ECOHYDROGEOLOGICAL CONCEPTUALISATION OF THE CENTRAL PILBARA REGION

ECOHYDROGEOLOGICAL CONCEPTUALISATION OF THE CENTRAL PILBARA REGION

Prepared by:

RPS
38 Station Street, Subiaco WA 6008
PO Box 465, Subiaco WA 6904
T: 61 8 9211 1111
F: 61 8 9211 1122
E: water@rpsgroup.com.au
W: rpsgroup.com.au

Our ref: 1549B/600/275f
Date: 2 September 2015

Prepared for:

BHP Billiton Iron Ore
125 St Georges Terrace
Perth WA 6000
Australia

Document Status

	Issue Date	Purpose of Document
Revision A	03/07/2014	Final
Revision B	15/07/2014	Minor updates
Revision C	20/10/2014	Updates following SEA review
Revision D	24/10/2014	Minor updates
Revision E	08/05/2015	Minor edits to figures
Revision F	02/09/2015	Minor edits to figures and text

	Name	Position	Signature	Date
Project Manager	Jane Puthiaparampil	Senior Hydrogeologist		02/09/2015
Author	Duncan Storey Jon Hall Vince Piper Emma Bolton Alan Woodford Alastair Hoare	Senior Principal Hydrogeologist Senior Principal Hydrogeologist Senior Principal Water Resources Engineer Principal Hydrogeologist Principal Hydrogeologist Principal Hydrogeologist		02/092015
Reviewer	Jon Hall Duncan Storey	Senior Principal Hydrogeologist Senior Principal Hydrogeologist		02/09/2015

Disclaimers

EXECUTIVE SUMMARY

Background and Approach

To support a Strategic Environmental Assessment of the Central Pilbara Region, an ecohydrological conceptualisation has been developed which incorporates the key ecohydrological processes and linkages occurring throughout 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 CPR including BHP Billiton Iron Ore's current operations at Mining Area C (MAC) and exploration projects at Jinidi, South Flank, Mudlark, Tandanya, South Parmelia and Gurinbiddy. Other mining operations within, or in close proximity to the CPR include Hope Downs, Hope Downs 4, Rhodes Ridge and the West Angela Mine, all operated by Rio Tinto Iron Ore.

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 three ecohydrological receptors being:

- Coondewanna Flats, an internally draining alluvial plain and wetland feature which is the terminus for surface water flow from the west of the CPR. The area supports and unusual combination of vegetation. Elements of Coondewanna Flats have been listed as Priority Ecological Communities (PEC Priorities 1 and 3) by the Department of Parks and Wildlife (2014).
- Weeli Wolli Spring, located where Weeli Wolli Creek flows through narrow gap or gorge in the Wildflower Range. The area supports an unusual combination of riparian vegetation and fauna and has been listed as a Priority Ecological Communities (PEC Priority 1).
- Ben's Oasis, a series of pools along the channel of Weeli Wolli Creek where there is a shallow basement rock bar. These pools support riparian woodland and forest associations.

Detailed ecohydrological conceptualisations have been developed for Weeli Wolli Spring and Coondewanna Flats, as the two main identified ecohydrological receptors. There are insufficient data to develop a reliable hydrological conceptualisation for Ben's Oasis at this time.

Regional Overview

The CPR spans four catchments. Most mining areas are within the Weeli Wolli Spring catchment that drains into the Upper Fortescue River, with the remaining mining areas being located in the Coondewanna catchment which is an internally draining basin within the Ashburton River Basin. Parts of some mining areas are located within the upper reaches of the Turee Creek East Branch catchment (also located in the Ashburton River Basin) and the Wanna Munna catchment which is an internally draining basin located in the Upper Fortescue River catchment.

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 CPR 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 CPR 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 and Transitional Landscape Units are characterised by a deep watertable (greater than 30 mbgl) and a steep topography that generates surface water runoff. In contrast, Lowland Landscape Units comprise a smaller extent and are associated with environments that are closely integrated 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.

The two key lowland ecohydrological features are Weeli Wolli Spring and Coondewanna Flats.

