steep and incised.

The regional groundwater throughflow is from northwest to southeast through the mining area and then to the north (beneath the Fortescue River valley) towards Ophthalmia Dam.

At Central, the orebody aquifer may be completely surrounded by low permeability unmineralised BIF below the watertable and, as such, pit dewatering may simply require desaturation of the orebody aquifer and then minor maintenance abstraction to accommodate low rate ongoing inflows from the surrounding aquitards. However, if the creek bed alluvium (where Western Creek cuts through the orebody) extends to below the watertable or there is a permeable fault zone beneath the creek, there may be some enhanced connection with the regional aquifer and longer term pit inflows might be higher. However, it is likely that longer term dewatering rates will still be lower than the initial dewatering rates required to desaturate the orebody aquifers.

At Western Buttes, the pit will be exposed to saturated Tertiary detritals and either exposed to, or in hydraulic connection with, the underlying dolomite of the regional aquifer. If the dolomite is permeable, dewatering will not only require desaturation of the orebody aquifers, but may also require sustained high rate abstraction to intercept or accommodate inflows from the regional aquifer.

Figure 5.17 shows the influence of the conceptual hydrogeology on dewatering requirements.

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Table 5.9: Orebody Overview - Ophthalmia

Orebody	**Western Buttes**	**Central**	**Red Buttes**
Ore Type	Detritals (and Marra Mamba?)	Marra Mamba	Marra Mamba
Current Status[1]	Proposed mining Limited drilling	Proposed mining Moderate drilling	Proposed mining Limited drilling
Previous Hydrogeological Studies[2]	Drilling: - WS	Nil	NA
Ore Below Watertable (BWT)[3]	50%	70%	Nil
Max Saturated Thickness[4] **(m)**	*55*	*51*	–
Strike Length (m)	3,500	5,000	7,000
Generic Type[5]	DET/BIF - Connected	BIF - Partially Connected	BIF - Above Watertable
Dewatering Requirements (and basis[6]**)**	HIGH (>10 ML/d) (generic model)	MOD (2 to <10 ML/d) (experience)	Nil
Key Dewatering Drivers[7]	Storage TD connection	Storage	NA
Interaction with Ethel Gorge	Distant Potential 0.2% reduction in runoff	Distant Hydraulically isolated Potential 0.1% reduction in runoff	Groundwater - Nil Potential 0.2% reduction in runoff

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in *italics* indicates saturated thickness is estimated from drillhole section data only.

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

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5.10 Prairie Downs

Prairie Downs is located approximately 50 km west of Newman to the south of the Ophthalmia Range (Figure 5.18), with most deposits located within the Spearhole Creek catchment (a tributary of the Fortescue River).

There are six Marra Mamba orebodies within the mining area, Prairie Downs Grids A to E and Prairie Downs East, the latter being in the Western Creek catchment.

An assessment of the water supply potential of the Prairie Downs area was carried out as part of a regional scale desktop study of potential supplementary groundwater supplies for Newman in 2012. Information from the desk-top study, coupled with the experience gained in other mining areas in the region, provide some confidence in the conceptual hydrogeological model.

An overview of the status and key hydrogeological features of each orebody is listed in Table 5.10.

5.10.1 Prairie Downs Conceptual Model

Western Creek and Spearhole Creek, tributaries of the Fortescue River, are the main surface water drainages the mining area (Figure 5.18). Western Creek drains the northeastern end of the mining area with a main channel gradient of approximately 0.3%. Spearhole Creek drains the remainder of the mining area, and Spearhole Creek flows on the south-west side with a main channel gradient of approximately 0.2%. Topography around the orebodies is hilly with numerous small sub-catchments discharging towards the two main creeks.

Groundwater throughflow is generally from northwest to southeast through the mining area, but becomes easterly downstream of the confluence of Western and Sperahole Creeks some 20 km downstream and then eventually northwards (beneath the Fortescue River valley) towards Ophthalmia Dam.

The Grid A and Grid D orebodies are located within a ridge of outcropping Marra Mamba and will be surrounded on all sides by low permeability unmineralised BIF and shales/siltstones. Dewatering will simply require desaturation of the orebody aquifer followed by maintenance pumping to accommodate low rate inflows from surrounding aquitards.

At the other orebodies, the pits are likely to be exposed to variable thicknesses of saturated Tertiary detritals and, in some cases, possibly also dolomite of the regional aquifer. At these pits, longer term dewatering will be higher than for the isolated pits as a result of inflows from the regional aquifer system.

Figure 5.19 shows the influence of the conceptual hydrogeology on dewatering requirements.

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Table 5.10: Orebody Overview – Prairie Downs

Orebody	Prairie Downs (Grid A, and Grid D)	Prairie Downs (Grid C, B, Grid E and East)
Ore Type	Marra Mamba	Marra Mamba
Current Status[1]	Proposed Mining, Moderate Drilling	Proposed Mining, Moderate Drilling
Previous Hydrogeological Studies[2]	Desktop water supply study only	Desktop water supply study only
Ore Below Watertable (BWT)[3]	60%	80%
Max Saturated Thickness[4] (m)	*78*	*78*
Strike Length (m)	Grid A – 4,000, and Grid D – 3,500	Grid C – 6,500, Grid B – 4,000, Grid E – Unknown and East – 2,000
Generic Type[5]	BIF - Isolated or Disconnected	BIF - Connected
Dewatering Requirements (and basis[6])	MOD (2 to 10 ML/d) (generic model only)	HIGH (>10 ML/d) (generic model only)
Key Dewatering Drivers[7]	Storage TD connection	Storage TD connection
Interaction with Ethel Gorge	Distant <0.1% reduction in runoff	Distant Potential 0.3% reduction in runoff

1 Mining status: Proposed (planned future mining but no regulatory approvals in place); Approved (planned mining with regulatory approvals in place); Mining (active mining)

2 Types of study: DW – dewatering; WS – water supply; EIA – environmental impact assessment; SW – surface water

3 Based on discrete geological and mine planning data packages provided by BHP Billiton Iron Ore.

4 Maximum saturated thickness estimated from mine planning data provided by BHP Billiton Iron Ore. Data in italics indicates saturated thickness is estimated from drillhole section data only.

5 Generic Orebody Types - BHP Billtion Iron Ore generic model based on ore type and hydrogeological setting, particularly degree or hydraulic connection between ore and the regional aquifer.

6 Generic model - BHP Billtion Iron Ore generic model based on ore type, BWT ore tonnes and life of mine; empirical model – generic model modified based on experience at other, similar orebodies; analytical model – simple model based on lumped parameters; numerical model – full 3D modelling; experience – no modelling available but value other than generic model adopted based on experience.

7 Storage – desaturation of orebody aquifer (where storage listed alone, the orebody aquifer is contained within aquitards); TD connection – pit in hydraulic connection with, and inflows expected from the regional aquifer.

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6. CONCLUSIONS

6.1 Approach

An ecohydrological conceptualisation model has been developed to consider the local and regional hydrology within a broader environmental context. The approach was based on the combined application of landscape and topographic, vegetation and environmental, rainfall and surface water, and geological and hydrogeological data sets.

A conceptual hydrological model was developed for Ethel Gorge, the identified ecohydrological receptor. This conceptual model identifies and quantifies the key hydrological processes that sustain the environment at Ethel Gorge.

6.2 Regional Conceptual Hydrological Model

The regional conceptual hydrological model for the EPR study area can be summarised as follows:

- The main aquifers are the Brockman and Marra Mamba orebodies themselves and a regional aquifer associated with Tertiary detritals and, in places, underlying Paraburdoo Member dolomite. Thus, the regional aquifer is aligned with the main surface water system. The orebody aquifers are associated with mineralised (hematitic) BIF within the Brockman and Marra Mamba and sometimes with mineralised footwall or hanging wall units.
- The regional aquifer comprises Tertiary detritals (comprising mostly sand, gravel and Calcrete within mixed sequences of sediments including clay). This is typically underlain by weathered and karstic dolomite.
- On the Fortescue River floodplain upstream and through Ethel Gorge, the Tertiary detritals comprise deep and shallow alluvial gravels separated by laterally extensive and thick clay. This results in a dual aquifer system comprising a deep confined aquifer and shallow unconfined aquifer.
- The orebody aquifers tend to be adjacent to aquitards; however, there can be some along-strike hydraulic connection between orebodies via faults and sub-grade mineralisation, and some cross-strike connection to the regional aquifer via faults. This is more common in Marra Mamba orebodies where there are commonly shallow angled thrust faults.
- Some orebodies (and pit slopes) will be in direct hydraulic connection with the regional aquifer, where the paleovalleys have been eroded down to result in the saturated Tertiary detritals being adjacent to the orebody aquifer.
- The aquifers are naturally recharged by the infiltration of rainfall runoff and discharge as groundwater throughflow to downstream areas and as baseflow or evapotranspiration in low lying areas.
- The majority of recharge in the EPR occurs on the Fortescue River floodplain and the majority of natural groundwater discharge occurs as evapotranspiration from dense vegetation on the Fortescue River floodplain.
- Since the commencement of mining in the EPR study area, recharge on the Fortescue River floodplain has been further enhanced near Ethel Gorge by seepage from Ophthalmia Dam and there has been additional discharge by water supply and dewatering abstraction.

6.3 Ecohydrological Landscape Units

The nine identified EHUs have been grouped into four landscape units:

- Upland Source Landscape Units comprising hills and plateaux and dissected slopes and plains.
- Upland Transitional Landscape Units comprising upland drainage channels.
- Lowland Transitional Landscape Units comprising sandplains, alluvial plains and calcrete plains.
- Lowland Receiving Landscape Units comprising major river channels and associated floodplains and claypans, flats and basins.

Upland Source and both the Transitional Landscape Units comprise much of the EPR study area. These are neither ecohydrologically unique nor critically dependent on unique hydrological conditions. Rather they represent conditions that are common throughout the Pilbara. They are characterised by a deep watertable (greater than 30 m depth to groundwater) and the ecohydrological risks resulting from a change in water level are small. The topography is such that surface water runs off and rapidly transits these areas. As such, there is little in the way of water dependency.

In the lowland areas, the environment is closely integrated with the hydrological system. Key ecohydrological characteristics of the lowland areas are:

- The topography and upstream catchment areas are such that surface water is present within the lowland areas for longer periods (than the upland and transitional areas), with greater flood magnitudes and durations.
- These have led to enhanced riparian environments and greater subsurface water availability through infiltration, soil moisture replenishment and groundwater recharge.
- The environment has adapted to greater water availability.
- Watertable is shallower (ranging from less than 1 m up to 30 m depth to groundwater), and accessible to phreatophytic vegetation and maintain saturated habitat for stygofauna.

6.4 Ethel Gorge

Ethel Gorge occurs where the Fortescue River flows through the Ophthalmia Range. Downstream of The Gorge, the river flows in a narrow channel to the north and then onto a broad floodplain and ultimately into the Fortescue Marsh.

Surface and groundwater flows from most of the EPR catchments (all except flows from the Jimblebar mining area and approximately 50% of the Shovelanna mining area) are focused into Ethel Gorge. From a landscape context, The Gorge can be characterised as a receiving environment comprising channels, floodplains and calcrete of the River and Calcrete Land Systems. The Ethel Gorge area is characterised by groundwater levels of less than 10 mbgl which give rise to interactions between the groundwater and terrestrial environments. In lowland areas, the environment is more closely integrated. Stygofauna are hosted in shallow alluvial aquifers (notably calcrete) and their habitat is maintained by saturation of these aquifers. Vegetation community comprises both obligate and facultive (opportunistic) phreatophytes that utilise the shallow groundwater.

The TEC has been identified at Ethel Gorge based on the presence of multiple species of stygofauna and uncommon communities of dense riparian and woodland vegetation within the major drainage lines and floodplains. The Ethel Gorge TEC has been defined by the extent of calcrete outcrop between Ethel Gorge south along the Fortescue River channel for approximately 15 km along with an additional 6 km buffer zone in all directions (DPaW 2012).

Recent investigations suggest the actual TEC is confined to approximately 10 km of Fortescue River paleo-channel aquifer (related to the sub-surface extent of saturated calcrete as opposed to the surface expression of calcrete used by DPaW) and extends from Ophthalmia Dam to approximately 5 km north of Ethel Gorge (Bennlongia 2013).

The conceptual hydrological model for the broad Ethel Gorge area and ecohydrological receptor are:

- The Ethel Gorge groundwater system is recharged by a combination of groundwater throughflow from up-catchment, infiltration of rainfall runoff (streamflow) beneath local drainage lines and seepage from Ophthalmia Dam.
- The hydraulic behaviour of the Ethel Gorge groundwater system (and the maintenance of shallow groundwater levels which support the key ecological communities) is dominated by recharge from Ophthalmia Dam. The water balance shows the following average inputs:
  - Recharge from Ophthalmia Dam of approximately 50,000 kL/d.
  - Infiltration of runoff along stream channels of approximately 24,000 kL/d.
  - Groundwater throughflow of approximately 2,000 kL/d.

- Discharge from the Ethel Gorge groundwater system is dominated by evapotranspiration, which occurs from extensive stands of vegetation that occur over some 3,650 ha on the Fortescue River floodplain. The water balance shows the following average outputs (for pre-mine dewatering conditions):
  - Evapotranspiration of approximately 63,000 kL/d.
  - Groundwater throughflow (through Ethel Gorge) of approximately 3,000 kL/d.
  - Water supply borefield abstraction of approximately 10,000 kL/d.
- Groundwater levels in the shallow alluvial aquifer that hosts the TEC have historically fluctuated through a large range; mostly related to climatic cycles of wetter and drier periods and also to variations in water supply abstraction from the existing borefield.
- Dewatering in the Ethel Gorge area (since 2007) has resulted in drawdown in deep aquifer water levels across a broad area but, apart from the immediate pit areas, drawdown in the shallow aquifer have been less than 10 m and the shallow aquifer has remained saturated.

Overall, then, the key hydrological processes that maintain the shallow groundwater conditions that support the TEC, are recharge from Ophthalmia Dam and infiltration of surface water flow through stream channels. Groundwater throughflow from areas upstream of Ethel Gorge (including all mining areas) provides only a very small fraction of total inputs to the water balance (less than 3%).

Groundwater and surface water flow from the Jimblebar mining area discharges through a gorge in Wheelarra Hill to the north into the Jimblebar Creek floodplain and eventually into the Fortescue River downstream of Ethel Gorge. Surface water flows maintain Innawally Pool on Jimblebar Creek.

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PLATES

Fortescue River at Ethel Gorge Plate 3.1

Whaleback Creek Plate 3.2

Ophthalmia Dam Overflowing March 2009 | Plate 3.3

Shovelanna Creek | Plate 3.4

Homestead Creek | Plate 3.5

Jimblebar Creek Innawally Pool March 2009 | Plate 3.6

Jimblebar Creek West Branch Plate 3.7

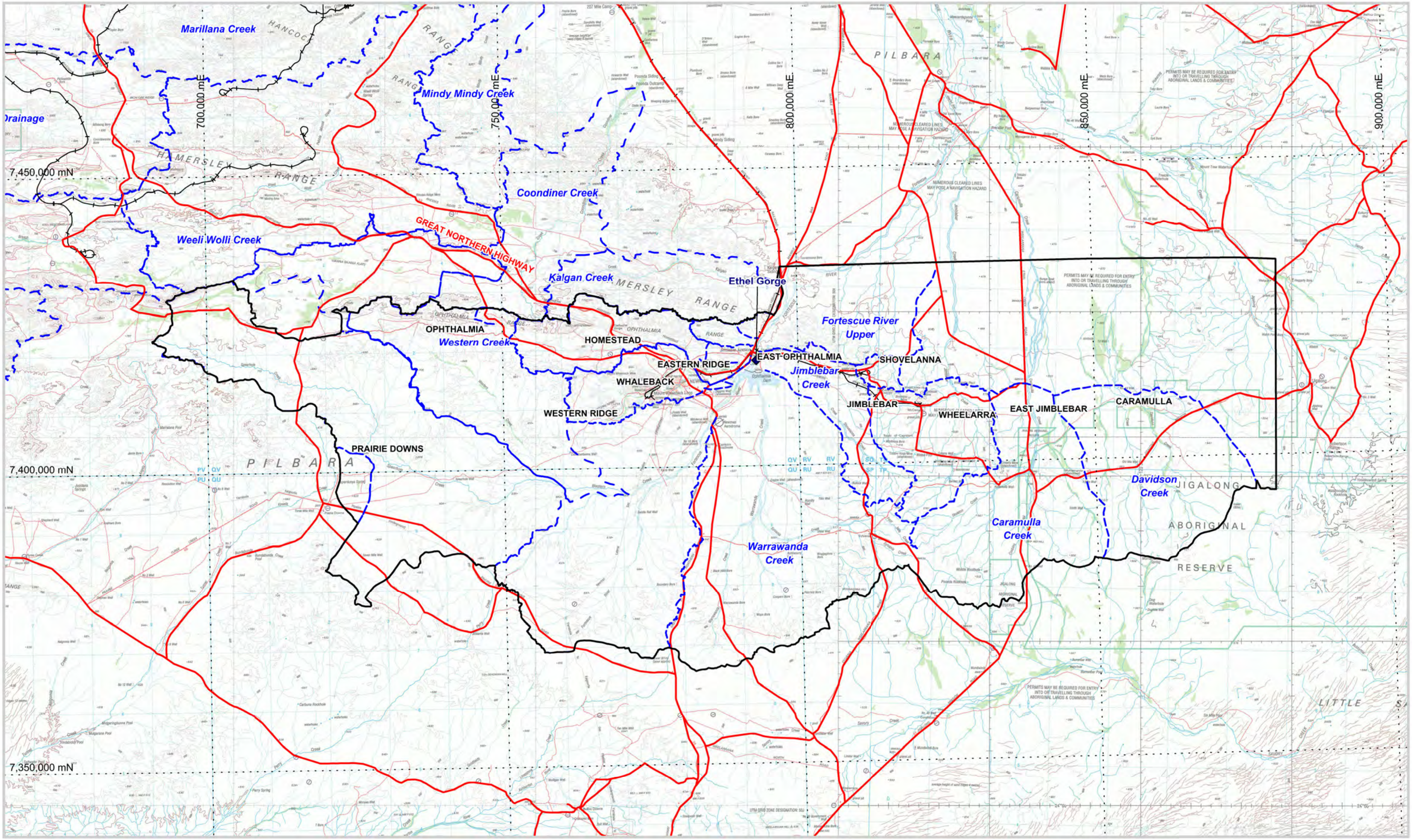
Copper Creek Plate 3.8

Caramulla Creek **Plate 3.9**

Davidson Creek **Plate 3.10**

Thirteen Creek **Plate 3.11**

FIGURES



AUTHOR: JP	REPORT NO: 198
DRAWN: MR	REVISION: d
DATE: 01/09/2015	JOB NO: 1606B

Location: F:\Jobs\1606\Spatial_Data\Mapinfo\Workspaces\129c\129c Figure 1.1 - Eastern Pilbara Hub Location Map

LEGEND

- Environmental Receptors
- Road
- Rail
- Surface Water Catchment
- EPR Study Area Boundary

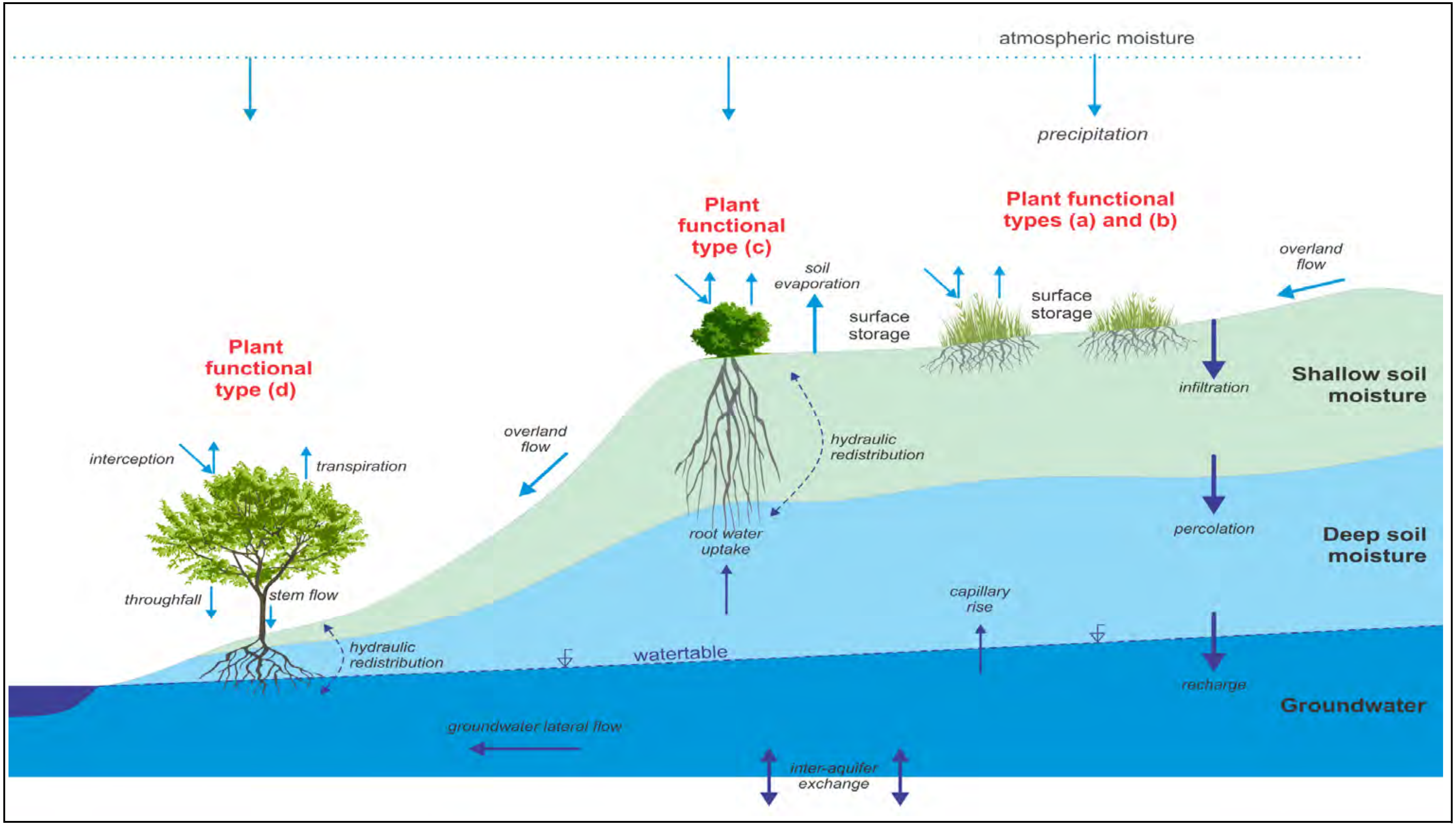
DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 1.1

LOCATION MAP
EASTERN PILBARA REGION

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from this conceptual map."



RPS

A conceptual diagram depicting lateral and vertical connectivity in an ecosystem with water as the primary medium (adapted from Miller et al. 2012). FIGURE 1.2

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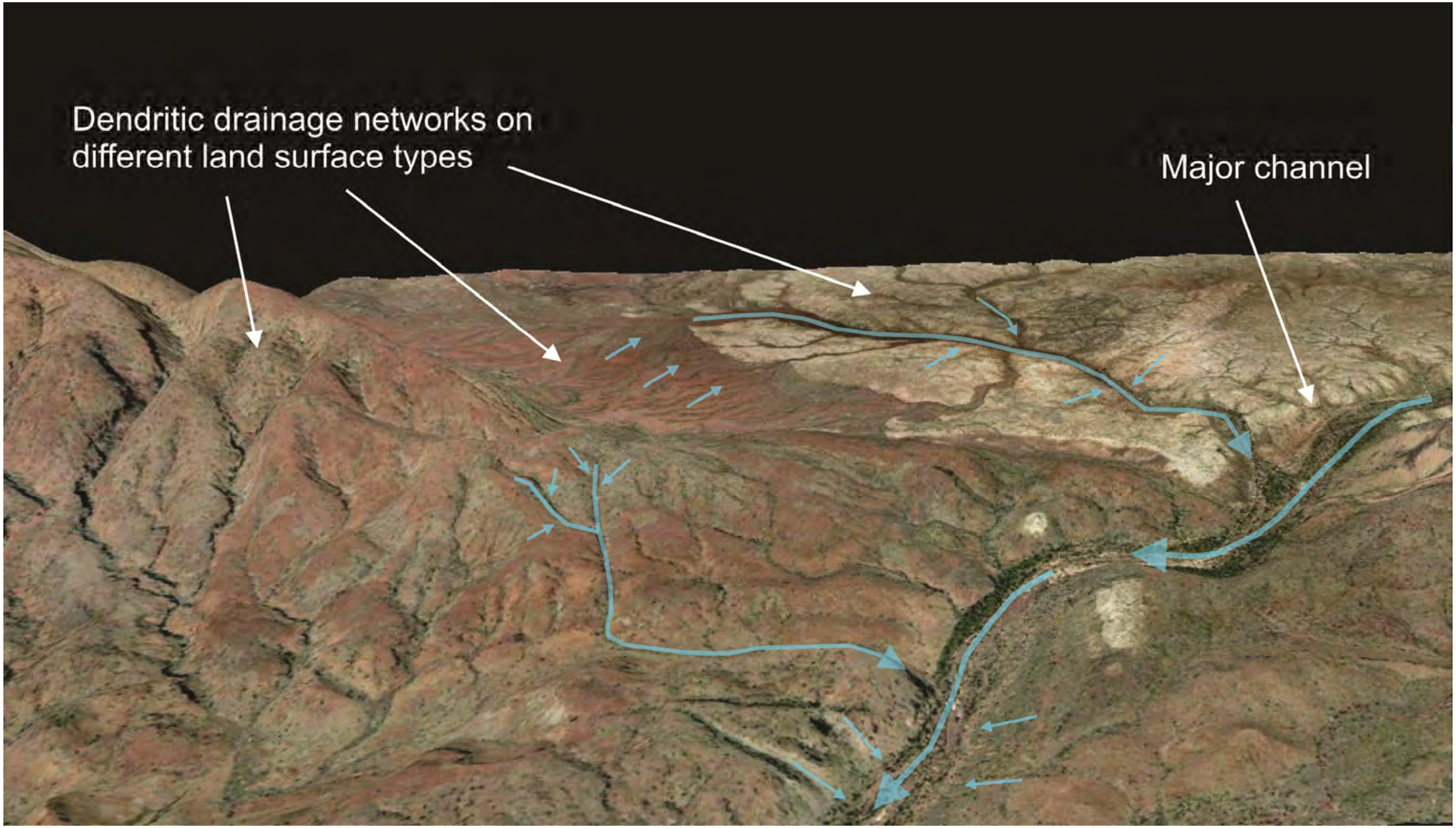

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Lateral and longitudinal connectivity in Pilbara uplands drainage systems. Note the concentration of denser vegetation along the major drainage lines. FIGURE 1.3

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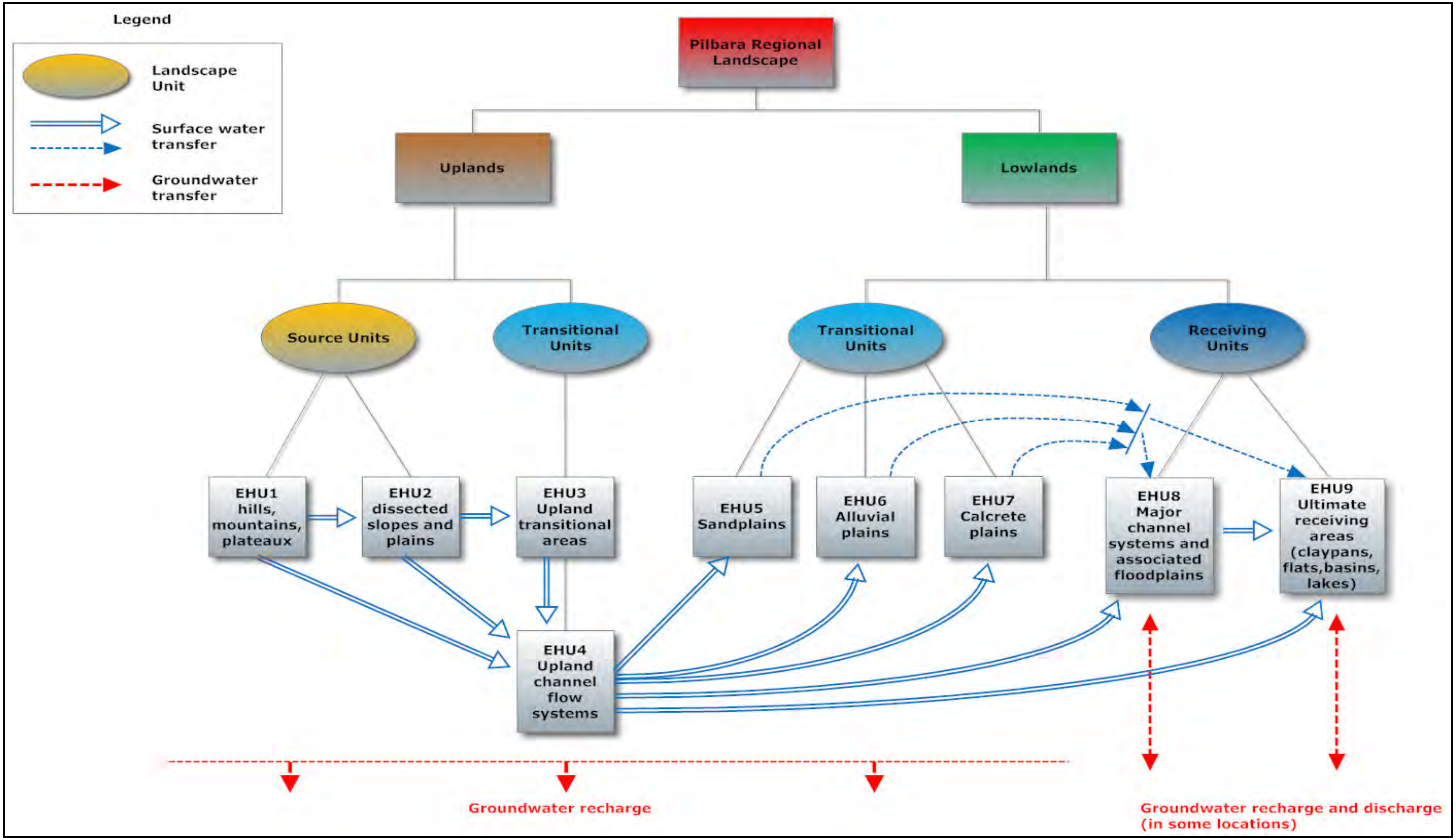

RPS

Landscape hierarchy of EHUs and major water flow connectivity FIGURE 1.4

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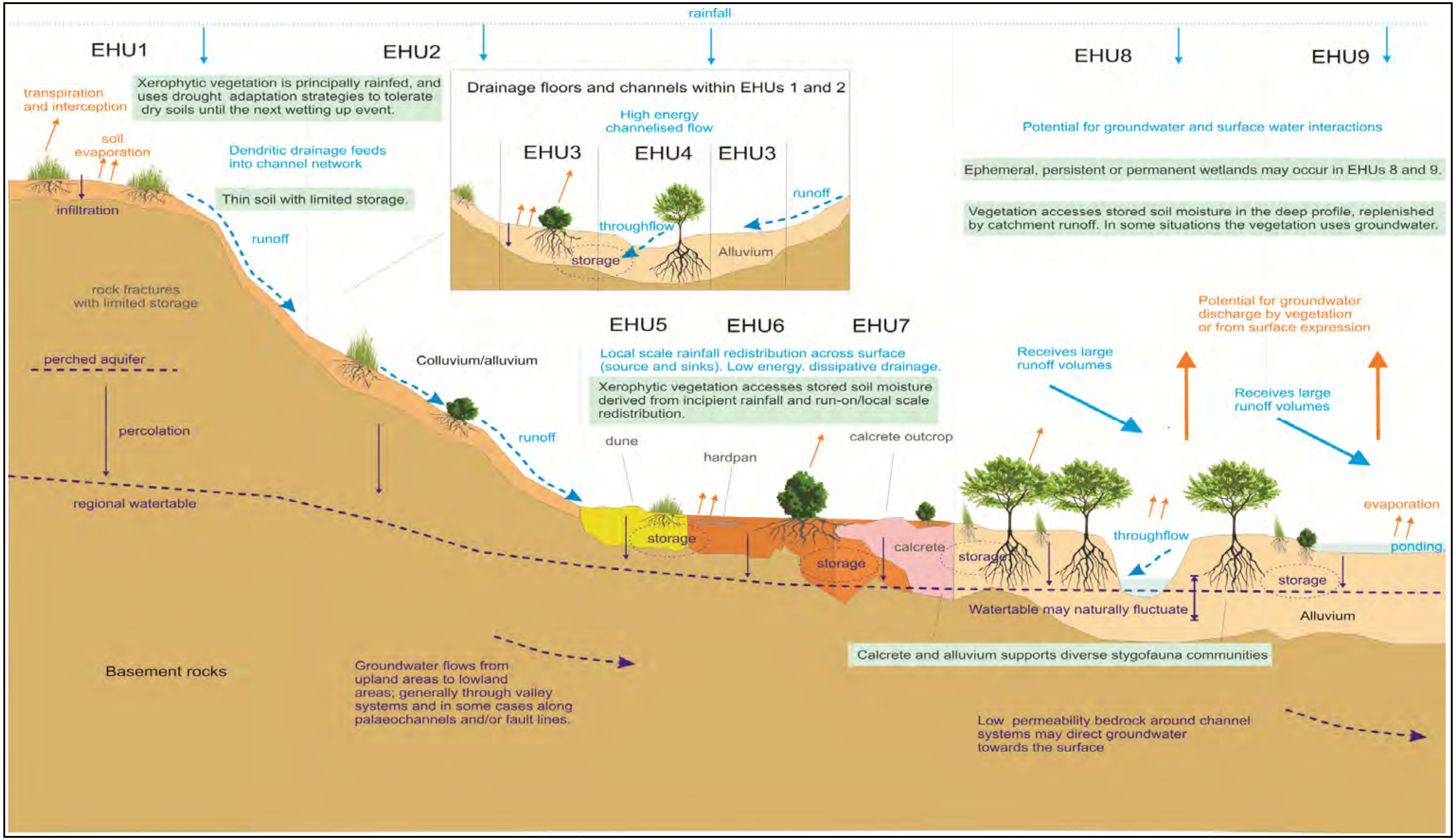

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EHUs Landscape Overview FIGURE 1.5

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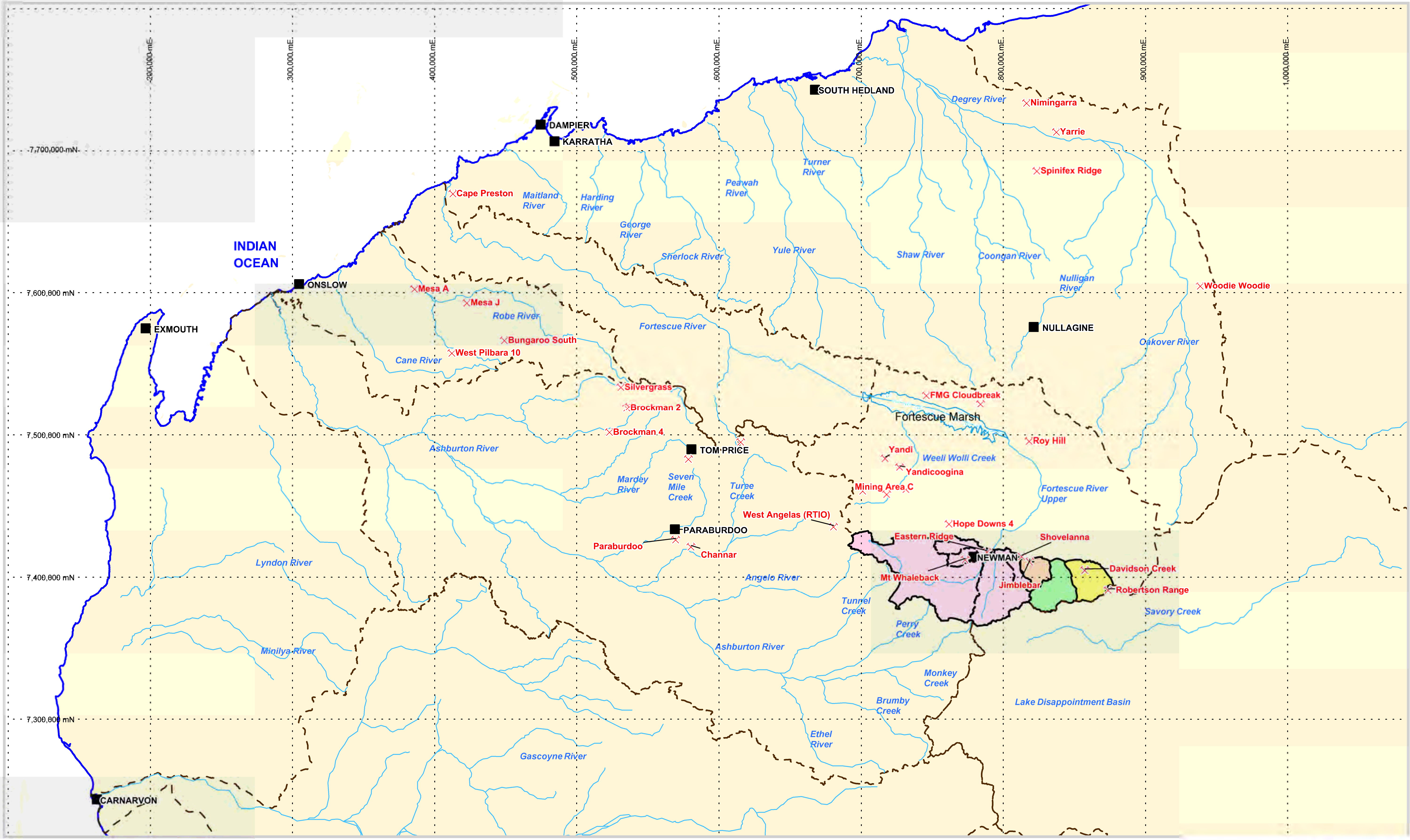

LOCATION MAP

AUTHOR:	LC	REPORT NO:	198
DRAWN:	OH	REVISION:	d
DATE:	01/09/2015	JOB NO:	1606C

LEGEND

- Major Town
- Existing Mine Site
- Creek
- Surface Water Catchment Boundary

Catchment Areas

- Ethel Gorge
- Jimblebar Creek (Innawally Pool)
- Caramulla Creek
- Davidson Creek

RPS

FIGURE 2.1

EASTERN PILBARA REGIONAL CATCHMENTS

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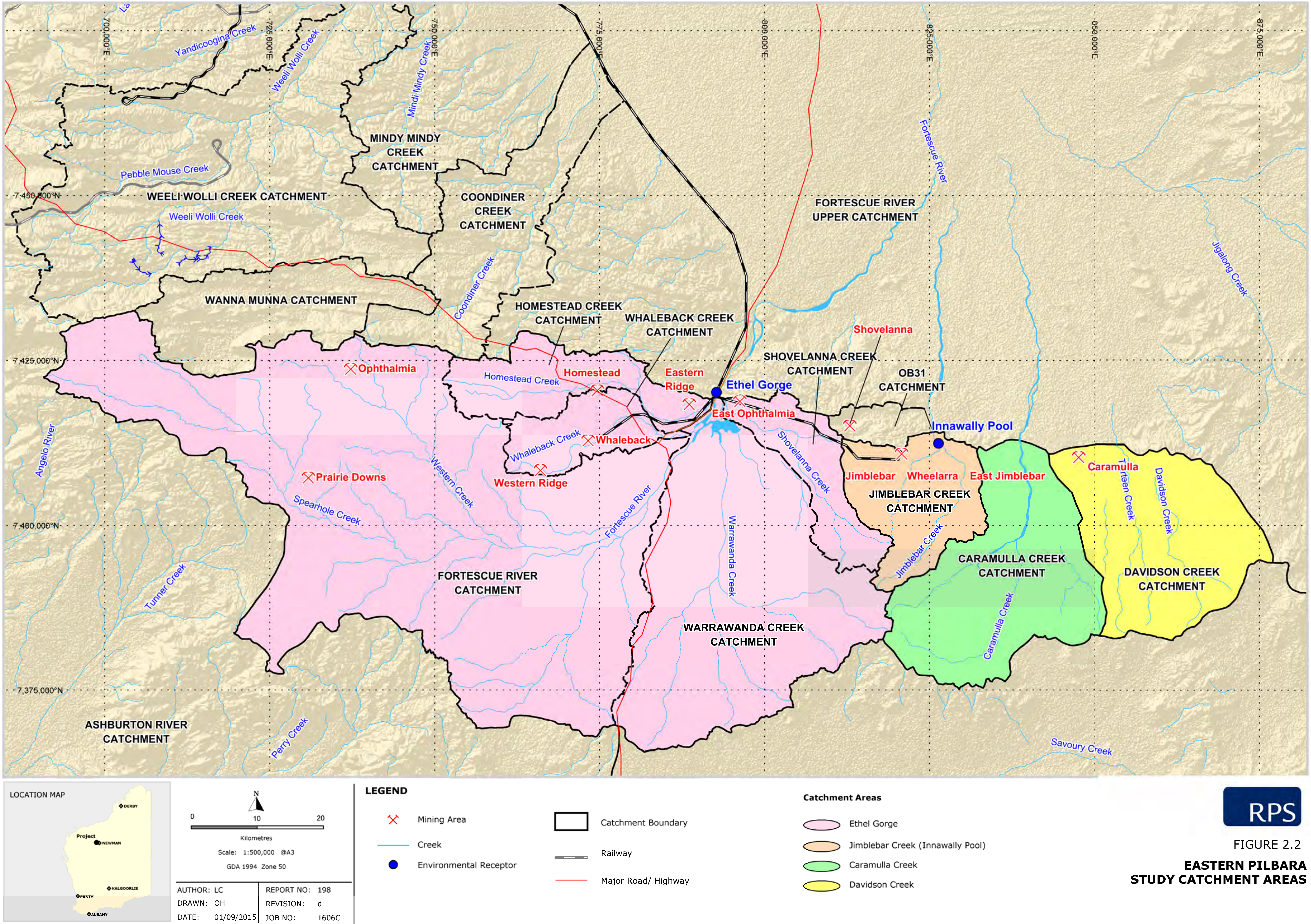

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GDA 1994 Zone 50

AUTHOR:	LC	REPORT NO:	198
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DATE:	01/09/2015	JOB NO:	1606C

LEGEND

- Mining Area
- Creek
- Environmental Receptor
- Catchment Boundary
- Railway
- Major Road/ Highway

Catchment Areas

- Ethel Gorge
- Jimblebar Creek (Innawally Pool)
- Caramulla Creek
- Davidson Creek

RPS

FIGURE 2.2

EASTERN PILBARA STUDY CATCHMENT AREAS

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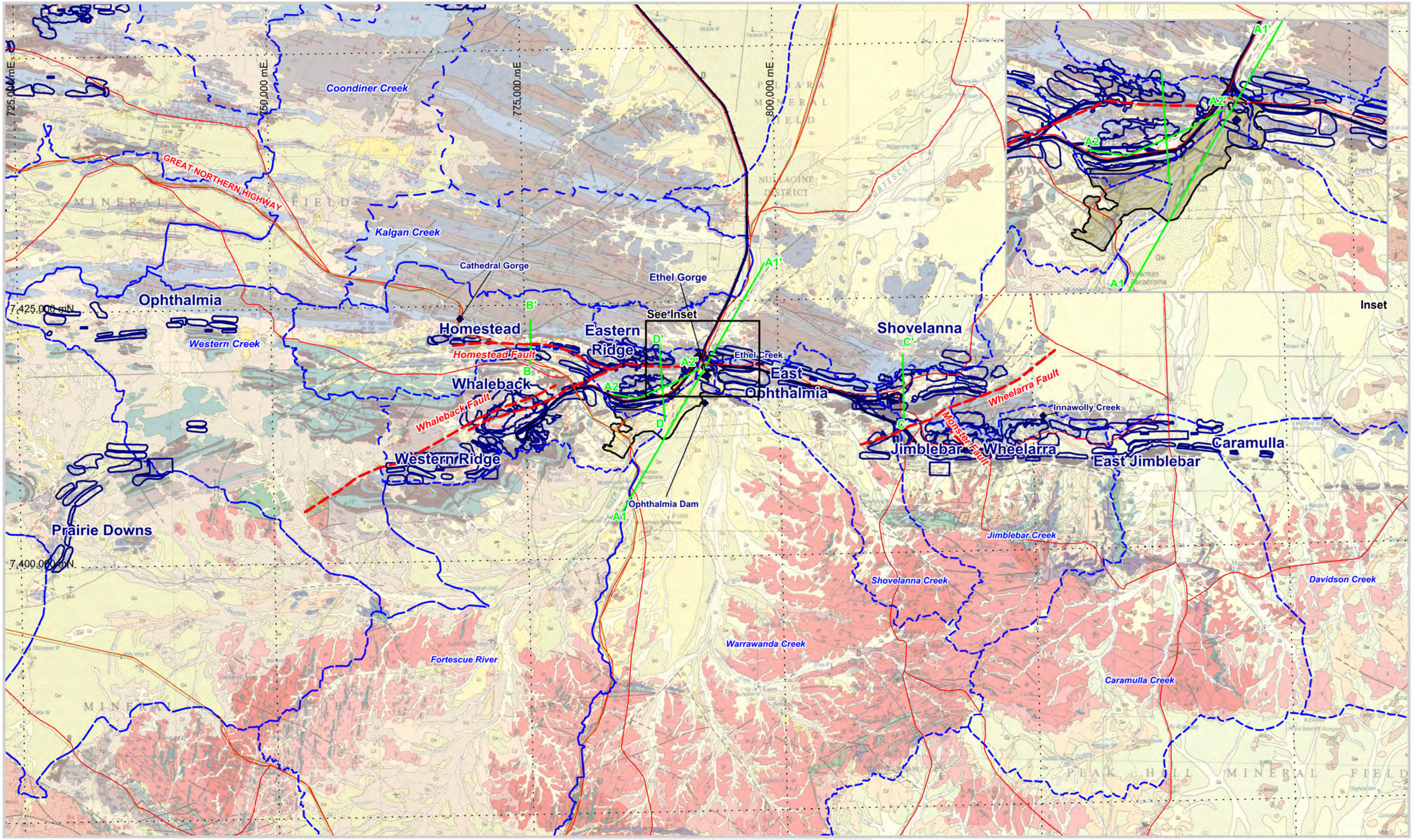

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GDA 1994 Zone 50

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DRAWN:	MR	REVISION:	d
DATE:	01/09/2015	JOB NO:	1606B

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\198b Figure 2.3 - Eastern Pilbara Hub Geological Map

LEGEND

- Environmental Receptors
- Section Line
- Road
- Rail
- Indicative BHP Billiton Iron Ore Disturbance
- Surface Water Catchment
- Ethel Gorge TEC Boundary

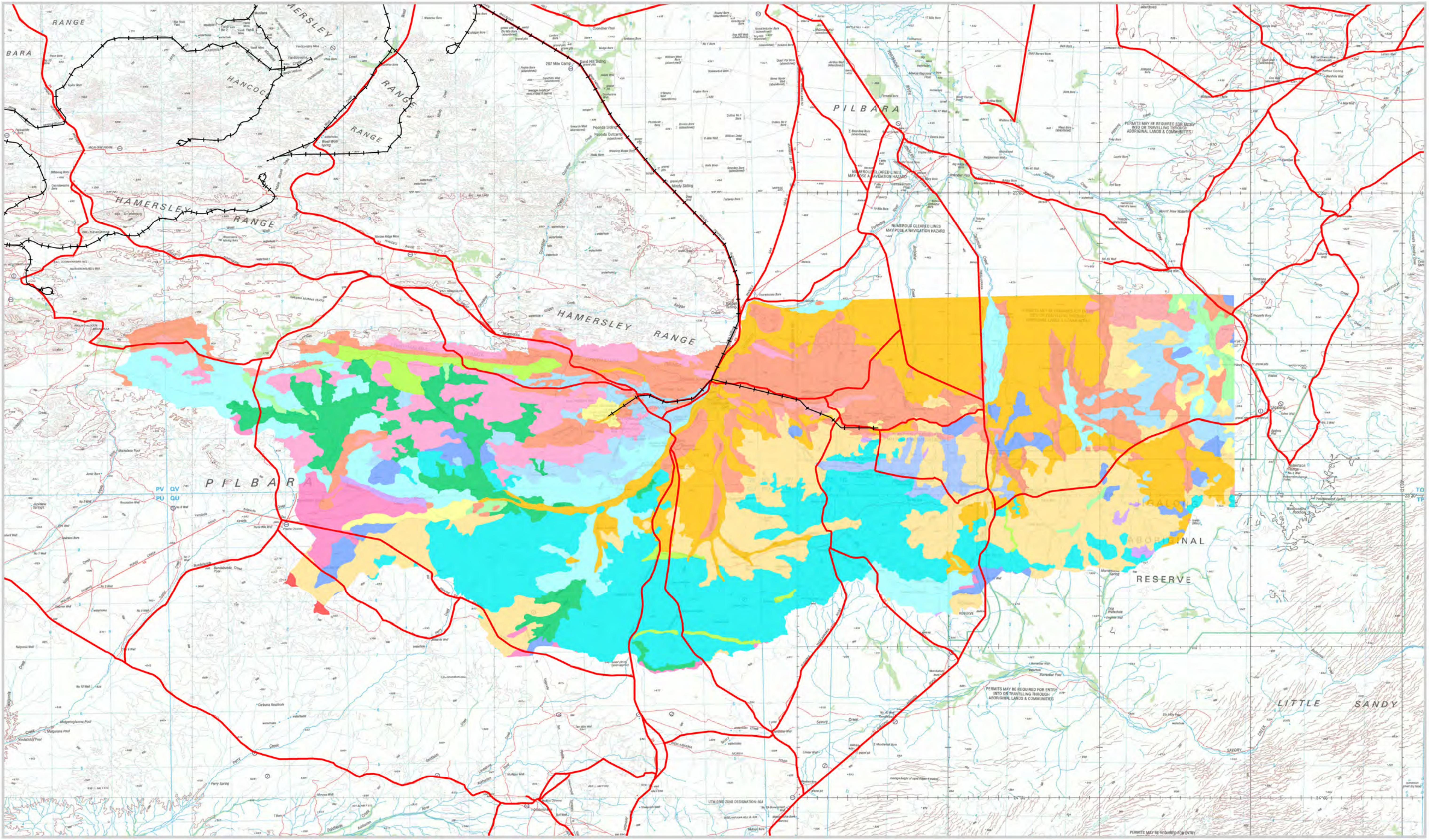
DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 2.3

GEOLOGICAL MAP
EASTERN PILBARA REGION

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed. As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from this conceptual map."