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 forms localised aquifers.
- The regional aquifers are aligned with the main surface water system.
- Beneath the confluence of North Flank and South Flank Valleys upstream of Weeli Wolli Spring, the Tertiary detritals comprise an extensive unit of shallow permeable calcrete. It is present from the surface to more 30 m below the watertable being underlain by poorly-sorted alluvium of clay, sands and gravels of variable permeability.
- Beneath Coondewanna Flats, the regional aquifer comprises an upper Tertiary sequence of variable sand, silt and gravel overlying a middle Tertiary sequence of variable calcrete and silty gravel overlying shale and dolomite of the Wittenoom Formation.
- 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 mineralization, 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.

- The majority of recharge occurs at Coondewanna Flats during periods of inundation in Lake Robinson, and in the area immediately upstream of Weeli Wolli Spring.
- Since the commencement of mining, there has also been groundwater abstraction to support mining activity (water supply and dewatering) in the CPR.
- Natural groundwater discharge occurs as baseflow to Weeli Wolli Spring, and loss due to evapotranspiration from dense vegetation at and upstream of the Spring.
- Since the commencement of mining at Rio Tinto Iron Ore's Hope Downs, excess mine water discharge to the Weeli Wolli Spring area has enhanced groundwater and surface water flows at the Spring.
- There is also minor groundwater and surface water discharge into the Turee Creek East Branch.

Ecohydrological Conceptualisation – Coondewanna Flats

Coondewanna Flats is an internally-draining, surface water wetland located upstream of Weeli Wolli Spring. Surface water runoff from the western half of the CPR flows into the flats from the north, west and south. Large flood events result in the inundation of Lake Robinson, before either infiltrating into the soil and groundwater or being lost to evapotranspiration from ponded surface water bodies and vegetation.

Coondewanna Flats hosts two PECs:

- Coolibah woodlands over lignum over swamp wandiree (designated Priority 1).
- Coolibah and Mulga woodland over lignum and tussock grass on clay plains (designated Priority 3).

Surface water flow from the surrounding catchments is focused towards the Flats which form an internally-draining basin comprising claypans and alluvial plains of the Wannamunna land system. The Flats are characterised as a receiving environment with groundwater levels being between 20 and 30 mbgl. The vegetation communities do not appear to rely on permanent groundwater for their survival; however, the hydrological environment at Coondewanna Flats plays a key role in supporting these vegetation communities through soil moisture replenishment associated with periodic inundation and infiltration.

The key features of the ecohydrological conceptualisation for Coondewanna Flats are:

- Long-term average runoff is approximately 5.8 GL/yr. Peak events have been as high as 100 GL (Cyclone Joan in 1975/76) but the 50% annual exceedance probability runoff is approximately 1.8 GL/yr.
- Runoff occurs in three out of four years on average, but runoff sufficient to cause inundation in Lake Robinson occurs in one out of four years on average.
- The groundwater system is recharged predominantly by infiltration of water from Lake Robinson and the broader Coondewanna Flats when it is inundated. The groundwater balance shows the infiltration of surface water of approximately 11,000 KL/d.
- Discharge from Coondewanna Flats is by evapotranspiration from the unsaturated zone and groundwater throughflow to the Weeli Wolli Spring catchment. The water balance suggests groundwater throughflow of approximately 11,000 KL/d.
- Groundwater levels have historically fluctuated by approximately 5 m in response to recharge events. This fluctuation has minimal influence on the PECs, as the vegetation is reliant on soil moisture in the unsaturated zone.

In summary, the key hydrological processes that support the PEC at Coondewanna Flats are surface water runoff and replenishment of soil moisture by the infiltration of surface water.

Ecohydrological Conceptualisation – Weeli Wolli Spring

Weeli Wolli Spring occurs where Weeli Wolli Creek flows through the Wildflower Range. Downstream of the Spring, the creek flows in a narrow channel immediately to the north, past the confluence with Marillana Creek (and Rio Tinto Iron Ore's Yandicoogina mine) and towards Fortescue Marsh.