LOCATION MAP

0 20

Kilometres

1:600,000 @ A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	198
DRAWN:	MR	REVISION:	b
DATE:	17/10/2014	JOB NO:	1606B

LEGEND

Rail Lines

Roads

Land Systems

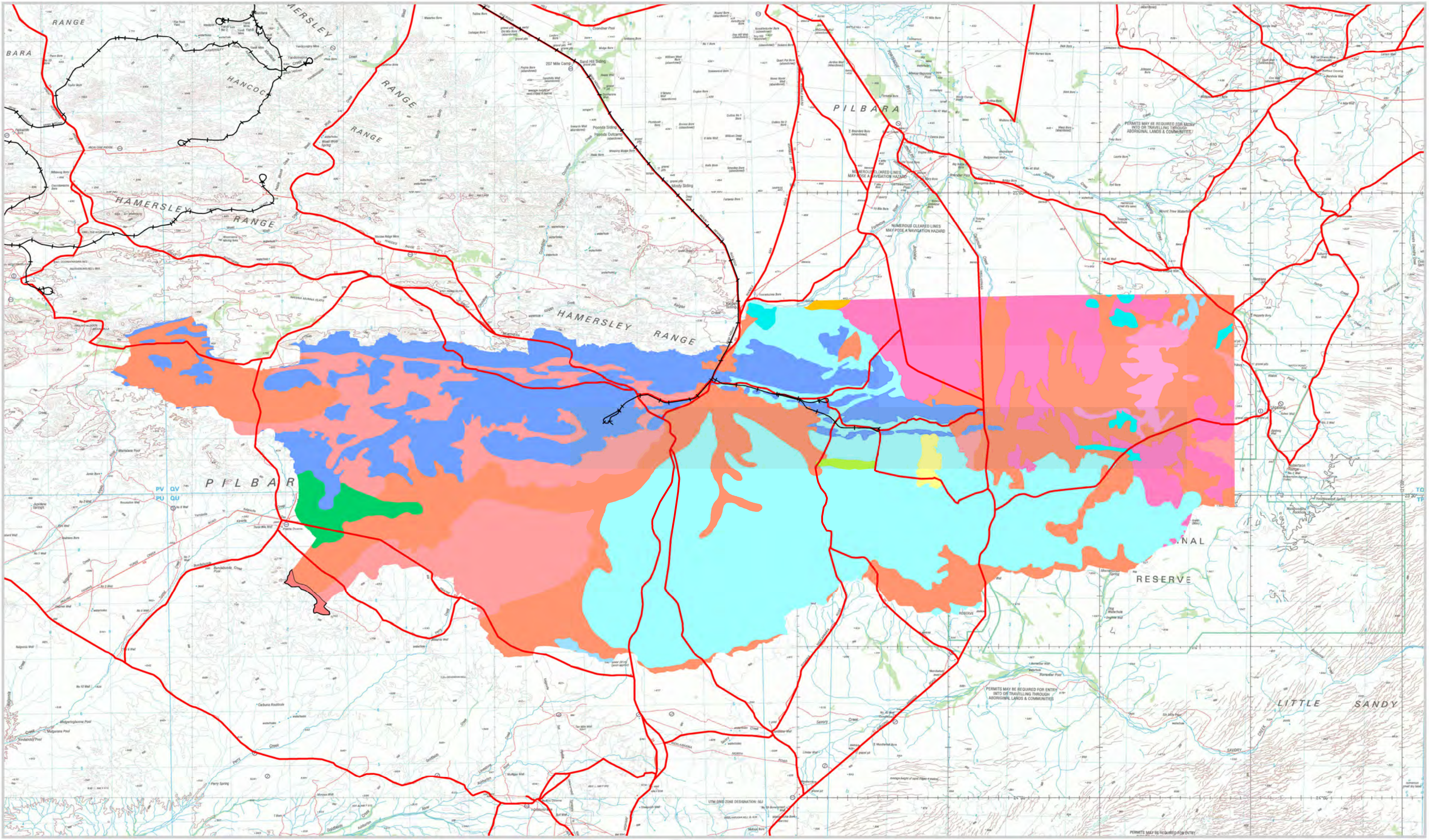
- Adrian Land System
- Augustus Land System
- Balfour Land System
- Boolgeeda Land System
- Cadgie Land System
- Calcrete Land System
- Charley Land System
- Collier Land System
- Divide Land System
- Egerton Land System
- Elimunna Land System
- Fan Land System
- Fortescue Land System
- Jamindie Land System
- Jigalong Land System
- Kunderong Land System
- Laterite Land System
- McKay Land System
- Mine
- Newman Land System
- Nirran Land System
- Nooingnin Land System
- Platform Land System
- Prairie Land System
- River Land System
- Robe Land System
- Robertson Land System
- Rocklea Land System
- Spearhole Land System
- Sylvania Land System
- Table Land System
- Talga Land System
- Turee Land System
- Wannamunna Land System
- Warri Land System
- Washplain Land System
- Zebra Land System

RPS

FIGURE 2.4

LAND SYSTEMS IN THE EPR STUDY AREA

Location: F:\Jobs\1606B\MapInfo\Workspaces\129c\129c Figure 2.4 - Land systems in the EPH Study Area



N

0 20

Kilometres

1:600,000 @ A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	198
DRAWN:	MR	REVISION:	b
DATE:	17/10/2014	JOB NO:	1606B

Location: F:\Jobs\1606B\MapInfo\Workspaces\129c\129c Figure 2.5 - vegetation Association

LEGEND

Rail Lines

Roads

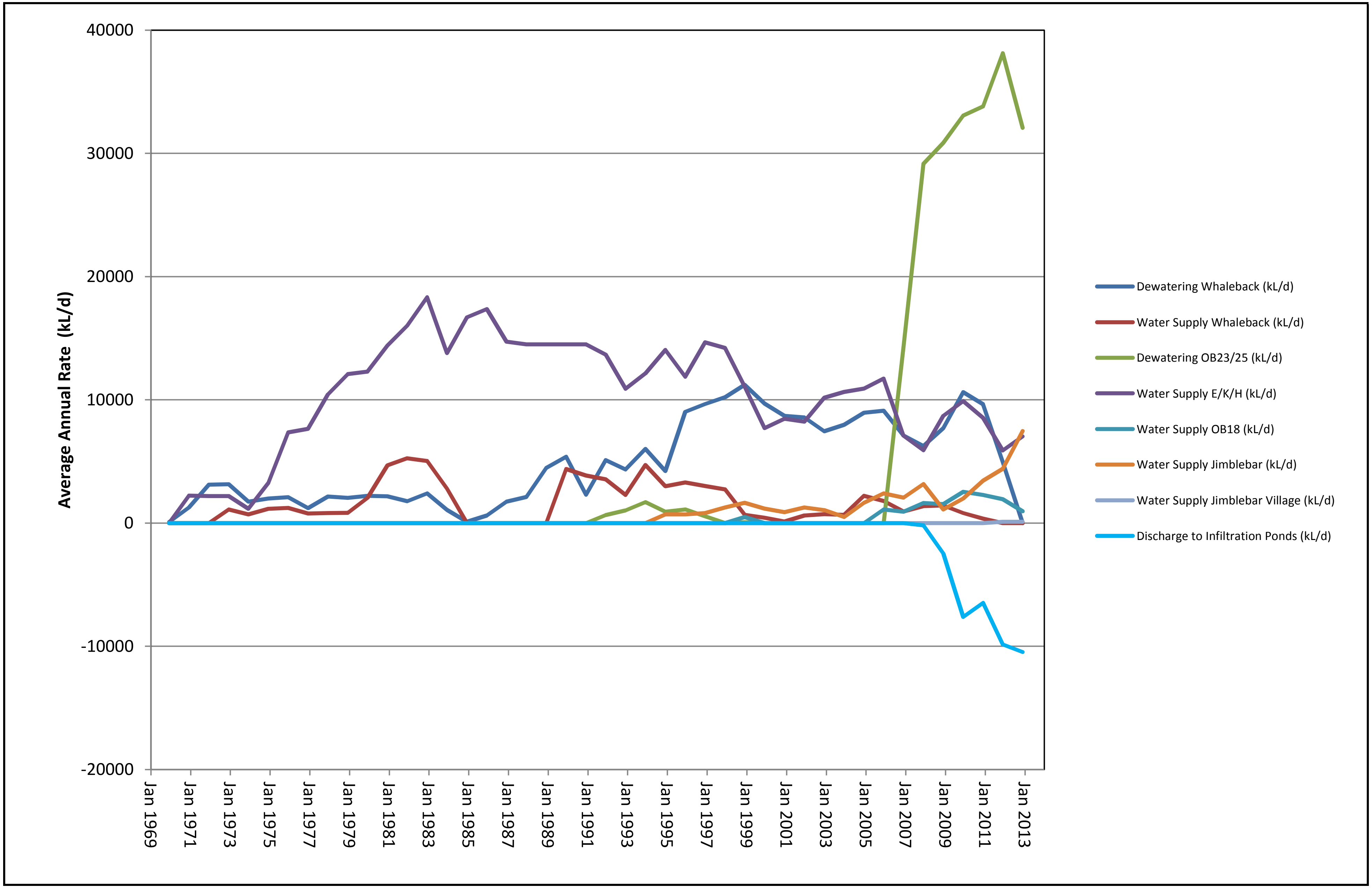
Vegetation Association Code (Beard)

18, 28, 29, 82, 111, 117, 157, 166, 175, 178, 199, 216

RPS

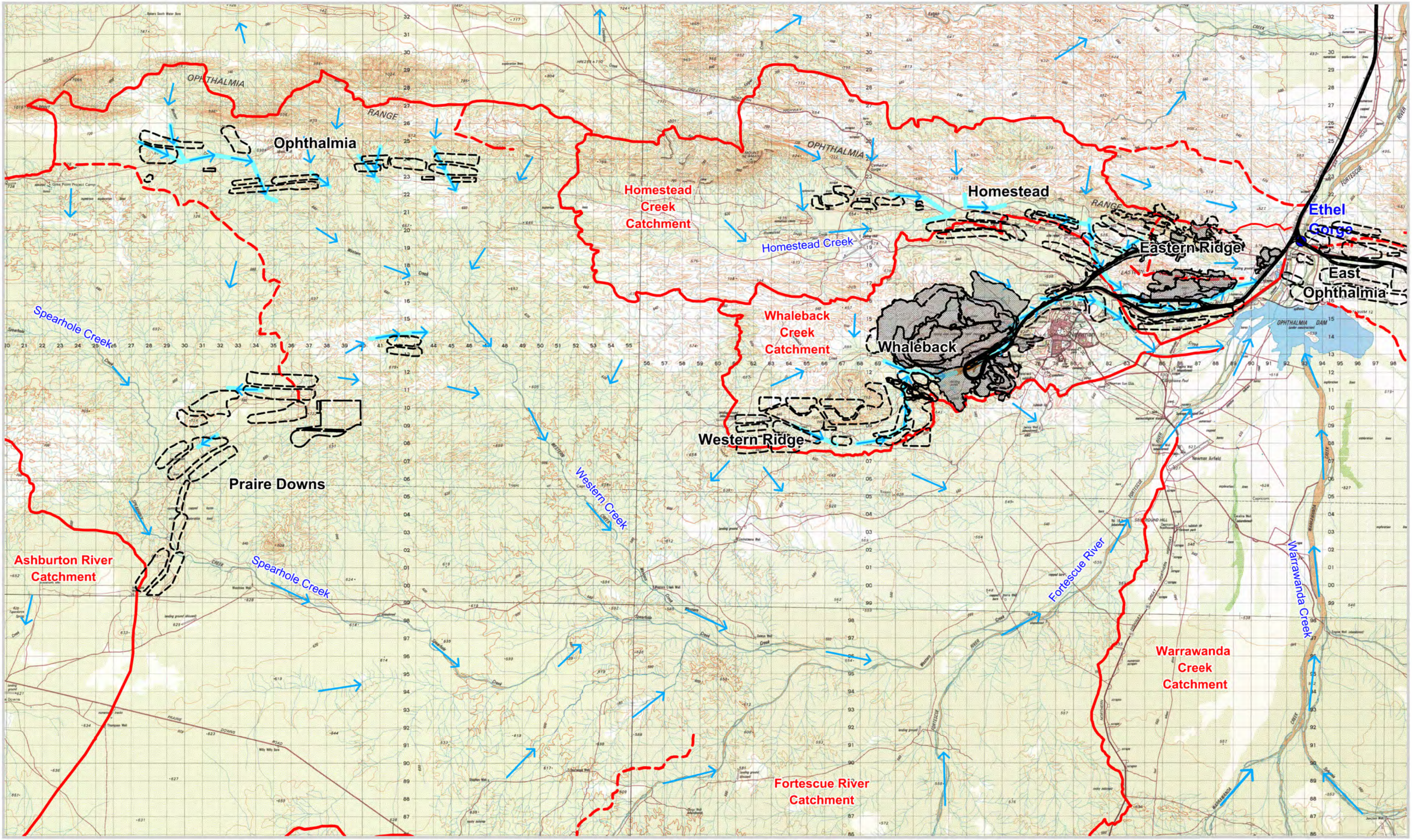
FIGURE 2.5

VEGETATION ASSOCIATIONS MAPPED BY BEARD (1975) IN THE EPR STUDY AREA, AND BHPBIO VEGETATION SURVEY AREAS



GROUNDWATER ABSTRACTION FIGURE 2.6

F:\Jobs\1606B\300\EPH\[Groundwater Abstraction for EPH.xlsx]Chart kLd



LOCATION MAP

N

0 5 10

Kilometres

Scale: 1:200,000 @A3

GDA 1994 Zone 50

AUTHOR:	VP	REPORT NO:	198
DRAWN:	OH	REVISION:	d
DATE:	01/09/2015	JOB NO:	1606C

LEGEND

- Main Catchment Boundary
- Sub-Catchment Boundary
- Existing Main Flow Path
- Main Drainage Corridor Within Orebody Area
- Existing Diversion
- Indicative BHP Billiton Iron Ore Disturbance
- Existing BHP Billiton Iron Ore Disturbance
- Rail

DATA SOURCES:
1:100,000 Topography Maps

RPS

FIGURE 3.1

FORTESCUE RIVER WEST CATCHMENT EPR DISTURBANCE AREAS

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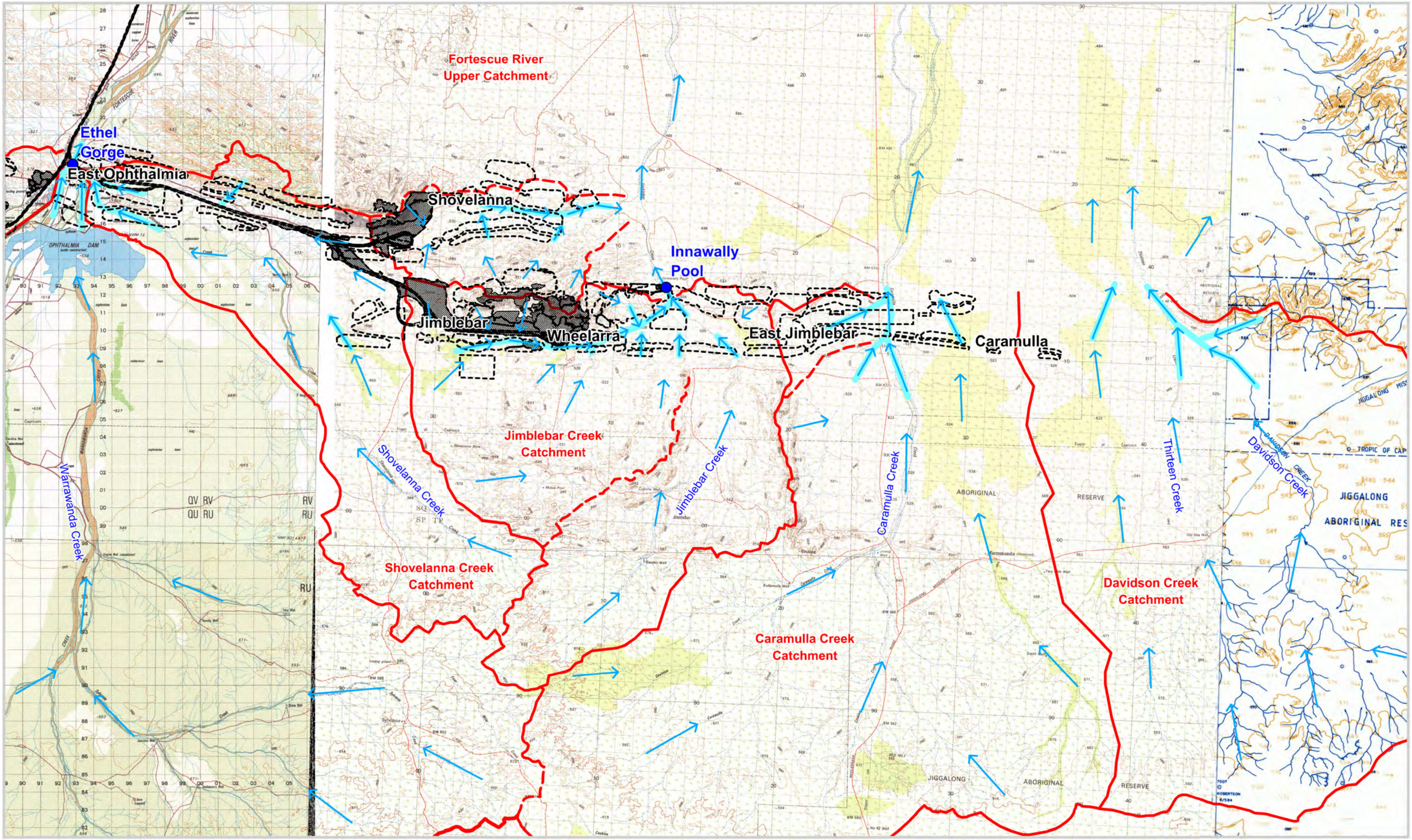
As project development is dependent upon future events, the outcome of which is uncertain and cannot be

Location: F:\Jobs\1606\Spatial_Data\MapInfo\Workspaces\198b Figure 3.1.wor



N

0 5 10

Kilometres

Scale: 1:200,000 @A3

GDA 1994 Zone 50

AUTHOR: VP	REPORT NO: 198
DRAWN: OH	REVISION: d
DATE: 02/09/2015	JOB NO: 1606C

LEGEND

- Main Catchment Boundary
- Sub-Catchment Boundary
- Existing Main Flow Path
- Main Drainage Corridor Within Orebody Area
- Railway
- Indicative BHP Billiton Iron Ore Disturbance
- Existing BHP Billiton Disturbance

DATA SOURCES:
1:100,000 Topography Maps

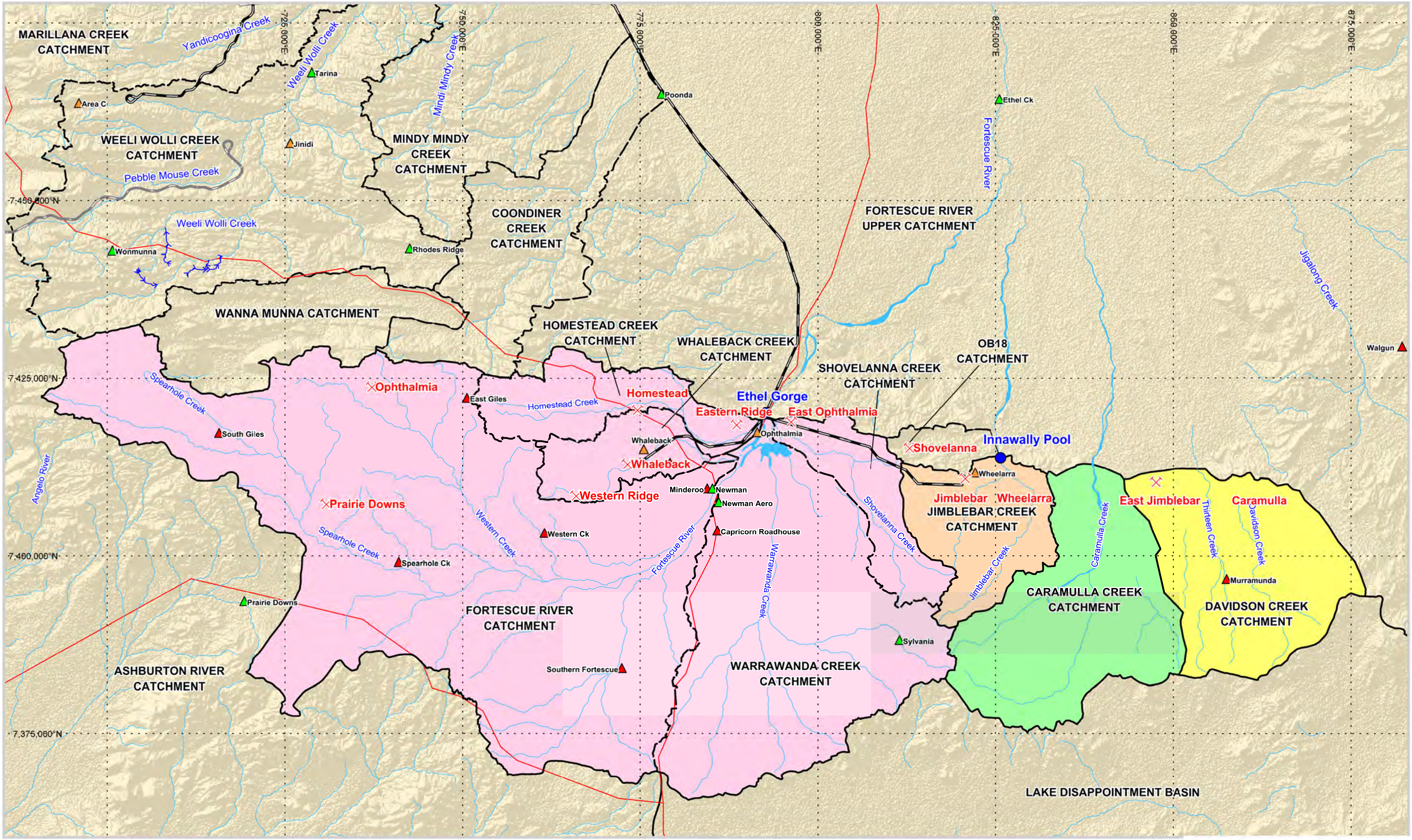
RPS

FIGURE 3.2

FORTESCUE RIVER EAST CATCHMENT EPR DISTURBANCE AREAS

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
As project development is dependent upon future events, the outcome of which is uncertain and cannot be

Location: F:\Jobs\1606B\Spatial_Data\MapInfo\Workspaces\198b Figure 3.2.wor



LOCATION MAP

Scale: 1:500,000 @A3

GDA 1994 Zone 50

AUTHOR:	LC	REPORT NO:	198
DRAWN:	OH	REVISION:	d
DATE:	01/09/2015	JOB NO:	1606C

Location: F:\Jobs\1606I\Spatial_Data\MapInfo\Workspaces\198b Figure 3.3.wor

LEGEND

- BHPBIO Monitoring Location
- BOM / DoW Monitoring Location - Open
- BOM / DoW Monitoring Location - Closed
- Mining Area
- Catchment Boundary
- Railway
- Major Road/ Highway
- Creek

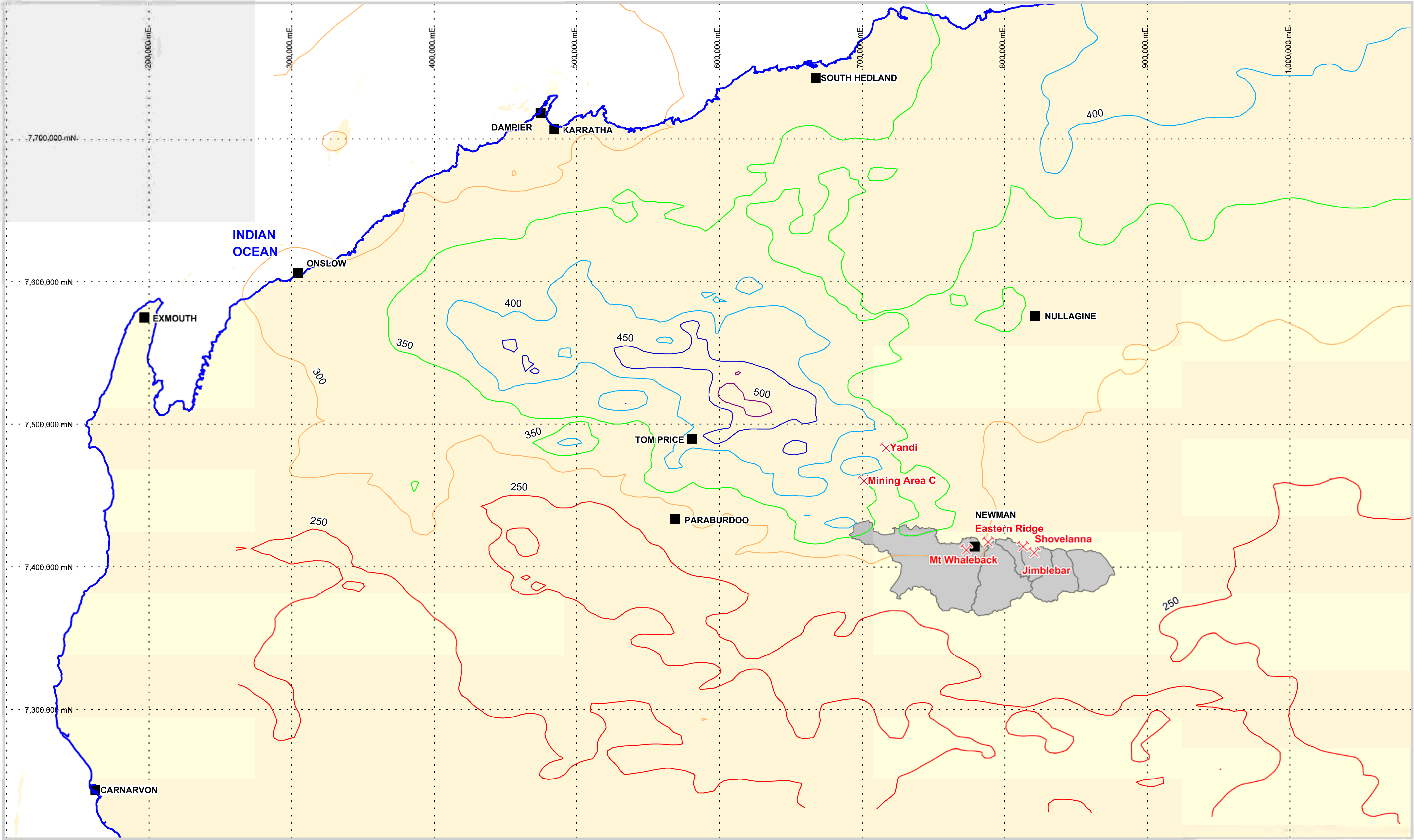
Catchment Areas

- Ethel Gorge
- Jimblebar Creek (Innawally Pool)
- Caramulla Creek
- Davidson Creek

RPS

FIGURE 3.3

EXISTING AND HISTORICAL RAINFALL MONITORING SITES



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50 0 50

Kilometres

Scale: 1:2,500,000 @A3

GDA 1994 Zone 50

AUTHOR: LC
DRAWN: LC
DATE: 05/05/2015

REPORT NO: 198
REVISION: d
JOB NO: 1606C

Location: F:\Jobs\1606I\Spatial_Data\MapInfo\Workspaces\129c\129c Figure 3.4 Ave Annual Rainfall.wor

LEGEND

- Major Town
- BHP Billiton Iron Ore Mine Site
- Average Annual Rainfall 50mm Contours
- Eastern Pilbara Region Catchment Area

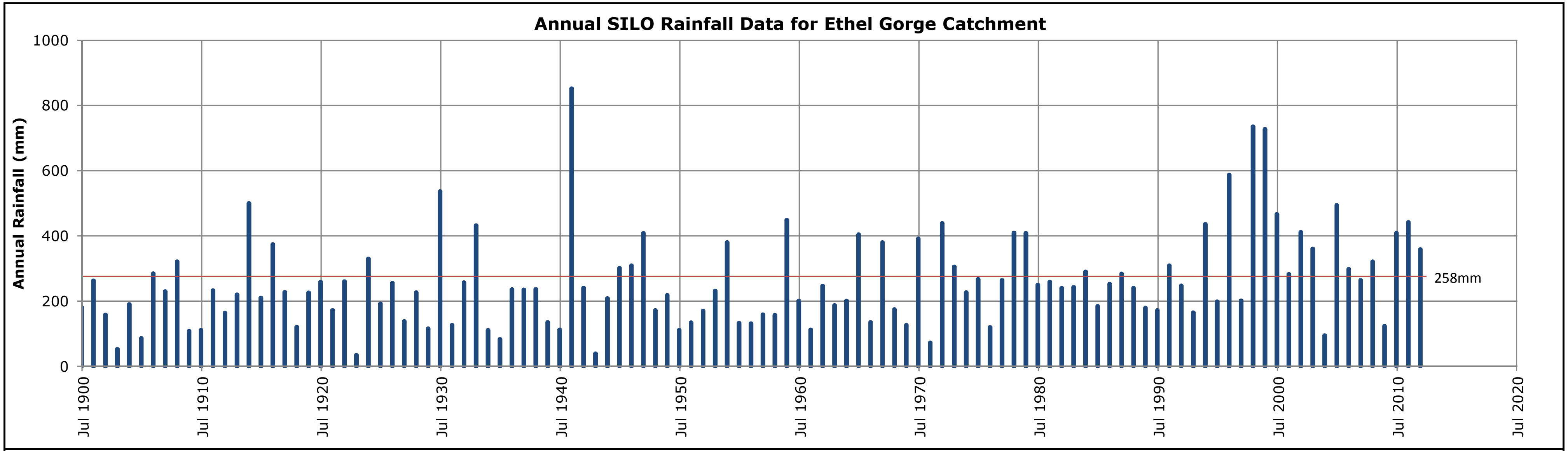
Average Annual Rainfall 50mm Contours

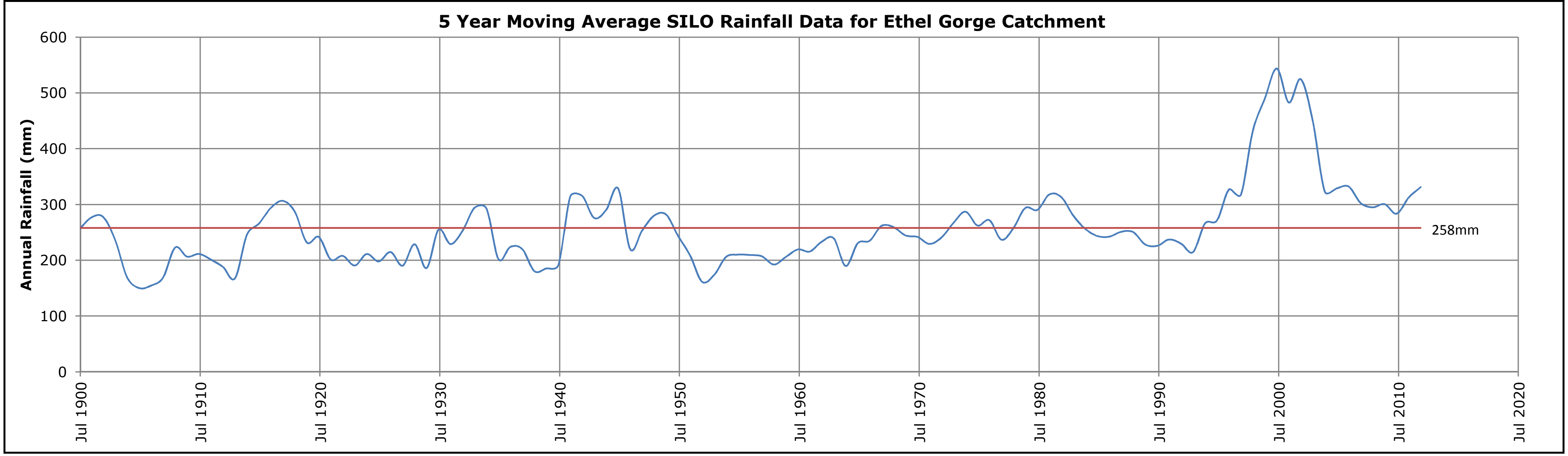
- 250mm
- 300mm
- 350mm
- 400mm
- 450mm
- 500mm

RPS

FIGURE 3.4

AVERAGE ANNUAL SILO RAINFALL DISTRIBUTION (1961 - 2012)

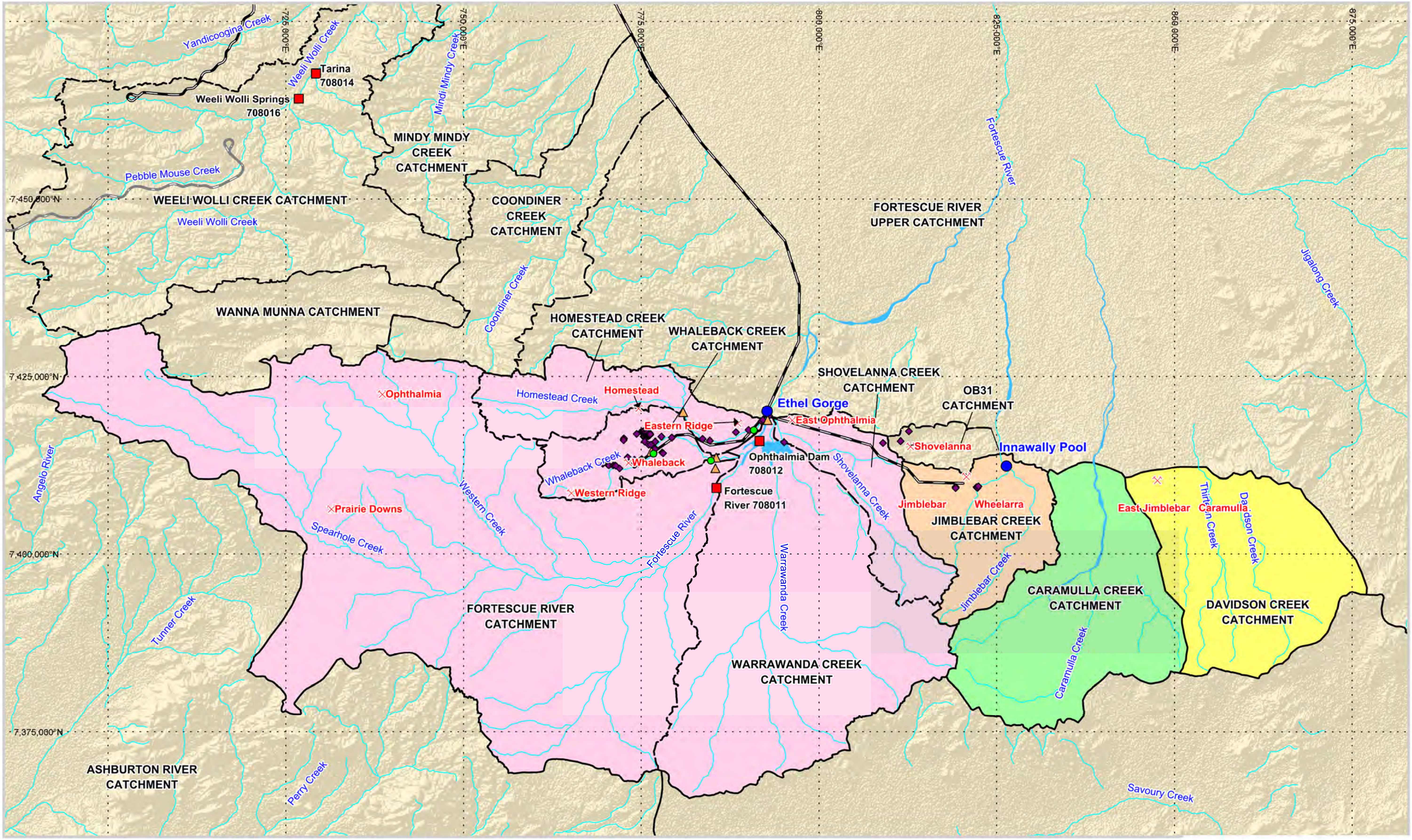




RPS

Ethel Gorge Catchment Annual Rainfall Data FIGURE 3.5

F:\Jobs\1606C\300\Rain and Streamflow Data\SILO\[SILO Data -Ethel Gorge Catchment Centroid.xls]129a Fig 3.5



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0 10 20

Kilometres

Scale: 1:500,000 @A3

GDA 1994 Zone 50

AUTHOR:	LC	REPORT NO:	198
DRAWN:	OH	REVISION:	d
DATE:	05/05/2015	JOB NO:	1606B

LEGEND

- Mining Area
- Creek
- DoW Streamflow Station
- DoW Sampling Station
- BHPBIO Surface Water Position (Water Level)
- BHPBIO Water Quality Sampling Location
- Catchment Boundary
- Railway

Catchment Areas

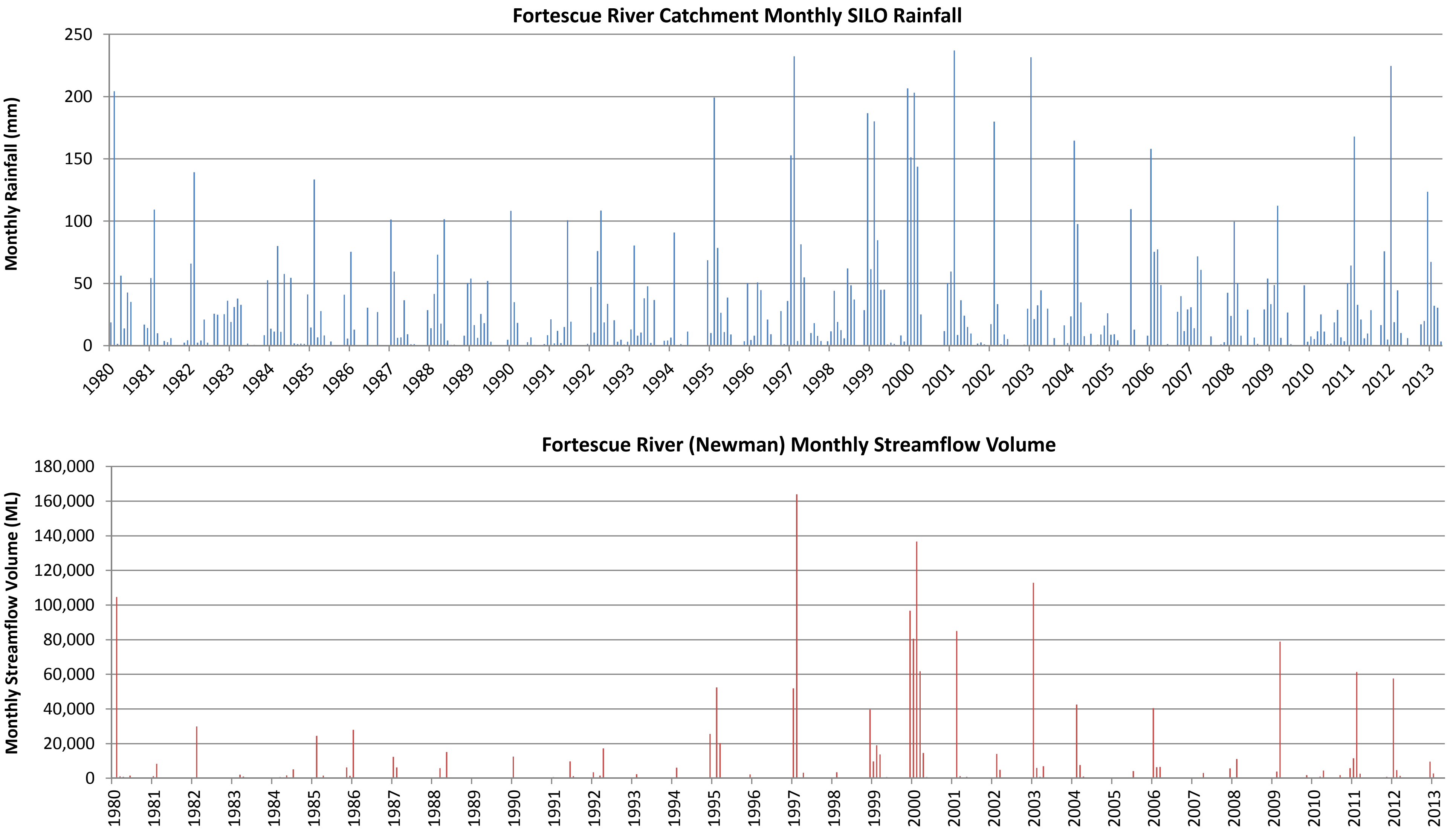
- Ethel Gorge
- Jimblebar Creek (Innawally Pool)
- Caramulla Creek
- Davidson Creek

RPS

FIGURE 3.6

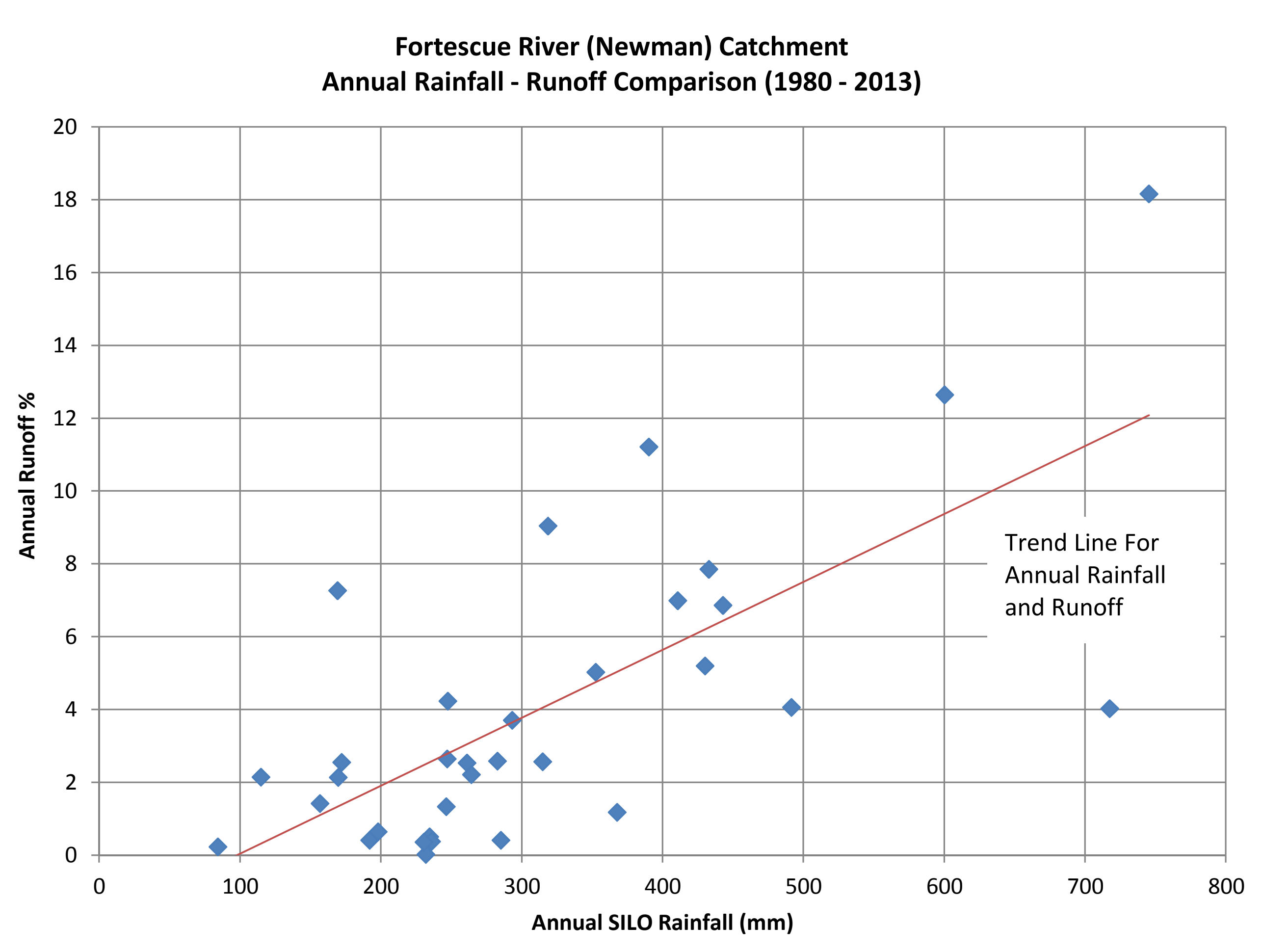
EXISTING SURFACE WATER MONITORING SITES

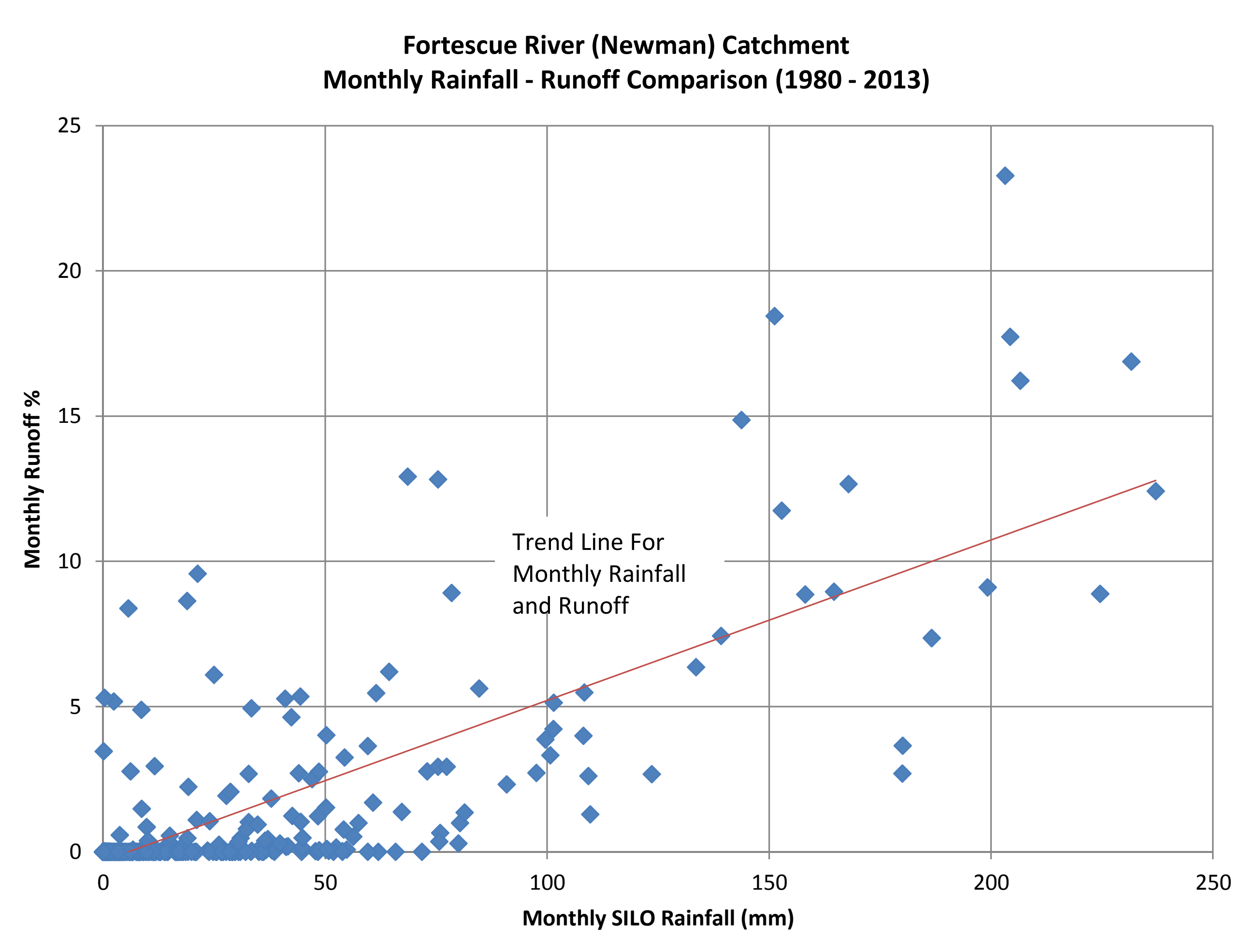
Location: F:\Jobs\1606I\Spatial_Data\MapInfo\Workspaces\129c\129c Figure 3.6.wor



Fortescue River (Newman) Catchment Rainfall and Runoff FIGURE 3.7

F:\Jobs\1606C\300\Rain and Streamflow Data\[Fig 3.7_3.8_3.10.xlsx]Fig 3.7

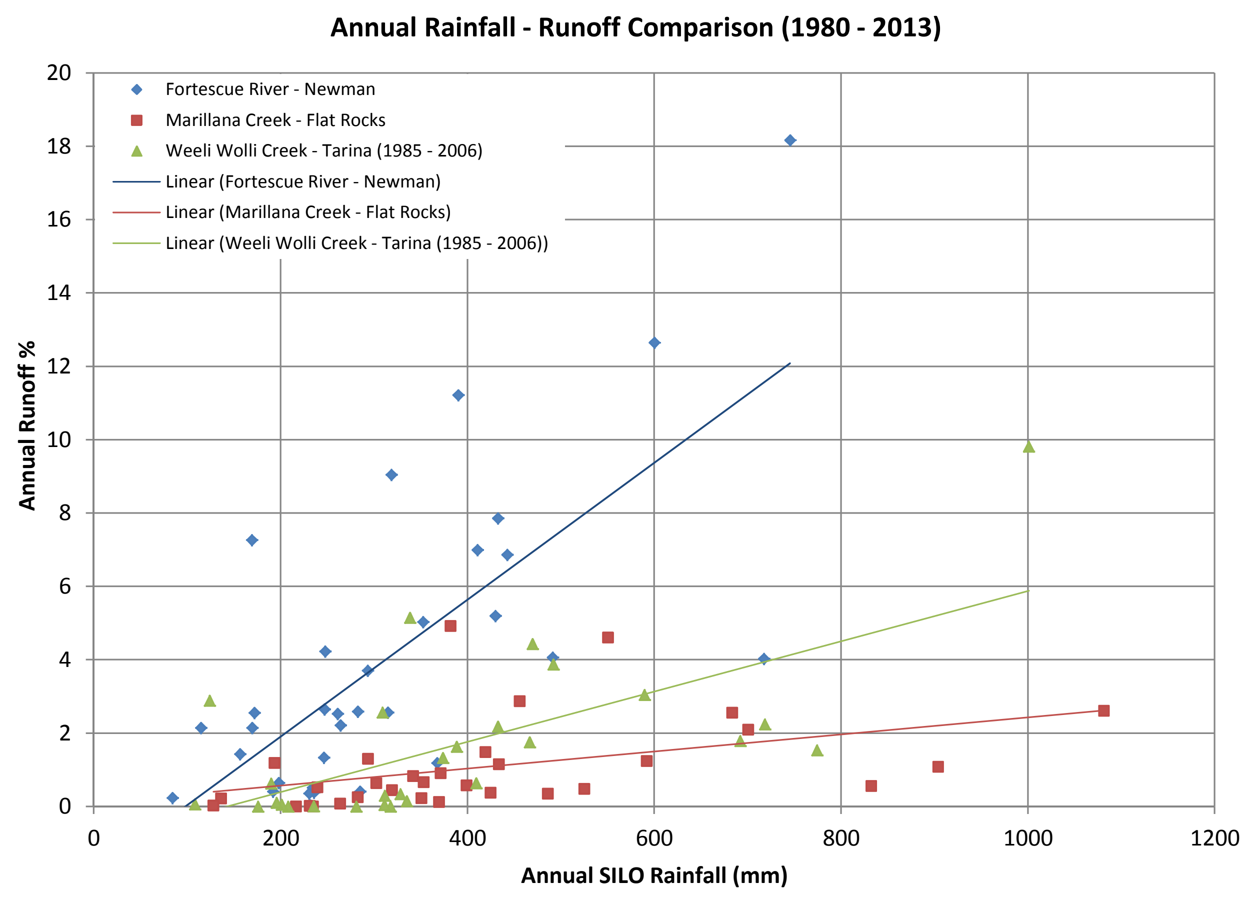


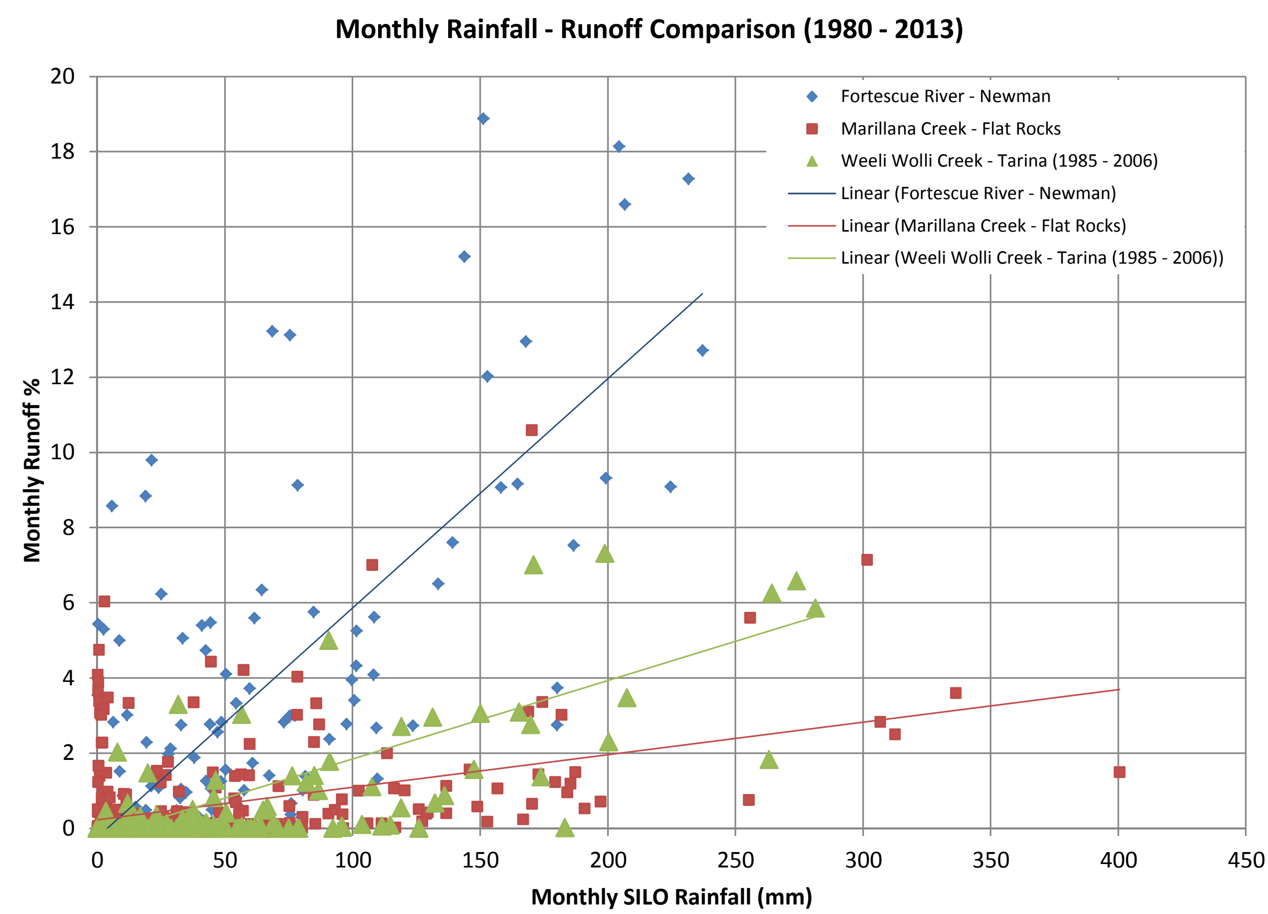


RPS

Fortescue River (Newman) Catchment Rainfall - Runoff Comparison FIGURE 3.8

F:\Jobs\1606C\300\Rain and Streamflow Data\[Fig 3.7_3.8_3.10.xlsx]Fig 3.8

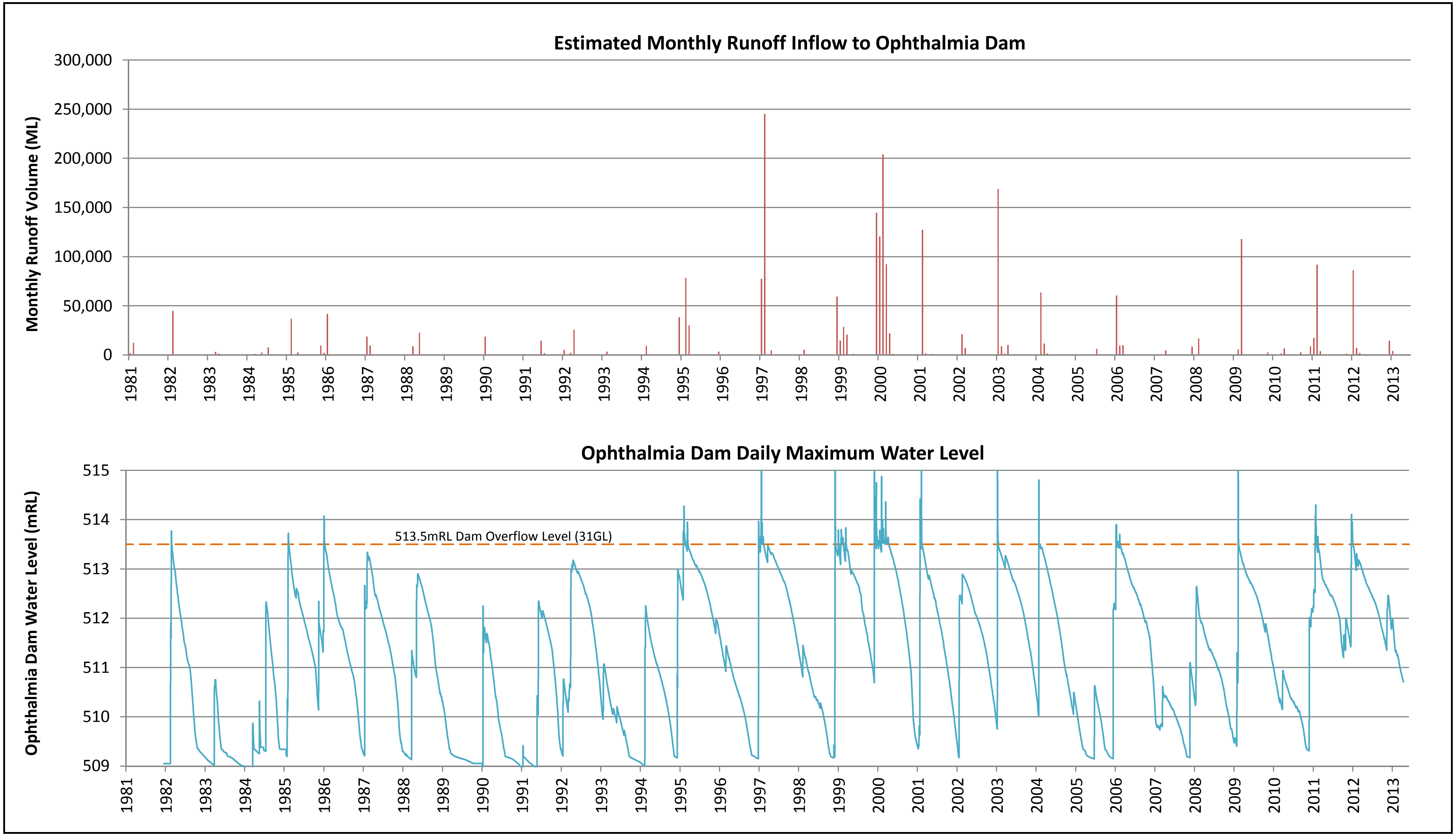




RPS

Pilbara Catchments Rainfall - Runoff Comparison FIGURE 3.9

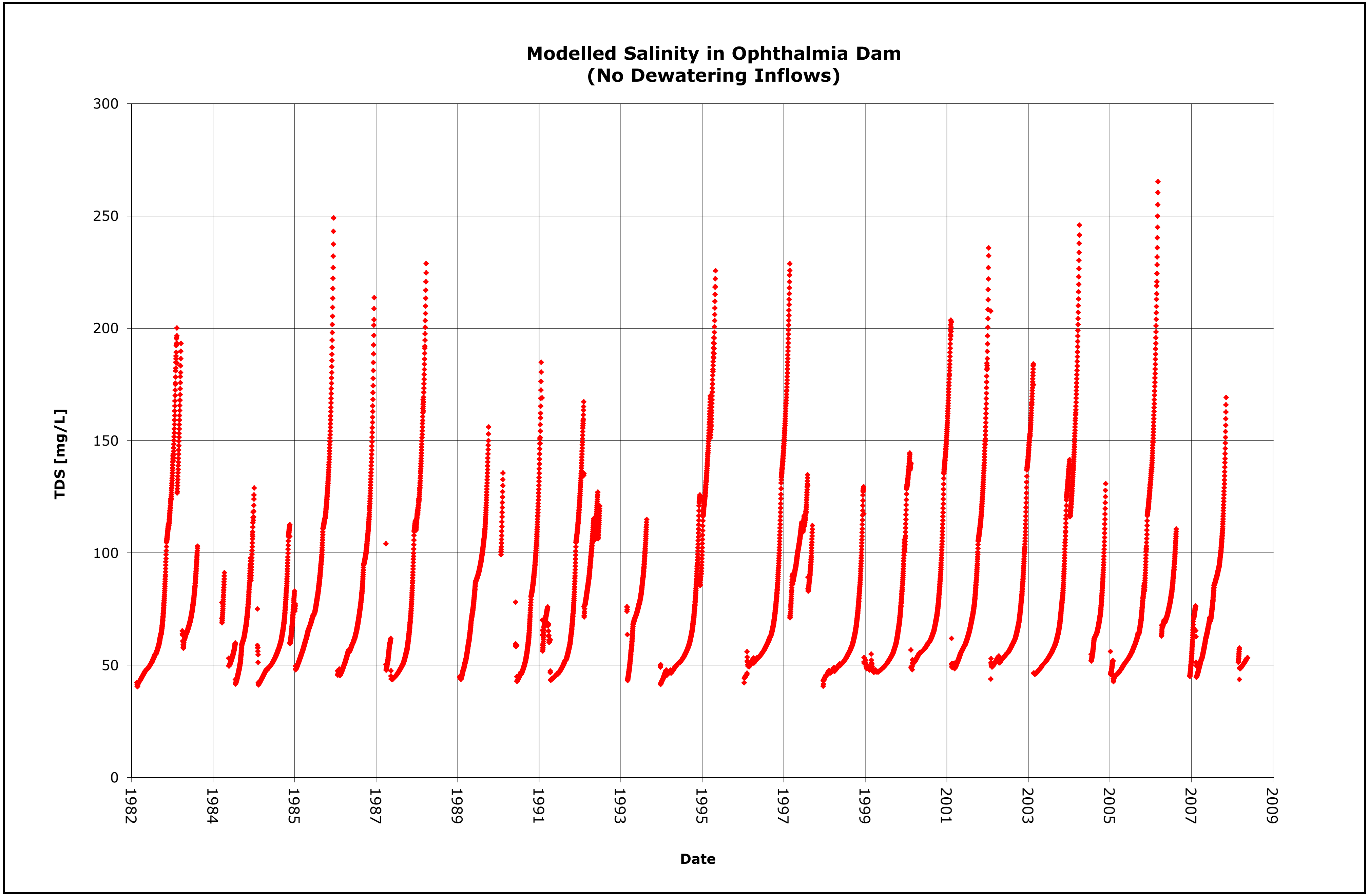
F:\Jobs\1606C\300\Rain and Streamflow Data\[Fig 3.9_Streamflow Input for 1606D.xlsx]Fig 3.9



RPS

Ophthalmia Dam Inflow and Water Levels FIGURE 3.10

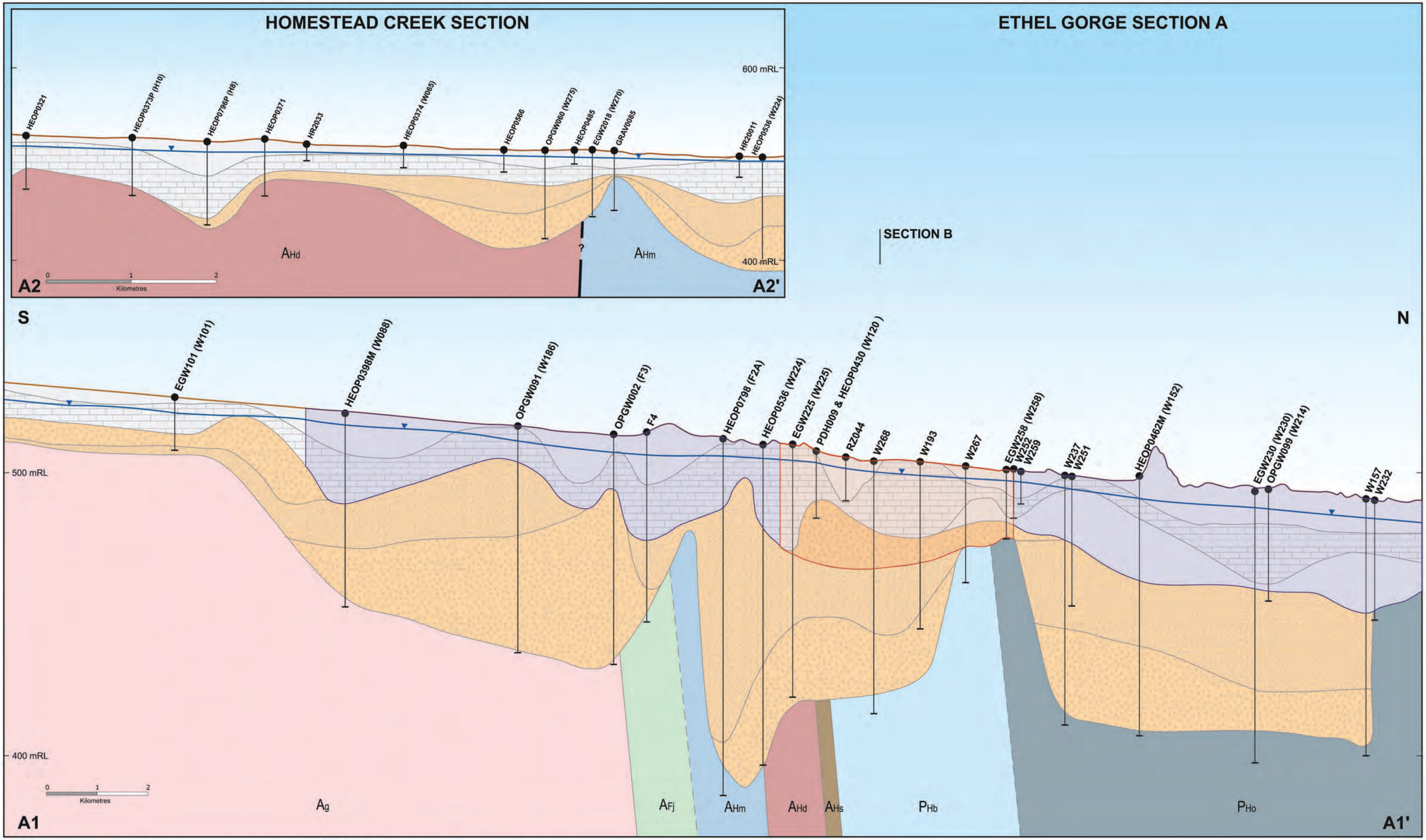
F:\Jobs\1606C\300\Rain and Streamflow Data\[Fig 3.6_3.7_3.9.xlsx]Fig 3.10



RPS

Modelled Salinity Levels in Ophthalmia Dam FIGURE 3.11

F:\Jobs\1606C\300\Rain and Streamflow Data\[Fig 3.11_Ref 1044.xls]Fig 3.10



LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj

Brockman Iron Fm
- PHb

- Revised TEC Boundary
- 14km TEC Boundary

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

- Ore
- Approximate Average Water Table (2000-2006)
- Potential Mine/Pit
- Drill Hole
- Fault

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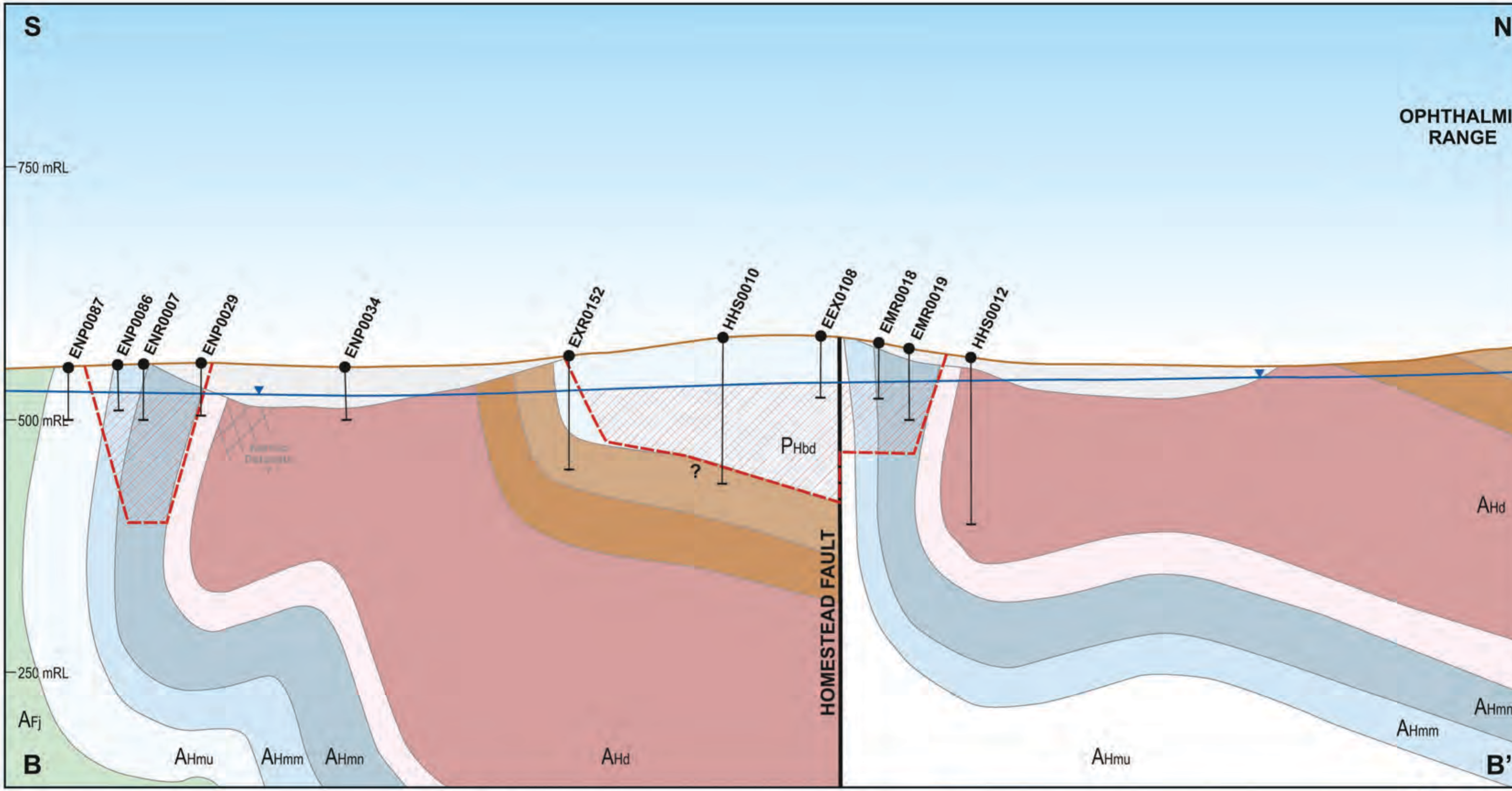
DATE:	31/08/2015	JOB NO:	1606B

RPS

FIGURE 3.12a

**SECTION A
FORTESCUE RIVER AND
HOMESTEAD CREEK**



Location: XXXX

0 250
Metres

AUTHOR:	JP	REPORT NO:	198
DRAW N:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj

- Ore

- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm Undifferentiated
- AHmn Mount Newman Member
- AHmm MacLeod Member
- AHmu Nammuldi Member

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 3.12b

SECTION B HOMESTEAD MINING AREA

DATA SOURCES:
Input data source here

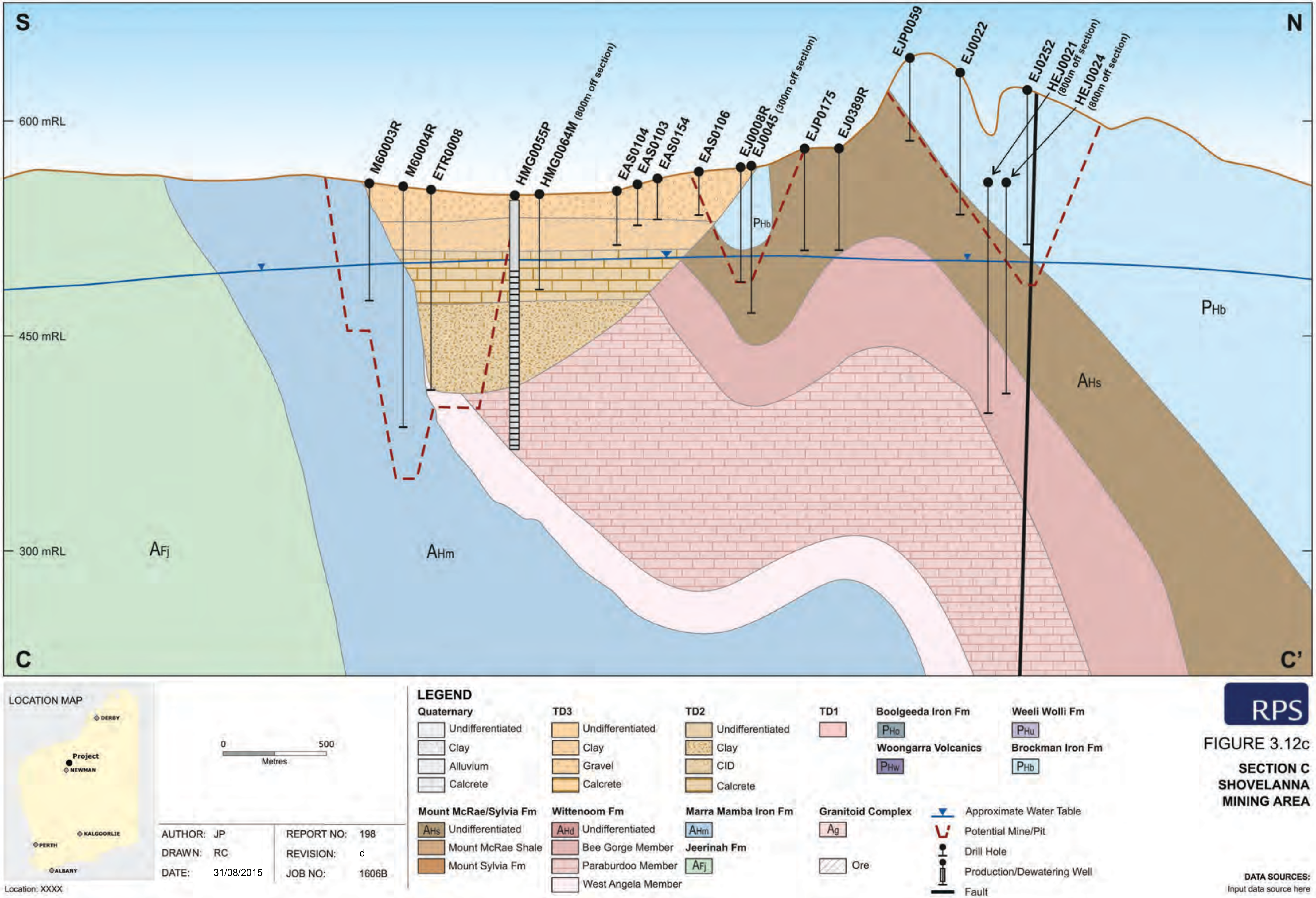


FIGURE 3.12c

SECTION C
SHOVELANNA
MINING AREA

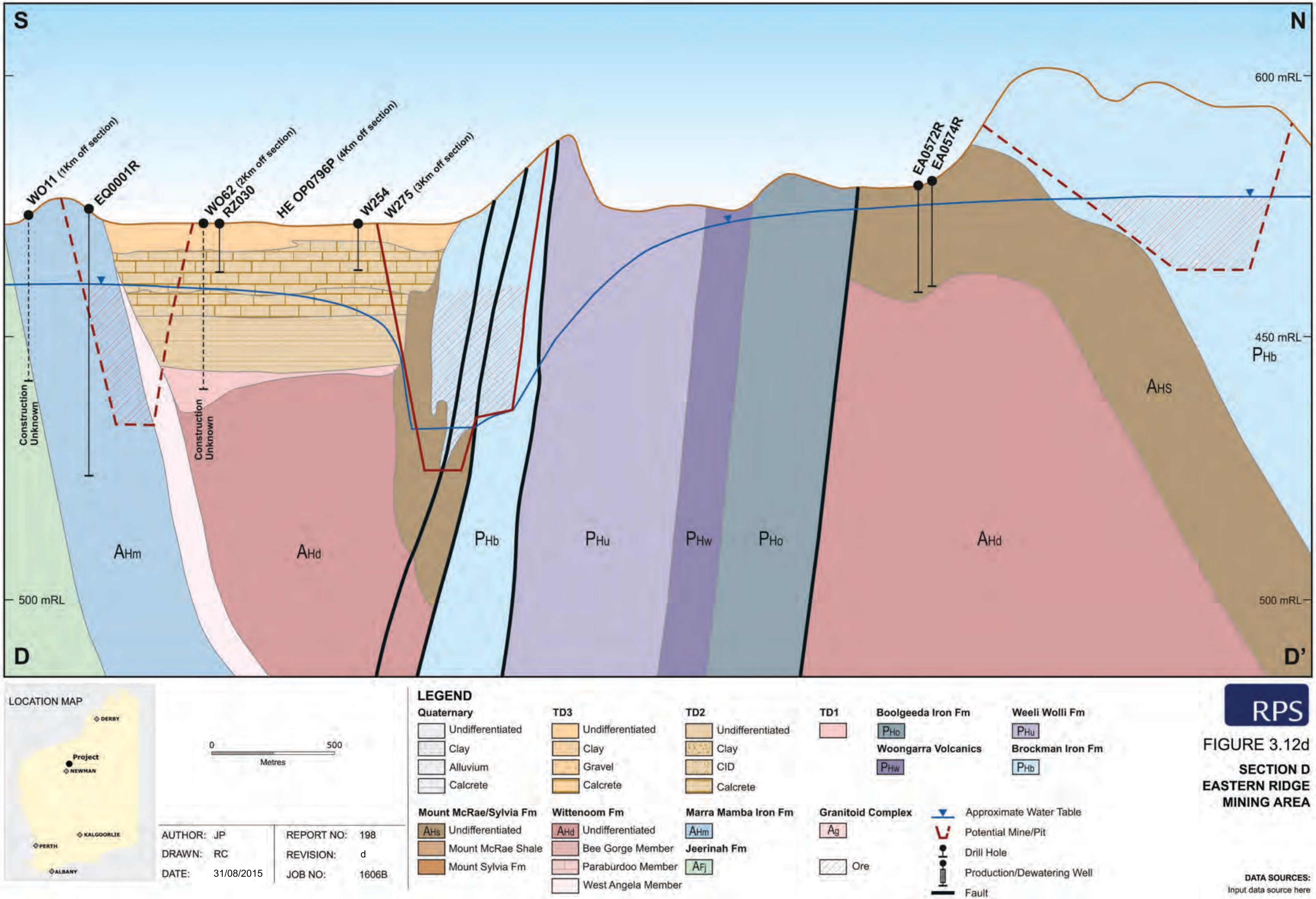
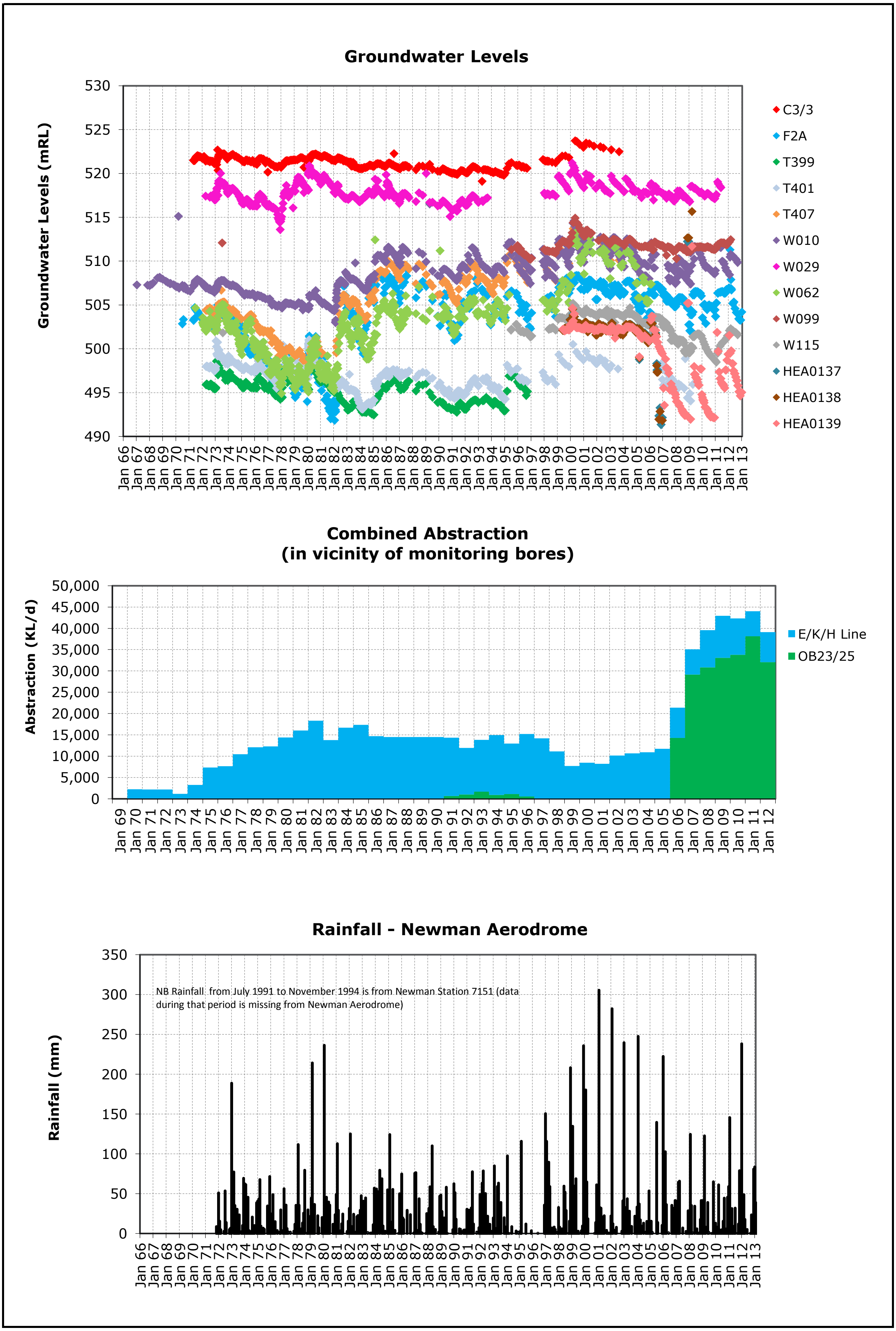
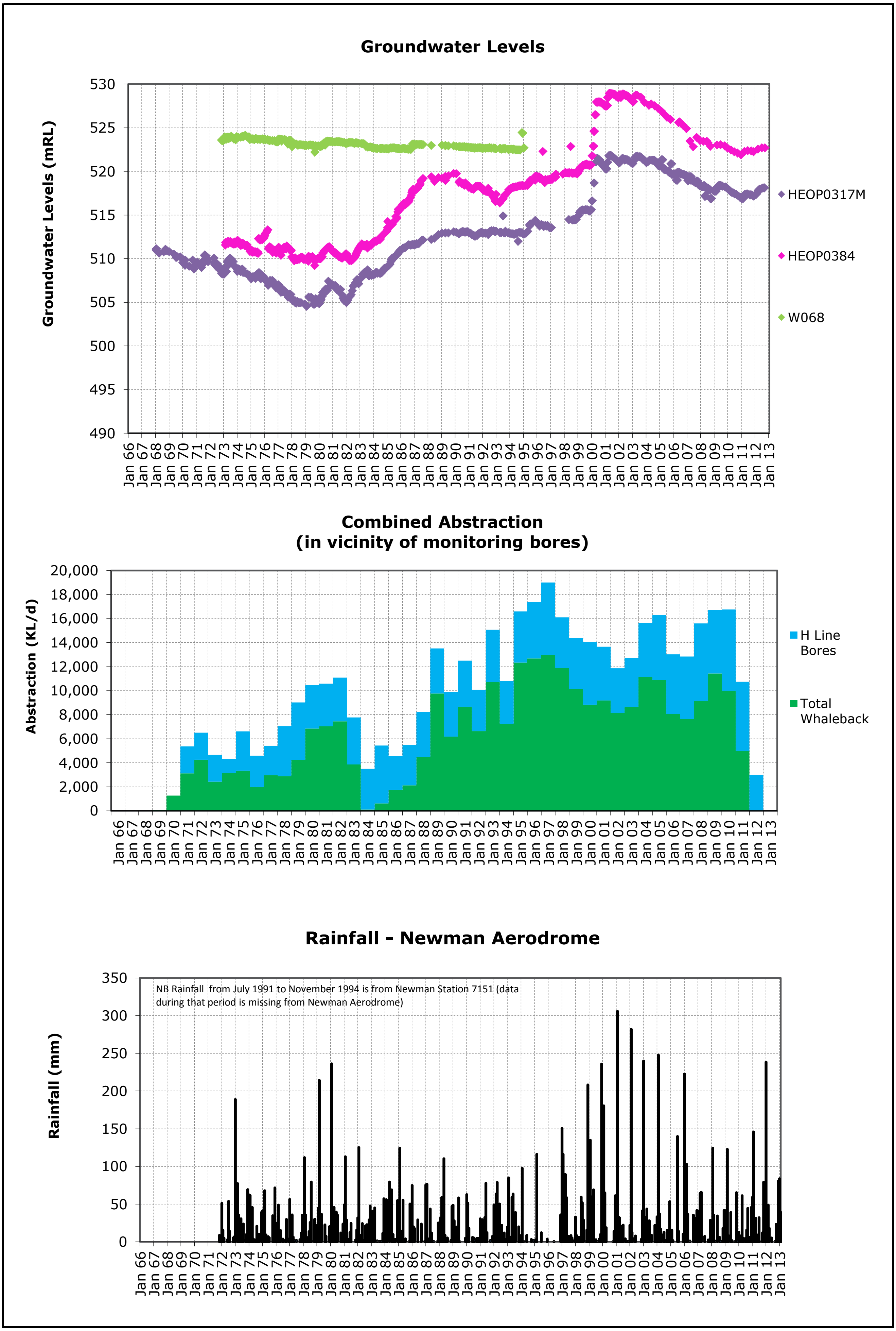


FIGURE 3.12d
SECTION D
EASTERN RIDGE
MINING AREA



EPR LOWER CATCHMENT AREA HYDROGRAPHS FIGURE 3.13a

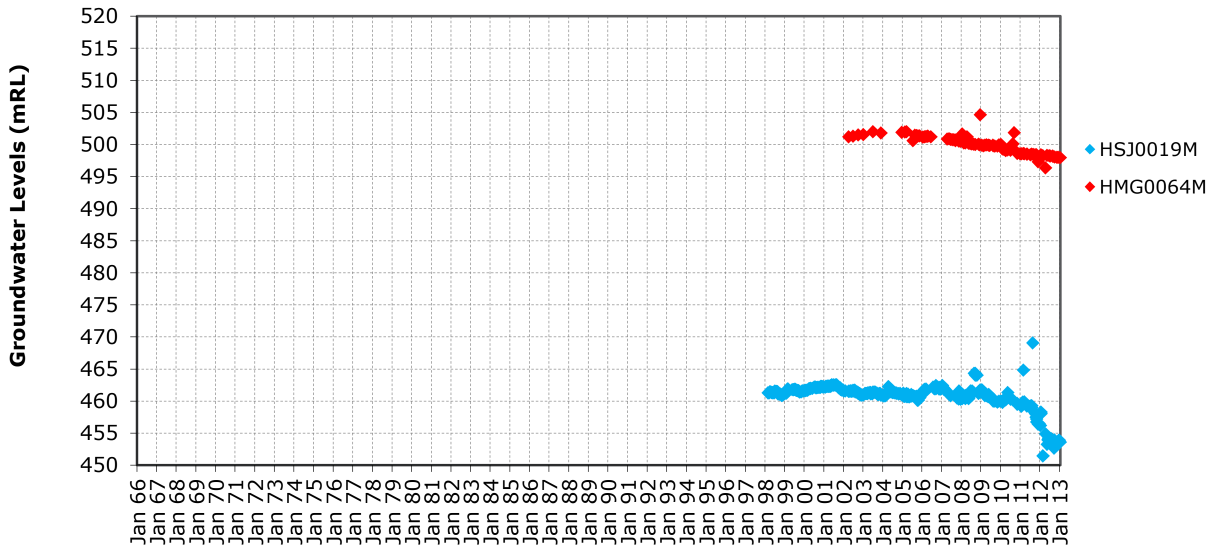
F:\Jobs\1606B\300\EPR\[191a EPR Hydrographs.xlsx]Figure 3.13a



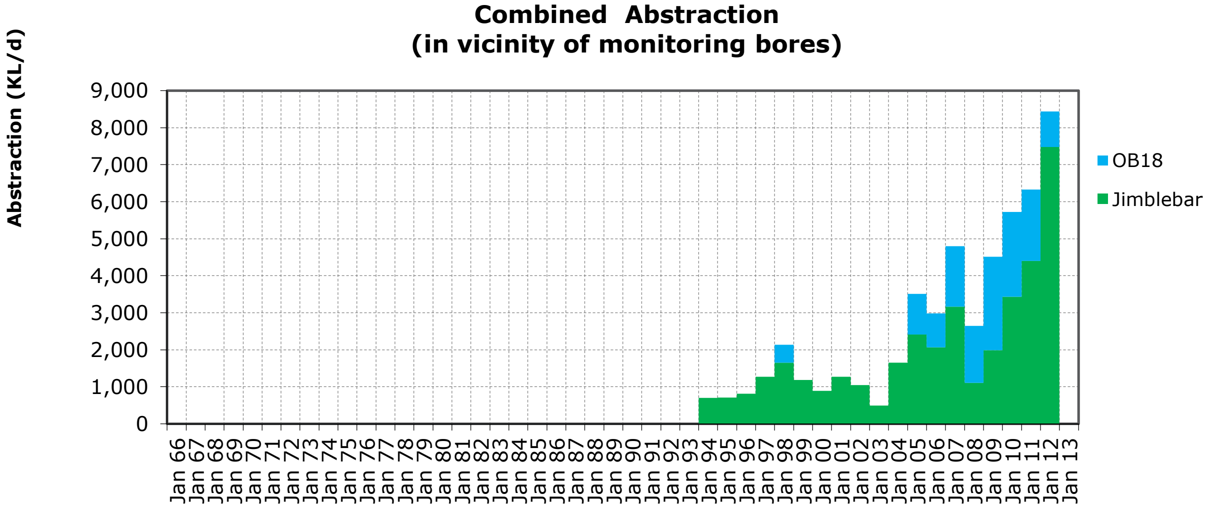
UPPER/WESTERN CATCHMENT AREA HYDROGRAPHS FIGURE 3.13b

F:\Jobs\1606B\300\EPR\[191a EPR Hydrographs.xlsx]Figure 3.13b

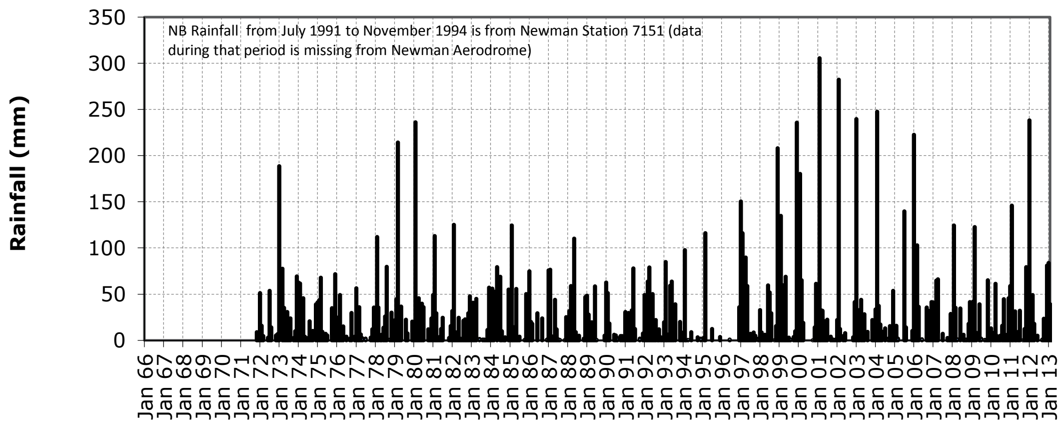
Groundwater Levels

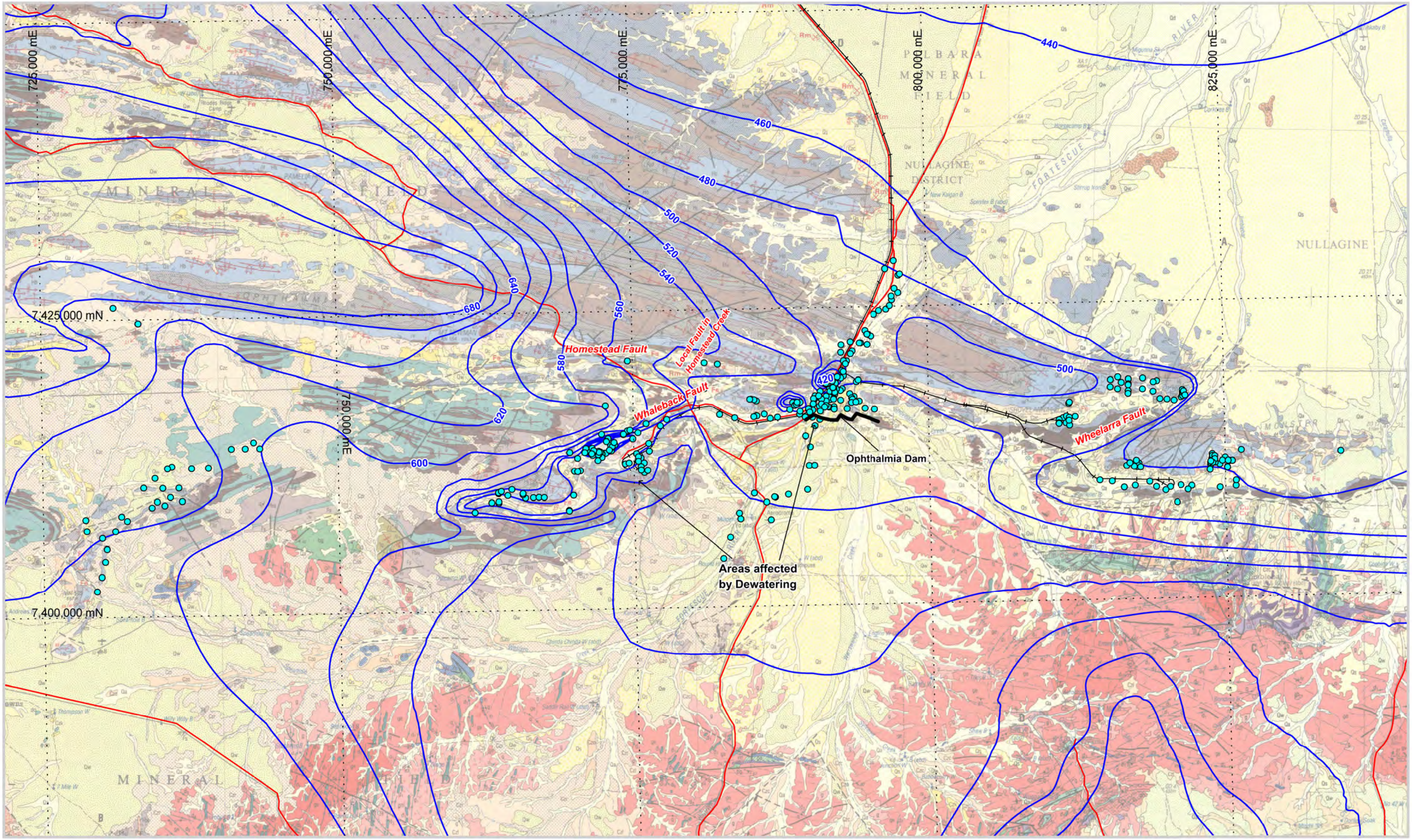


Combined Abstraction (in vicinity of monitoring bores)