The spring occurs upstream of the creek entrance into the gorge, and is designated a PEC (Priority 1) owing to the following rare flora and fauna communities:

- Fringing forest of Melaleuca argentea (Paperbark) and Eucalyptus camaldulensis (River Red Gum) over trees of Eucalyptus victrix (Coolibah) and a dense shrub layer dominated by an assortment of wattles, in particular Acacia citrinoviridis (Black Mulga). In addition, the spring is characterised by an unusual composition of understory vegetation, including sedges and herbs that fringe many of the pools and associated water bodies along the main channel.
- The shallow aquifer in proximity to the spring hosts a large diversity of stygofauna.

Surface water and groundwater flows from most of the CPR catchments are focused into Weeli Wolli Spring and, from a landscape context, the spring area is characterised as a receiving environment that comprises channels, floodplains and calcrete of the River and Calcrete Land Systems. The Weeli Wolli Spring area has shallow groundwater (less than 5 mbgl) in the immediate area of the Spring resulting in interaction and connectivity between the groundwater and terrestrial environment (through both surface water connection and vegetation).

The key ecological features have evolved and adapted to this shallow groundwater regime. Stygofauna are hosted in shallow aquifers (notably calcrete) and their habitat is maintained by saturation of these aquifers. The vegetation community comprises both obligate and facultive (opportunistic) phreatophytes that utilise this shallow groundwater.

The key features of the ecohydrological conceptualisation for Weeli Wolli Spring are:

- The groundwater system is recharged by a combination of groundwater throughflow from up-catchment and infiltration of rainfall runoff (streamflow) beneath local flowpath lines upstream of the Spring.
- The water balance suggests average inputs of:
  - Runoff infiltration along stream channels of approximately 2,500 kL/d.
  - Groundwater throughflow of approximately 11,000 kL/d.
- Discharge from the groundwater system is dominated by baseflow to Weeli Wolli Spring and groundwater throughflow. The water balance suggests average outputs for pre-mine dewatering conditions of:
  - Baseflow to the Spring of approximately 7,000 kL/d.
  - Groundwater throughflow in the aquifer of approximately 4,000 kL/d.
  - Evapotranspiration from vegetation around the spring of approximately 2,600 kL/d.
- Groundwater levels in the shallow aquifer that hosts the PEC have historically fluctuated in the order of 1 to 2 m being responsive to climatic cycles.
- Since 2006, dewatering abstraction at Hope Downs 1 has resulted in significant drawdown around the pit. The extent of drawdown has been minimised through active water management with the discharge of excess water into Weeli Wolli Creek. This approach has resulted in only minor groundwater drawdown (1 to 2 m) immediately upstream of the Spring and groundwater levels remaining at pre-mining levels closer to the Spring.

In summary, the key hydrological processes that maintain the shallow groundwater conditions and support the PEC are groundwater throughflow from up-catchment and infiltration of streamflow near the Spring. In the past decade, there has been additional recharge associated with excess water discharge from Hope Downs 1 that has maintained groundwater levels at the Spring.

TABLE OF CONTENTS

TABLES

PLATES (compiled at end of report)

FIGURES (compiled at end of report)

APPENDICES

1. INTRODUCTION

1.1 Description

1.1.1 Location and Extent

The Central Pilbara Region (CPR) study area is shown in Figure 1.1. The study area includes the Weeli Wolli Spring catchment, located approximately 100 km northwest of Newman in Western Australia. There are a number of existing and proposed mining operations including BHP Billiton Iron Ore's current operations at Mining Area C (MAC) and exploration projects at Jinidi, South Flank, Mudlark, Tandanya, South Parmelia and Gurinbiddy. Other mining operations within the study area (or in close proximity to it) include Hope Downs, Hope Downs 4, Rhodes Ridge and the West Angela Mine, all operated by Rio Tinto Iron Ore.

1.1.2 Areas of Importance or Significance

1.1.2.1 Mining areas and orebodies

There are 41 orebodies in the CPR, which have been grouped into eight 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.

1.1.2.2 Receptors

There are three identified ecohydrological receptors in the CPR:

- Coondewanna Flats is an internally draining alluvial plain and wetland feature which is the terminus for surface water flow from the west of the CPR. The area supports and unusual combination of vegetation.
- Weeli Wolli Spring is located where Weeli Wolli Creek flows through narrow gap or gorge in the Wildflower Range. The area supports an unusual combination of riparian vegetation and fauna.
- Ben's Oasis is a series of pools along the channel of Weeli Wolli Creek where there is a shallow basement rock bar. These pools support riparian woodland and forest associations.

A detailed description of Coondewanna Flats is presented in Section 4.2, and Weeli Wolli Spring (and Ben's Oasis) in Section 4.3.

Table 1.1: Below Watertable Orebodies in the Central Pilbara Region

Mining Area	Owner	Orebody	Host-Geology*	Operating Status**	% Below Watertable	Remarks
GURINBIDDY	BHP Billiton Iron Ore	OREBODY 40	MM	EXP	54	
	BHP Billiton Iron Ore	GURINBIDDY	MM	EXP	70	
JINIDI, OB10, OB11 AND OB12	BHP Billiton Iron Ore	OREBODY 13	BRK	EXP	48	
	BHP Billiton Iron Ore	OREBODY 41	BRK	EXP	4	
	BHP Billiton Iron Ore	OREBODY 14 &15	BRK	EXP	5	
	BHP Billiton Iron Ore	OREBODY 16	BRK	EXP	38	
	BHP Billiton Iron Ore	OB10, OB11, OB12	BRK	EXP	5	
MUDLARK WELL	BHP Billiton Iron Ore	PARALLEL RIDGE	MM	EXP	25	
	BHP Billiton Iron Ore	ALLIGATOR SOUTH	MM	EXP	26	
	BHP Billiton Iron Ore	ALLIGATOR JAWS	MM	EXP	31	
	BHP Billiton Iron Ore	GOVERNOR RANGE	BRK	EXP	10	
	BHP Billiton Iron Ore	SOUTHEAST CORNER	MM	EXP	25	
	BHP Billiton Iron Ore	ALLIGATOR NORTH	MM	EXP	35	
	BHP Billiton Iron Ore	BOUNDARY RIDGE NORTH, GRASSLANDS	MM	EXP	Data not available	Data Not Available
MAC	BHP Billiton Iron Ore	DEAD END	MM	EXP	17	
	BHP Billiton Iron Ore	R1 DEPOSIT	MM	EXP	8	
	BHP Billiton Iron Ore	R2 DEPOSIT	MM	EXP	25	
	BHP Billiton Iron Ore	E DEPOSIT	MM	M	26	Current BWT mining, active dewatering
	BHP Billiton Iron Ore	D DEPOSIT	MM	EXP	1	
	BHP Billiton Iron Ore	C DEPOSIT	MM	M	29	Current BWT mining, active dewatering
	BHP Billiton Iron Ore	B2 DEPOSIT	MM	EXP	10	
	BHP Billiton Iron Ore	A DEPOSIT	MM	M	20	
	BHP Billiton Iron Ore	F DEPOSIT	MM	M	0	Documented as AWT but requiring minor dewatering.
PACKSADDLE	BHP Billiton Iron Ore	PACKSADDLE 1	BRK		6	
	BHP Billiton Iron Ore	PACKSADDLE 3	BRK		1	
	BHP Billiton Iron Ore	PACKSADDLE WEST	BRK		10	
SOUTH FLANK	BHP Billiton Iron Ore	SOUTH FLANK PIT 1	MM		20	
	BHP Billiton Iron Ore	SOUTH FLANK PIT 3	MM		1	
	BHP Billiton Iron Ore	SOUTH FLANK PIT 4	MM		3	
	BHP Billiton Iron Ore	SOUTH FLANK	MM		35	
SOUTH PARMELIA	BHP Billiton Iron Ore	OREBODY 4	BRK	EXP	40	
TANDANYA	BHP Billiton Iron Ore	CAMP HILL	MM	EXP	50	
	BHP Billiton Iron Ore	FLOOD PLAIN	BRK	EXP	25	
	BHP Billiton Iron Ore	THE NOOSE	BRK	EXP	25	
	BHP Billiton Iron Ore	HILL 65	BRK	EXP	15	
	BHP Billiton Iron Ore	RAIL LINK	MM	EXP	85	
	BHP Billiton Iron Ore	FORK NORTH	BRK	EXP	15	
	BHP Billiton Iron Ore	RAILWAY, JOCELYN, MILLI DOWNS	MM	EXP	Data not available	Data Not Available
	BHP Billiton Iron Ore	TAYLOR BORE, SWEET VIEW	BRK	EXP	Data not available	Data Not Available
	BHP Billiton Iron Ore	RAILWAY EAST	MM/DET	EXP	Data not available	Data Not Available
HOPE DOWNS	Rio Tinto Iron Ore	HOPE NORTH	MM	M	Data not available	Current BWT mining, active dewatering
	Rio Tinto Iron Ore	HOPE SOUTH	MM	M	Data not available	Current BWT mining, active dewatering
RHODES RIDGE	Rio Tinto Iron Ore	n/a	MM	EXP	Data not available	Current BWT mining, active dewatering
WONNA MUNNA	Rico Resources	n/a	MM	EXP	Data not available	Current AWT mining, ; water supply abstraction