Rainfall - Newman Aerodrome





N

0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	198
DRAWN:	MR	REVISION:	b
DATE:	09/10/2014	JOB NO:	1606B

LEGEND

- Key Bore
- EPR Regional Contours (mRL)
- Road
- Rail

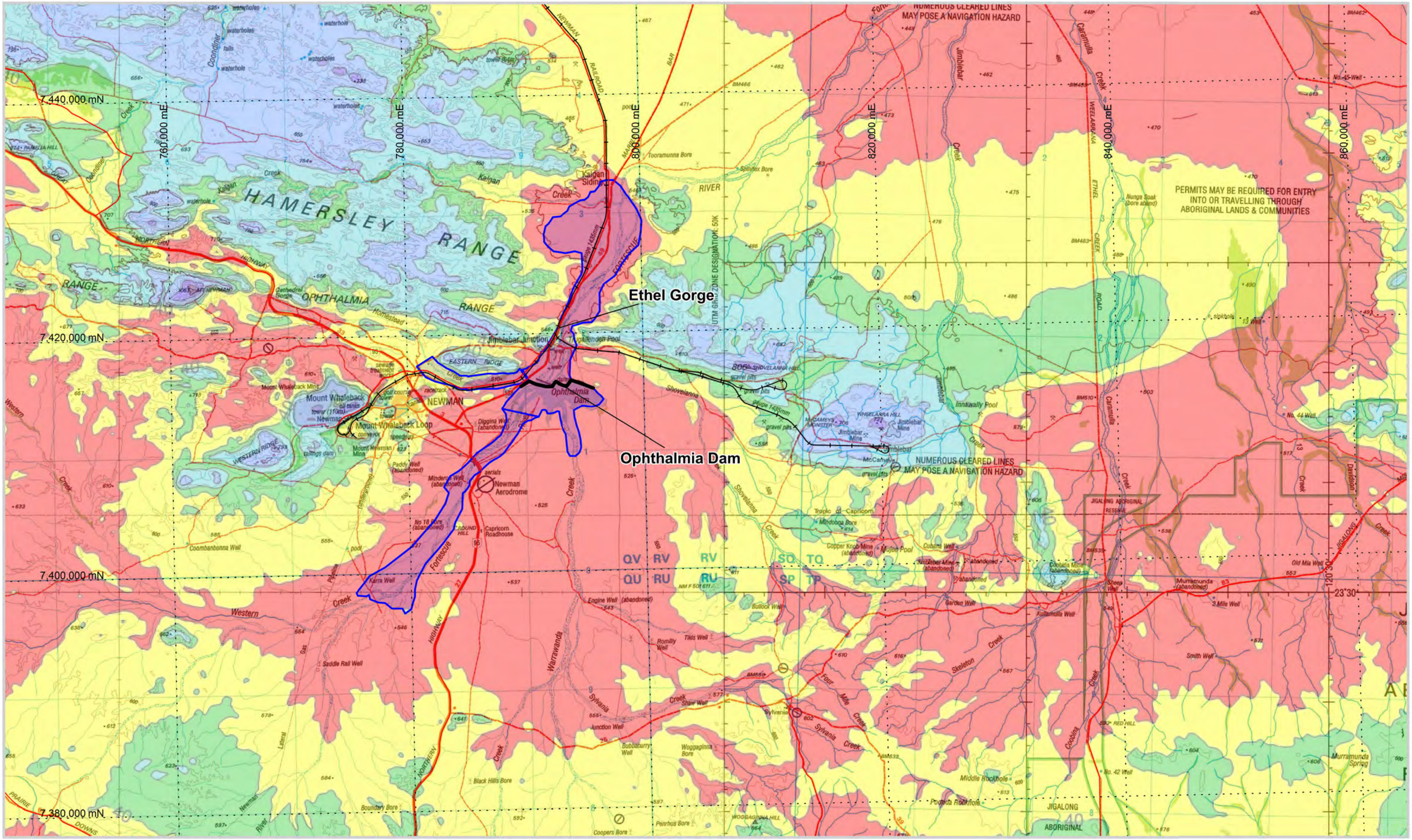
DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 3.14

CURRENT GROUNDWATER LEVEL CONTOURS (2012) EASTERN PILBARA REGION

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\129c\129c Figure 3.14 - Groundwater Level Contours Prior to Dewatering and Current (2012) EPH



LOCATION MAP

N

0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR: JP	REPORT NO: 198
DRAWN: MR	REVISION: b
DATE: 09/10/2014	JOB NO: 1606B

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\198b Figure 3.15 - Depth to Water CPH

LEGEND

- Environmental Receptor
- Road
- Rail
- Main Recharge Location

DATA SOURCES:
BHPB Iron Ore

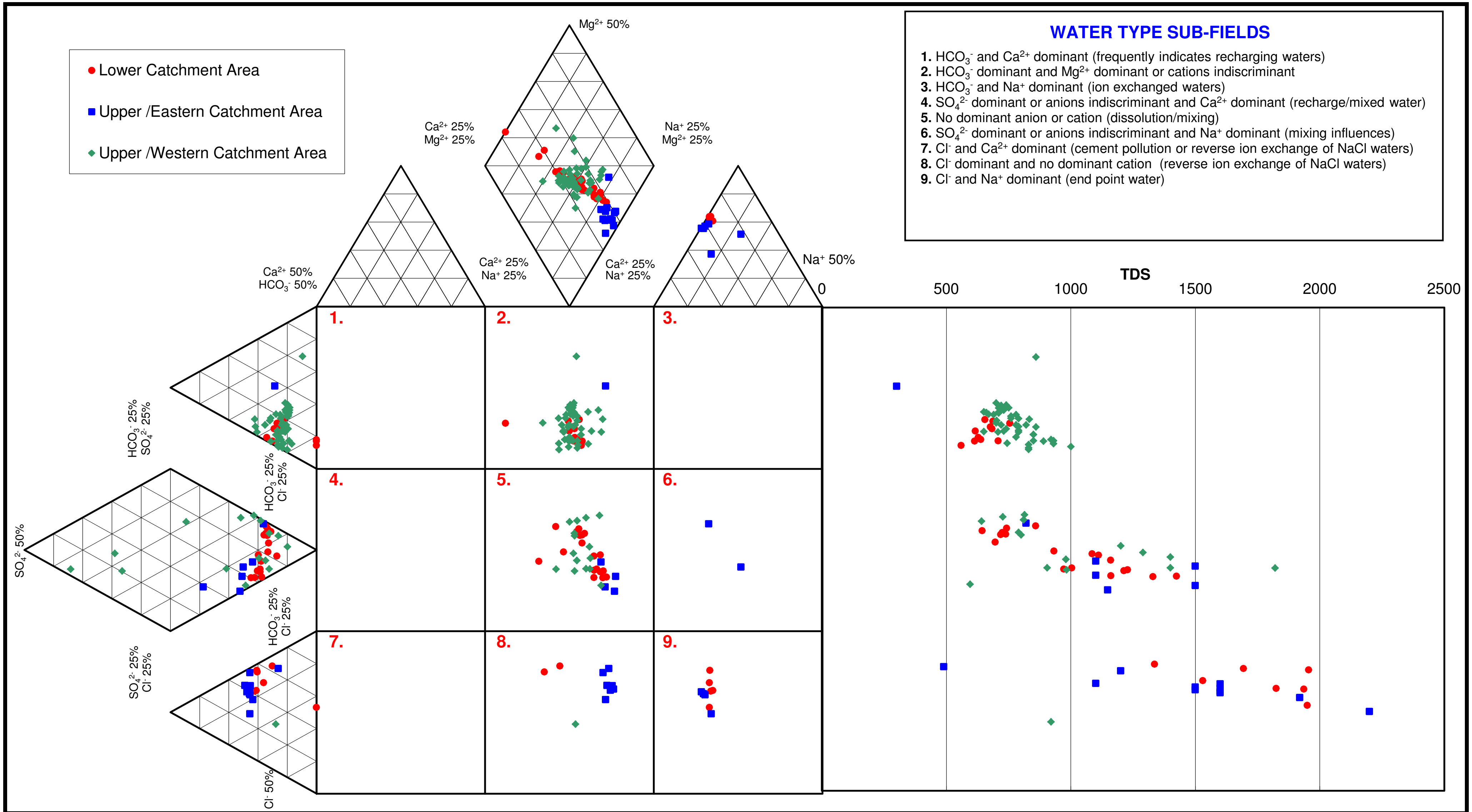
Depth to Water (m)

500
300
200
100
60
40
20
0

RPS

FIGURE 3.15

DEPTH TO WATER
EASTERN PILBARA REGION



RPS

Expanded Durov Diagram

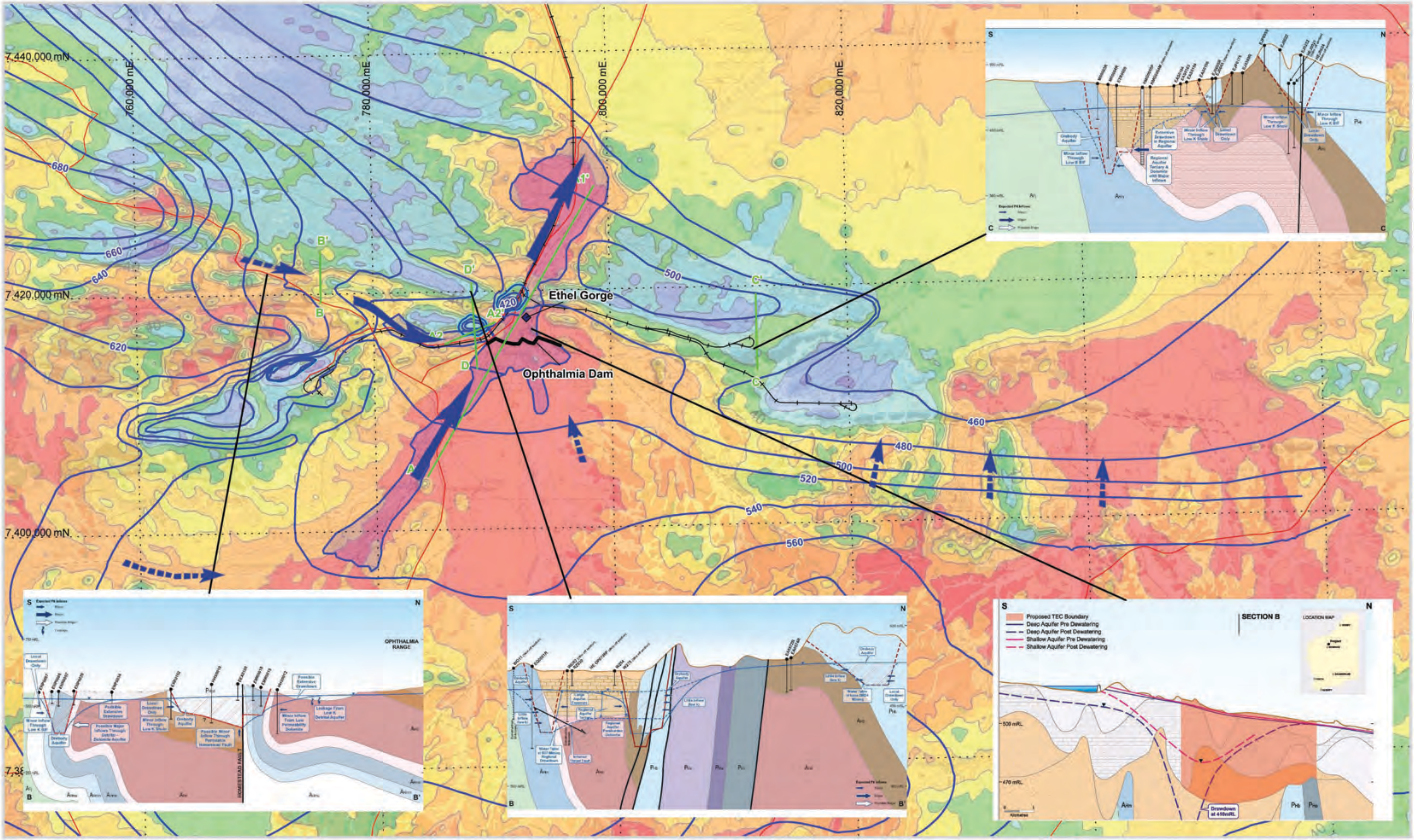
Figure 3.16

Date: 09/10/14

F:\Jobs\1606B\300\EPR\[192a EPR_HydroCHEM2.xls]Project Information

Project:	EPR Conceptual Model	Description:	EPR
Project No:	1606B	Client:	BHPBIO

HydroCHEM 2.0



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0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	198
DRAWN:	MR	REVISION:	
DATE:	02/09/2015	JOB NO:	1606B

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\129c\129c Figure 3.17 - Conceptual Hydrogeology EPH

LEGEND

- Environmental Receptor
- EPR Regional Contour
- Road
- Rail
- Area Affected by Drawdown
- Main Recharge Location
- Major Groundwater Flow
- Minor Groundwater Flow
- Section Line

DATA SOURCES:
Input data source here

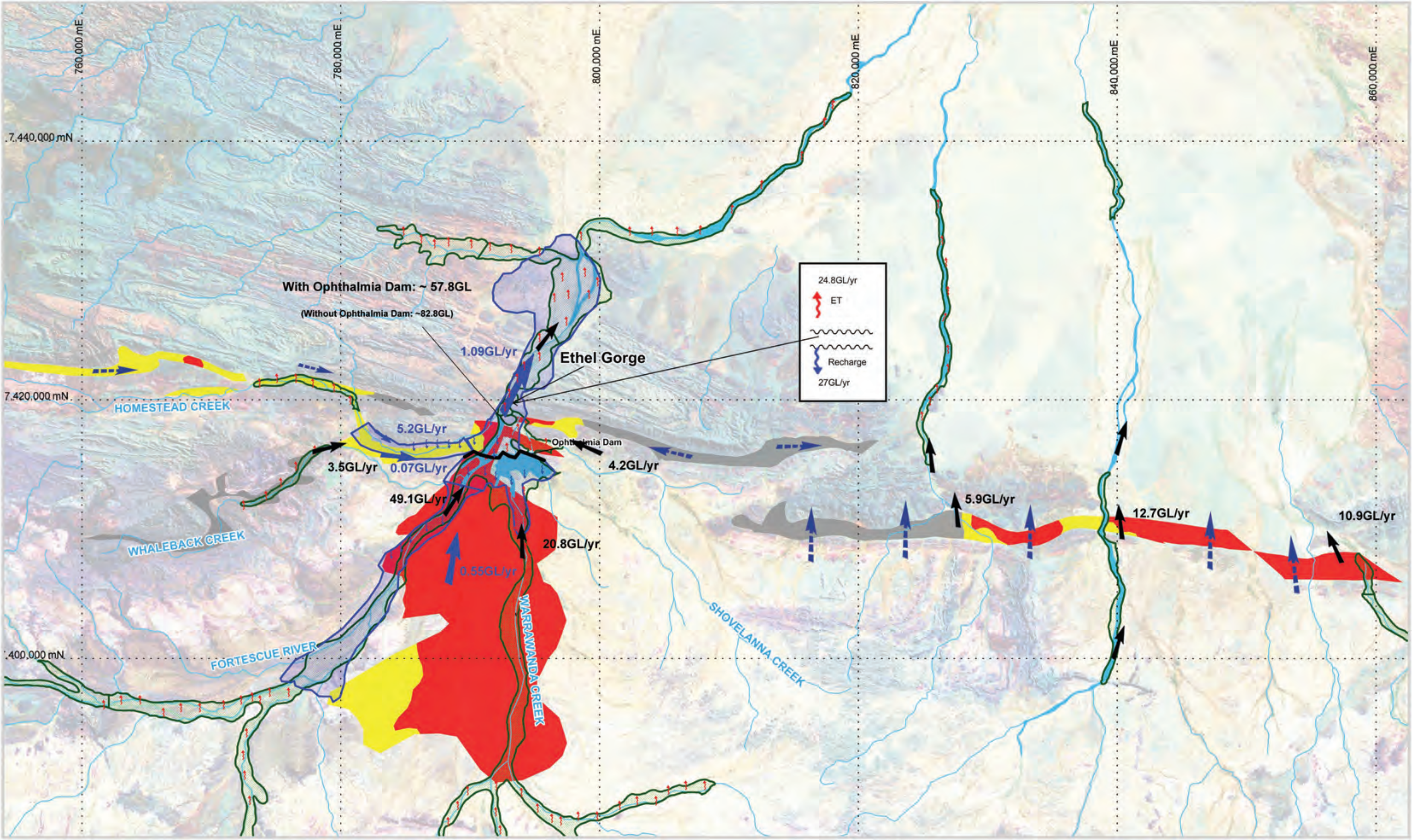
Depth to Water (m)

500
300
200
100
60
40
30
20
10
0

RPS

FIGURE 3.17

CONCEPTUAL HYDROGEOLOGY
EASTERN PILBARA REGION



LOCATION MAP

N

0 5 10

Kilometres

Scale: 1:275,000 @A3

GDA 1994 Zone 50

AUTHOR: DS	REPORT NO: 198
DRAWN: MR	REVISION: b
DATE: 09/10/2014	JOB NO: 1606B

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\129a\129a Figure 3.18 - EPH Eco Hydrological System

LEGEND

Stream/ River

Zones of Groundwater/ Surface water interaction

- Main Recharge Zone
- ET Discharge Zone

- Major Groundwater Flow (with Flux)
- Minor Groundwater Flow
- Surface Water Inflow (with Flux)
- Recharge Flux
- ET Flux

Depth to Water

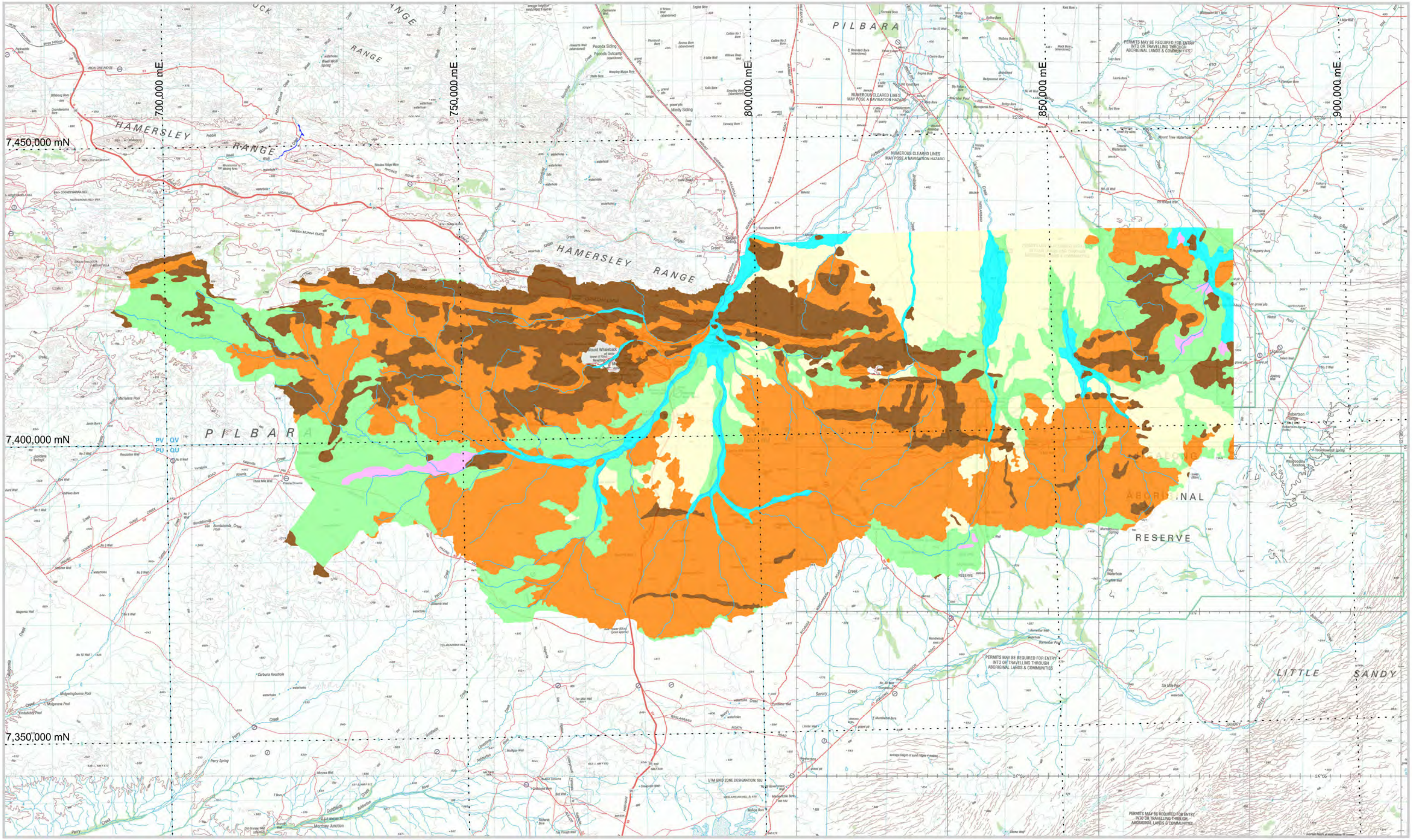
Main Aquifers

- >30m
- 10-30m
- 0-10m

RPS

Figure 3.18

EASTERN PILBARA REGION ECO-HYDROLOGICAL SYSTEM



LOCATION MAP

N

0 10 20

Kilometres

Scale: 1:600,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	198
DRAWN:	MR	REVISION:	b
DATE:	17/10/2014	JOB NO:	1606B

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\198a\198a Figure 4.1 - EHUs in the EPH Study Area

LEGEND

Road

Rail

EHU Categories

- EHU 1 UPLAND Hills, Mountains, Plateaux*
- EHU 2 UPLAND Slopes and Plains*
- EHU 5 LOWLAND Sandplains
- EHU 6 LOWLAND Alluvial Plains
- EHU 7 LOWLAND Calcrete Plains
- EHU 8 LOWLAND Major channels and floodplains

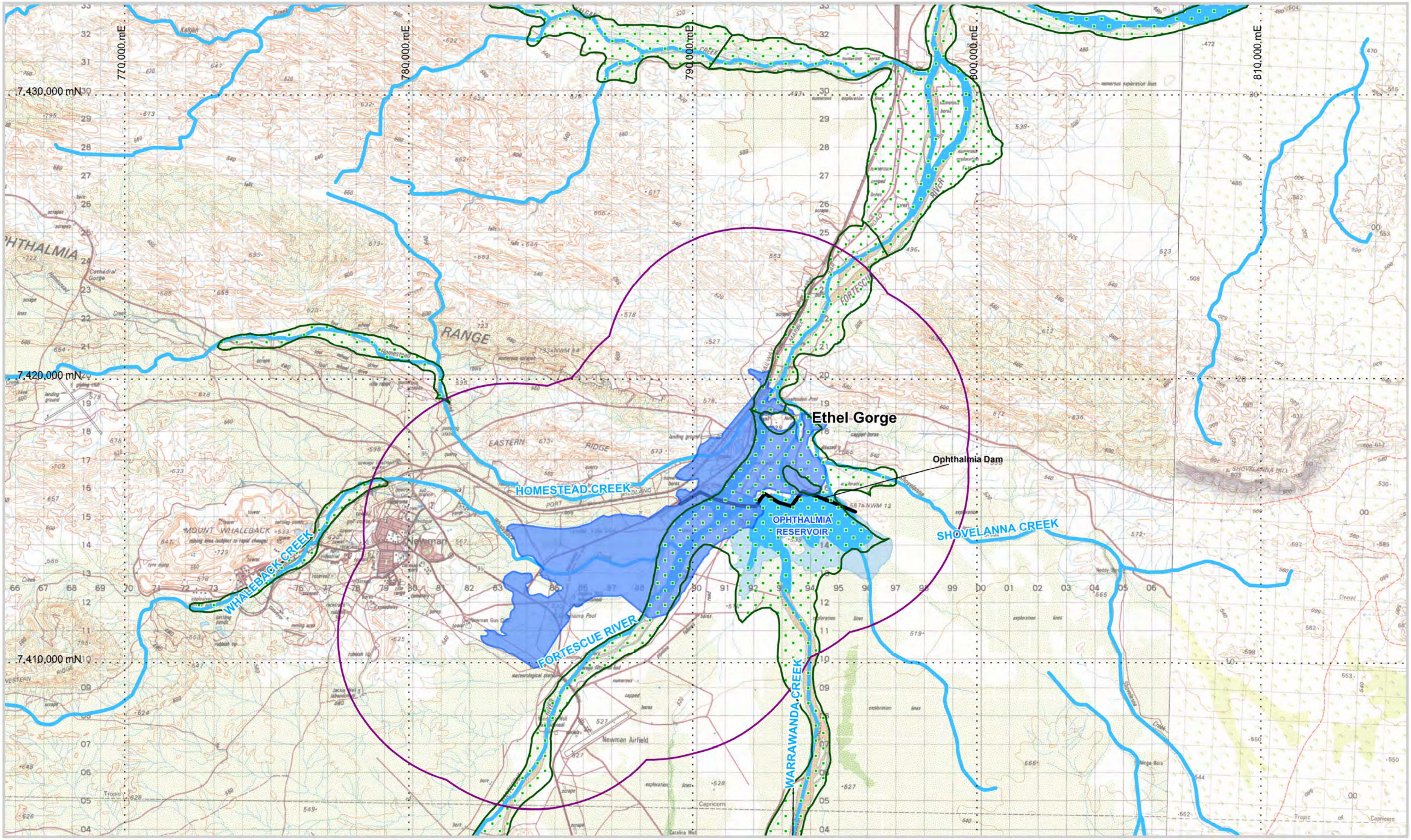
*EHU's 3 & 4 are present within EHU's 1 & 2

DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 4.1

SPATIAL DISTRIBUTION OF EHUS IN THE EPR STUDY AREA



0 2.5 5
Kilometres
Scale: 1:125,000 @A3
GDA 1994 Zone 50

AUTHOR:	DS	REPORT NO:	198
DRAWN:	MR	REVISION:	b
DATE:	11/06/2014	JOB NO:	1606B

LEGEND

- Ethel Gorge TEC Buffer
- Orebody Aquifer
- Ethel Gorge TEC Boundary
- Riparian Vegetation Communities

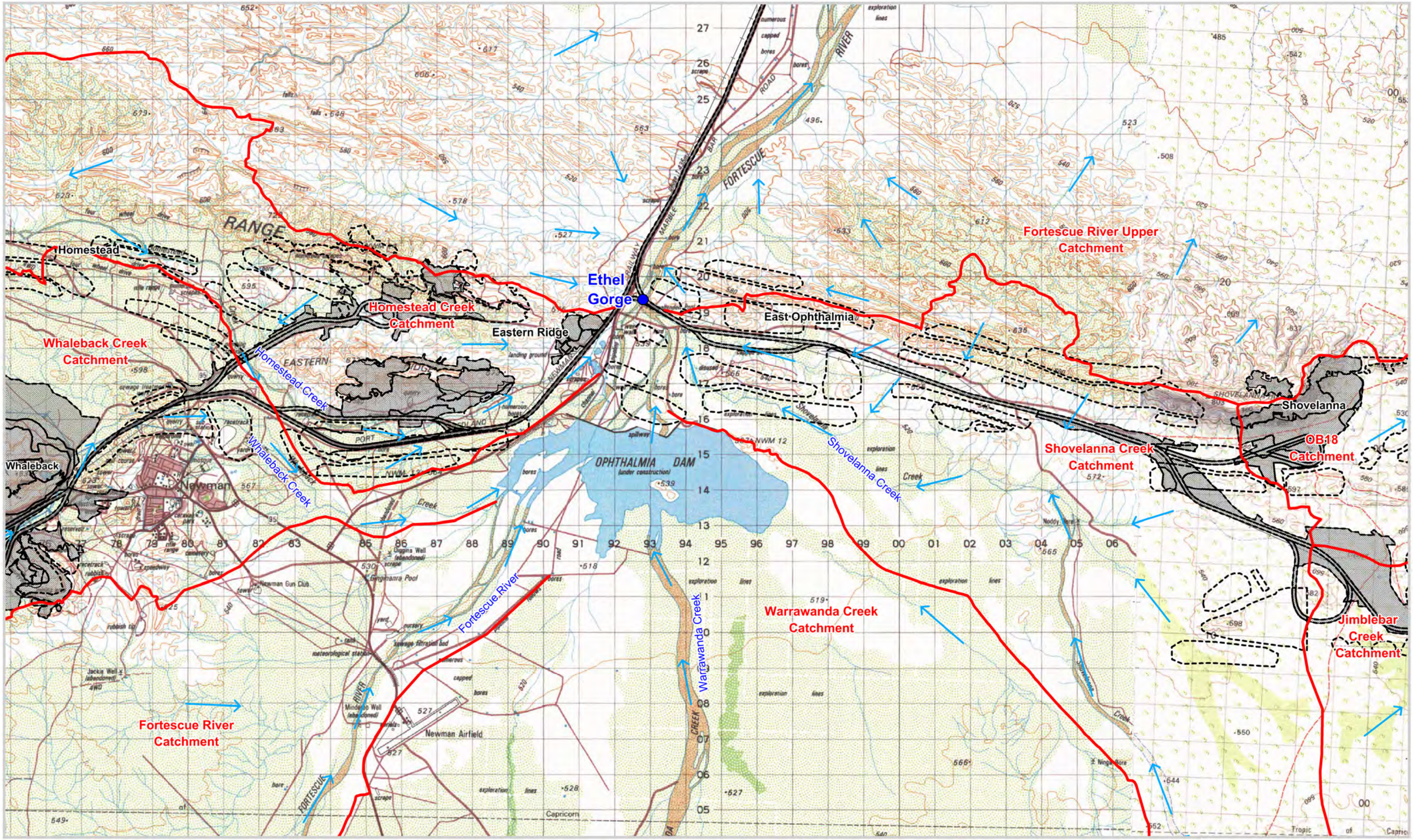
DATA SOURCES:
BHPBIO

RPS

Figure 4.2

ETHEL GORGE LOCATION PLAN

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\198a\Ethel Gorge\198a Figure 4.2 - Location Plan



N

0 2 4

Kilometres

Scale: 1:100,000 @A3

GDA 1994 Zone 50

AUTHOR:	LC	REPORT NO:	198
DRAWN:	OH	REVISION:	d
DATE:	02/09/2015	JOB NO:	16068

Location: F:\Jobs\16061\Spatial_Data\MapInfo\Workspaces\198a\198a Figure 4.3.wor

LEGEND

- Main Catchment Boundary
- Sub-Catchment Boundary
- Existing Flow Path
- Rail
- Indicative BHP Billiton Iron Ore Disturbance
- Existing BHP Billiton Iron Ore Disturbance

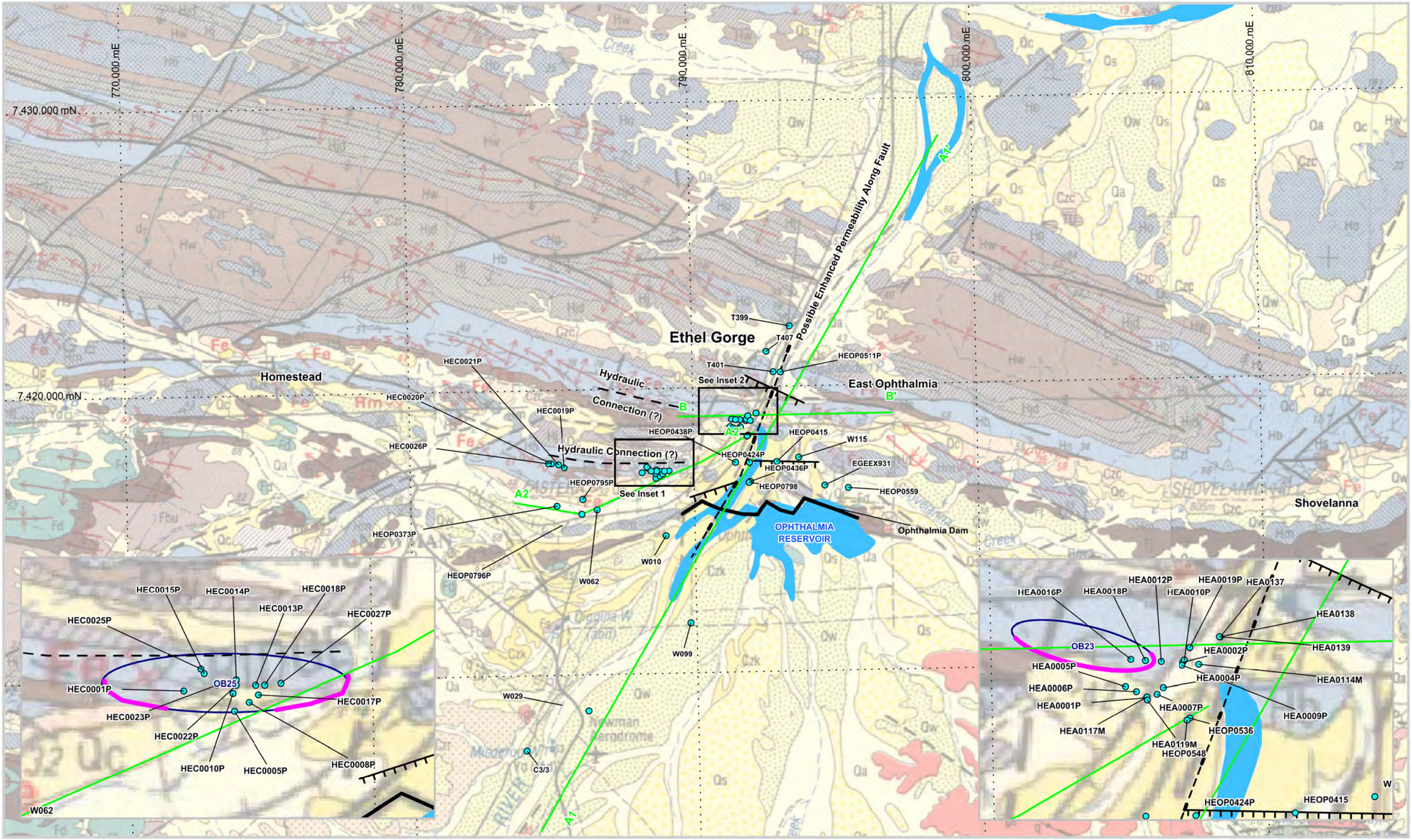
DATA SOURCES:
1:100,000 Topography Maps

RPS

FIGURE 4.3

ETHEL GORGE
LOCAL CATCHMENTS AND FLOWPATHS

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
As project development is dependent upon future events, the outcome of which is uncertain and cannot be



LOCATION MAP

N

0 2.5 5

Kilometres

Scale: 1:125,000 @A3

GDA 1994 Zone 50

AUTHOR: DS	REPORT NO: 198
DRAWN: MR	REVISION: d
DATE: 02/09/2015	JOB NO: 1606B

LEGEND

- Shallow Basement
- Cross Section Line
- Orebody Aquifer (Pink = Zone of Potential Connection with Regional System)
- Key Bore
- Fault

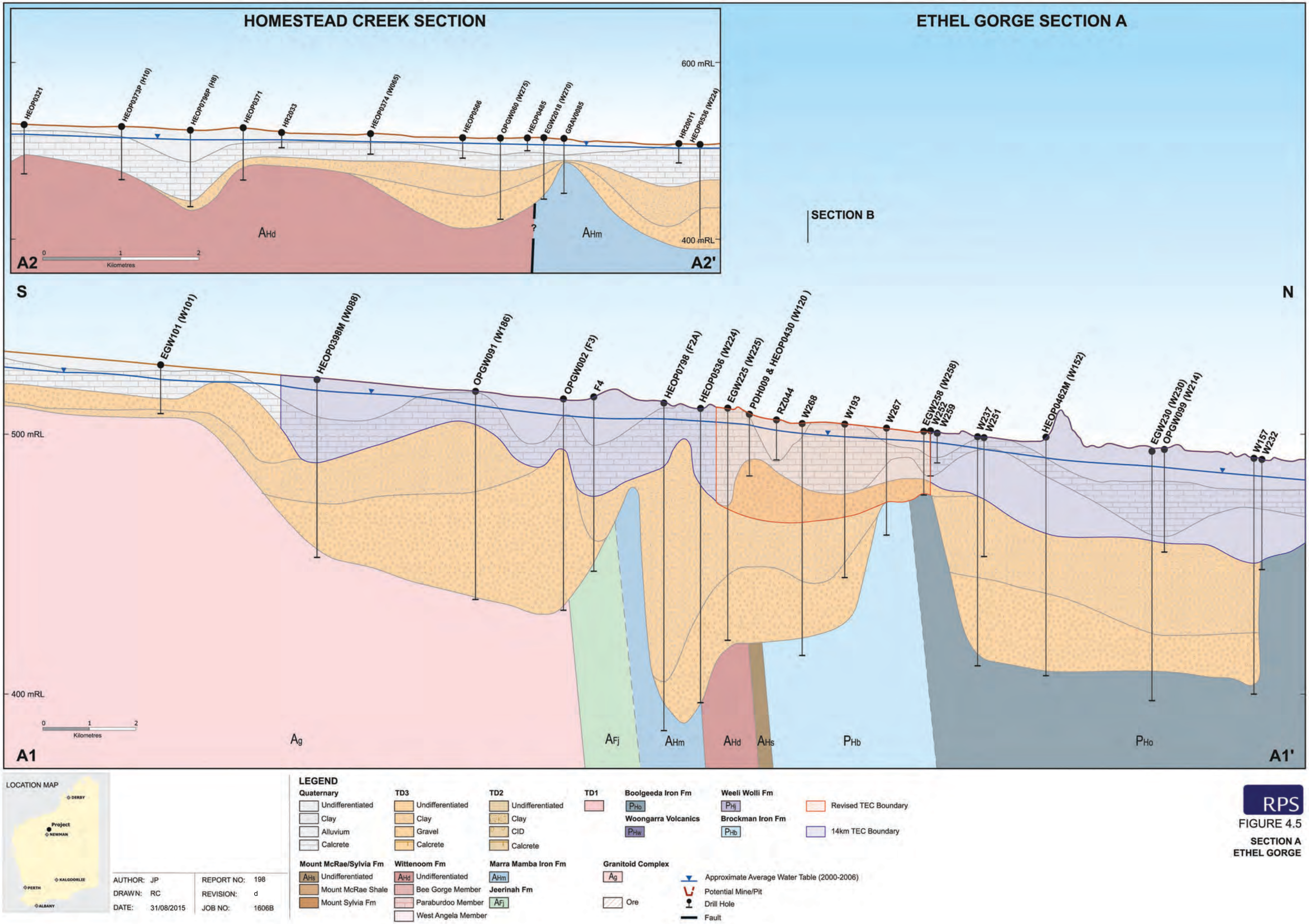
DATA SOURCES:
BHPBIO

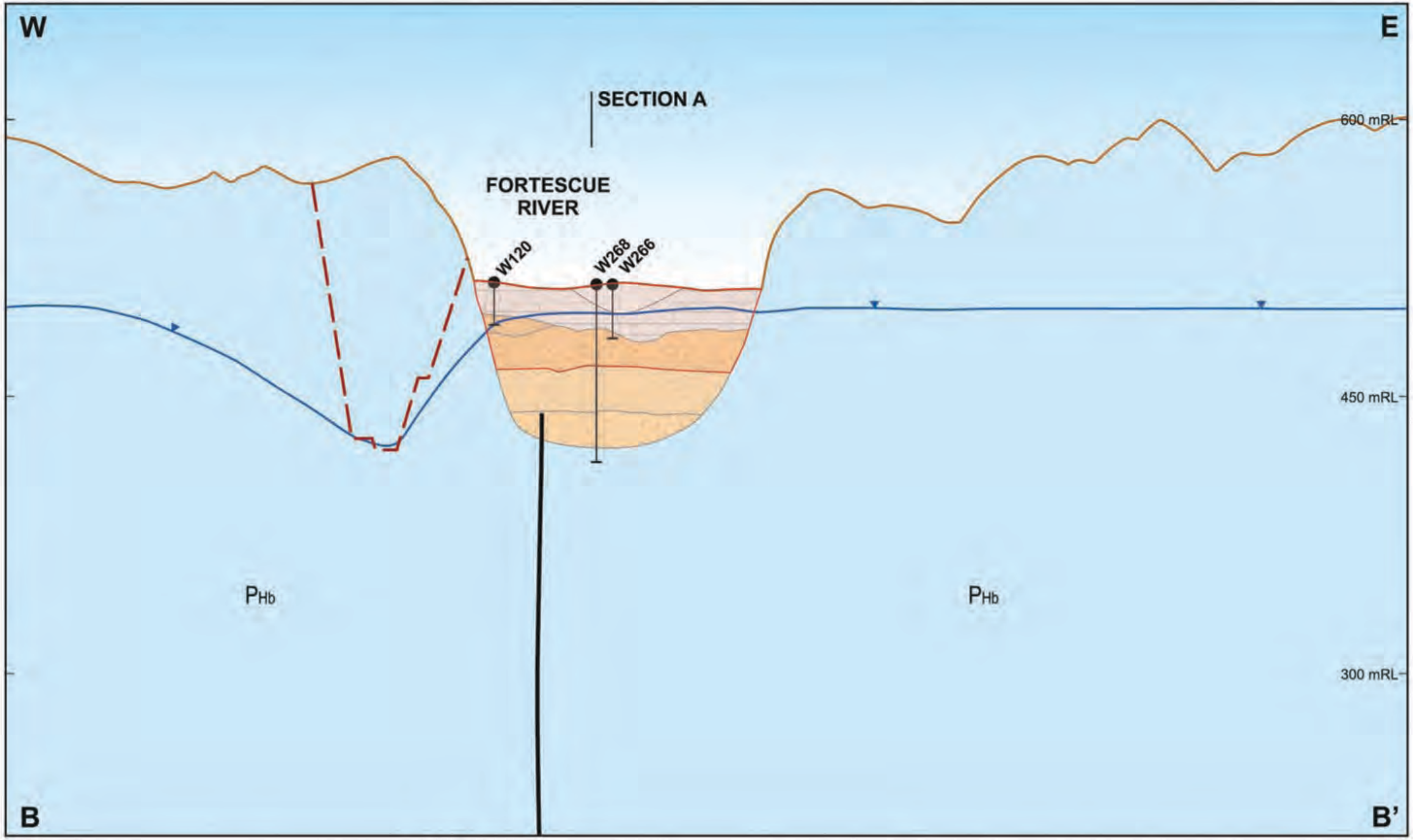
RPS

Figure 4.4

ETHEL GORGE GEOLOGY

Location: F:\Jobs\1606\Spatial_Data\Mapinfo\Workspaces\198a\198a Figure 4.4 - Ethel Gorge Geology


HOMESTEAD CREEK SECTION
600 mRL
400 mRL
HEOP0321
HEOP0373P (H10)
HEOP0796P (H8)
HEOP0371
HR2033
HEOP0374 (W065)
HEOP0566
OPGW060 (W275)
HEOP0485
EGW2018 (W270)
GRAV0085
HR20011
HEOP0536 (W224)
AHd
AHm
A2
A2'
Kilometres
ETHEL GORGE SECTION A
SECTION B
S
N
500 mRL
400 mRL
EGW101 (W101)
HEOP0398M (W088)
OPGW091 (W186)
OPGW002 (F3)
F4
HEOP0798 (F2A)
HEOP0536 (W224)
EGW225 (W225)
PDH009 & HEOP0430 (W120)
RZ044
W268
W193
W267
EGW258 (W258)
W252
W259
W237
W251
HEOP0462M (W152)
EGW230 (W230)
OPGW099 (W214)
W157
W232
Ag
AFj
AHm
AHd
AHs
PHb
PHo
A1
A1'
Kilometres
LOCATION MAP
DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY
LEGEND
Quaternary
Undifferentiated
Clay
Alluvium
Calcrete
TD3
Undifferentiated
Clay
Gravel
Calcrete
TD2
Undifferentiated
Clay
CID
Calcrete
TD1
Boolgeeda Iron Fm
PHo
Woongarra Volcanics
PHw
Weeli Wolli Fm
PHj
Brockman Iron Fm
PHb
Revised TEC Boundary
14km TEC Boundary
Mount McRae/Sylvia Fm
AHs Undifferentiated
Mount McRae Shale
Mount Sylvia Fm
Wittenoom Fm
AHd Undifferentiated
Bee Gorge Member
Paraburdoo Member
West Angela Member
Marra Mamba Iron Fm
AHm
Jeerinah Fm
AFj
Granitoid Complex
Ag
Ore
Approximate Average Water Table (2000-2006)
Potential Mine/Pit
Drill Hole
Fault
AUTHOR: JP
DRAWN: RC
DATE: 31/08/2015
REPORT NO: 198
REVISION: d
JOB NO: 1606B
RPS
FIGURE 4.5
SECTION A
ETHEL GORGE



Location: XXXX

0 500 1000
metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Calcrete
- Alluvium
- Clay

TD3
- Undifferentiated
- Gravel
- Clay

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHu

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag
- Ore

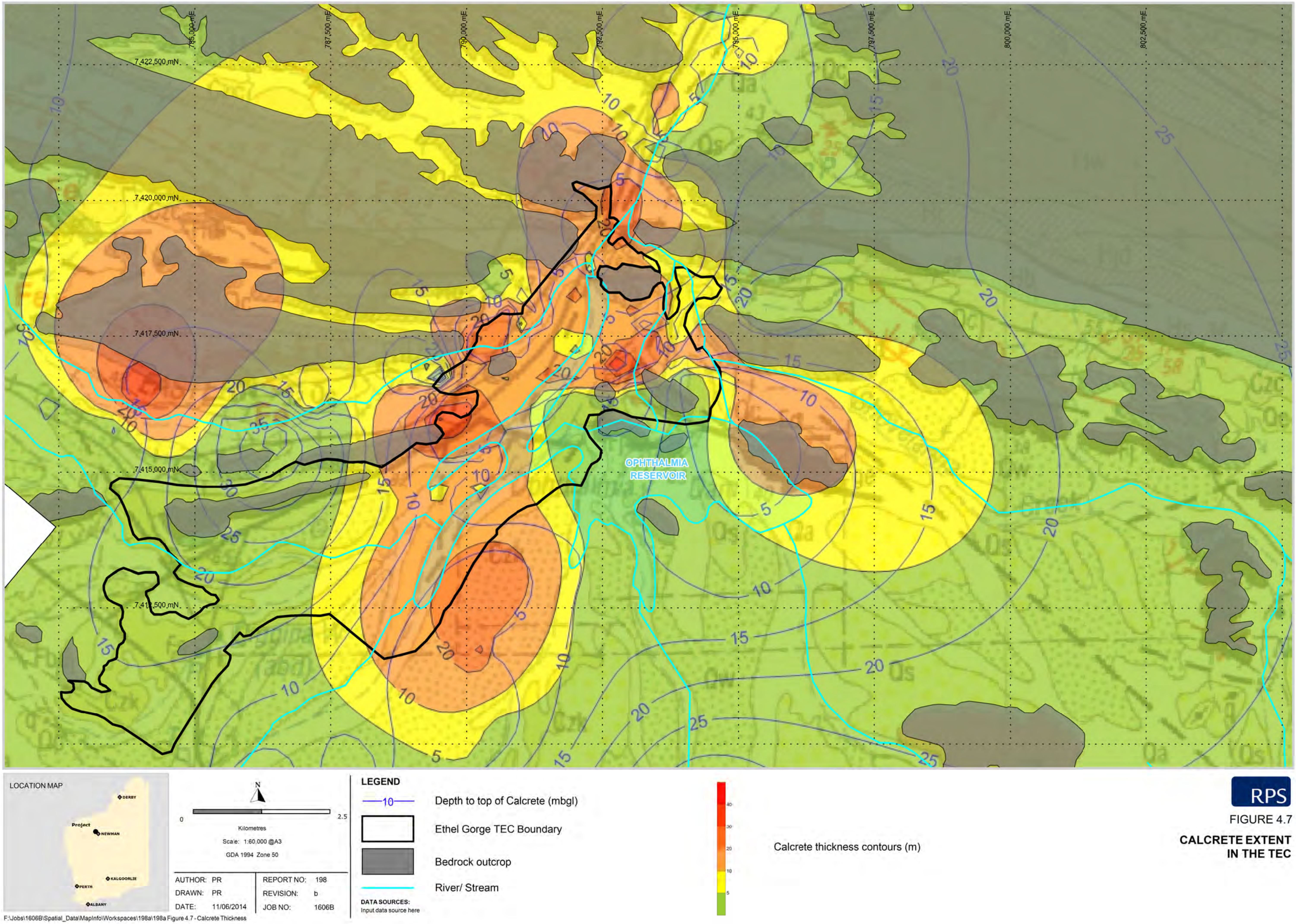
- Revised TEC Boundary
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

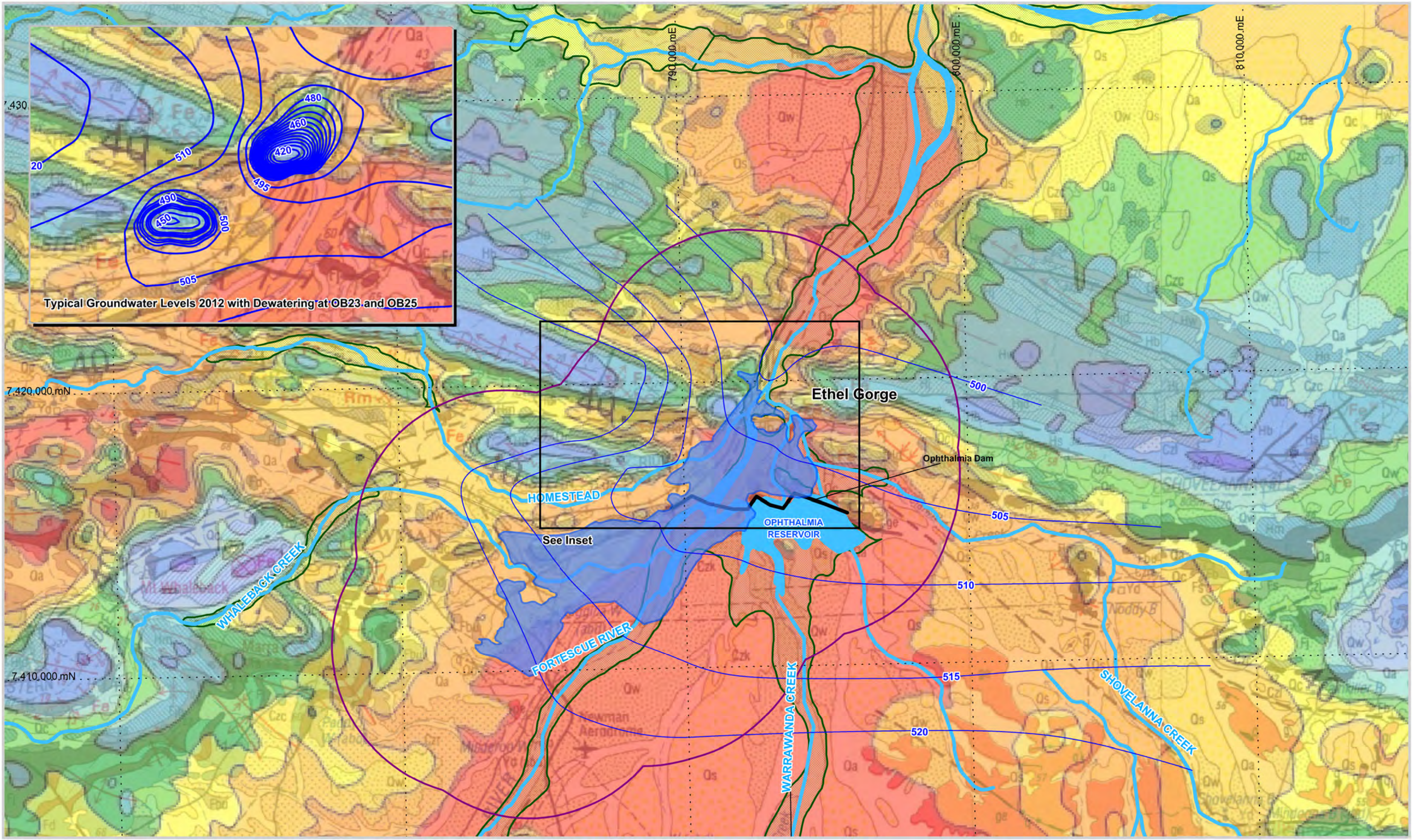
FIGURE 4.6

SECTION B
ETHEL GORGE

DATA SOURCES:
Input data source here



7,422,500 mN
7,420,000 mN
7,417,500 mN
7,415,000 mN
785,000 mE
787,500 mE
790,000 mE
792,500 mE
795,000 mE
797,500 mE
800,000 mE
802,500 mE
OPHTHALMIA RESERVOIR
LOCATION MAP
DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY
N
0
2.5
Kilometres
Scale: 1:60,000 @A3
GDA 1994 Zone 50
LEGEND
10
Depth to top of Calcrete (mbgl)
Ethel Gorge TEC Boundary
Bedrock outcrop
River/ Stream
Calcrete thickness contours (m)
DATA SOURCES:
Input data source here
AUTHOR: PR
DRAWN: PR
DATE: 11/06/2014
REPORT NO: 198
REVISION: b
JOB NO: 1606B
RPS
FIGURE 4.7
CALCRETE EXTENT IN THE TEC
F:\Jobs\1606B\Spatial_Data\MapInfo\Workspaces\198a\198a Figure 4.7 - Calcrete Thickness



N

0 2.5 5

Kilometres

Scale: 1:125,000 @A3

GDA 1994 Zone 50

AUTHOR: DS	REPORT NO: 198
DRAWN: MR	REVISION: b
DATE: 11/06/2014	JOB NO: 1606B

LEGEND

- Pre-Mining WL Contours (mAHD)
- Ethel Gorge TEC Buffer
- Ethel Gorge TEC Boundary
- Riparian Vegetation Community

DATA SOURCES:
BHPBIO

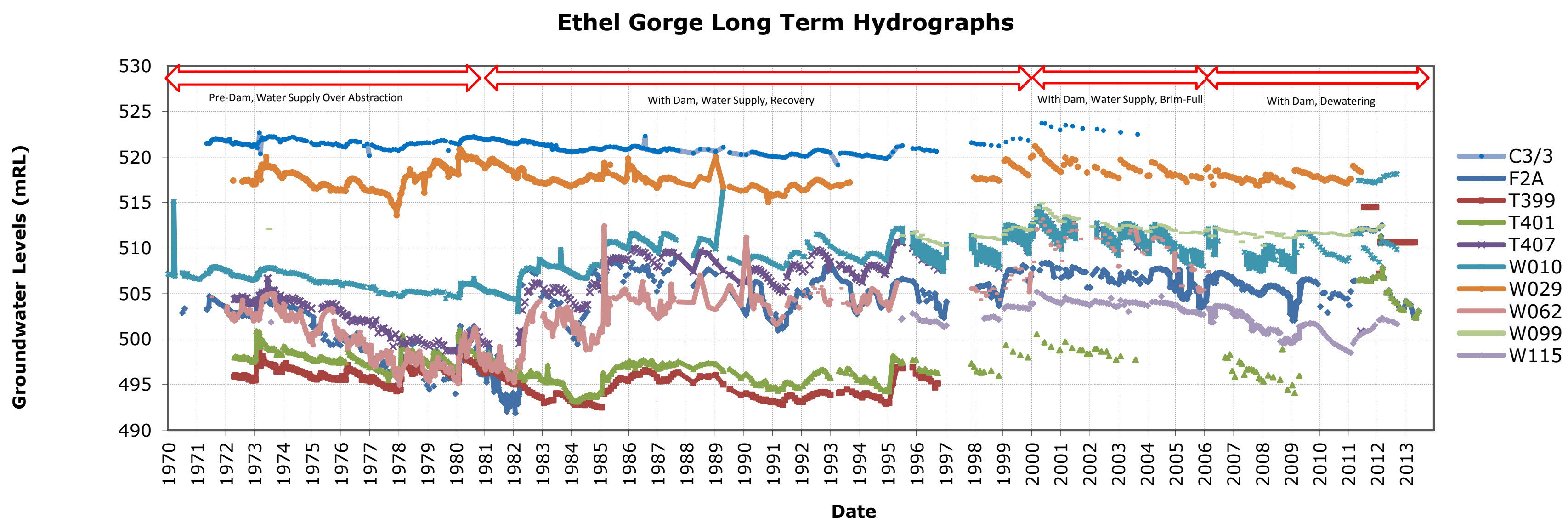
500, 300, 200, 100, 60, 40, 30, 20, 10, 0 — Depth to Water (mbgl)

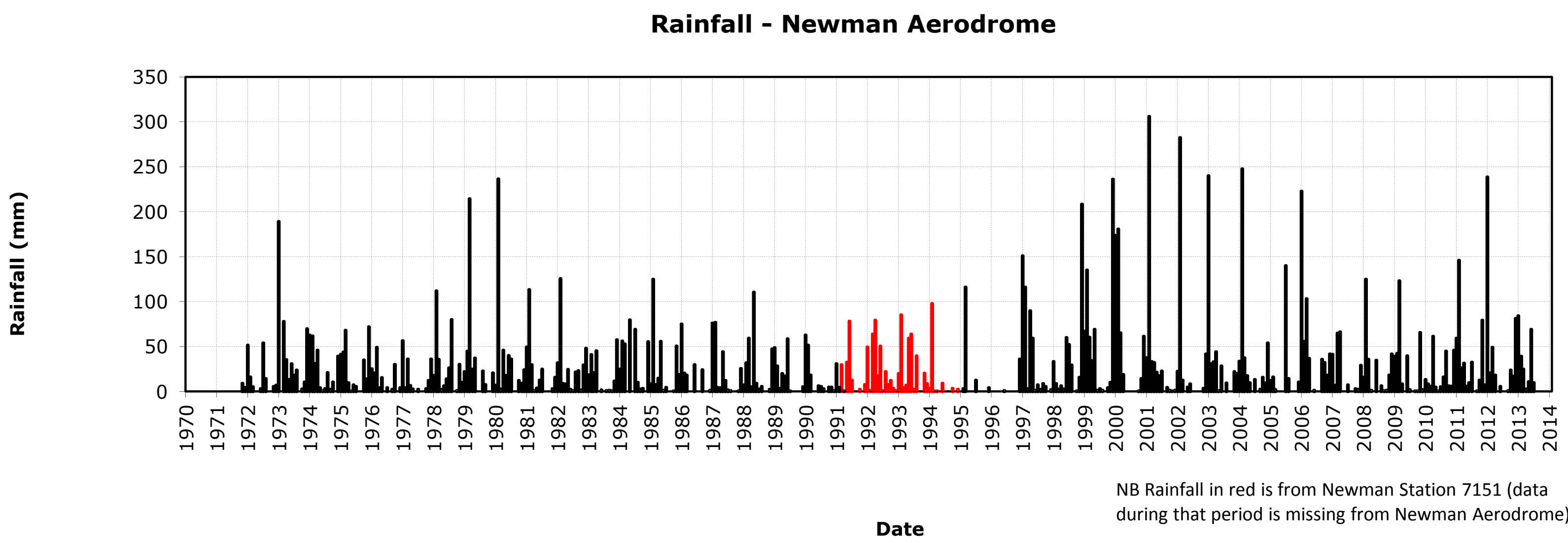
RPS

Figure 4.8

ETHEL GORGE GROUNDWATER LEVELS

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\198a\198a Figure 4.8 - Water Level Contours with TEC

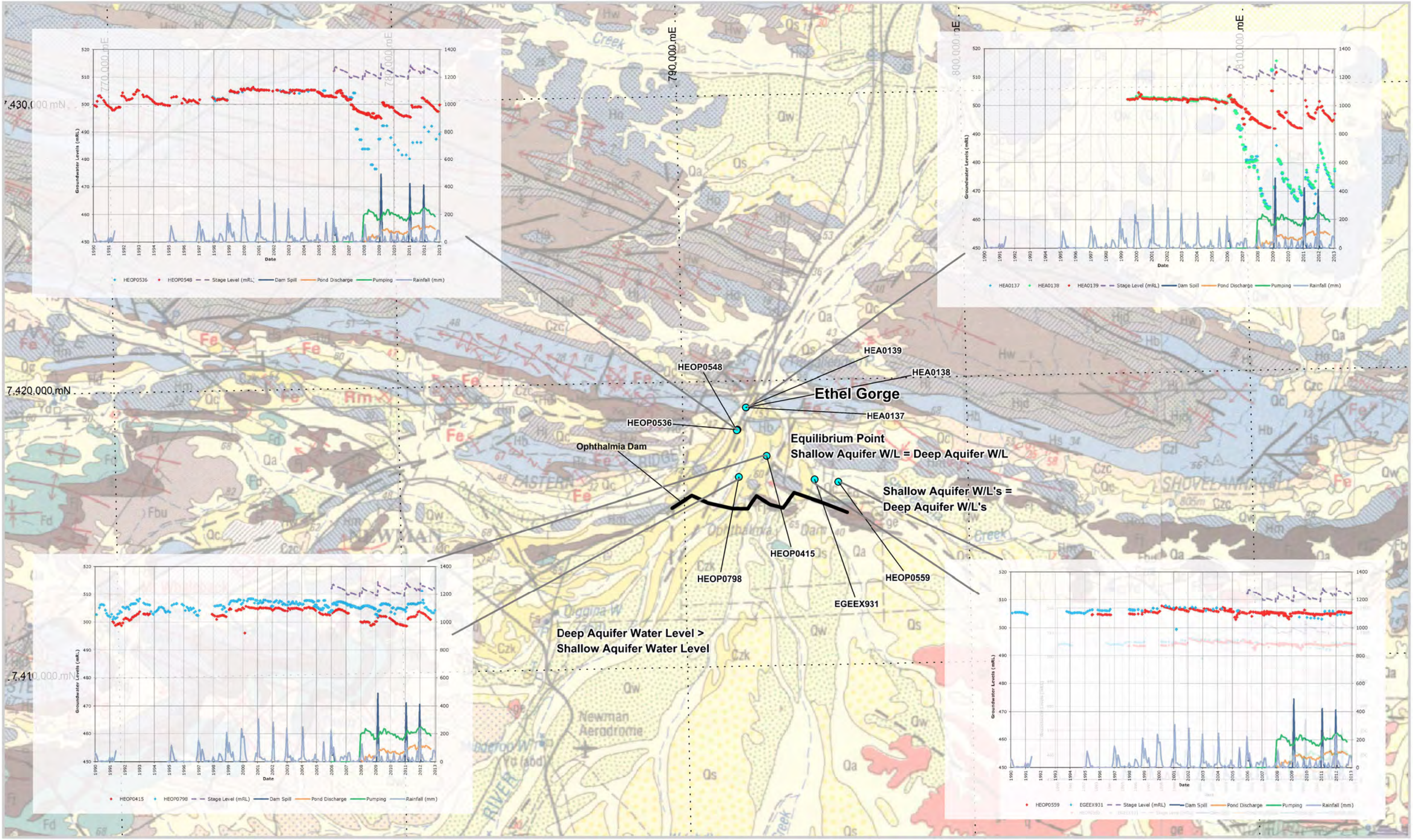




NB Rainfall in red is from Newman Station 7151 (data during that period is missing from Newman Aerodrome)

ETHEL GORGE LONG TERM HYDROGRAPHS FIGURE 4.9

F:\Jobs\1606B\300\Ethel Gorge Case Study\[173a Long Term (1970-2012) Hydrographs.xlsx]Figure 4.9



LOCATION MAP

N

0 2.5 5

Kilometres

Scale: 1:125,000 @A3

GDA 1994 Zone 50

AUTHOR: DS	REPORT NO: 198
DRAWN: MR	REVISION: b
DATE: 11/06/2014	JOB NO: 1606B

LEGEND

Key Bore

DATA SOURCES:
BHPBIO

RPS

Figure 4.10

KEY BORES AND HYDROGRAPH DATA

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\198a\198a Figure 4.10 - Key Bores and Hydrograph Data

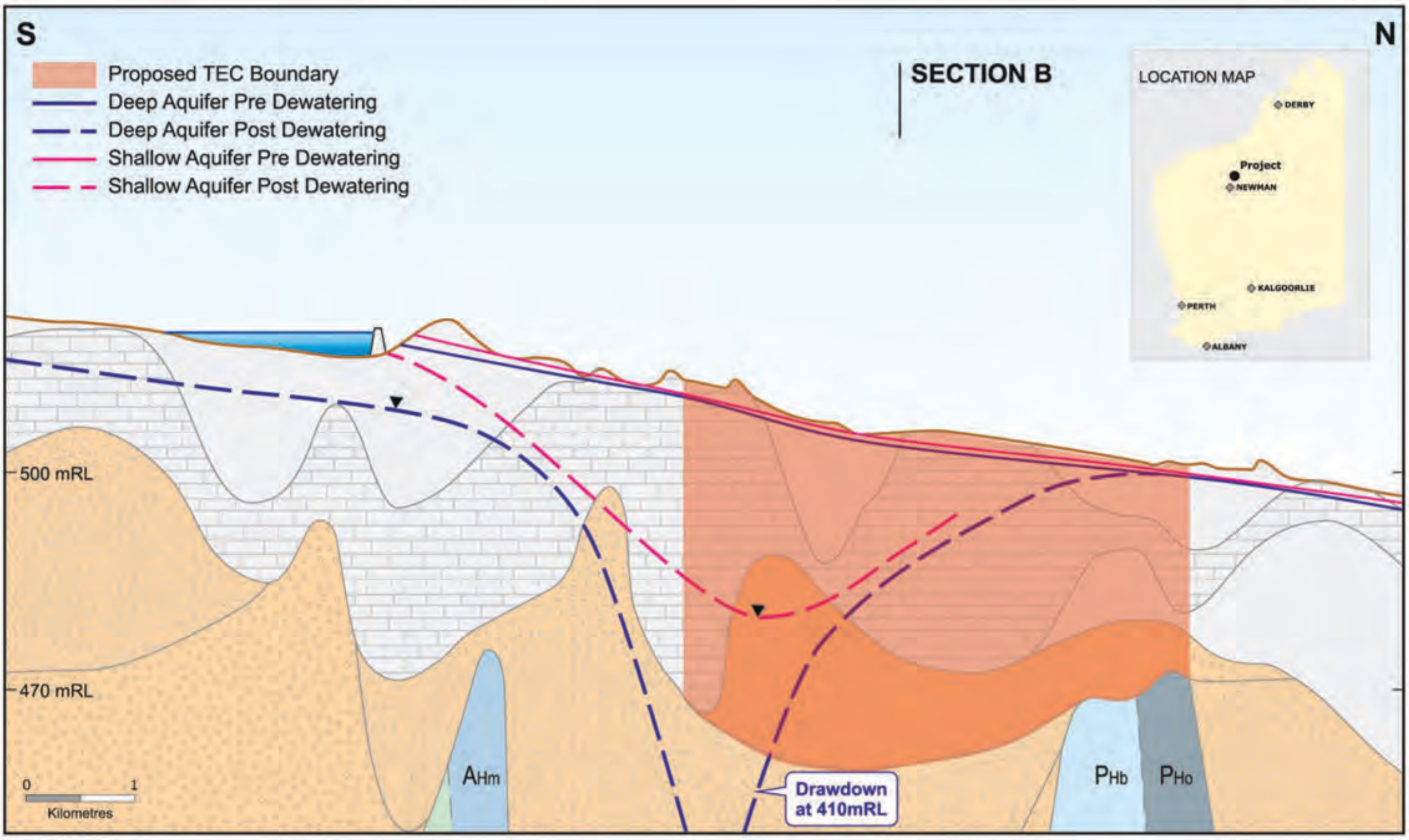


Figure 4.11a

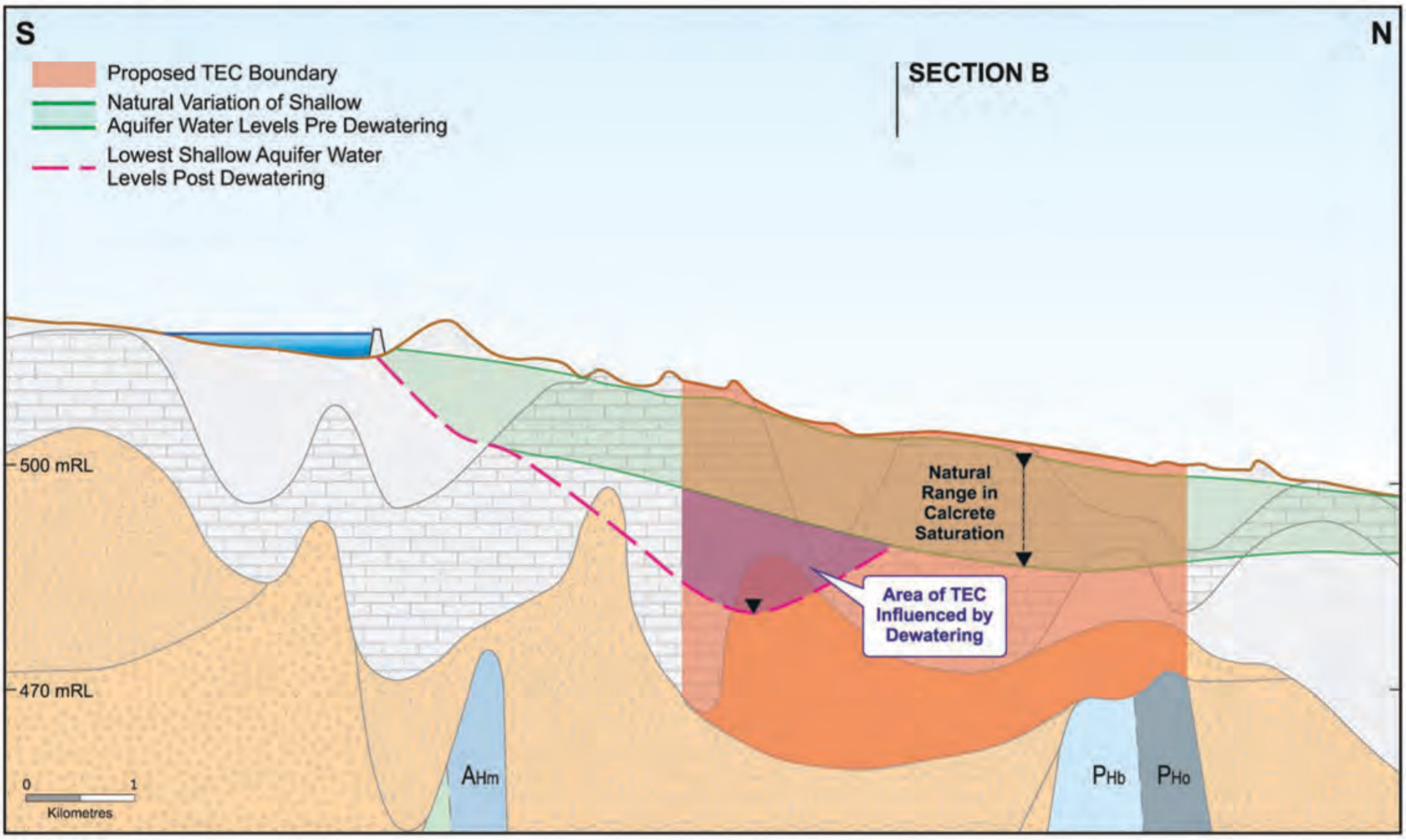


Figure 4.11b

LEGEND

Quaternary: Undifferentiated; Clay; Alluvium; Calcrete

TD3: Undifferentiated; Clay; Gravel; Calcrete

TD2: Undifferentiat; Clay; CID; Calcrete

TD1

Boolgeeda Iron Fm: PHo

Woongarra Volcanics: PHw

Weeli Wolli Fm: PHj

Ore

Jeerinah Fm: AFj

Granitoid Complex: Ag

Approximate Water Table

Potential Mine/Pit

Drill Hole

Fault

Mount McRae/Sylvia Fm: AHs Undifferentiated; Mount McRae Shale; Mount Sylvia Fm

Wittenoom Fm: AHd Undifferentiated; Bee Gorge Member; Paraburdoo Member; West Angela Member

Marra Mamba Iron Fm: AHm Undifferentiated; AHmn Mount Newman Member; AHmm MacLeod Member; AHmu Nammuldi Member

Brockman Iron Fm: PHb Undifferentiated; PHbj Joffre Member; PHbw Whaleback Shale Member; PHbd Dales Gorge Member

AUTHOR: JP	REPORT NO: 198
DRAWN: RC	REVISION: b
DATE: 03/02/2014	JOB NO: 1606B

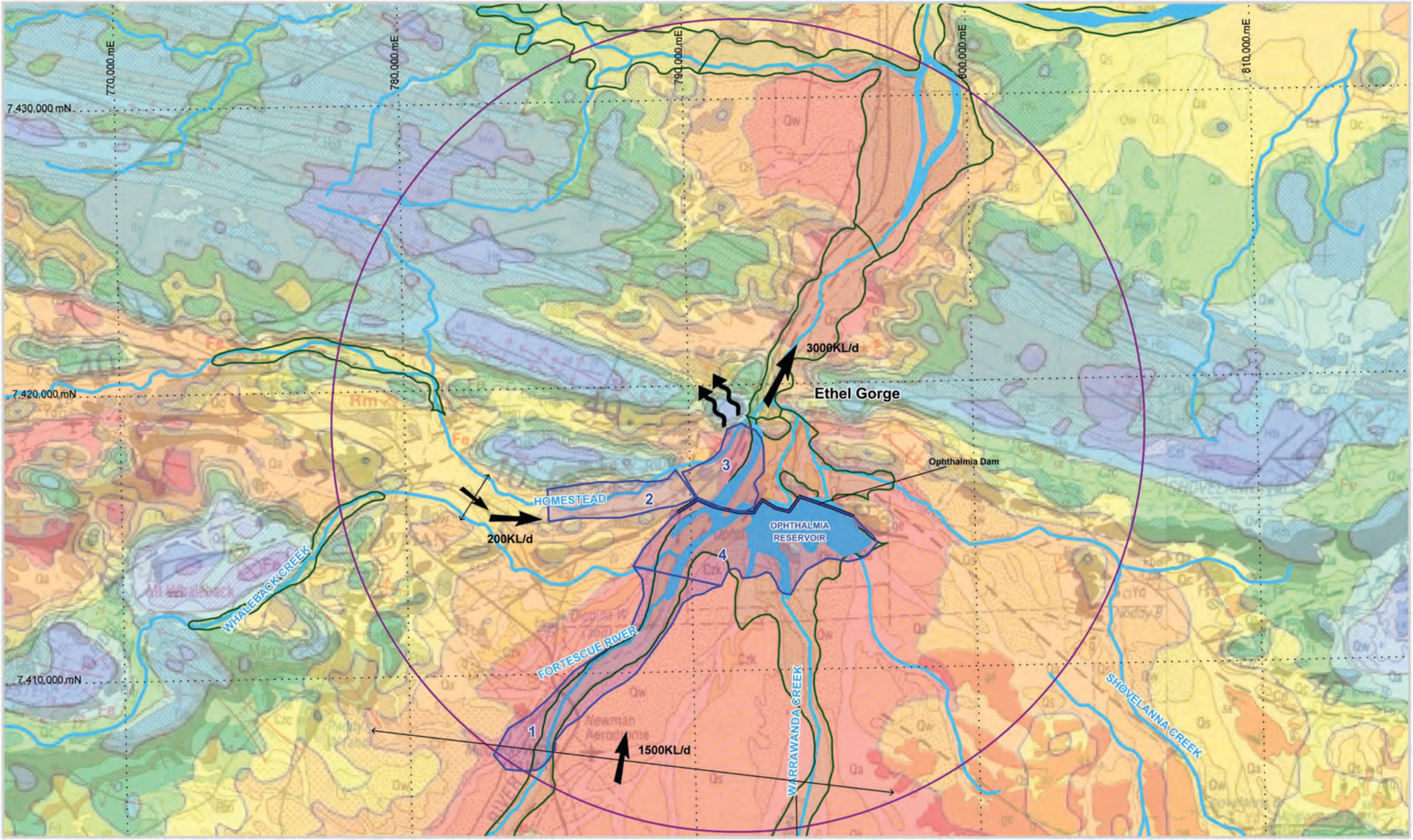
Location: XXXX

RPS

FIGURE 4.11

ETHEL GORGE MINING AREA GROUNDWATER LEVELS AND THE TEC

DATA SOURCES:
Input data source here



LOCATION MAP

DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY

N

0 2.5 5

Kilometres

Scale: 1:125,000 @A3

GDA 1994 Zone 50

AUTHOR: DS	REPORT NO: 198
DRAWN: MR	REVISION: b
DATE: 11/06/2014	JOB NO: 1606B

LEGEND

Stream/ River

Recharge Zone: -
1. Fortescue River
2. Homestead Creek
3. Fortescue Flood Plain
4. Seepage From Dam

Discharge Zone (River Land System Boundary)

Groundwater Flow

Evapotranspiration

500
300
200
100
60
40
30
20
10
0

Depth to Water (mbgl)

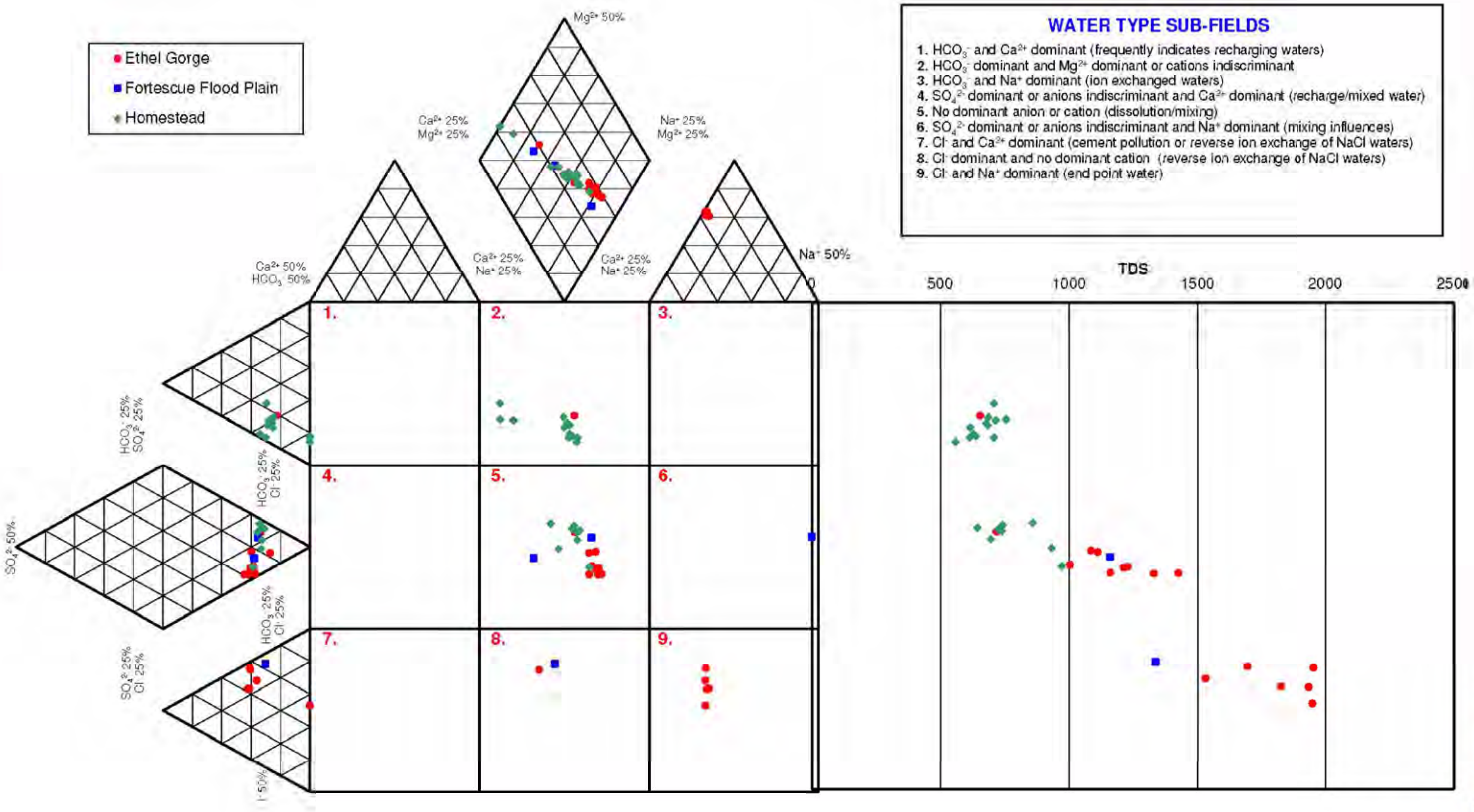
DATA SOURCES:
BHPBIO

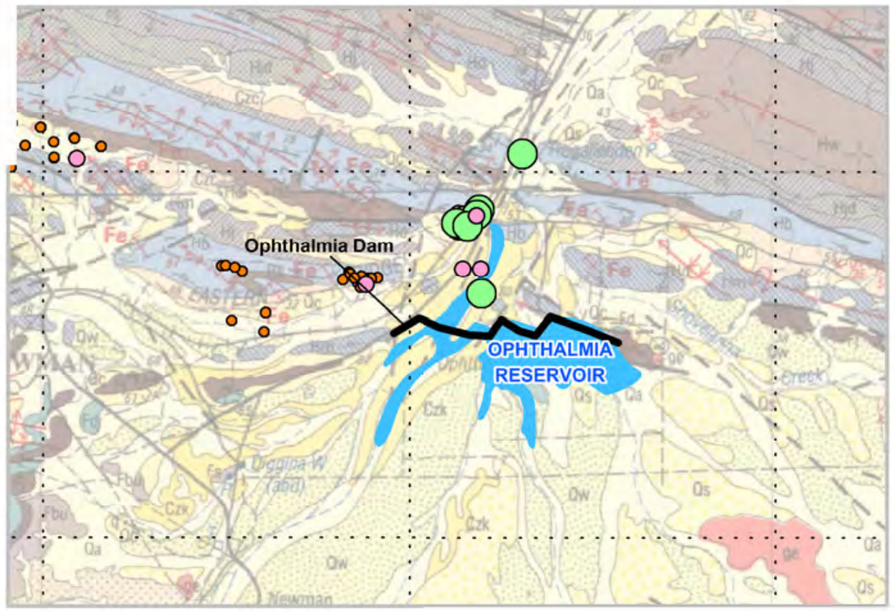
RPS

Figure 4.12

PRE-DEWATERING GROUNDWATER RECHARGE AND DISCHARGE

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\129c\129c Figure 4.12 - Groundwater Recharge





LOCATION MAP

N

0 2.5 5

Kilometres

Scale: 1:200,000 @A3

GDA 1994 Zone 50

AUTHOR: DS
DRAWN: MR
DATE: 11/06/2014

REPORT NO: 198
REVISION: b
JOB NO: 1606B

Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\198a\198a Figure 4.13 - Key Bores and Water Quality Data

LEGEND

Chloride Concentration (Average mg/L)

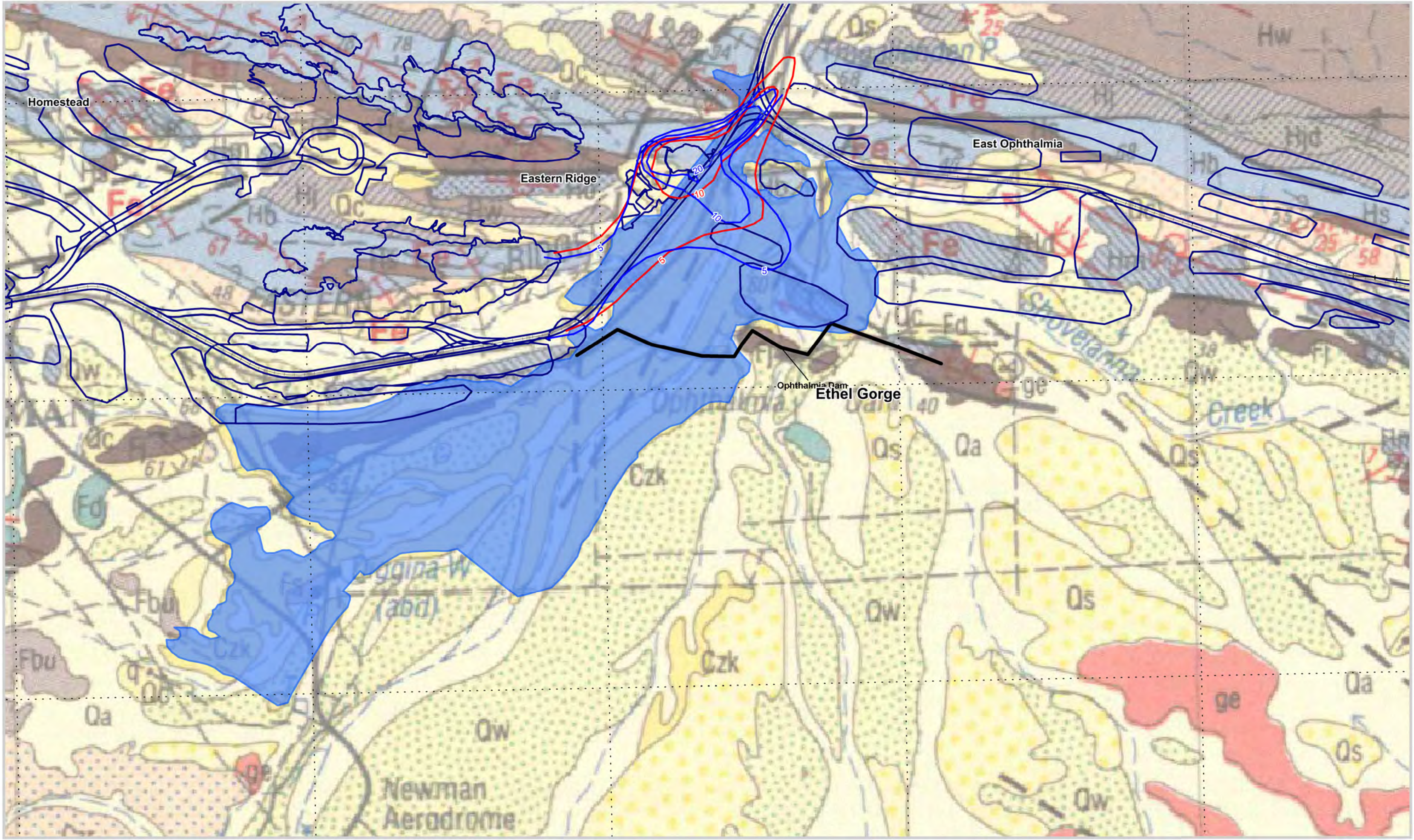
- 25-200
- 200-400
- 400-655

DATA SOURCES:
BHPBIO

RPS

Figure 4.13

KEY BORES AND WATER QUALITY DATA



LOCATION MAP

N

0 2.5

Kilometres

Scale: 1:60,000 @A3

GDA 1994 Zone 50

AUTHOR:	DS	REPORT NO:	198
DRAWN:	MR	REVISION:	d
DATE:	02/09/2015	JOB NO:	1606B

LEGEND

5 Drawdown due to Dewatering (m)

5 Depressurisation due to Dewatering (m)

Ethel Gorge TEC Boundary

Indicative BHP Billiton Iron Ore Disturbance

Rail

DATA SOURCES:
BHPBIO

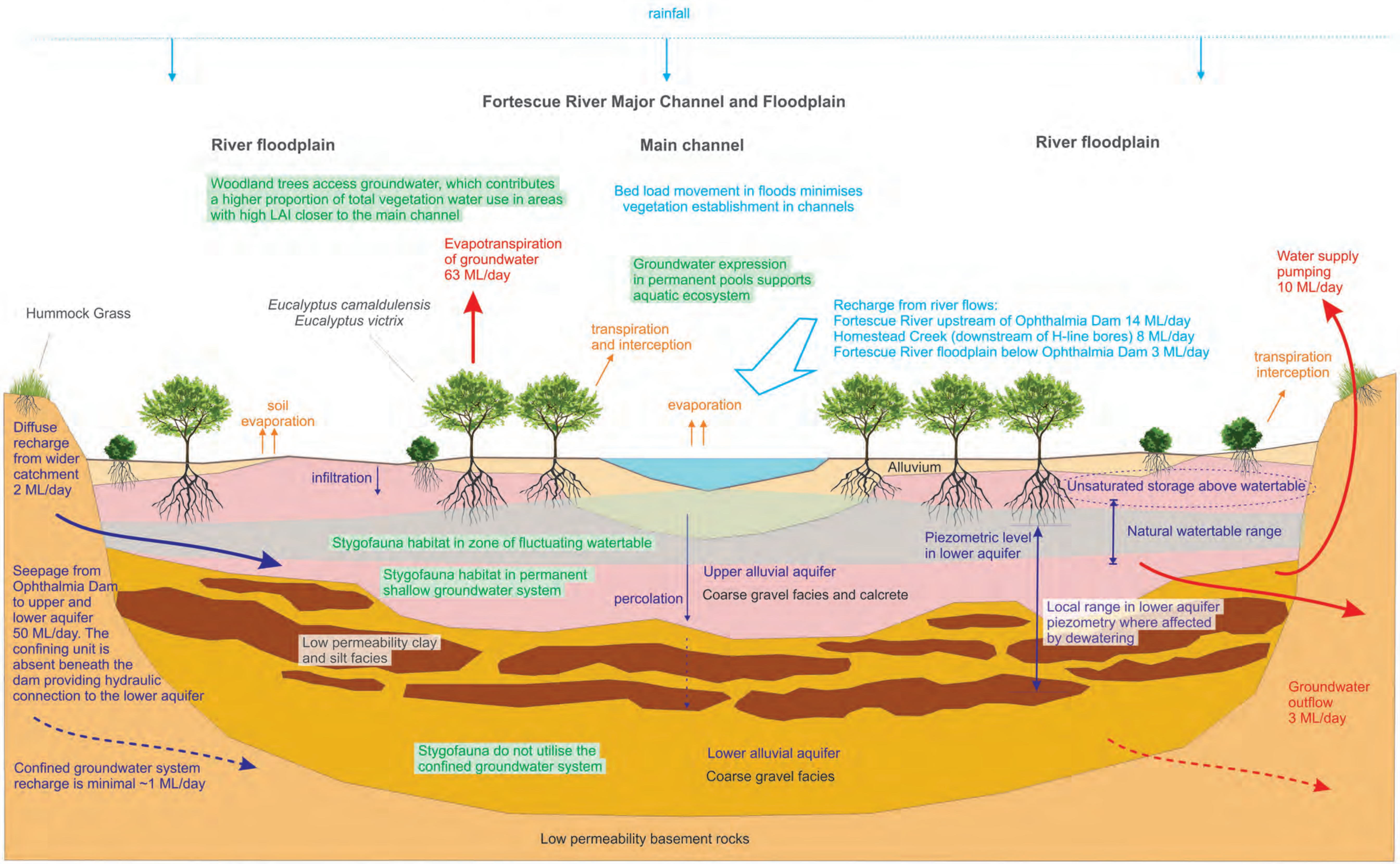
Location: F:\Jobs\1606B\Spatial_Data\Mapinfo\Workspaces\198b\198b Figure 4.14 - Orebodies below WT near Ethel Gorge

RPS

Figure 4.14

DISTURBANCE AREAS CONTAINING BELOW WATER TABLE OREBODIES NEAR ETHEL GORGE

Ethel Gorge ecohydrological conceptualisation



N

NOT TO SCALE

AUTHOR: JP
DRAWN: MR
DATE: [illegible]

REPORT NO: 198
REVISION: b
JOB NO: 1606B

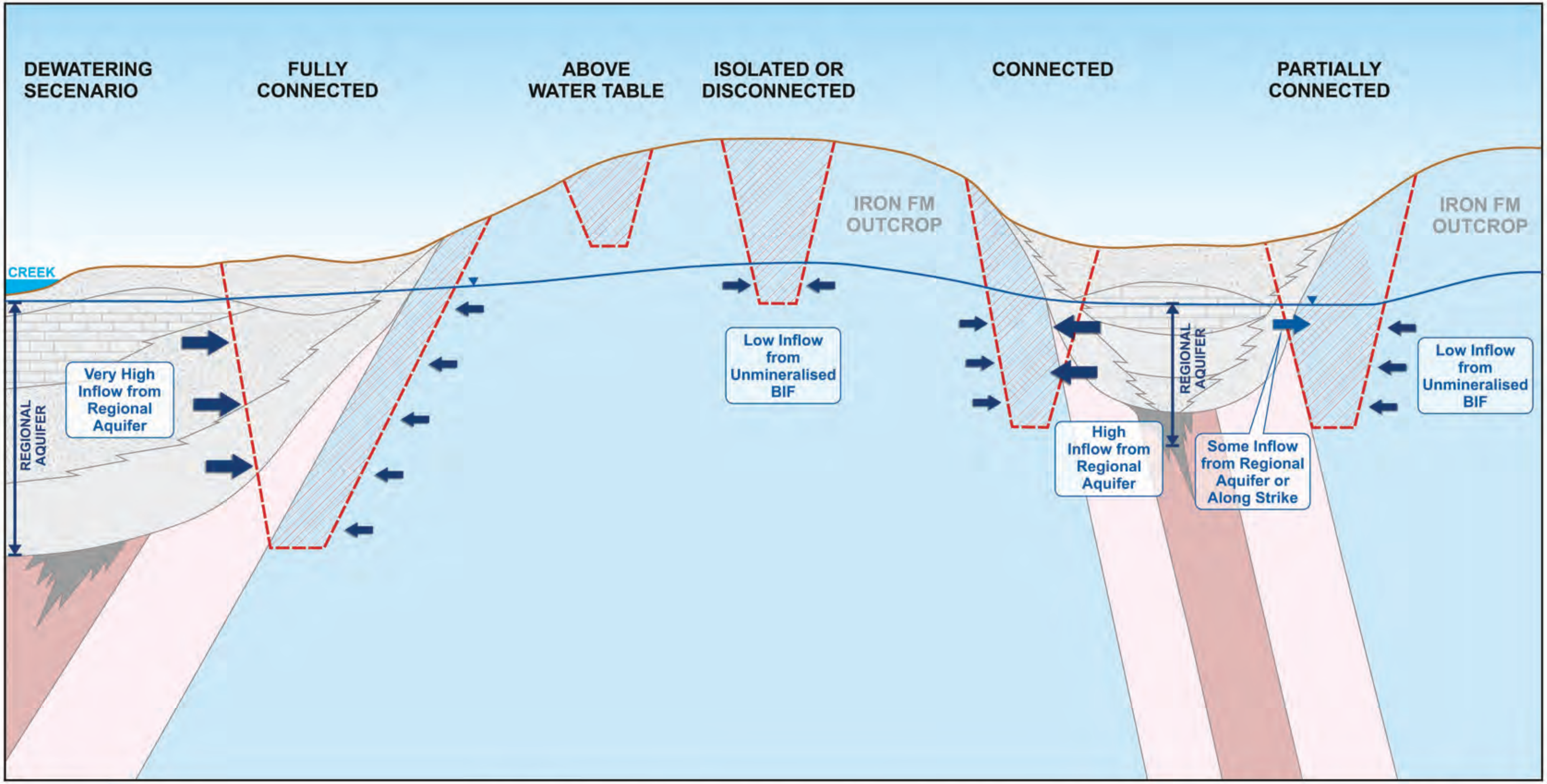
LEGEND

DATA SOURCES:
Input data source here

Location: F:\Jobs\1606B\Spatial_Data\MapInfo\Workspaces\129a\Ethel Gorge

RPS

FIGURE 4.15
ETHEL GORGE GROUNDWATER DEPENDENT ECOSYSTEM CONCEPTUAL ECOHYDROLOGICAL MODEL



Location: XXXX

NOT TO SCALE

AUTHOR: JP
DRAWN: RC
DATE: 29-3-2014
REPORT NO: 198
REVISION: b
JOB NO: 1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