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

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

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.

1.2 Scope and Objectives

1.2.1 Study Objectives

RPS were engaged by BHP Billiton Iron Ore to develop a ecohydrological conceptualisation model for the CPR that can be used to develop an understanding of the ecohydrology, identify hydrological processes that provide critical support for the environment and support future work in the area including the assessment of the effects of future dewatering.

The study has been commissioned to:

- Provide a solid knowledge basis of the natural water resources system in the CPR and the possible impacts of BHP Billiton Iron Ore operations (current and future) on that system with particular focus on the ecohydrological receptors and orebodies.
- Develop an understanding of the ecohydrology through the identification of hydrological processes that sustain the ecology.
- Provide a conceptual hydrological model to support the further development of a groundwater model used to predict the long term hydrological change resulting from groundwater abstraction in the catchments of Coondewanna Flats and Weeli Wolli Spring.
- Provide a conceptual model to support future numerical modelling that may be undertaken either at a regional scale or in support of specific orebody developments.
- Support the Strategic Environmental Assessment being undertaken by BHP Billiton Iron Ore by way of demonstrating an understanding of ecohydrological conditions and processes.

1.2.2 Study Approach

The overall approach to this study was to:

- Build a conceptual ecohydrological model that incorporates the key ecohydrological processes, linkages, and thresholds 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 outcomes of the ecohydrological conceptualisation and specific details on the identified key environmental receptors (Coondewanna Flats and Weeli Wolli Spring). This includes a conceptual hydrological/hydrogeological understanding for the receptor and key hydrological processes that support the receptor, and identification (through a quasi-catchment approach) of which orebodies could possibly affect the key drivers for Coondewanna Flats and Weeli Wolli Spring.

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 key ecohydrological receptors (Coondewanna Flats and Weeli Wolli Spring).

All data used for the CPR 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 sub discipline 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 CPR 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 flowpath (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 (flowpaths) 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 flowpaths are generally large and incised, and often exhibit regular bed load movement. They receive the combined flows and energy of minor flowpaths, 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 flowpath characteristics in zones of energy dissipation extending some distance from the base of the uplands across flatter country.
- Type (c) - Low energy flowpaths are commonly braided, meandering and/or anabranching. They are prevalent in areas of low relief (predominantly broad alluvial plains) where the energy of upstream flows is dissipated. Low energy flowpaths often feature channel flow retardation structures related to avulsion, floodouts and splays.
- Type (d) - Flowpath 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 flowpath 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-flowpath 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 flowpath 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:

- 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.).

- 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).
- 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. flowpath lines and floodplains).
- 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 flowpaths 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 flowpath 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 flowpath systems that are now dissected by more recent flowpaths. 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 flowpath, 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 CPR 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 F (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 flowpath 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 Central 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 – flowpath 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 flowpath but some tracts receive surface water flow from upland units.
- EHU 6 Lowland alluvial plains – typically of low relief and featuring low energy, dissipative flowpath.
- EHU 7 Lowland calcrete plains – generally bordering major flowpath 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 - flowpath 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 included:

- Landscape position and land surface types, including soil characteristics.
- Landscape water balance processes.
- Surface flowpath/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.