Permability
- Low Permeability BIF
- Low Permeability Shale and BIF
- Variable Permeability Dolomite
- Moderate to High Permeability Ore

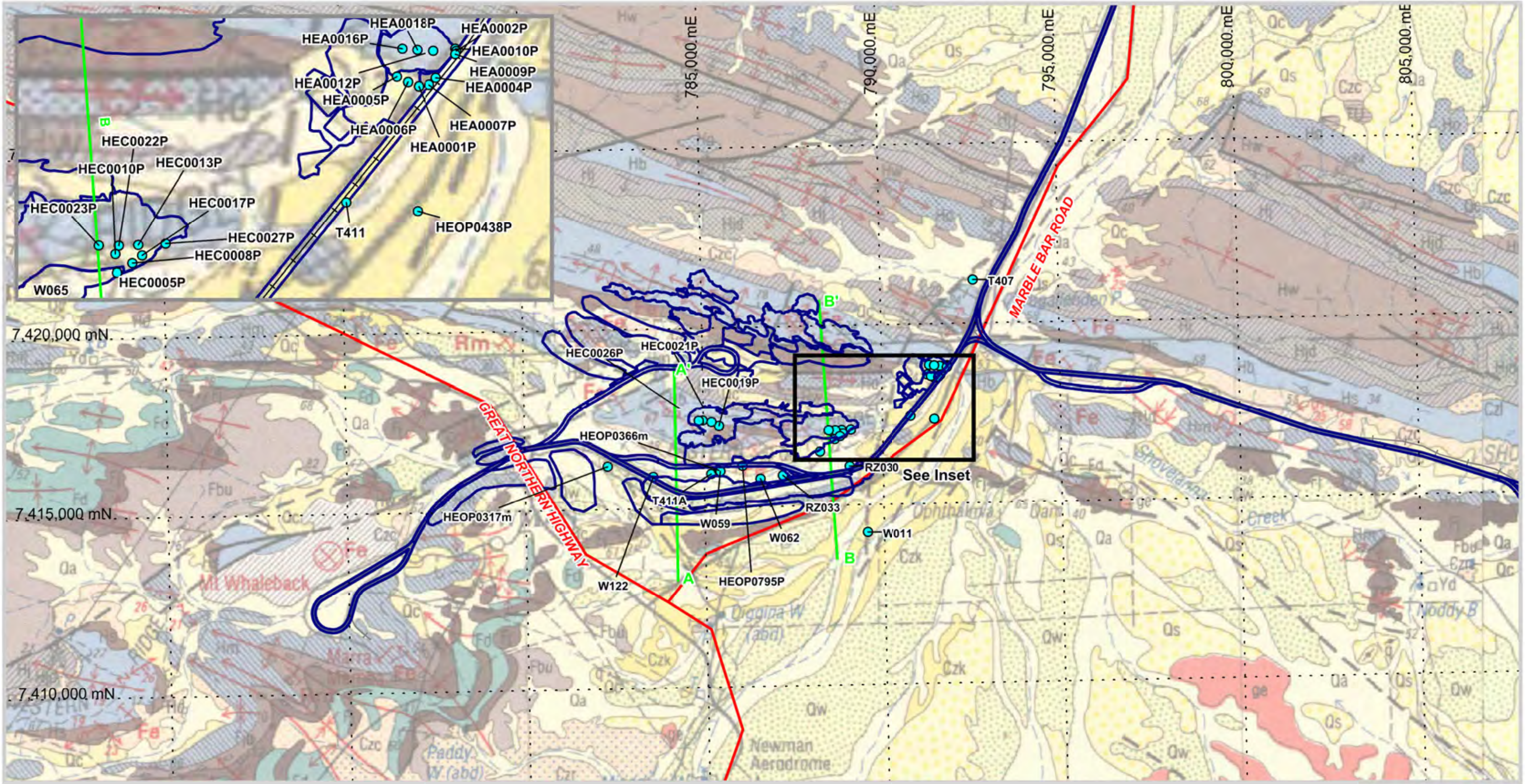
- Regional Water Table
- Potential Pit

Hydraulic Connection
- High
- Moderate
- Low

RPS

FIGURE 5.1

HYDROGEOLOGICAL SETTING AND DEWATERING SCENARIOS



N

0 2.5 5

Kilometres

Scale: 1:150,000 @A4

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	198
DRAWN:	MR	REVISION:	d
DATE:	02/09/2015	JOB NO:	1606B

F:\Jobs\1606I\Spatial_Data\Mapinfo\Workspaces\198a\198a Figure 5.2

LEGEND

- Bore
- Cross Section Lines
- Road
- Rail
- Indicative BHP Billiton Iron Ore Disturbance

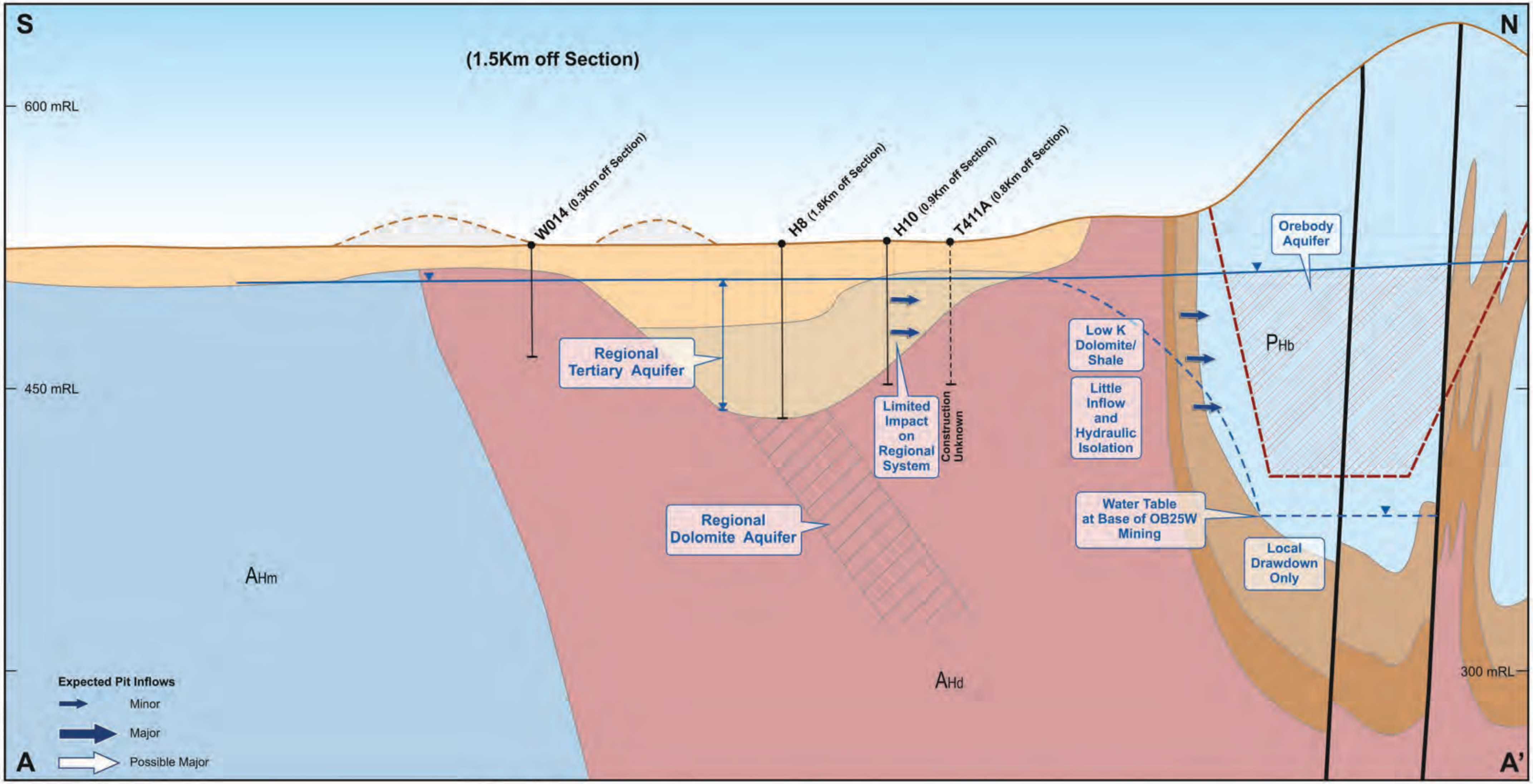
DATA SOURCES:
BHPB Iron Ore

RPS

Figure 5.2

LOCATION PLAN EASTERN RIDGE MINING AREA

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from this conceptual map."



0 500
Metres

AUTHOR: JP
DRAWN: RC
DATE: 31/08/2015
REPORT NO: 198
REVISION: d
JOB NO: 1606B

LEGEND

Quaternary: Undifferentiated; Clay; Alluvium; Calcrete

TD3: Undifferentiated; Clay; Gravel; Calcrete

TD2: Undifferentiated; Clay; CID; Calcrete

TD1

Boolgeeda Iron Fm: PHo

Woongarra Volcanics: PHw

Weeli Wolli Fm: PHu

Brockman Iron Fm: PHb

Mount McRae/Sylvia Fm: AHs Undifferentiated; Mount McRae Shale; Mount Sylvia Fm

Wittenoom Fm: AHd Undifferentiated; Bee Gorge Member; Paraburdoo Member; West Angela Member

Marra Mamba Iron Fm: AHm

Jeerinah Fm: AFj

Granitoid Complex: Ag

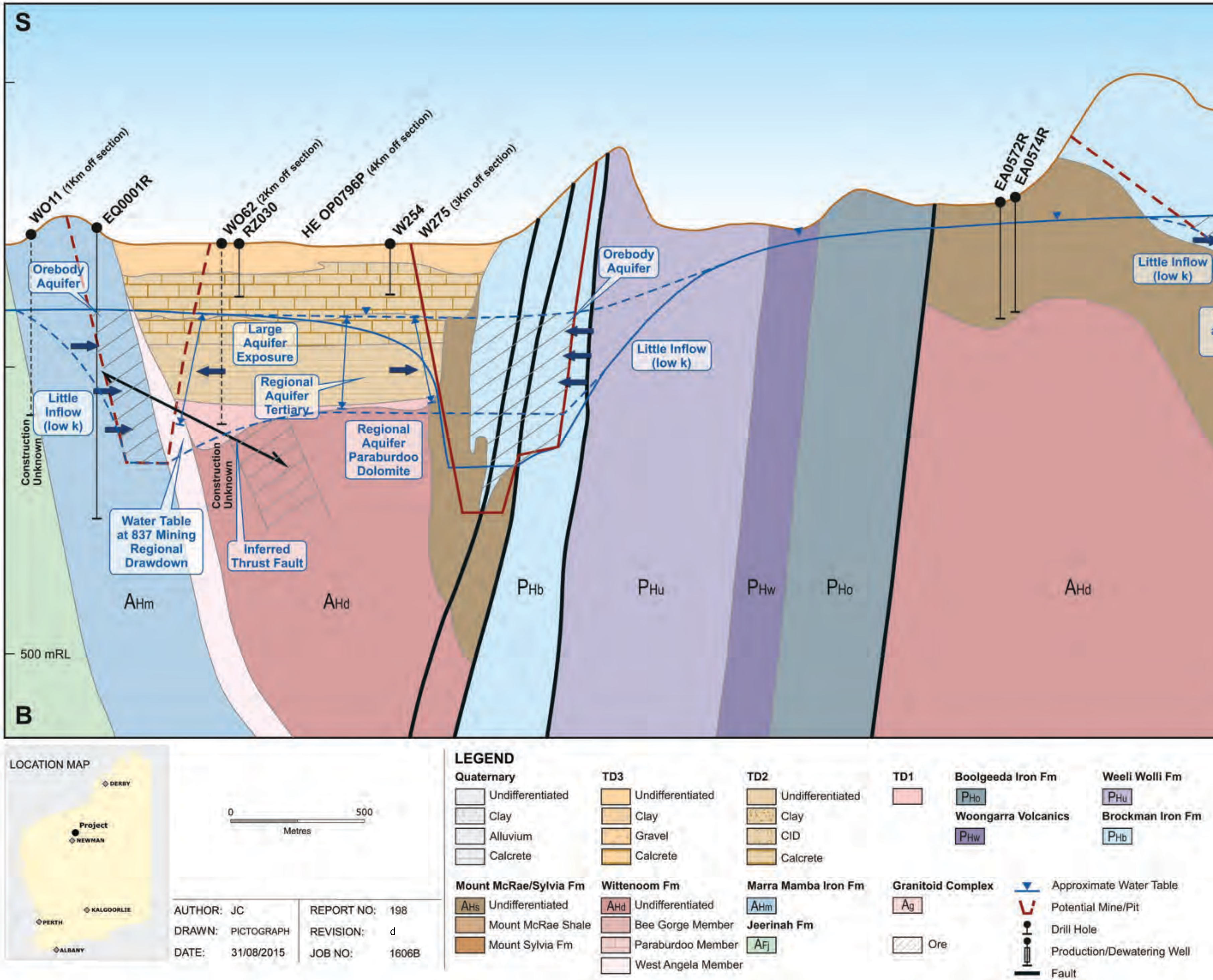
Ore

Approximate Water Table
Potential Mine/Pit
Drill Hole
Production/Dewatering Well
Fault

RPS

FIGURE 5.3a
INFLUENCE OF DEWATERING
SECTION A
EASTERN RIDGE

DATA SOURCES:
Input data source here



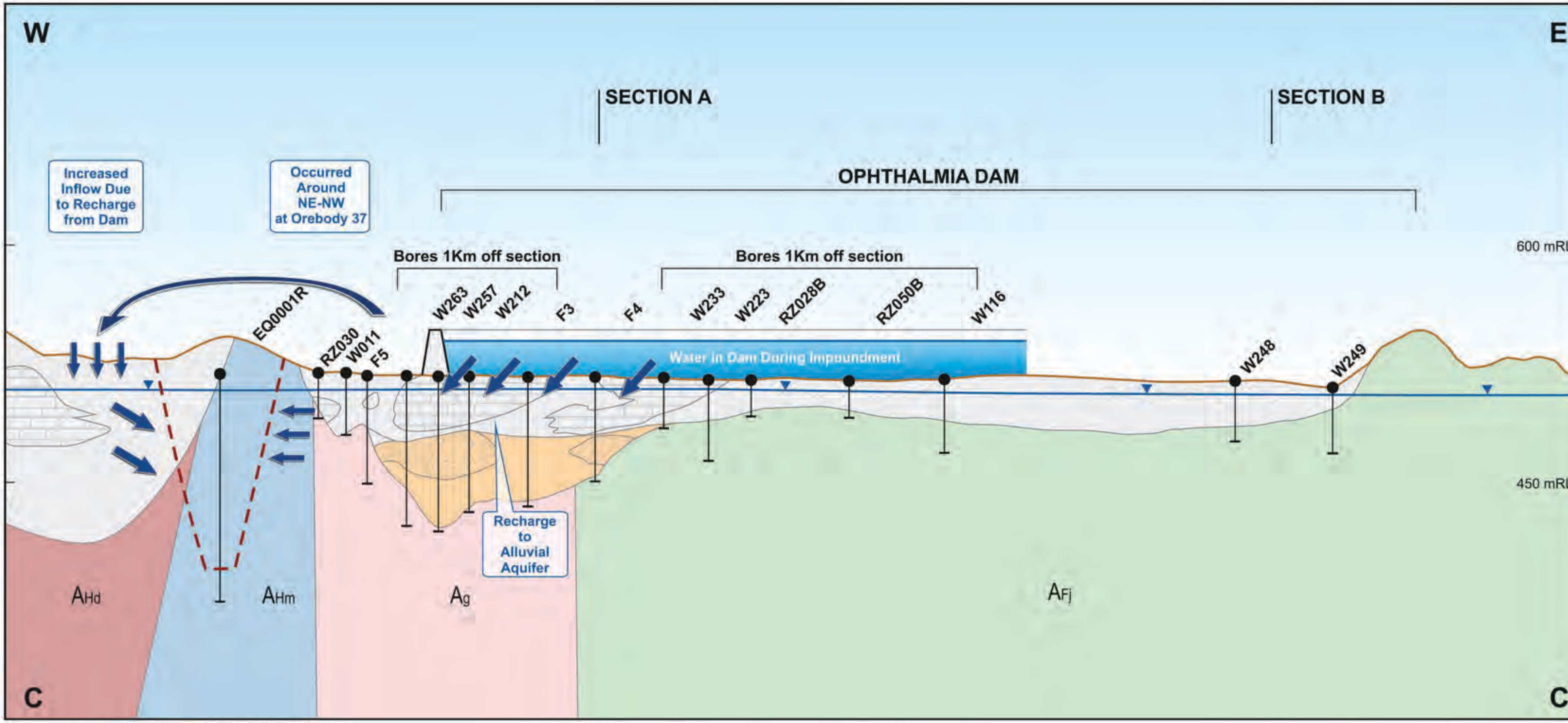
AUTHOR:	JC	REPORT NO:	198
DRAWN:	PICTOGRAPH	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

RPS

FIGURE 5.3b

SECTION B
INFLUENCE OF
DEWATERING
EASTERN RIDGE

DATA SOURCES:
Input data source here



Location: XXXX

0 500 1000
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHu

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

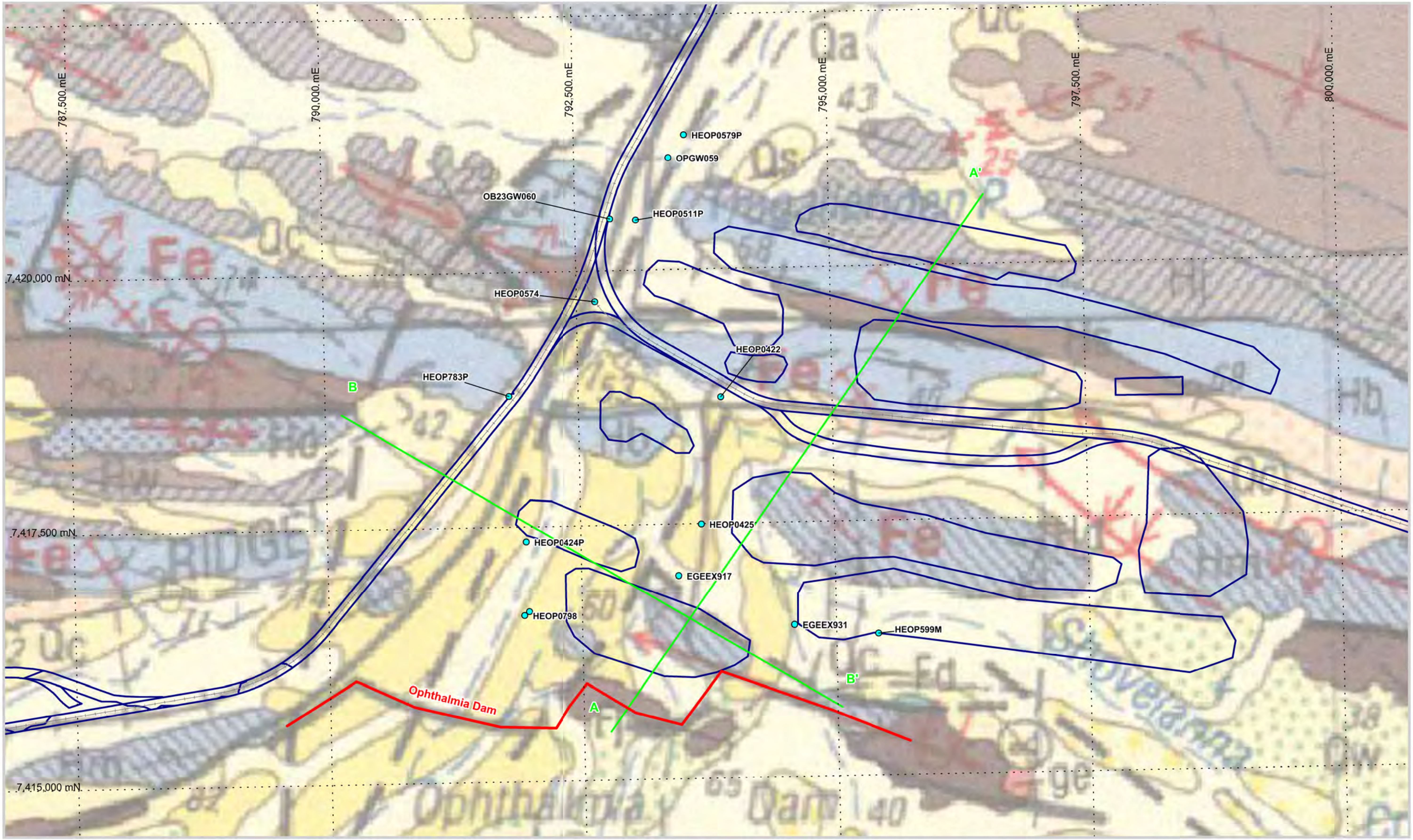
- Ore
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 5.3c

CONCEPTUAL HYDROGEOLOGY OREBODY 37 AND OPHTHALMIA DAM

DATA SOURCES:
Input data source here



N

0 500 1000

Metres

Scale: 1:35,000 @A3

GDA 1994 Zone 50

AUTHOR:	PR	REPORT NO:	198
DRAWN:	MR	REVISION:	d
DATE:	02/09/2015	JOB NO:	1606B

F:\Jobs\1606I\Spatial_Data\MapInfo\Workspaces\198a\198a Fig 5.4 location map.WOR

LEGEND

Key Bore

Section line

Indicative BHP Billiton Iron Ore Disturbance

Rail

DATA SOURCES:
Input data source here

RPS

FIGURE 5.4

LOCATION PLAN EAST
OPHTHALMIA MINING AREA

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from this conceptual map."

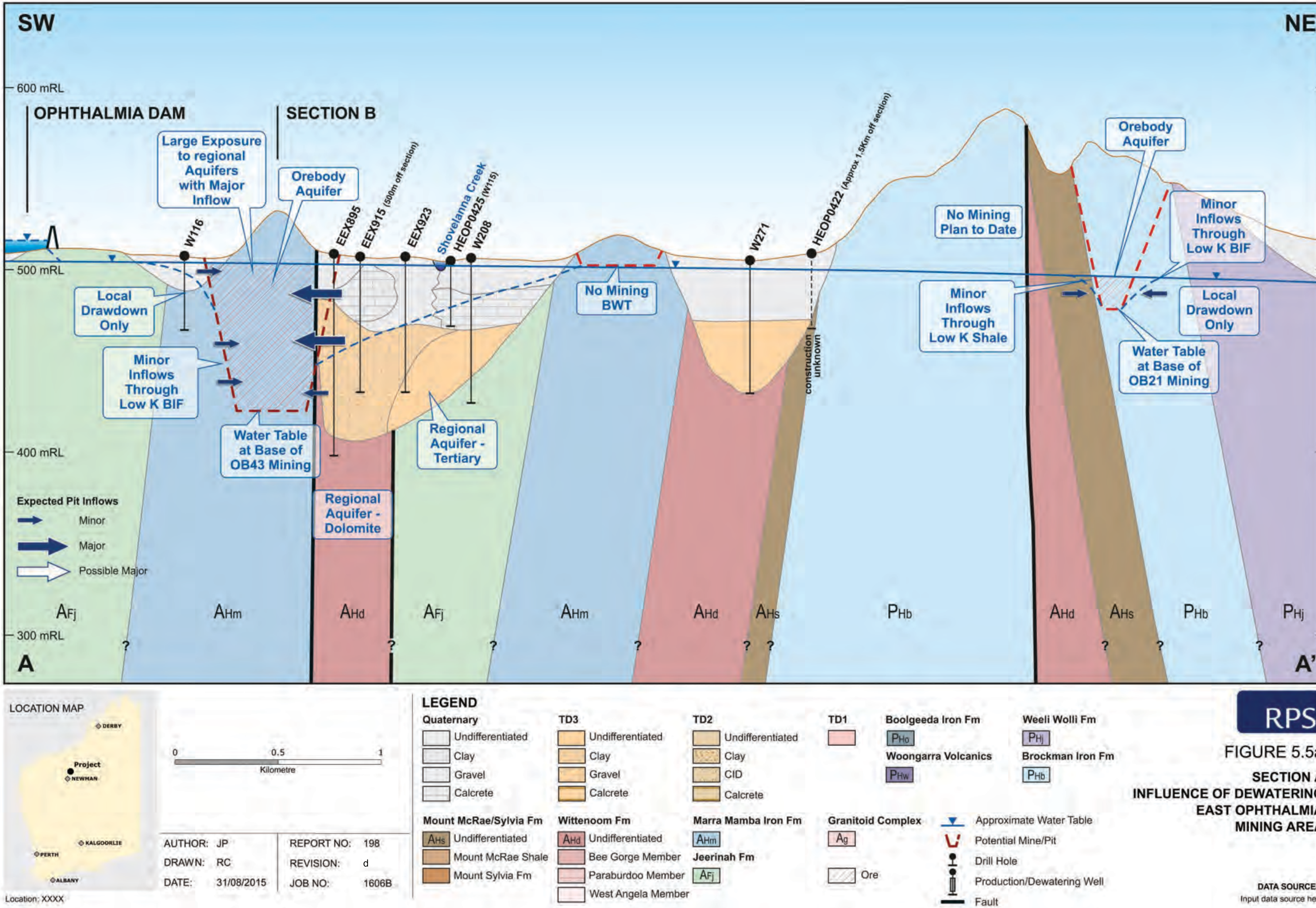
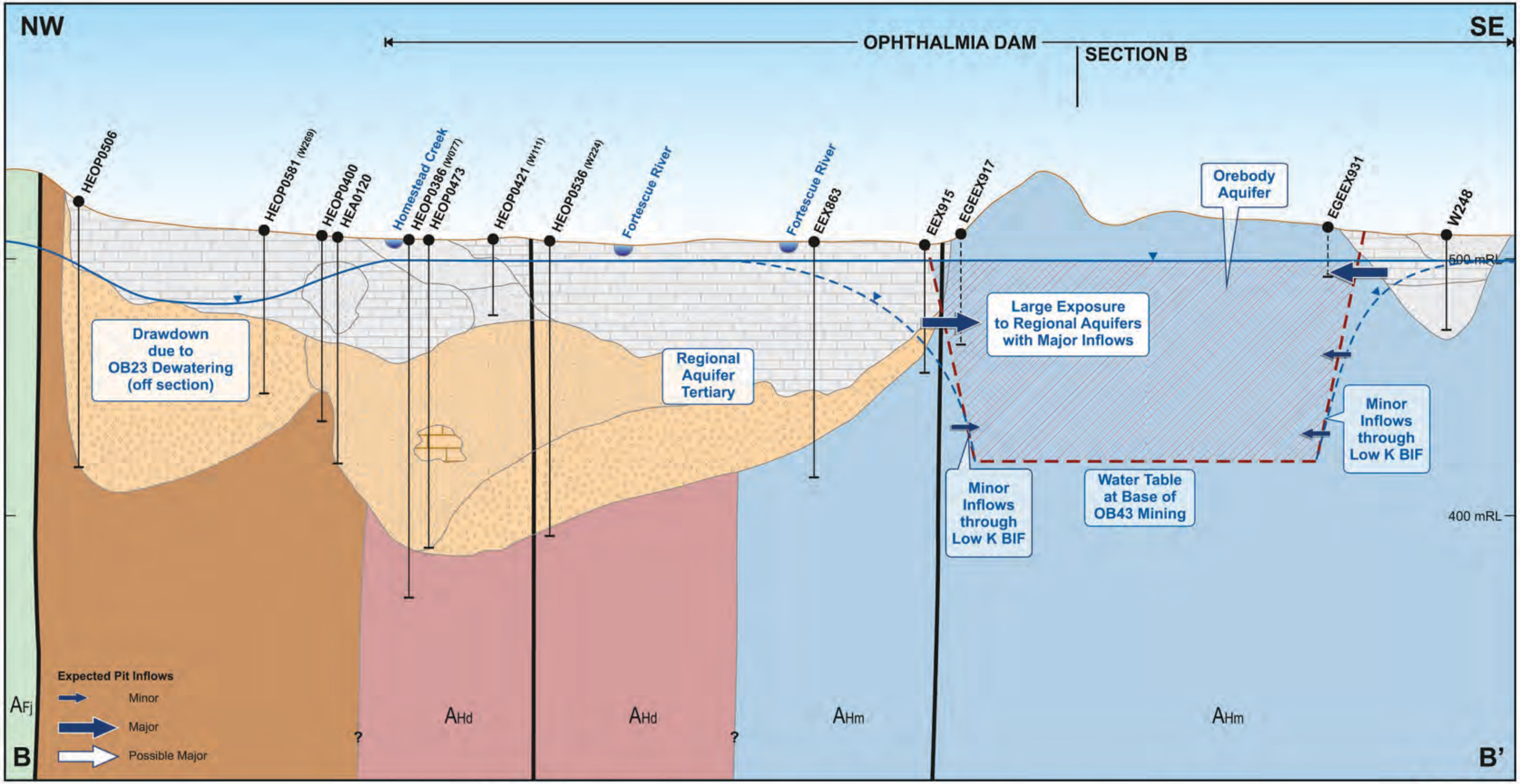


FIGURE 5.5a

SECTION A
INFLUENCE OF DEWATERING
EAST OPHTHALMIA
MINING AREA



Location: XXXX

0 500
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag
- Ore

- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 5.5b

SECTION B
INFLUENCE OF DEWATERING
EAST OPHTHALMIA
MINING AREA

DATA SOURCES:
Input data source here

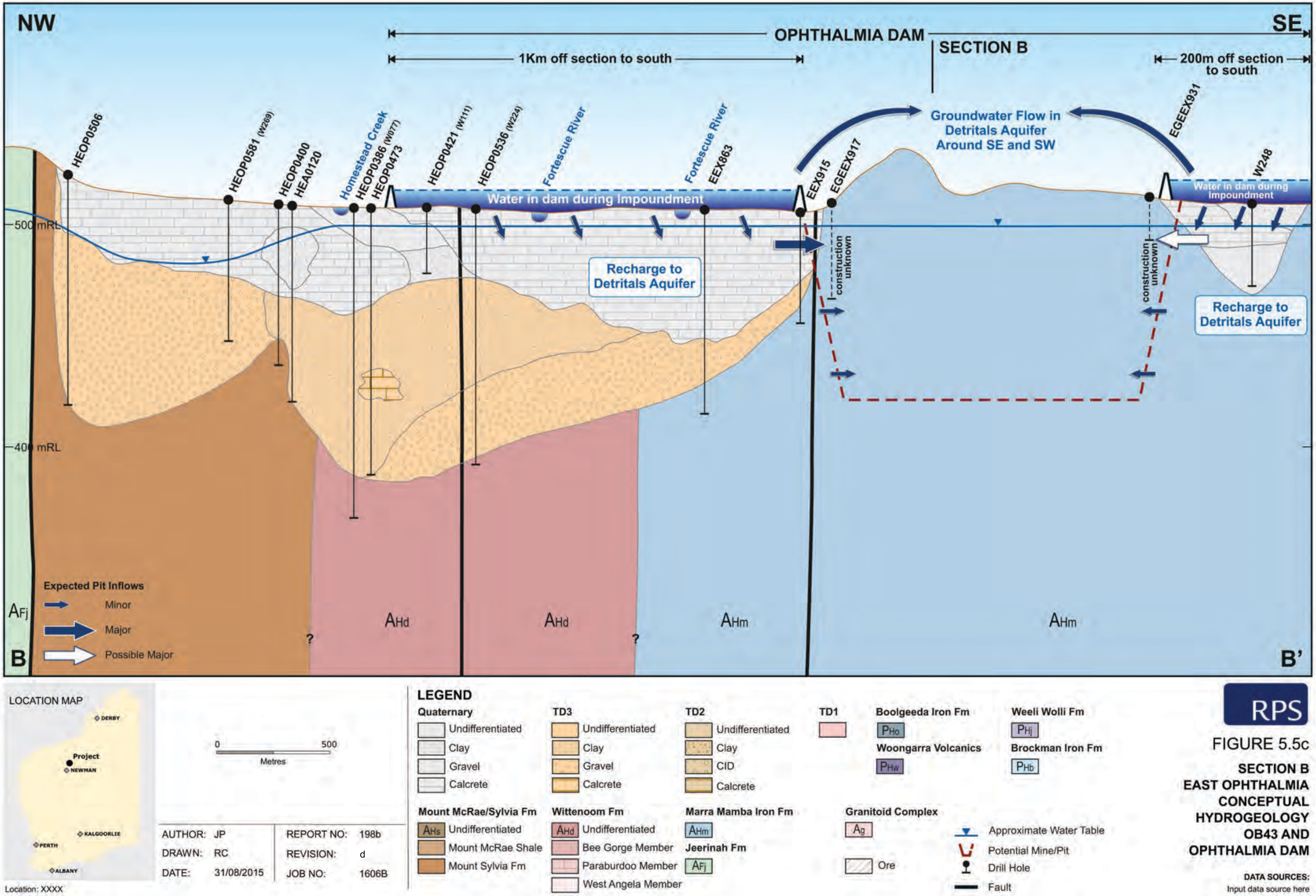
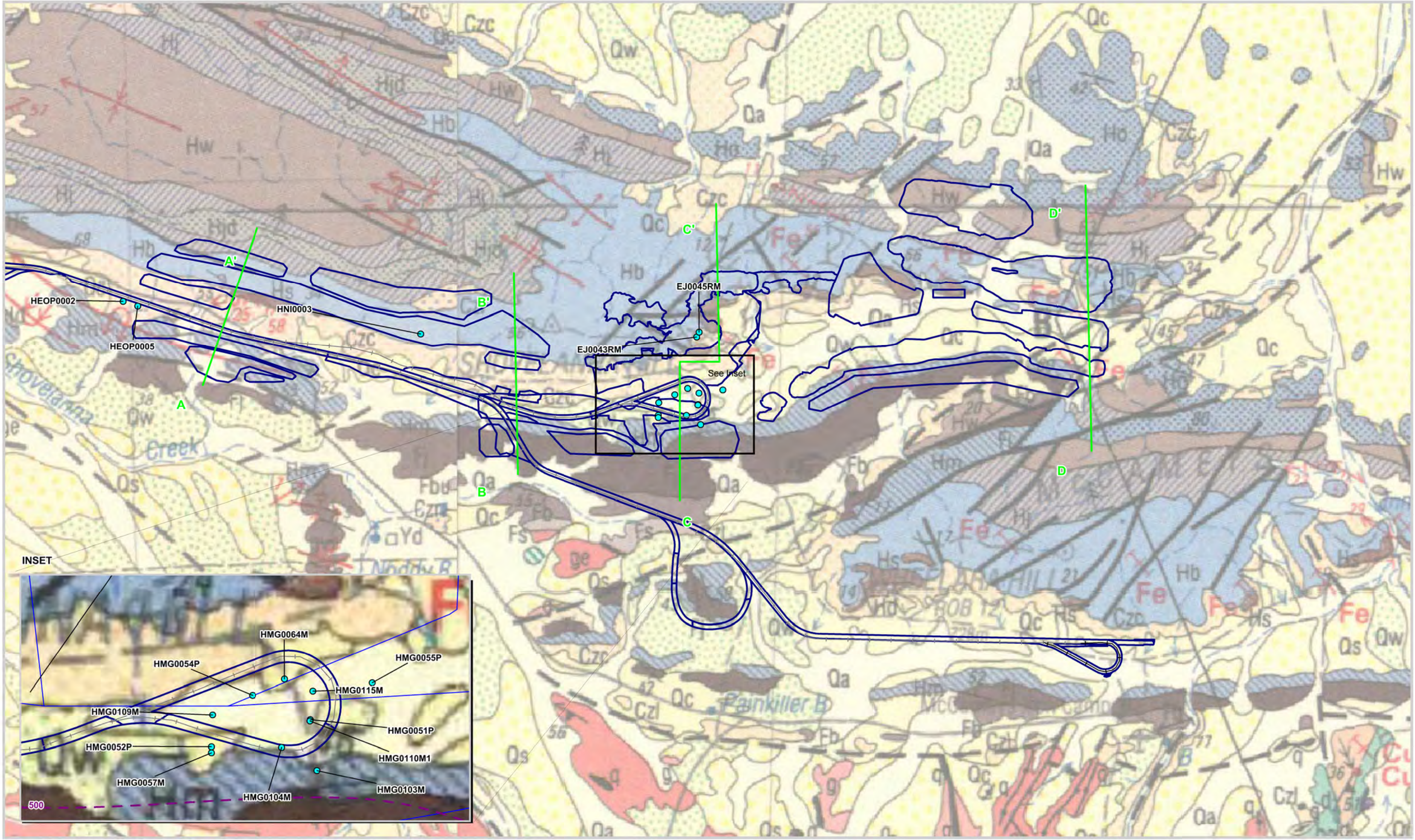


FIGURE 5.5c
SECTION B
EAST OPHTHALMIA
CONCEPTUAL
HYDROGEOLOGY
OB43 AND
OPHTHALMIA DAM



N

0 2.5

Kilometres

Scale: 1:75,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	198
DRAWN:	MR	REVISION:	d
DATE:	02/09/2015	JOB NO:	1606B

Location: F:\Jobs\1606\Spatial_Data\Mapinfo\Workspaces\198a\198a Figure 5.6 Location Plan

LEGEND

- Key Bore
- Cross Section Line
- Indicative BHP Billiton Iron Ore Disturbance
- Road
- Rail

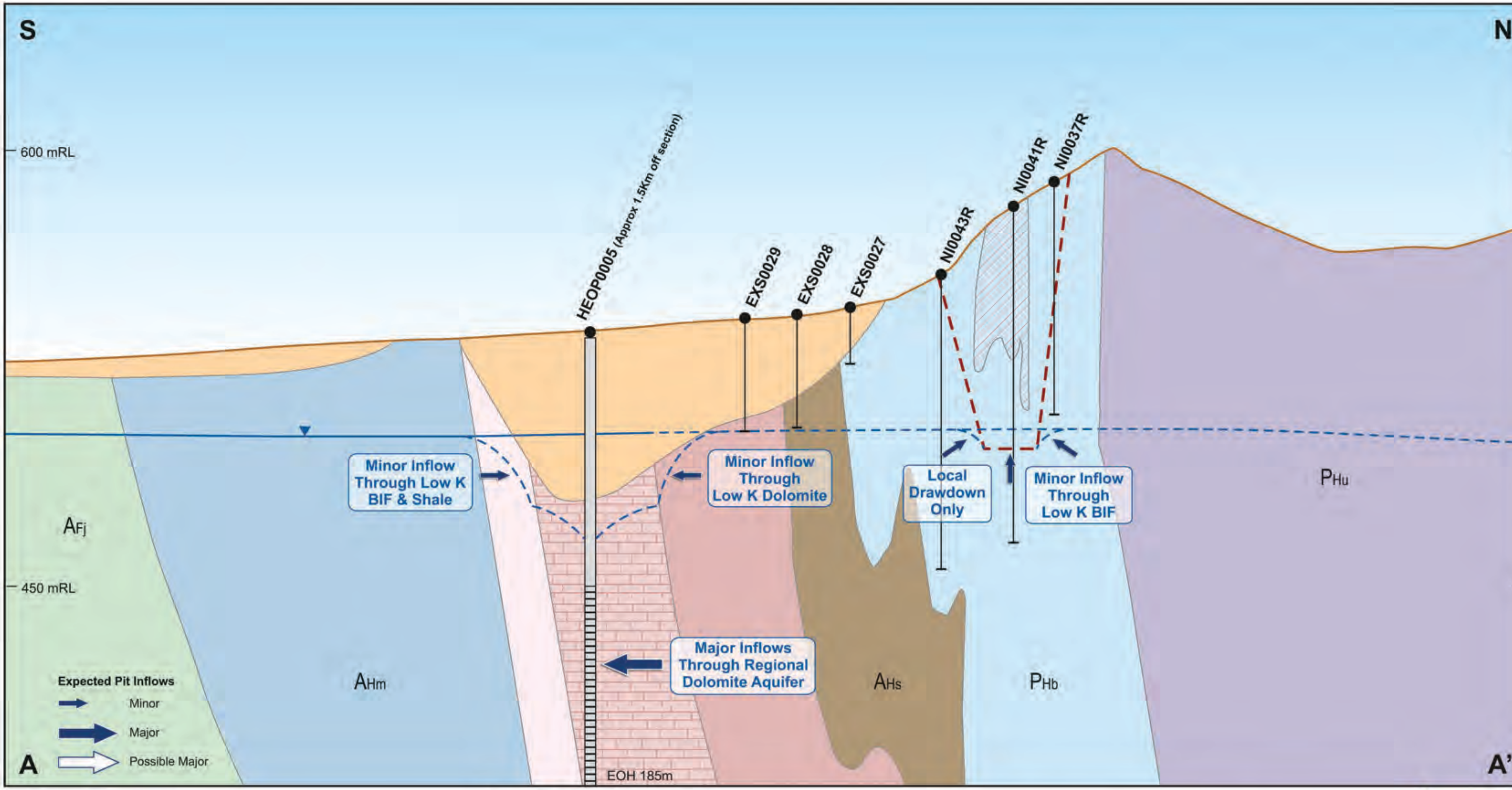
DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 5.6

LOCATION PLAN
SHOVELANNA MINING AREA

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from this conceptual map."