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 flowpath/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 flowpath networks (1^{st}, 2^{nd} and 3^{rd} 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 flowpath systems (mainly 1^{st} to 4^{th} 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 – flowpath 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 flowpath floors support hummock grasslands; larger flowpath 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 $\geq 5^{th}$ 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 1 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 flowpath. 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 flowpath/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 flowpath 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 flowpath 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 flowpath/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 flowpath 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 flowpath/connectivity processes	Level of connectivity to groundwater systems	Major vegetation types
Lowland Landscape	Lowland 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 - flowpath 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)	Flowpath termini receive inflows from up-gradient flowpath 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 approximately 0 °C in winter (Bureau of Meteorology [BOM]). The nearest open BOM climatic station to the CPR 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 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

2.2.1.1 Annual 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.

2.2.1.2 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.

2.2.1.3 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 bound by rolling-hills (Figure 1.1). 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) (cf Section 2.5). The highest peaks in the area are in excess of 1000 m AHD (The Governor and Mt Robinson) while the valley floors range between 700 m AHD down to 550 m AHD.

The study area comprises the Weeli Wolli Creek drainage basin. The greater Turee Creek drainage basin is adjacent to the west; tributaries of the greater Upper Fortescue River drainage basin are to the south and east. In these fringing areas, the drainage divide is not distinct but rather is marked by flat-lying internally draining areas - Coondewanna Flats to the west and Wanna Munna Flats to the south.

Weeli Wolli Creek is the main creek draining the area. It has one major named tributary - Pebble Mouse Creek and there are numerous other unnamed tributary creeks. Elevations at the edge of the study area range between 700 m AHD (Coondewanna Flats) and 750 m AHD (Wanna Munna Flats). The elevation at the outflow from the study area at Weeli Wolli Spring is 550 m AHD. The creeks have an average gradient of 0.4% across the study area, typical of streams in an inter-montane/piedmont environment.

2.4 Regional Drainage

The regional catchments and main river systems in the Pilbara region are shown in Figure 2.1. The CPR study catchments together with the main iron ore mine sites are highlighted in more detail in Figure 2.2. These study catchments (Coondewanna, Upper Weeli Wolli, Wanna Munna and Turee Creek East Branch) are located from approximately 50 km to 120 km to the northwest from Newman.

The regional drainage basins which contain the CPR deposits are the Fortescue River Basin and the Ashburton River Basin, with the Upper Weeli Wolli and Wanna Munna catchments located within the Fortescue River Basin and the Coondewanna and Turee Creek East Branch catchments located in the Ashburton River Basin.

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. The lower portion of the Fortescue River, downstream from the Fortescue Marsh, drains in a general north-westerly direction to the coast.

Although Wanna Manna catchment is located in the Upper Fortescue River catchment, surface water runoff in Wanna Manna is internally draining (discussed later in report) without discharge to the Fortescue (or Ashburton) River system.

2.4.2 Ashburton River Basin

The Ashburton River Basin with a catchment area of approximately 79,000 km^2 similarly drains west to northwest towards the Indian Ocean. The river starts approximately 50 km south from Newman and travels some 680 km to reach the coast at a point approximately 20 km southwest of Onslow. The river has many large tributaries with the Turee Creek and Angelo River being the main two tributaries closest to the CPR study area. The Rio Tinto Iron Ore mining centres of Tom Price, Paraburdoo and West Angelas are located within the Ashburton River catchment.

Although Coondewanna catchment is located in the Ashburton River catchment, surface water runoff in Coondewanna Flats is internally draining (discussed later in report) without discharge to the Ashburton River system.

2.4.3 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 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 may 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 one Department of Water (DoW) gauge located in the CPR study area, namely Tarina (gauge S708016). The Tarina gauge is located on Weeli Wolli Creek approximately 3 km downstream of Weeli Wolli Spring and 30 km east from MAC. This gauging station records streamflow from the Weeli Wolli catchment for the area above Weeli Wolli Spring (approximately 1,450 km^2) - in effect measuring surface water outflow from the entire CPR including surface water discharge from Hope Downs.

Peak streamflow discharges from ungauged catchments in the Pilbara region can be estimated using empirical techniques, such as those recommended in “Australian Rainfall and Runoff” (Institute of Engineers, 2013).

2.5 Geology

2.5.1 Tectonic Setting and Structure

The geology of the CPR 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. 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 CPR 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.

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. The Paraburdoo Member 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.