Location: XXXX

0 0.5
Kilometres

AUTHOR:	JP	REPORT NO:	198b
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHu

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag
- Ore

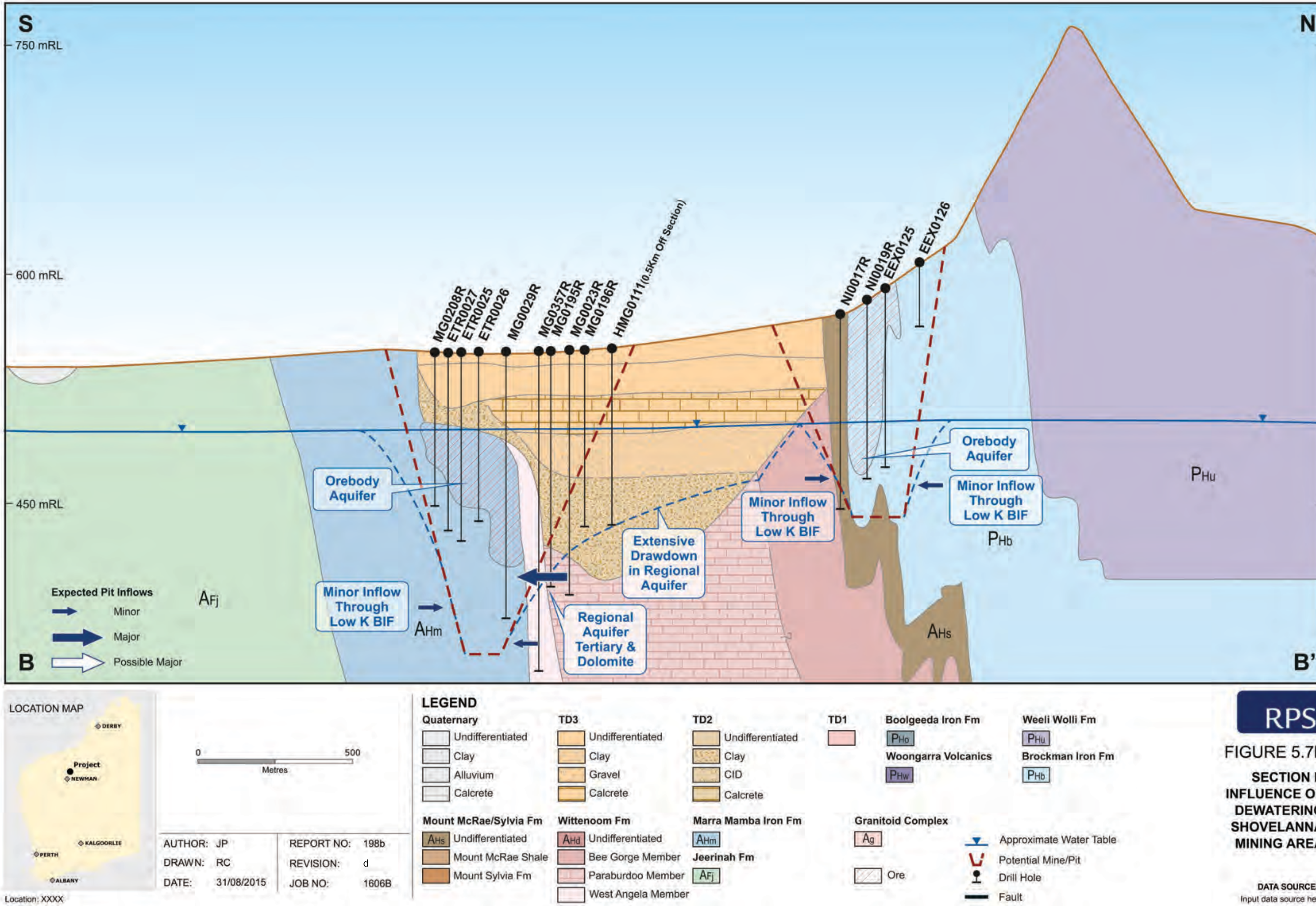
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

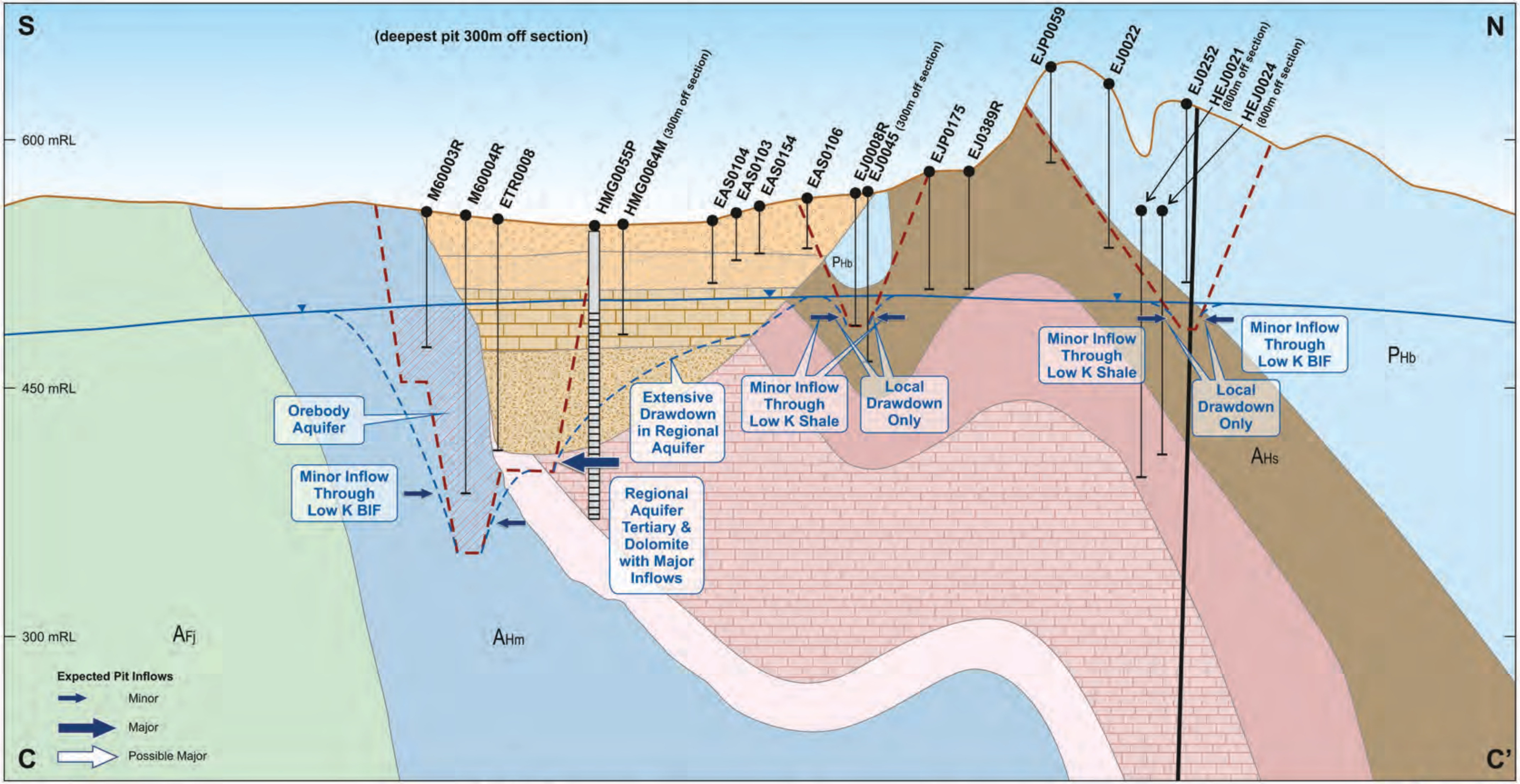
FIGURE 5.7a

SECTION A INFLUENCE OF DEWATERING SHOVELANNA MINING AREA

DATA SOURCES:
Input data source here



S
N
750 mRL
600 mRL
450 mRL
MG0208R
ETR0027
ETR0025
ETR0026
MG0029R
MG0357R
MG0195R
MG0023R
MG0196R
HMG0111(0.5Km Off Section)
NI0017R
NI0019R
EEX0125
EEX0126
Orebody Aquifer
Orebody Aquifer
Minor Inflow Through Low K BIF
Minor Inflow Through Low K BIF
Minor Inflow Through Low K BIF
Extensive Drawdown in Regional Aquifer
Regional Aquifer Tertiary & Dolomite
AFj
AHm
AHs
PHu
PHb
Expected Pit Inflows
Minor
Major
Possible Major
B
B'
LOCATION MAP
DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY
Location: XXXX
0
500
Metres
AUTHOR: JP
DRAWN: RC
DATE: 31/08/2015
REPORT NO: 198b
REVISION: d
JOB NO: 1606B
LEGEND
Quaternary
Undifferentiated
Clay
Alluvium
Calcrete
TD3
Undifferentiated
Clay
Gravel
Calcrete
TD2
Undifferentiated
Clay
CID
Calcrete
TD1
Boolgeeda Iron Fm
PHo
Woongarra Volcanics
PHw
Weeli Wolli Fm
PHu
Brockman Iron Fm
PHb
Mount McRae/Sylvia Fm
AHs Undifferentiated
Mount McRae Shale
Mount Sylvia Fm
Wittenoom Fm
AHd Undifferentiated
Bee Gorge Member
Paraburdoo Member
West Angela Member
Marra Mamba Iron Fm
AHm
Jeerinah Fm
AFj
Granitoid Complex
Ag
Ore
Approximate Water Table
Potential Mine/Pit
Drill Hole
Fault
RPS
FIGURE 5.7b
SECTION B
INFLUENCE OF DEWATERING
SHOVELANNA MINING AREA
DATA SOURCES:
Input data source here



Location: XXXX

0 500
Metres

AUTHOR:	JP	REPORT NO:	198b
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHu

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

- Ore

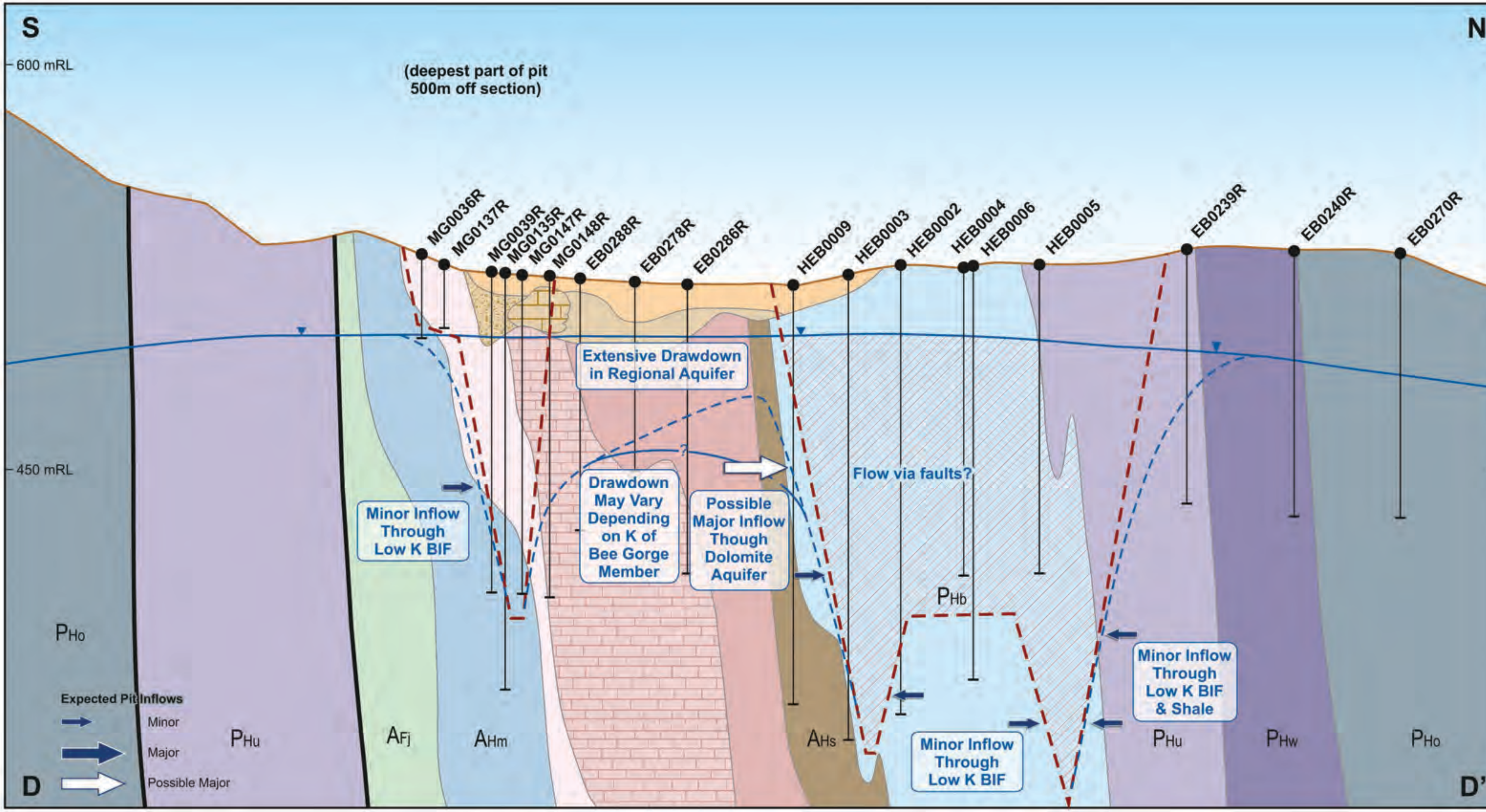
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Production/Dewatering Well
- Fault

RPS

FIGURE 5.7c

SECTION C
INFLUENCE OF
DEWATERING
SHOVELANNA
MINING AREA

DATA SOURCES:
Input data source here



Location: XXXX

0 500
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHu

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag
- Ore

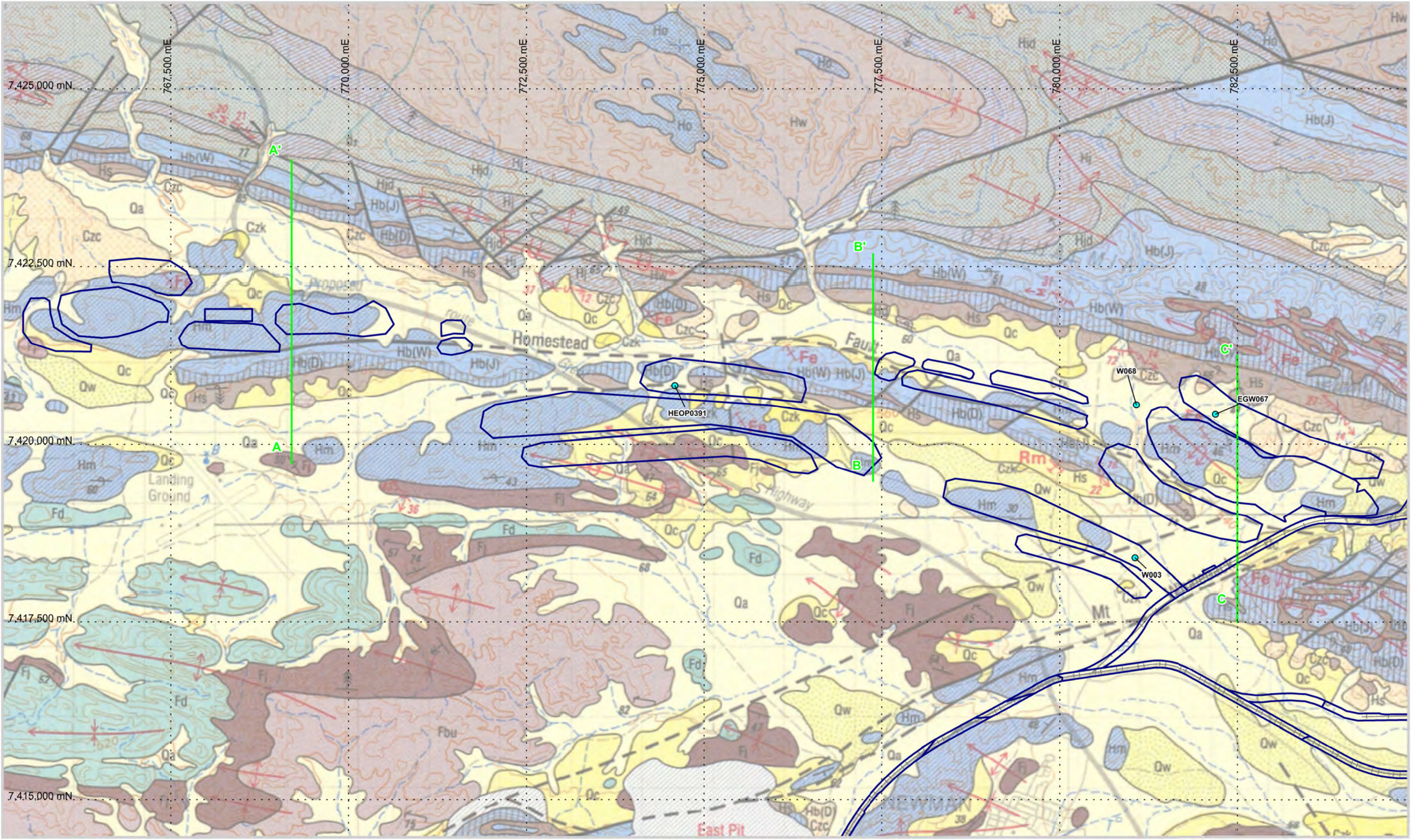
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 5.7d

**SECTION D
INFLUENCE OF
DEWATERING
SHOVELANNA
MINING AREA**

DATA SOURCES:
Input data source here



LOCATION MAP

DERBY
NEWMAN
Project
KALGOORLIE
PERTH
ALBANY

N

0 1 2

Kilometres

Scale: 1:50,000 @A3

GDA 1994 Zone 50

AUTHOR:	RS	REPORT NO:	198
DRAWN:	RS	REVISION:	d
DATE:	02/09/2015	JOB NO:	1606B

Location: F:\Jobs\1606\Spatial_Data\MapInfo\Workspaces\198a\198a Fig 5.8 location map

LEGEND

- Key Bore
- Section line
- Railway
- Indicative BHP Billiton Iron Ore Disturbance

DATA SOURCES:
BHPBIO

RPS

FIGURE 5.8

LOCATION PLAN
HOMESTEAD MINING AREA

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
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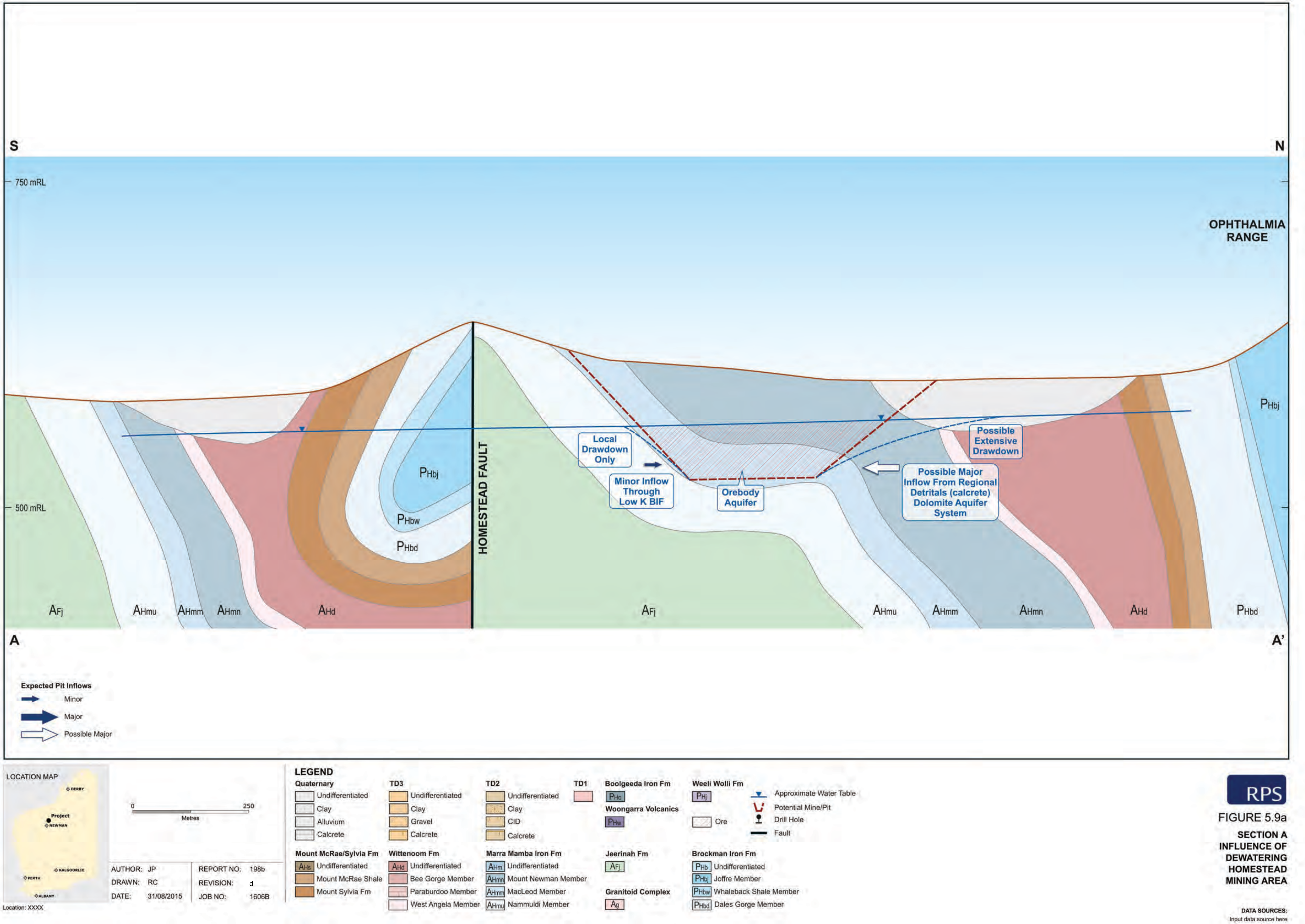

S
N
750 mRL
500 mRL
OPHTHALMIA RANGE
PHbj
PHbw
PHbd
HOMESTEAD FAULT
Local Drawdown Only
Minor Inflow Through Low K BIF
Orebody Aquifer
Possible Extensive Drawdown
Possible Major Inflow From Regional Detritals (calcrete) Dolomite Aquifer System
AFj
AHmu
AHmm
AHmn
AHd
AFj
AHmu
AHmm
AHmn
AHd
PHbd
A
A'
Expected Pit Inflows
Minor
Major
Possible Major
LOCATION MAP
DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY
Location: XXXX
0
250
Metres
AUTHOR: JP
DRAWN: RC
DATE: 31/08/2015
REPORT NO: 198b
REVISION: d
JOB NO: 1606B
LEGEND
Quaternary
Undifferentiated
Clay
Alluvium
Calcrete
TD3
Undifferentiated
Clay
Gravel
Calcrete
TD2
Undifferentiated
Clay
CID
Calcrete
TD1
Boolgeeda Iron Fm
PHo
Woongarra Volcanics
PHw
Weeli Wolli Fm
PHj
Ore
Approximate Water Table
Potential Mine/Pit
Drill Hole
Fault
Mount McRae/Sylvia Fm
AHs Undifferentiated
Mount McRae Shale
Mount Sylvia Fm
Wittenoom Fm
AHd Undifferentiated
Bee Gorge Member
Paraburdoo Member
West Angela Member
Marra Mamba Iron Fm
AHm Undifferentiated
AHmn Mount Newman Member
AHmm MacLeod Member
AHmu Nammuldi Member
Jeerinah Fm
AFj
Granitoid Complex
Ag
Brockman Iron Fm
PHb Undifferentiated
PHbj Joffre Member
PHbw Whaleback Shale Member
PHbd Dales Gorge Member
RPS
FIGURE 5.9a
SECTION A
INFLUENCE OF DEWATERING
HOMESTEAD MINING AREA
DATA SOURCES:
Input data source here

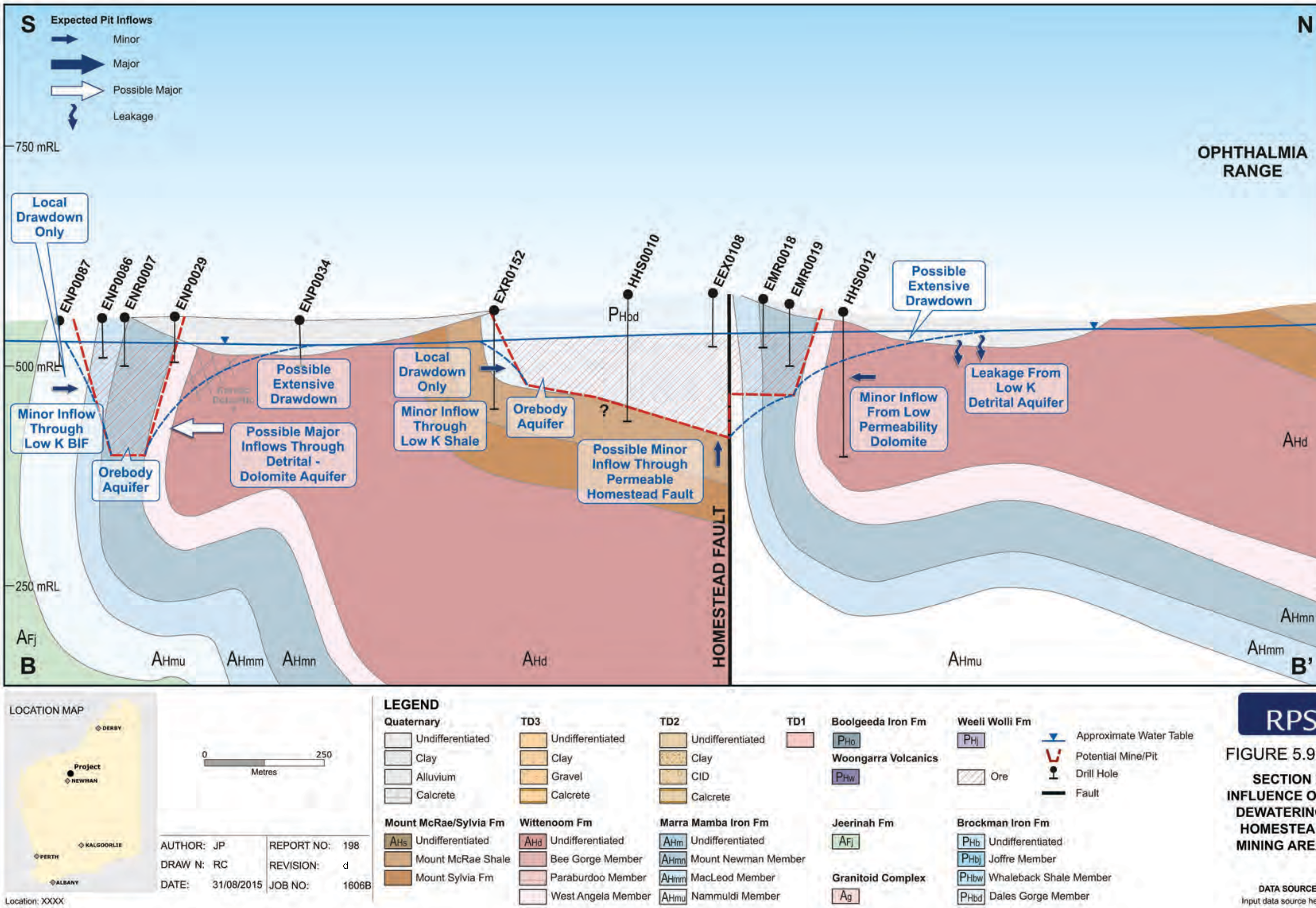
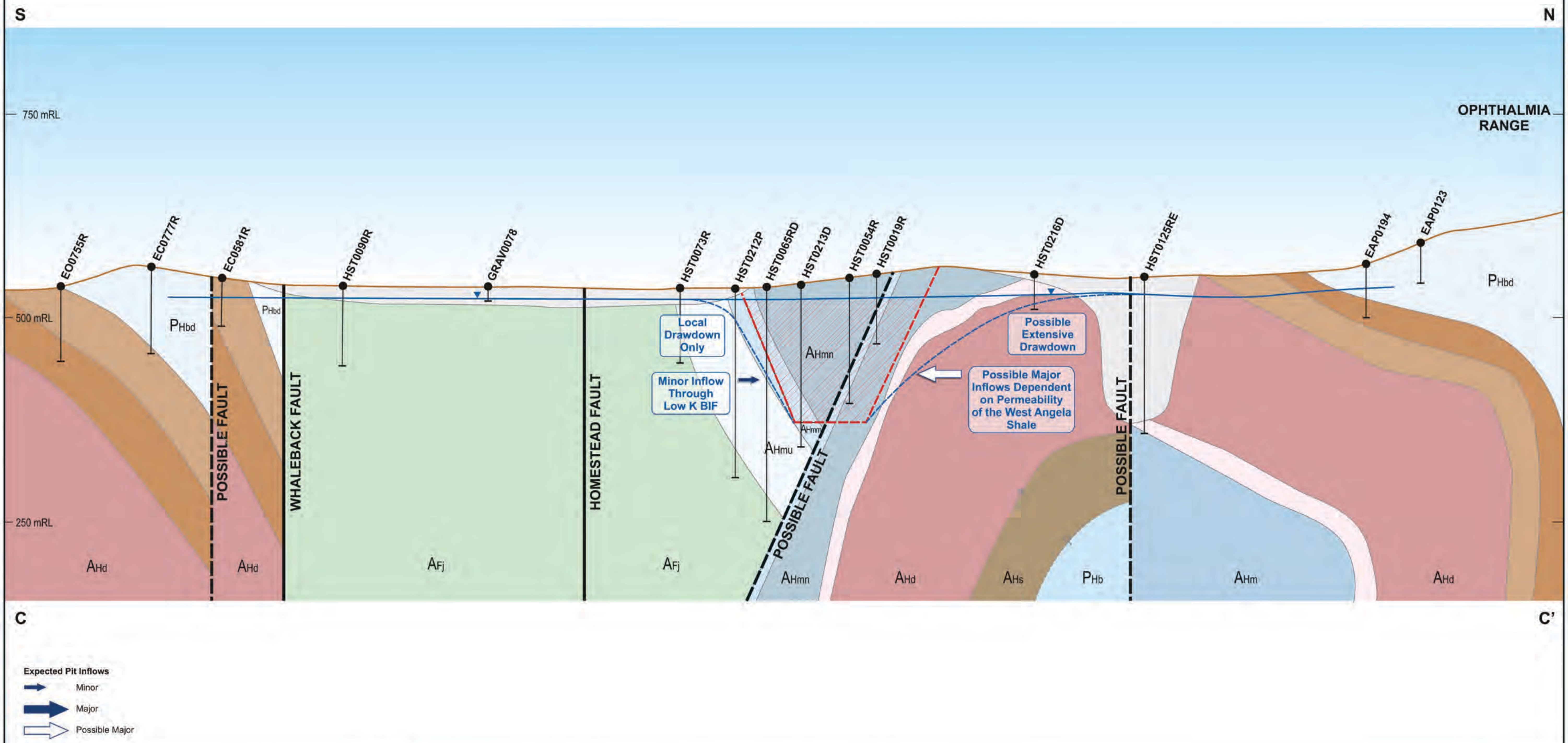


FIGURE 5.9b
SECTION B INFLUENCE OF DEWATERING HOMESTEAD MINING AREA



LOCATION MAP

DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY

Location: XXXX

0 500
Metres

AUTHOR: JP
DRAWN: RC
DATE: 31/08/2015
REPORT NO: 198
REVISION: d
JOB NO: 1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj
- Ore

- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm Undifferentiated
- AHmn Mount Newman Member
- AHmm MacLeod Member
- AHmu Nammuldi Member

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

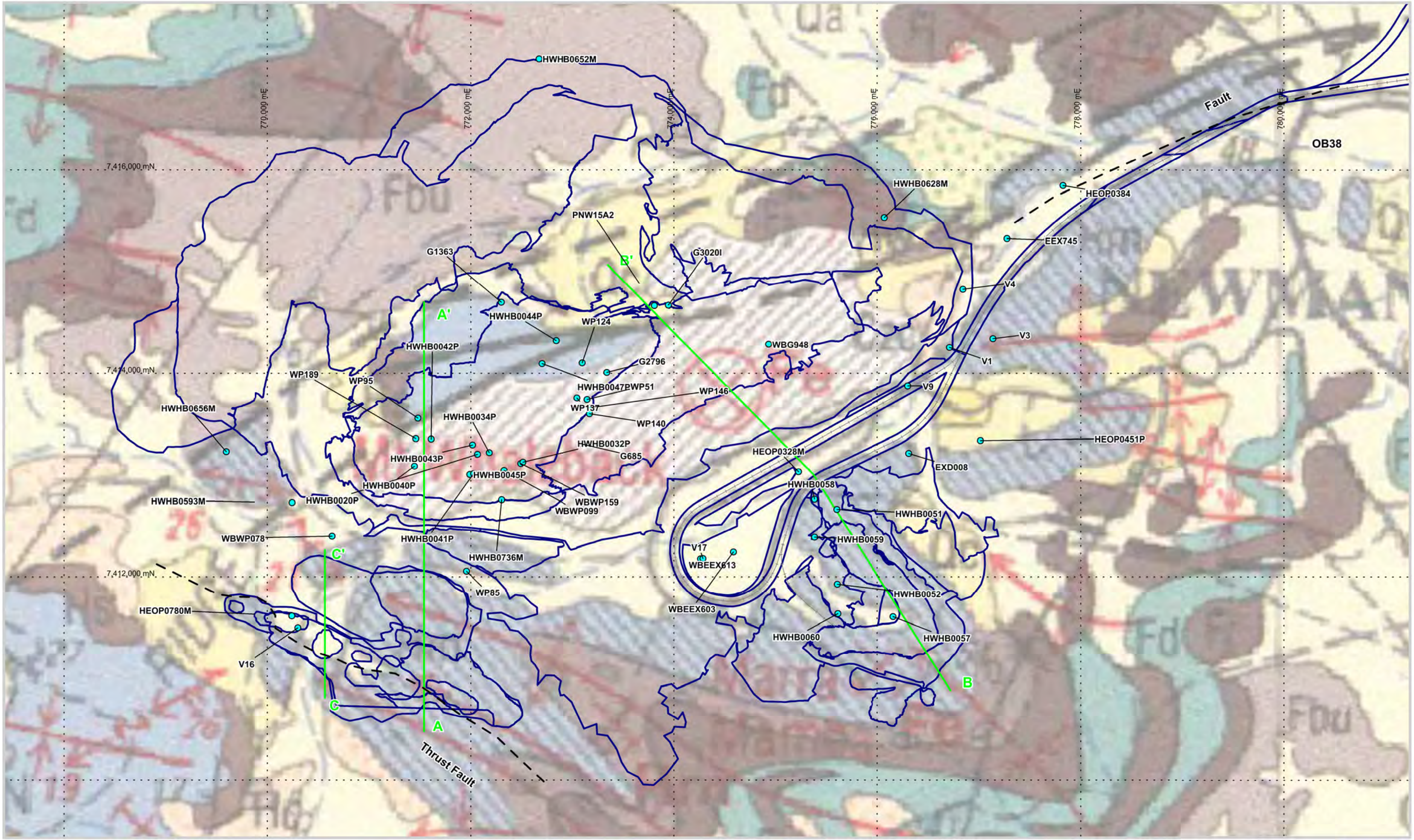
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.9c

SECTION C INFLUENCE OF DEWATERING HOMESTEAD MINING AREA

DATA SOURCES:
Input data source here



LOCATION MAP

N

0 1

Kilometres

Scale: 1:35,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	198
DRAWN:	MR	REVISION:	d
DATE:	02/09/2015	JOB NO:	1606B

Location: F:\Jobs\1606\Spatial_Data\MapInfo\Workspaces\198a\198a Fig 5.10 Location Map

LEGEND

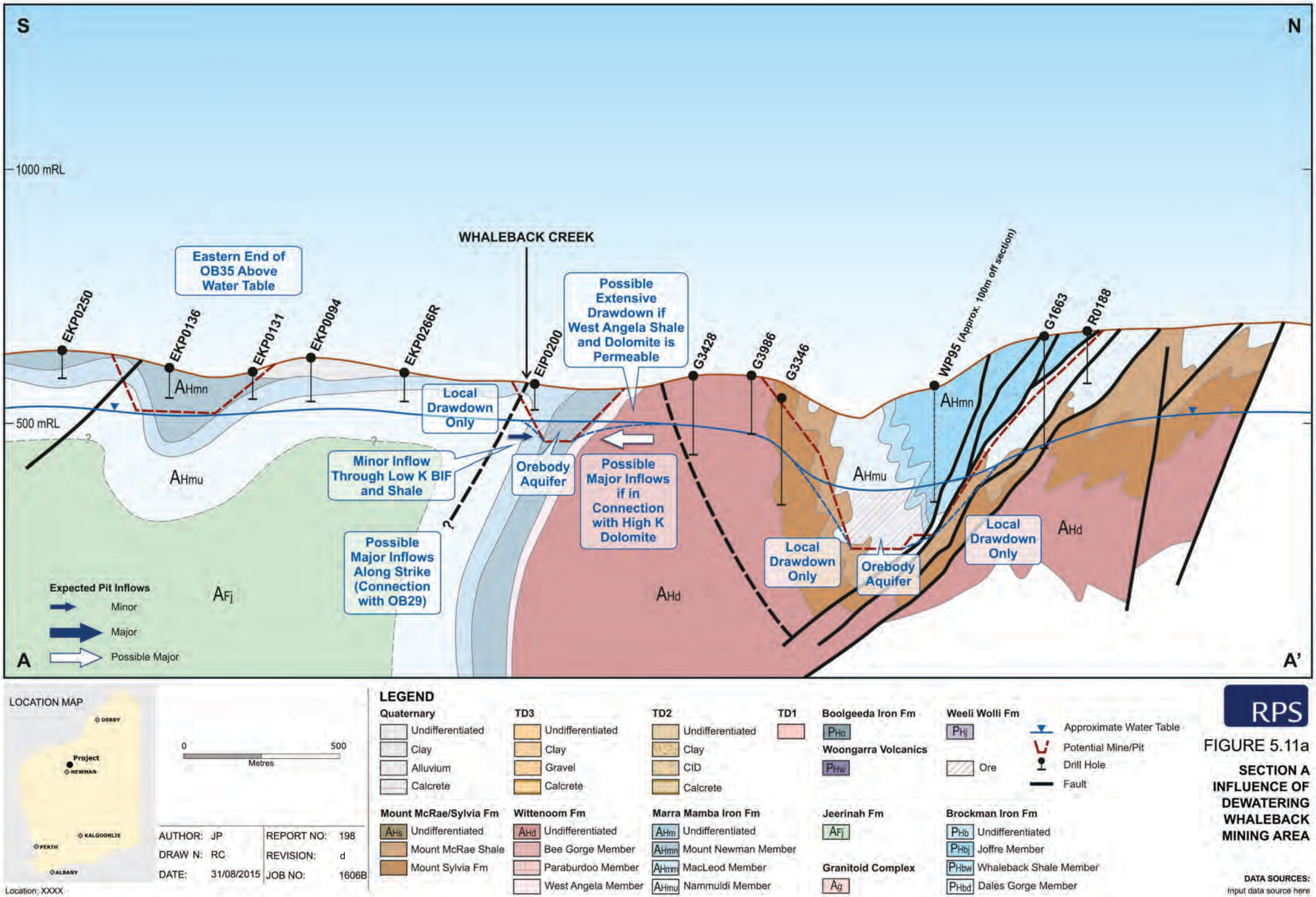
- Key Bore
- Section Line
- Fault
- Indicative BHP Billiton Iron Ore Disturbance
- Rail

DATA SOURCES:
Input data source here

RPS

FIGURE 5.10

LOCATION PLAN
WHALEBACK MINING AREA


S
N
1000 mRL
500 mRL
WHALEBACK CREEK
Eastern End of OB35 Above Water Table
Possible Extensive Drawdown if West Angela Shale and Dolomite is Permeable
EKP0250
EKP0136
EKP0131
EKP0094
EKP0266R
EIP0200
G3428
G3986
G3346
WP95 (Approx. 100m off section)
G1663
R0188
AHmn
AHmu
AHd
AFj
Local Drawdown Only
Minor Inflow Through Low K BIF and Shale
Orebody Aquifer
Possible Major Inflows if in Connection with High K Dolomite
Possible Major Inflows Along Strike (Connection with OB29)
Expected Pit Inflows
Minor
Major
Possible Major
A
A'
LOCATION MAP
DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY
Location: XXXX
0
500
Metres
AUTHOR: JP
DRAW N: RC
DATE: 31/08/2015
REPORT NO: 198
REVISION: d
JOB NO: 1606B
LEGEND
Quaternary
Undifferentiated
Clay
Alluvium
Calcrete
TD3
Undifferentiated
Clay
Gravel
Calcrete
TD2
Undifferentiated
Clay
CID
Calcrete
TD1
Boolgeeda Iron Fm
PHo
Woongarra Volcanics
PHw
Weeli Wolli Fm
PHj
Ore
Approximate Water Table
Potential Mine/Pit
Drill Hole
Fault
Mount McRae/Sylvia Fm
AHs Undifferentiated
Mount McRae Shale
Mount Sylvia Fm
Wittenoom Fm
AHd Undifferentiated
Bee Gorge Member
Paraburdoo Member
West Angela Member
Marra Mamba Iron Fm
AHm Undifferentiated
AHmn Mount Newman Member
AHmm MacLeod Member
AHmu Nammuldi Member
Jeerinah Fm
AFj
Granitoid Complex
Ag
Brockman Iron Fm
PHb Undifferentiated
PHbj Joffre Member
PHbw Whaleback Shale Member
PHbd Dales Gorge Member
RPS
FIGURE 5.11a
SECTION A
INFLUENCE OF DEWATERING
WHALEBACK MINING AREA
DATA SOURCES:
Input data source here

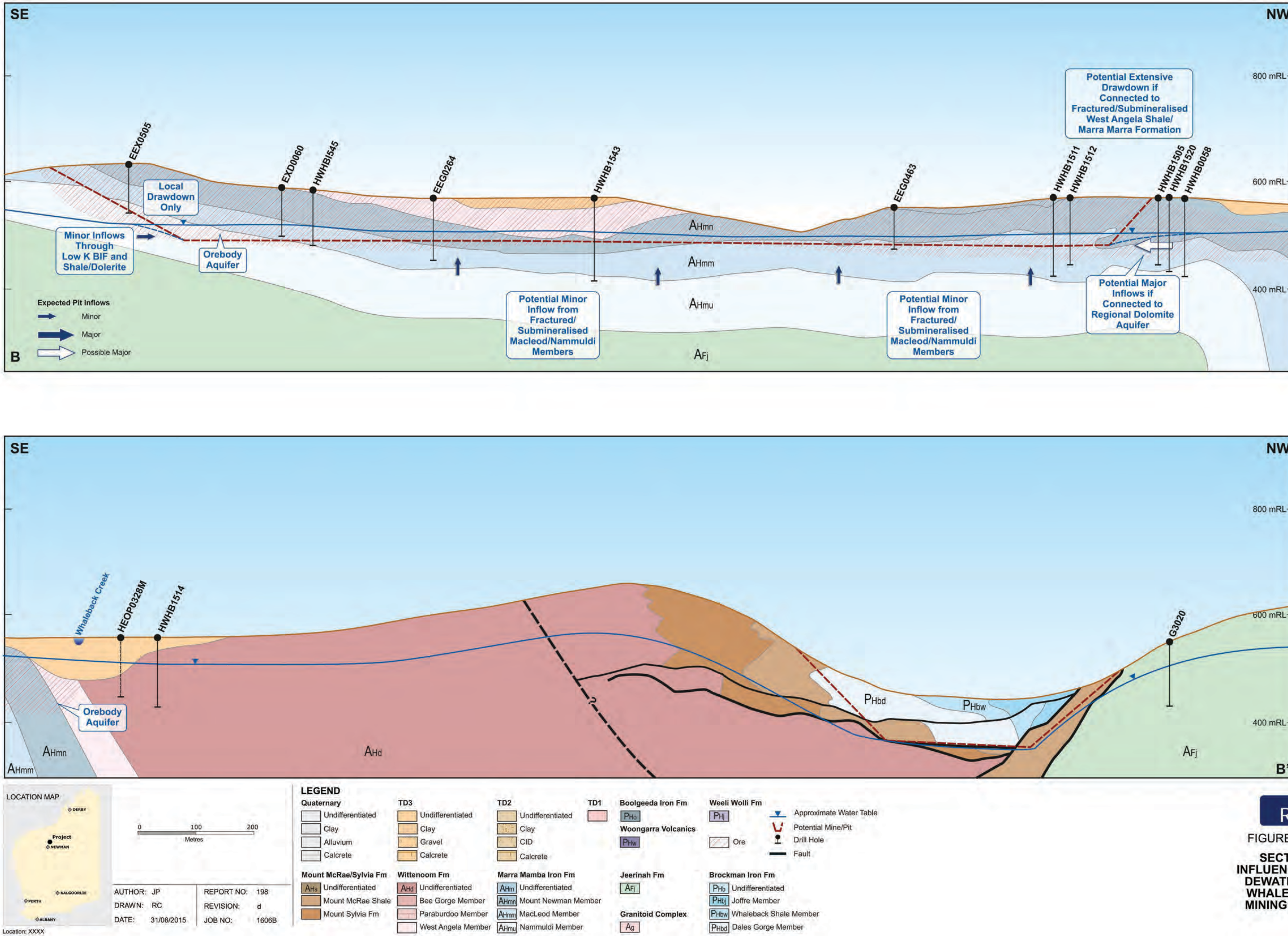
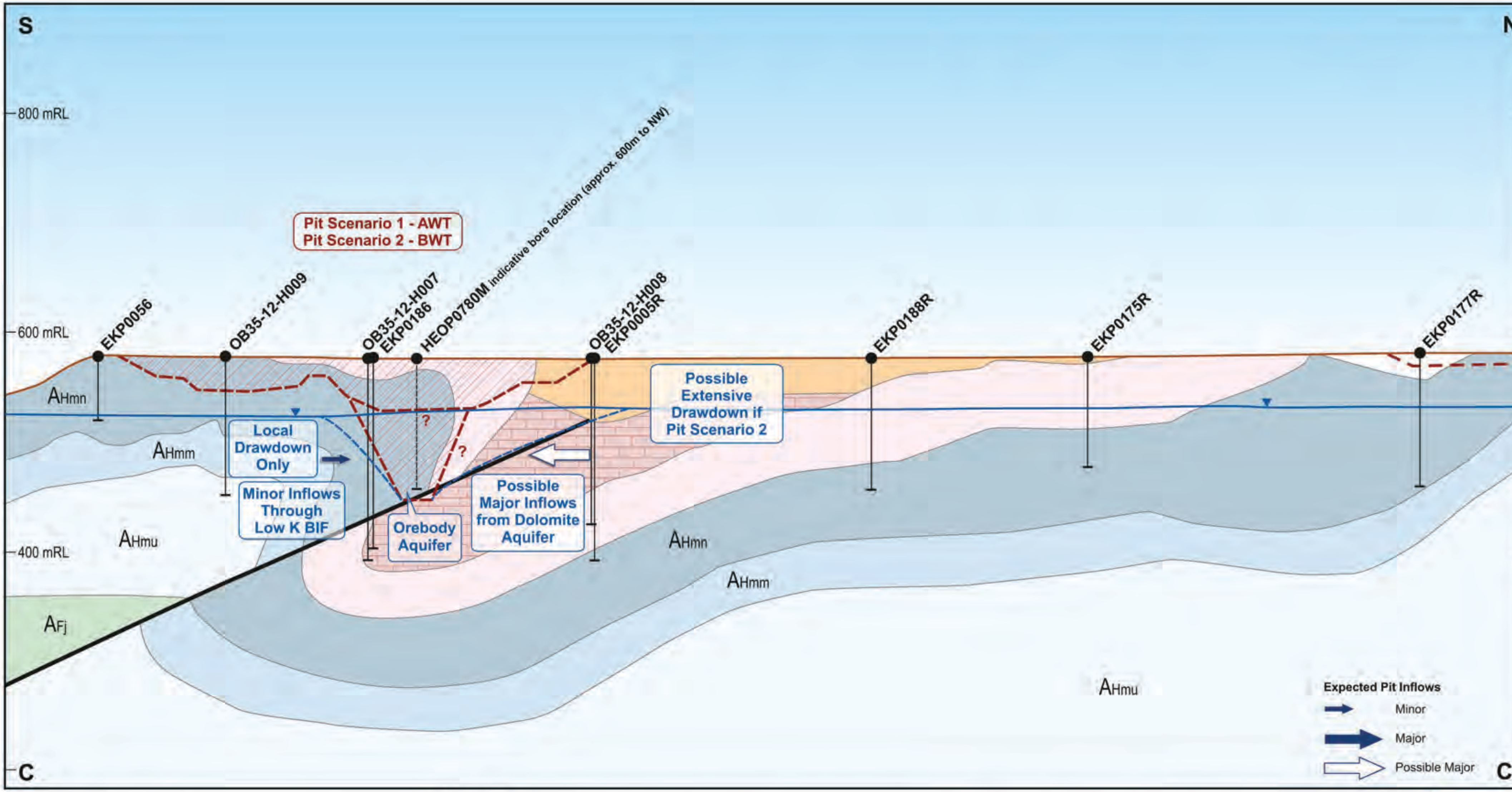


FIGURE 5.11b

SECTION B INFLUENCE OF DEWATERING WHALEBACK MINING AREA



LOCATION MAP

Location: XXXX

0 1
Kilometre

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606b

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj
- Ore

- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm Undifferentiated
- AHmn Mount Newman Member
- AHmm MacLeod Member
- AHmu Nammuldi Member

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

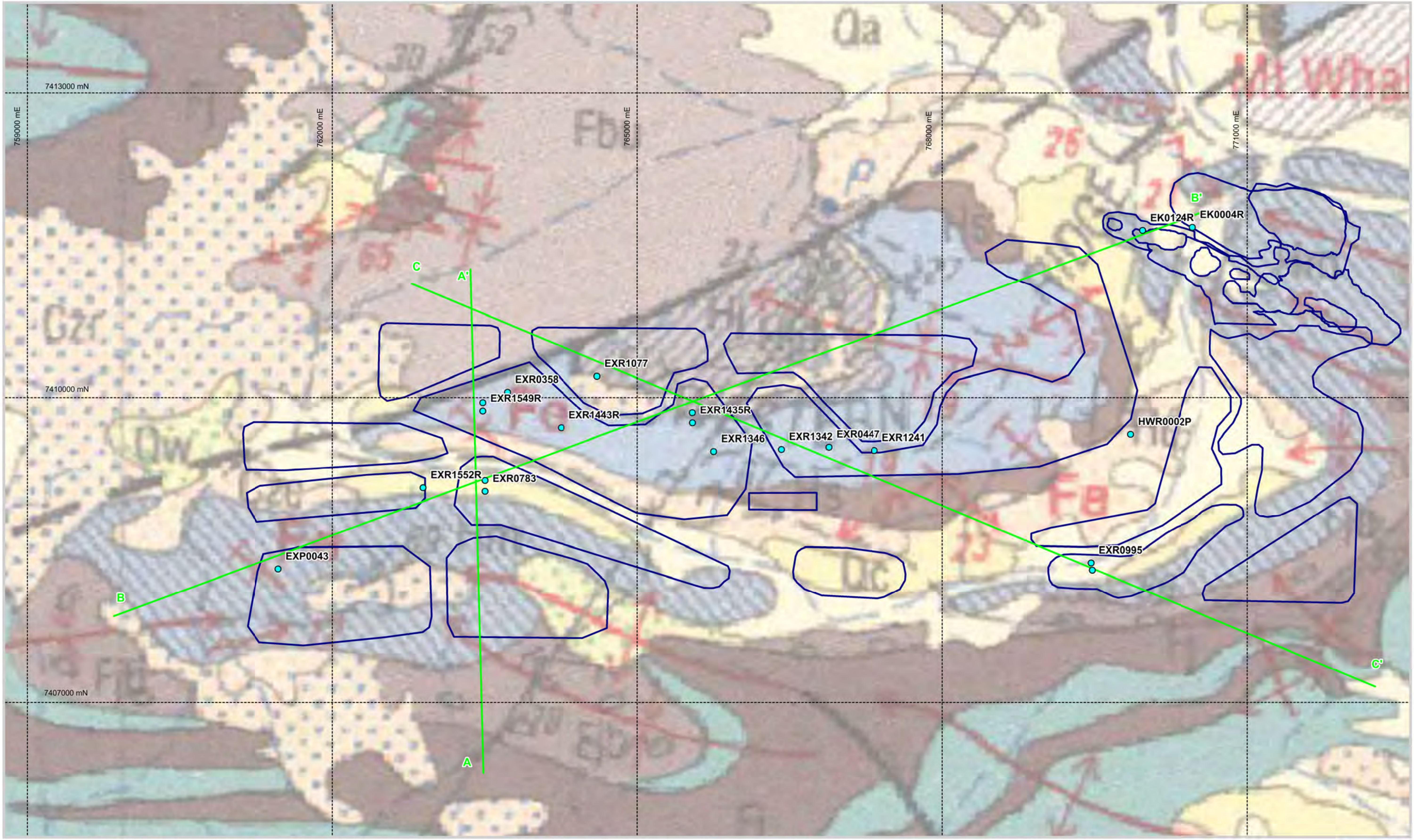
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.11c

**SECTION C
INFLUENCE OF
DEWATERING
WHALEBACK
MINING AREA**

DATA SOURCES:
Input data source here



N

0 1

Kilometres

Scale: 1:35,000 @A3

GDA 1994 Zone 50

AUTHOR: JP	REPORT NO: 198
DRAWN: MR	REVISION: d
DATE: 02/09/2015	JOB NO: 1606B

Location: F:\Jobs\1606\Spatial_Data\MapInfo\Workspaces\198a\198a Fig 5.12 Location Map

LEGEND

- Key Bore
- Section Line
- Indicative BHP Billiton Iron Ore Disturbance

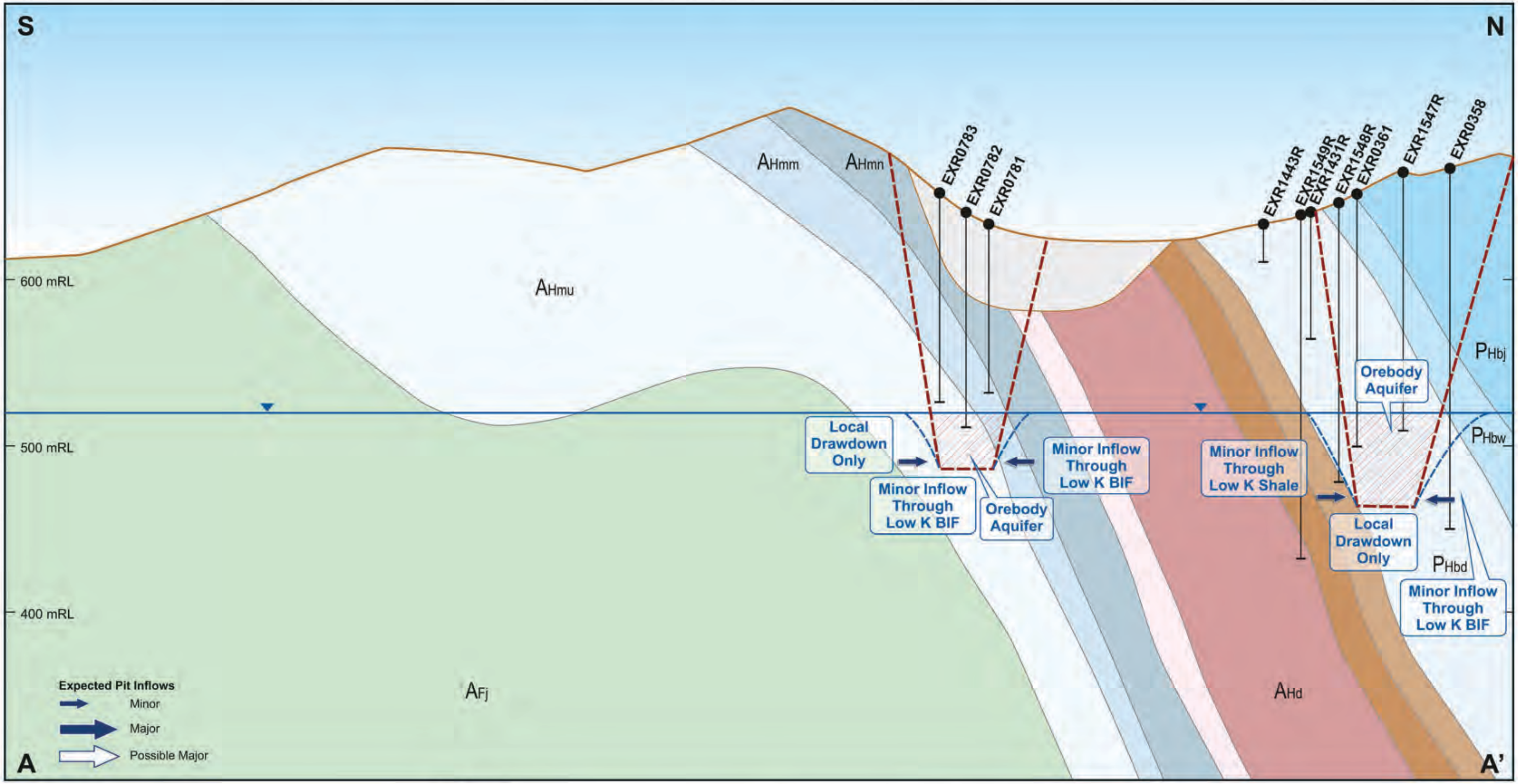
DATA SOURCES:
Input data source here

RPS

FIGURE 5.12

LOCATION PLAN
WESTERN RIDGE MINING AREA

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from this conceptual map."



LOCATION MAP

DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY

Location: XXXX

0 200
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj

- Ore

- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm Undifferentiated
- AHmn Mount Newman Member
- AHmm MacLeod Member
- AHmu Nammuldi Member

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.13a

SECTION A
DEWATERING
WESTERN RIDGE
MINING AREA

DATA SOURCES:
Input data source here

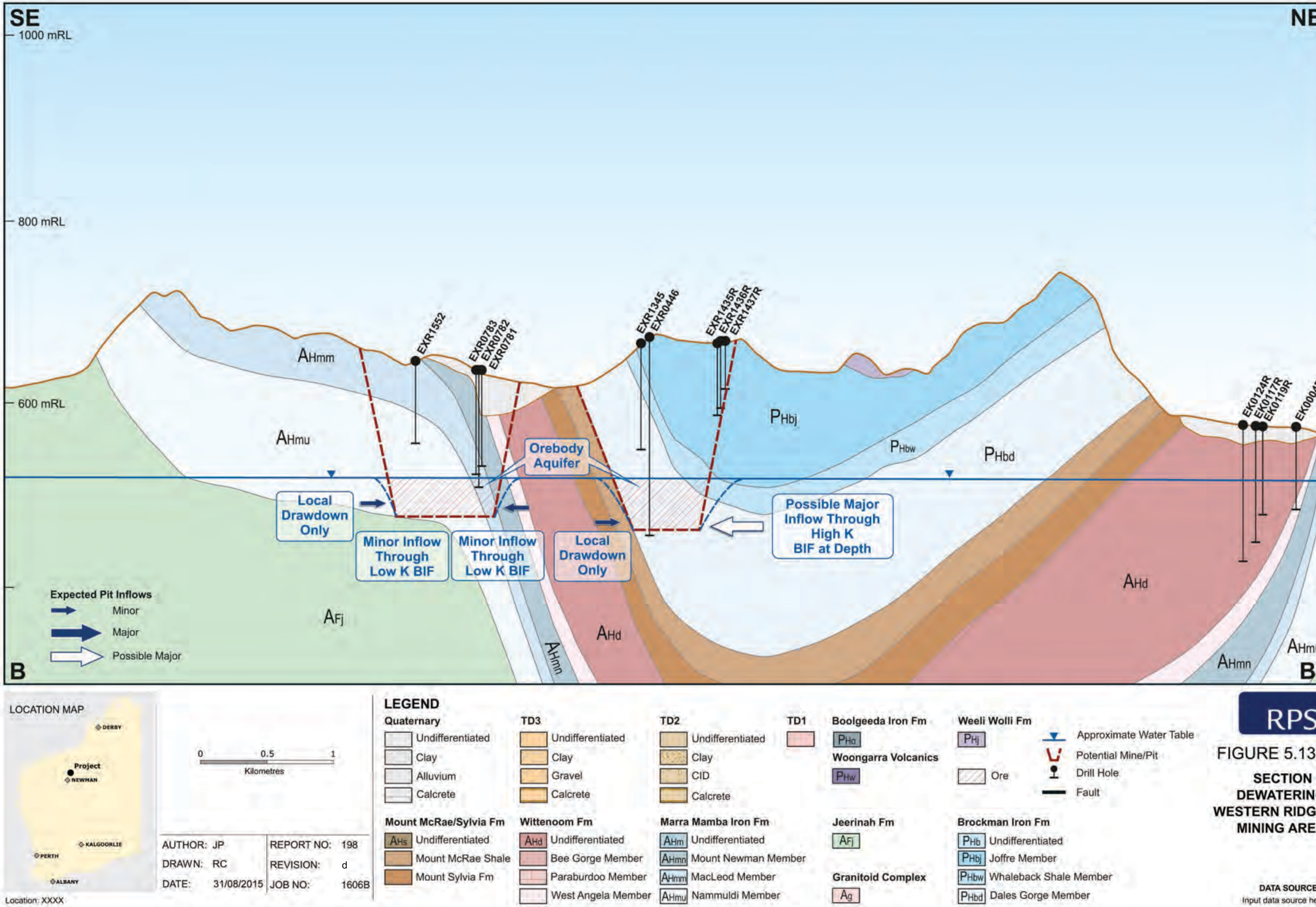
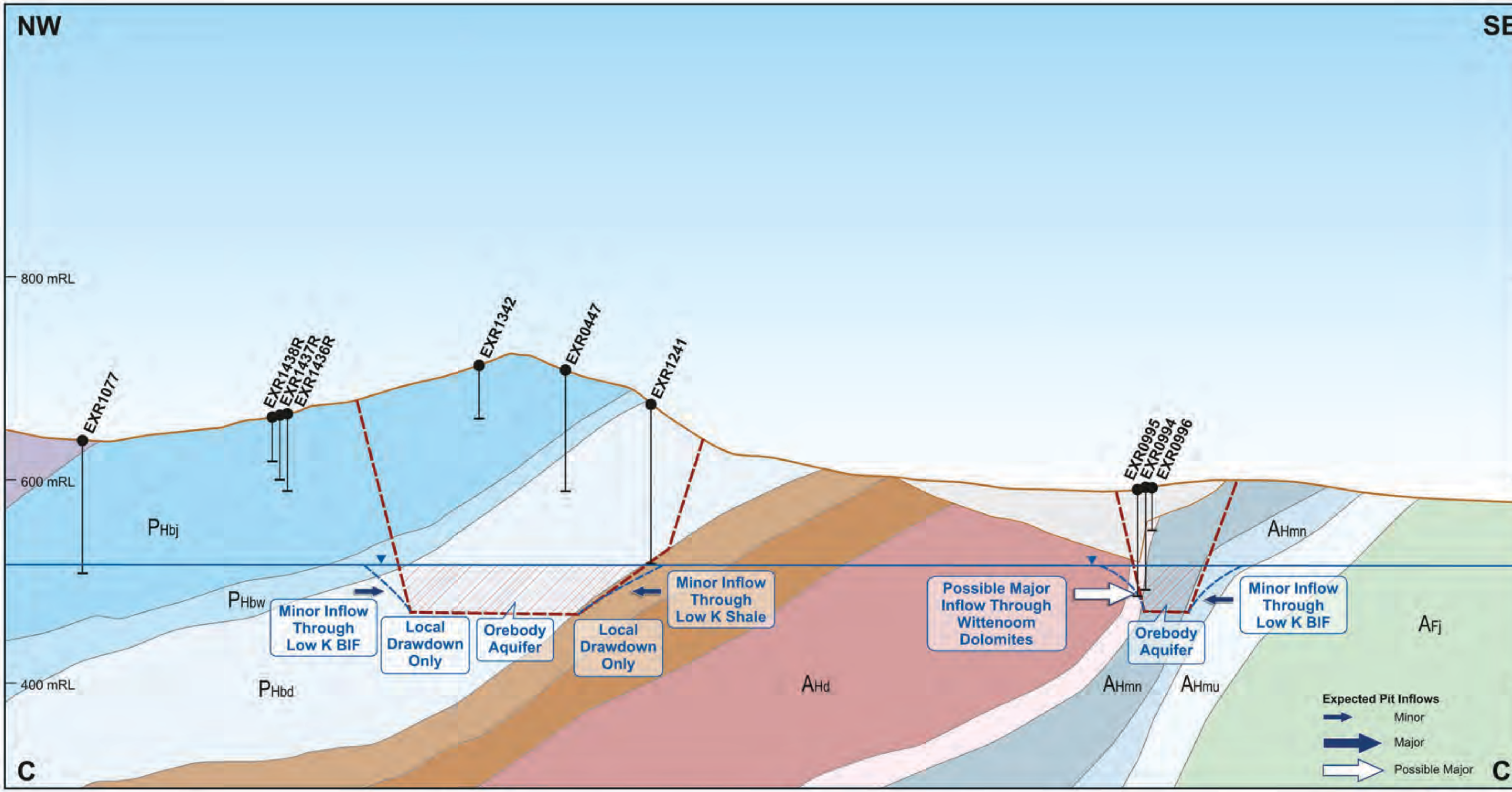


FIGURE 5.13b
SECTION B
DEWATERING
WESTERN RIDGE
MINING AREA



0 0.5 1
Kilometres

AUTHOR: JP
DRAWN: RC
DATE: 31/08/2015
REPORT NO: 198
REVISION: d
JOB NO: 1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj

- Ore

- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm Undifferentiated
- AHmn Mount Newman Member
- AHmm MacLeod Member
- AHmu Nammuldi Member

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

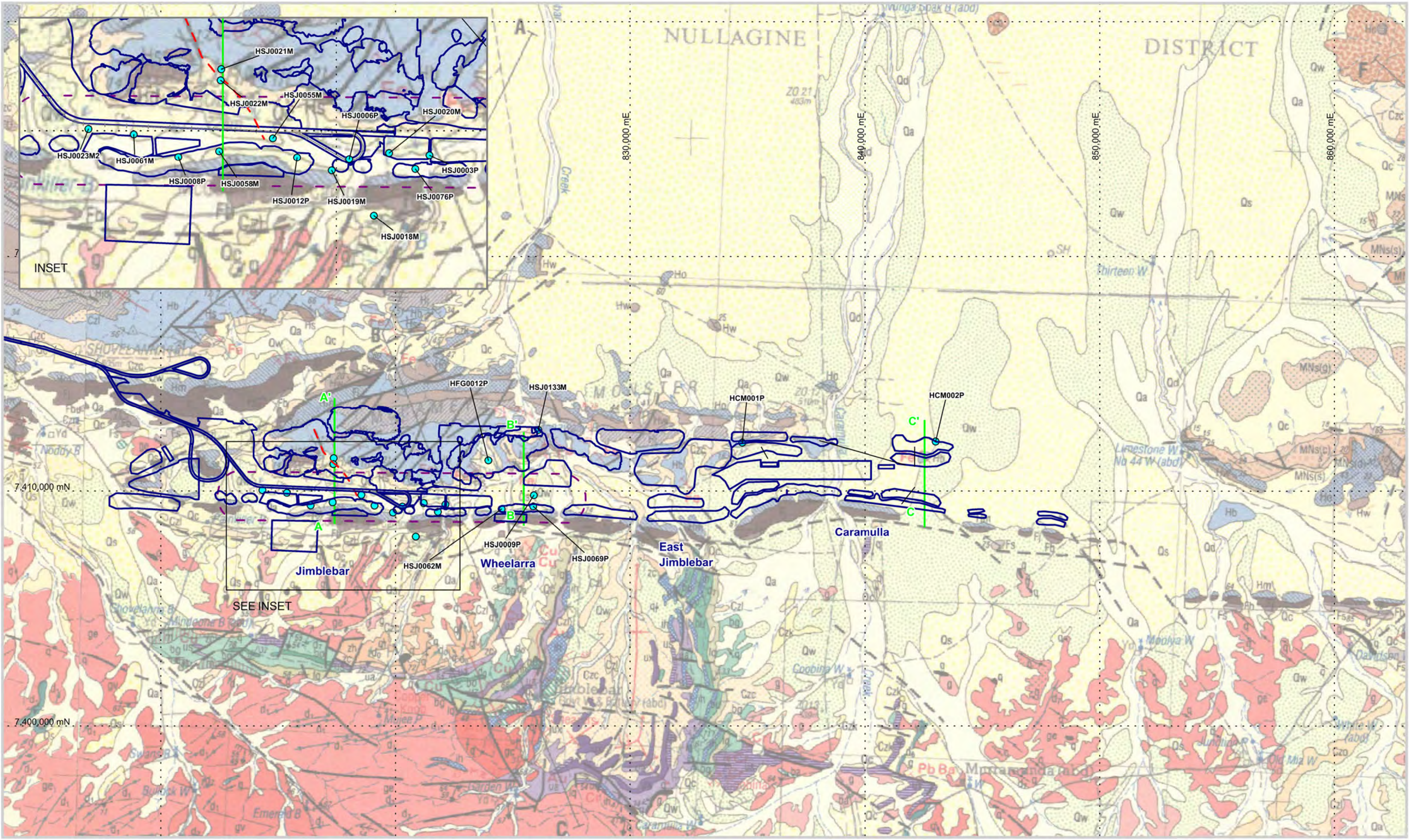
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.13c

SECTION C DEWATERING WESTERN RIDGE MINING AREA

DATA SOURCES:
Input data source here



N

0 2.5 5

Kilometres

Scale: 1:150,000 @A3

GDA 1994 Zone 50

AUTHOR: JB	REPORT NO: 198
DRAWN: MR	REVISION: d
DATE: 02/09/2015	JOB NO: 1606B

Location: F:\Jobs\1606I\Spatial_Data\MapInfo\Workspaces\198a\198a Fig 5.14 location map.WOR

LEGEND

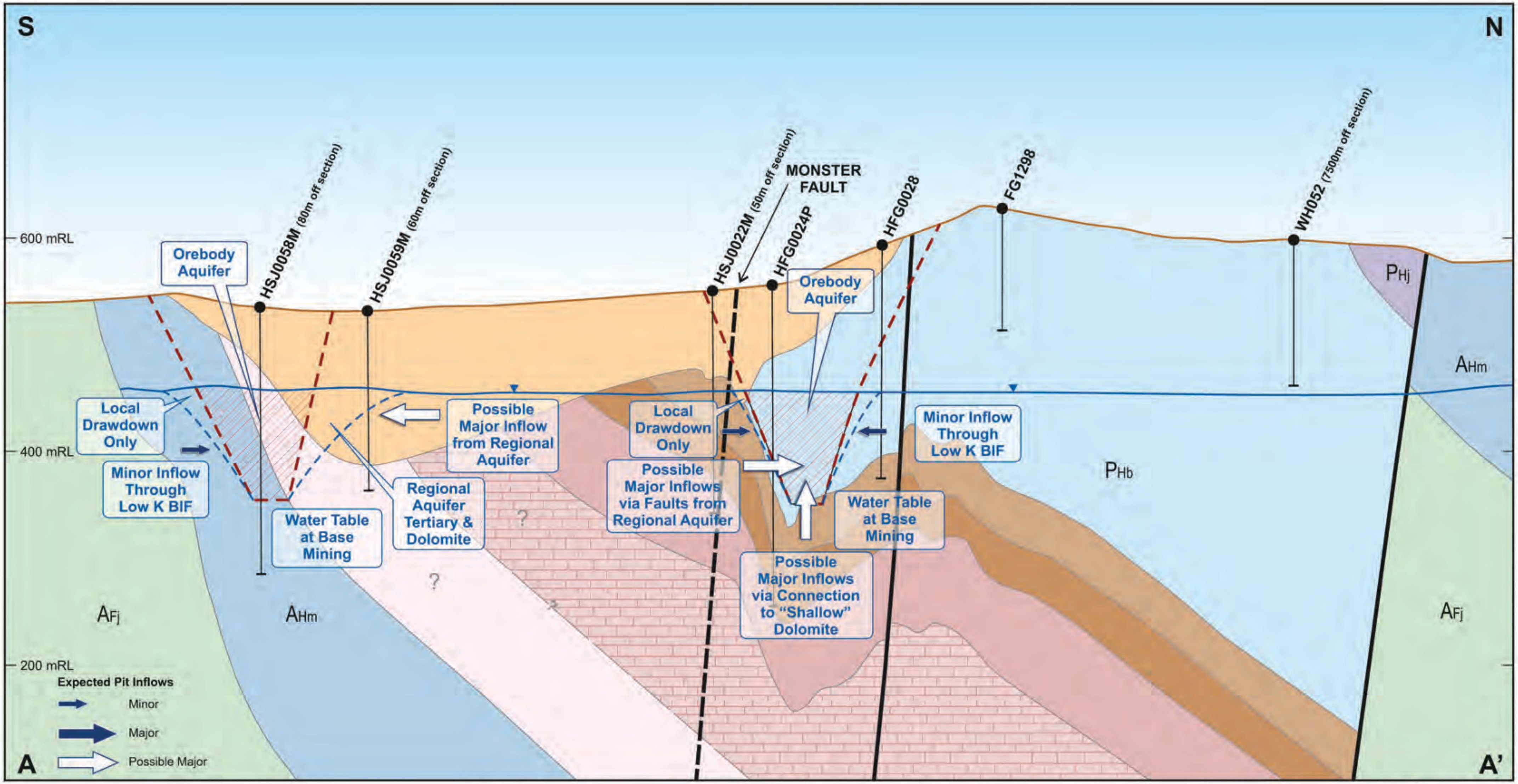
- Key Bore
- Section line
- Monster Fault
- Railway
- Indicative BHP Billiton Iron Ore Disturbance
- Jimblebar Borefield

RPS

FIGURE 5.14

LOCATION PLAN
JIMBLEBAR MINING AREA

The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental Protection Act 1986 (WA) and Environment Protection and Biodiversity Conservation Act 1999 and is not intended for use for any other purpose. No representation or warranty is given that project development associated with any or all of the disturbance indicated on this map will actually proceed.
As project development is dependent upon future events, the outcome of which is uncertain and cannot be assured, actual development may vary materially from this conceptual map."



Location: XXXX

0 500
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag
- Ore

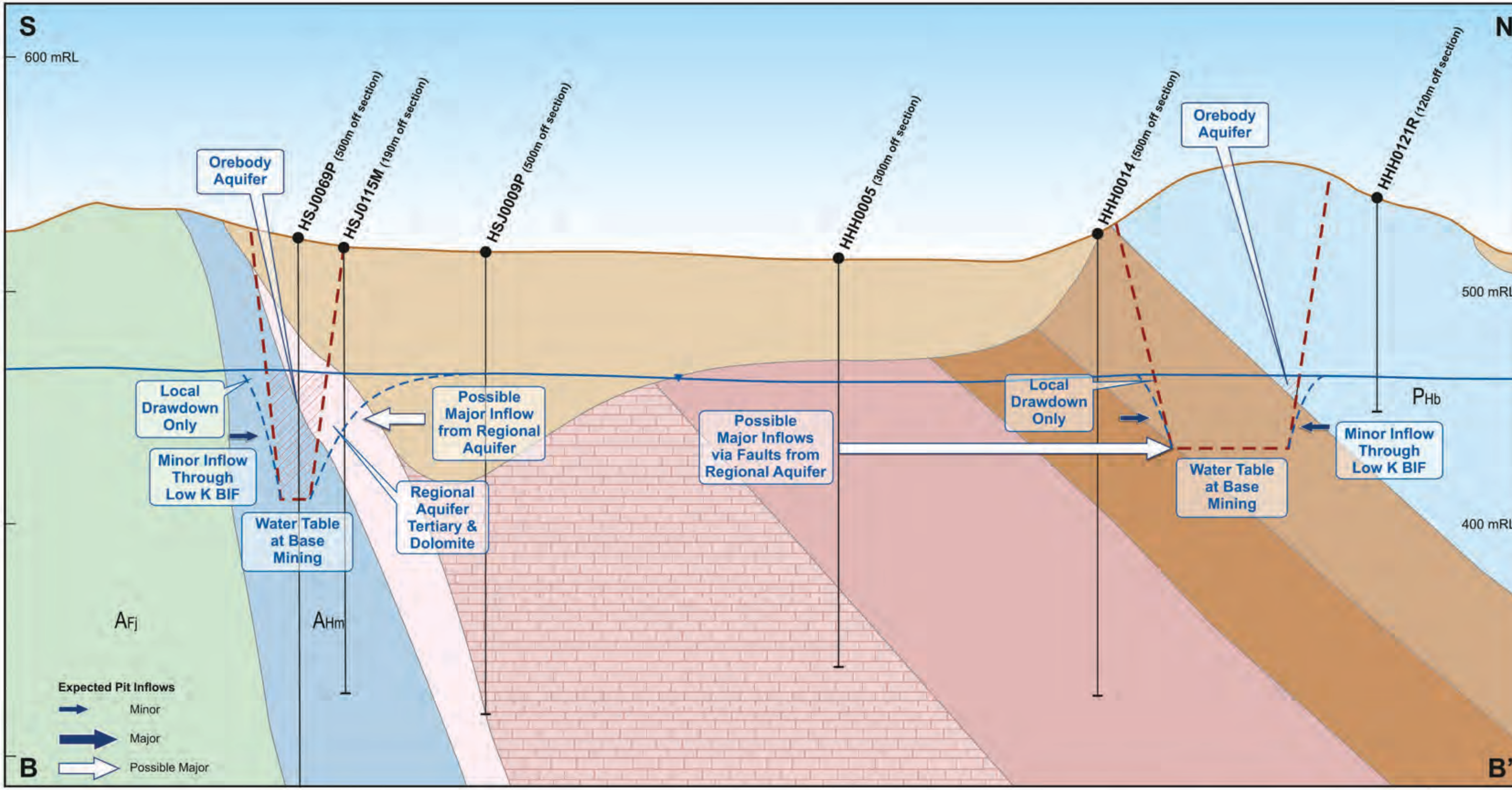
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 5.15a

SECTION A
INFLUENCE OF DEWATERING
JIMBLEBAR
MINING AREA

DATA SOURCES:
Input data source here



0 500
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary: Undifferentiated; Clay; Alluvium; Calcrete

TD3: Undifferentiated; Clay; Gravel; Calcrete

TD2: Undifferentiated; Clay; CID; Calcrete

TD1

Boolgeeda Iron Fm: PHo

Woongarra Volcanics: PHw

Weeli Wolli Fm: PHj

Brockman Iron Fm: PHb

Mount McRae/Sylvia Fm: AHs Undifferentiated; Mount McRae Shale; Mount Sylvia Fm

Wittenoom Fm: AHd Undifferentiated; Bee Gorge Member; Paraburdoo Member; West Angela Member

Marra Mamba Iron Fm: AHm

Jeerinah Fm: AFj

Granitoid Complex: Ag

Ore

Approximate Water Table

Potential Mine/Pit

Drill Hole

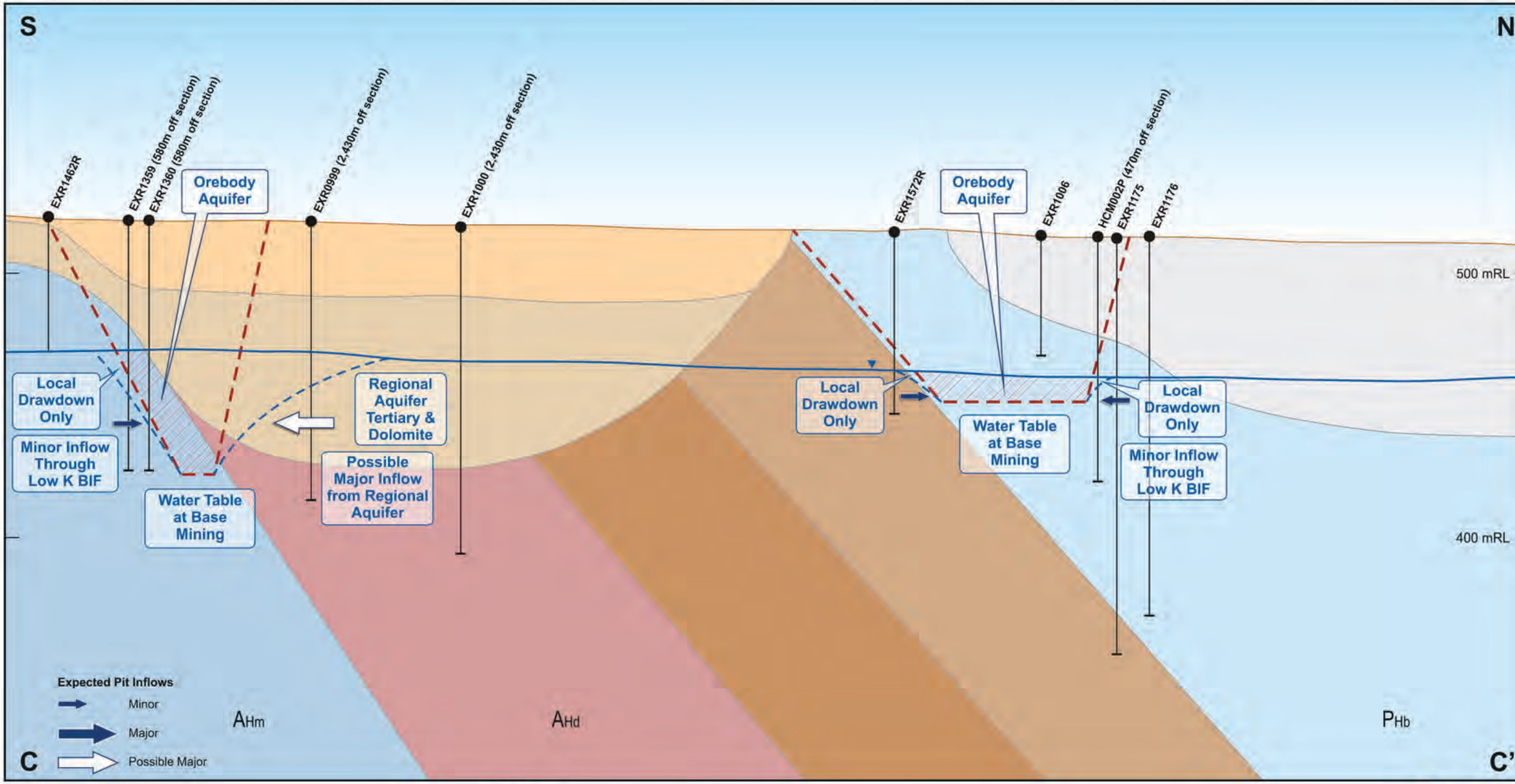
Fault

RPS

FIGURE 5.15b

SECTION B
INFLUENCE OF DEWATERING
JIMBLEBAR
MINING AREA

DATA SOURCES:
Input data source here



0 500
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	d
DATE:	31/08/2015	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag
- Ore

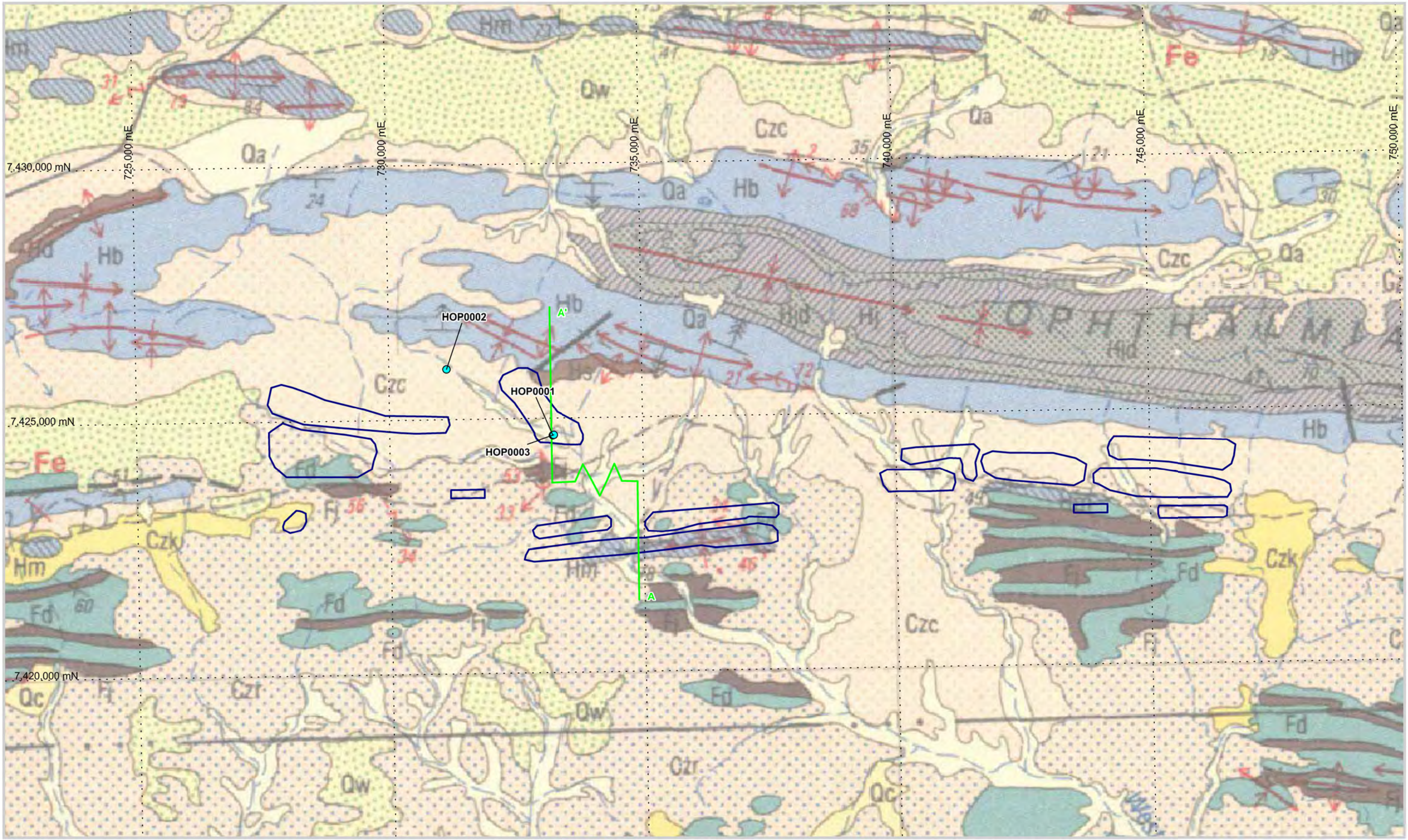
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 5.15c

SECTION C
INFLUENCE OF DEWATERING
JIMBLEBAR
MINING AREA

DATA SOURCES:
Input data source here



N

0 1 2.5

kilometres

Scale: 1:70,000 @A3

GDA 1994 Zone 50

AUTHOR:	PR	REPORT NO:	198
DRAWN:	MR	REVISION:	d
DATE:	02/09/2015	JOB NO:	1606B

F:\Jobs\1606I\Spatial_Data\MapInfo\Workspaces\198a\198a Fig 5.16 location map.WOR

LEGEND

Key Bore

Section line

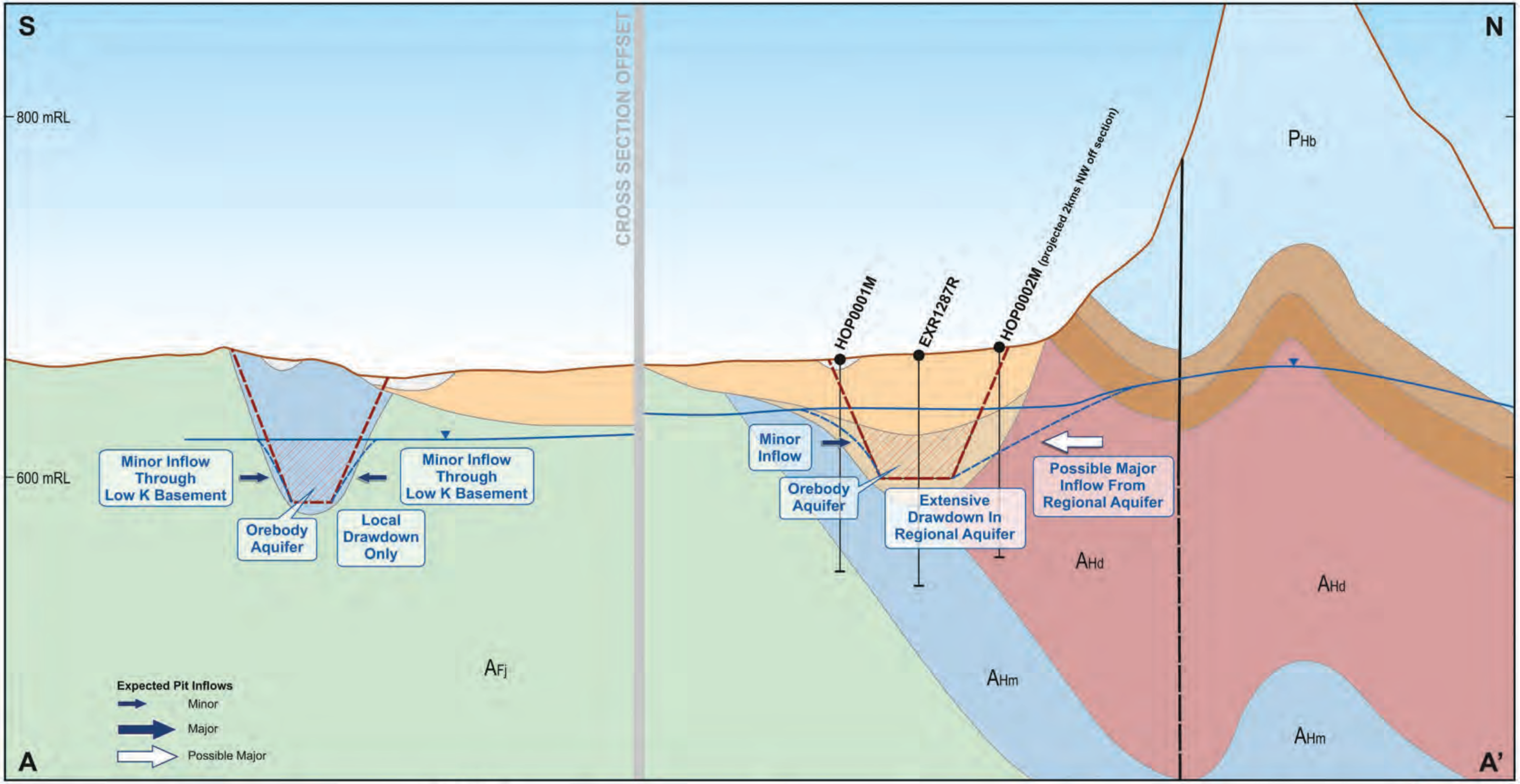
Indicative BHP Billiton Iron Ore Disturbance

DATA SOURCES:
Input data source here

RPS

FIGURE 5.16

LOCATION PLAN
OPHTHALMIA MINING AREA



Location: XXXX

0 250 500
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	b
DATE:	03/02/2014	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHj

- Ore

- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm Undifferentiated
- AHmn Mount Newman Member
- AHmm MacLeod Member
- AHmu Nammuldi Member

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

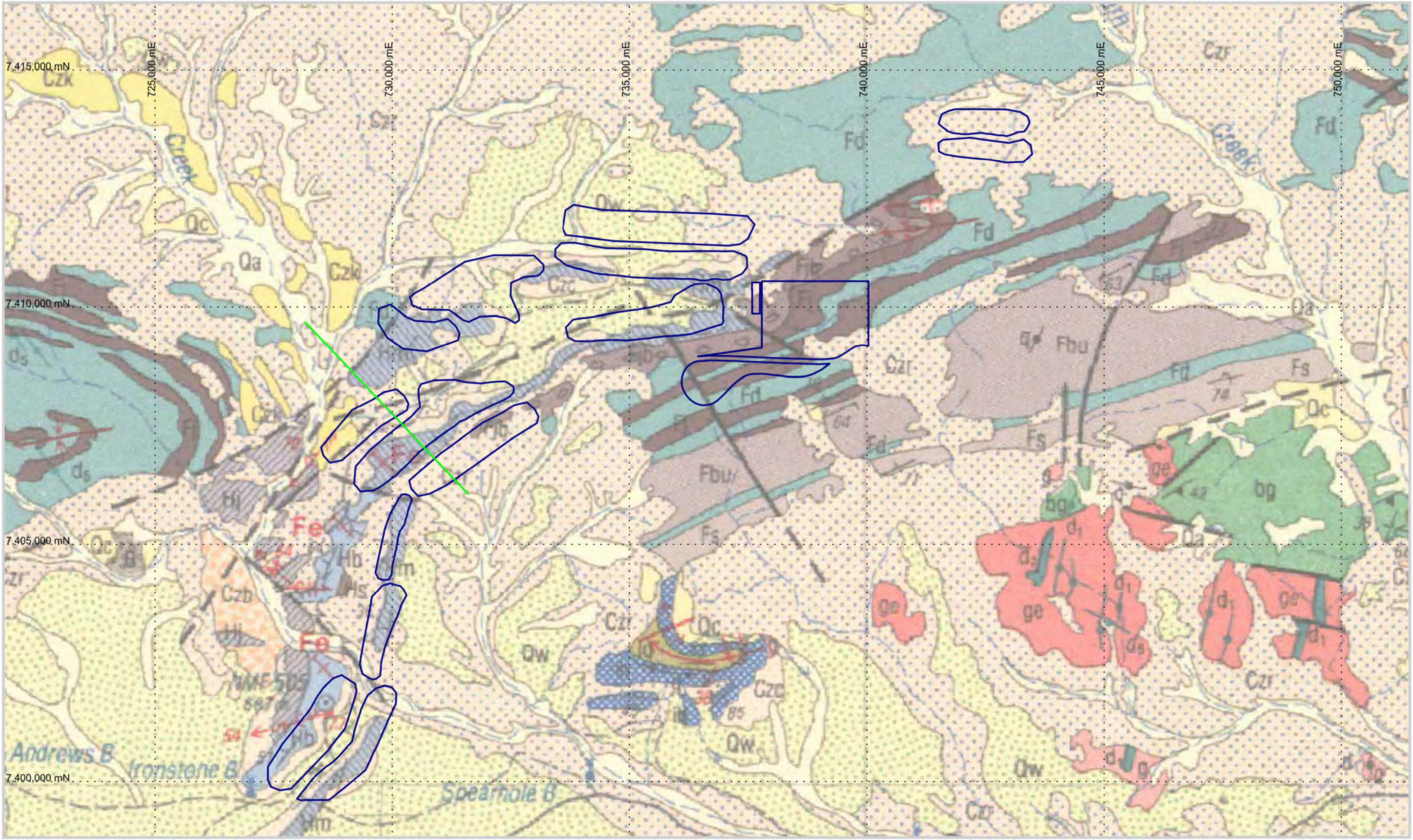
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.17

SECTION A DEWATERING OPHTHALMIA MINING AREA

DATA SOURCES:
Input data source here



N

0 1.5 3

Kilometres

Scale: 1:75,000 @A3

GDA 1994 Zone 50

AUTHOR:	LP	REPORT NO:	198
DRAWN:	MR	REVISION:	d
DATE	02/09/2015	JOB NO:	1606B

Location: F:\Jobs\1606B\Spatial_Data\MapInfo\Workspaces\198a\198a Fig 5.18 Location Map

LEGEND

Section Line

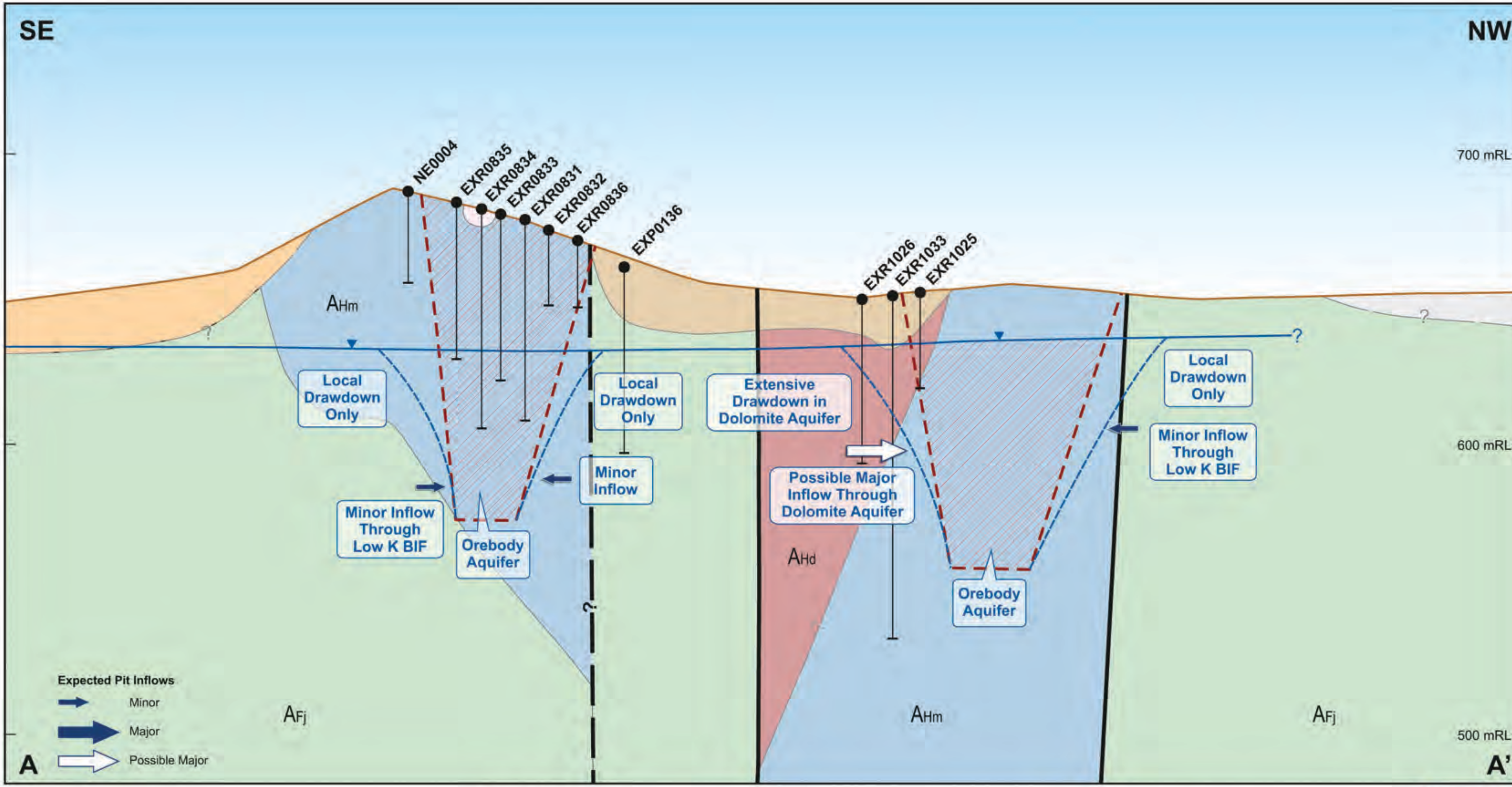
Indicative BHP Billiton Orebody Disturbance

DATA SOURCES:
Input data source here

RPS

FIGURE 5.18

LOCATION PLAN
PRAIRIE DOWNS MINING AREA



LOCATION MAP

Location: XXXX

0 — 500
Metres

AUTHOR:	JP	REPORT NO:	198
DRAWN:	RC	REVISION:	b
DATE:	03/02/2014	JOB NO:	1606B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

TD3
- Undifferentiated
- Clay
- Gravel
- Calcrete

TD2
- Undifferentiated
- Clay
- CID
- Calcrete

TD1

Boolgeeda Iron Fm
- PHo

Woongarra Volcanics
- PHw

Weeli Wolli Fm
- PHu

Brockman Iron Fm
- PHb

Mount McRae/Sylvia Fm
- AHs Undifferentiated
- Mount McRae Shale
- Mount Sylvia Fm

Wittenoom Fm
- AHd Undifferentiated
- Bee Gorge Member
- Paraburdoo Member
- West Angela Member

Marra Mamba Iron Fm
- AHm

Jeerinah Fm
- AFj

Granitoid Complex
- Ag

- Ore
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 5.19

CROSS SECTION INFLUENCE OF DEWATERING PRAIRIE DOWNS MINING AREA

DATA SOURCES:
Input data source here

APPENDIX A:
DATA INVENTORY

APPENDIX A - DATA INVENTORY

Discipline		Data Sources
Topography and drainage		• Topographic Survey Maps 1:100,000 • BHP Billiton Iron Ore Digital Elevation Model
Climate		• Bureau of Meteorology (BOM) climatic data • Department of Agriculture evaporation data • BHP Billiton Iron Ore weather climatic monitoring data
Geology		• Geological Survey Maps 1:250,000 and Explanatory Notes • Discrete geological and mine planning data packages provided by BHP Billiton Iron Ore (Commercial in Confidence)
Hydrology	Surface Water	• Department of Water streamflow gauging station data • BHP Billiton Iron Ore surface water monitoring data • Surface Water Reports prepared for BHP Billiton Iron Ore
	Groundwater	• Department of Water bore monitoring data • BHP Billiton Iron Ore monitoring data • BHP Billiton Iron Ore Aquifer Reviews • Hydrogeological Investigation Reports prepared for BHP Billiton Iron Ore • Hydrogeological Reports available in the Public domain • Research papers
Ecology / Environment / Ecosystems		• Department of Agriculture Land System Mapping • Department of Environment and Conservation's Threatened and Priority Ecological Communities (TECs and PECs) Listings • BHP Billiton Iron Ore Vegetation mapping • Ecological reports prepared for BHP Billiton Iron Ore • Research papers
Mining Operations	Active Mining Sites	• Discrete geological and mine planning data packages provided by BHP Billiton Iron Ore (Commercial in Confidence) • BHP Billiton Iron Ore Aquifer Reviews • Reports available in the Public domain for third party mines
	Proposed Mining Sites	• Discrete geological and mine planning data packages provided by BHP Billiton Iron Ore (Commercial in Confidence) • Indicative BHP Billiton Iron Ore SEA disturbance footprints