The CPR area is cross-cut by vertical transverse faults generally striking between NW-SE to NE-SW and movement of up to 3 km along these faults has occurred. Where seen in outcrop, the faults are narrow (<30 cm in width) and brecciation in the surrounding rock is limited (Keppert 2001).

The region has also been intruded by a series of dolerite dykes which also trend NW-SE to NE-SW. These mafic dykes readily weather to clay and form a low-permeability barrier to groundwater flow, particularly as their orientation transects the predominantly east-west orientated strike valleys along which regional groundwater flow tends to occur.

2.5.2 Lithology

The outcrop geology of the CPR 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 CPR.

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 Wanna Munna area in the south of the CPR, the Hamersley Group is absent exposing members of the Jeerinah Formation of the Fortescue Group that underlies the Hamersley Group. The lithology comprises basalt, dolerite sills and mudstone.

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 Tertiary detrital 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 groundwatertable and occurs typically over a wide area where groundwater is at shallow depth. Active calcrete formation at the watertable pushes 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 stygofauna community.

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 450m	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	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	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

2.6 Landscape and Environment

2.6.1 Bioregion

The CPR study area is situated within the Pilbara bioregion as defined under the Interim Biogeographic Regionalisation for Australia (IBRA).

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

- Chichester subregion: encompasses the granite/greenstone terranes of the northern Pilbara Craton but also includes the Chichester Plateau of the Hamersley Basin. While the broader Chichester subregion 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 subregion: delineated by the Fortescue River valley, which cuts through the sedimentary rocks of the Hamersley Basin. This region consists of salt marshes, mulga-bunch and short grass communities, with eucalypt (*Eucalyptus* spp.) woodlands along floodplains and associated with permanent springs.
- Hamersley subregion: the most prominent mountainous area in Western Australia, comprised 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 CPR study area is wholly located within the Hamersley sub-region.

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 CPR study area includes 17 land systems, the characteristics of which are outlined 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 flowpath patterns (Figure 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).

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

Land system	Land surface type	Percent of Project Area	Description	Geomorphology and soils
Boolgeeda	8	22.6%	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.
Calcrete	18	0.5%	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.
Egerton	5	2.1%	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	0.4%	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).
Jamindie	12	0.5%	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.
McKay	1	1.2%	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.
Marandoo	2	0.1%	Basalt Hills and restricted stony plains supporting grassy mulga shrublands.	Erosional surfaces including hills and ridges, steep upper slopes, more gently inclined lower slopes and stony interfluves, widely spaced tributary drainage floors and channels. Soils are generally shallow and stony.
Newman	1	37.4%	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.
Oakover	3	0.8%	Breakaways, mesas, plateaux and stony plains of calcrete supporting hard spinifex grasslands.	Erosional and depositional surfaces including mesas and buttes with steep breakaway faces descending onto calcareous plains dissected by channels. Soils are dominated by calcareous shallow loams.
Paraburdoo	10	0.4%	Basalt derived stony gilgai plains and stony plains supporting snakewood and mulga shrublands with spinifex and tussock grasses.	Mostly depositional surfaces, with isolated low basalt hills separated by broad plains dissected by braided or major drainage channels. Soils include a mixture of clays, loams and earths.
Pindering	12	1.2%	Gravelly hardpan plains supporting groved mulga shrublands with hard and soft spinifex.	Depositional surfaces including level to gently undulating stony and gravelly plains on hardpan. Numerous small linear or arcuate drainage foci. Soils are generally red shallow loams and duplex types.
Platform	5	8.1%	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.
River	17	0.3%	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	0.02%	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	8.9%	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	6.2%	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.
Table	4	0.1%	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).
Wannamunna	12	9.4%	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.

2.6.3 Vegetation and Flora

The CPR 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; 1990) are summarised in Table 2.6 and spatially depicted in Figure 2.5.

Table 2.5: Description of vegetation associations in the CPR Study Area (Beard, 1975)

Vegetation Association Reference	Percent of Study Area	Description
18	40.8%	Low woodland; mulga (*Acacia aneura* and its close relatives). Extensive in the broad valley systems across much of the study area
29	11.0%	Sparse low woodland; mulga, discontinuous in scattered groups. Generally associated with the Wannu Munna Flats in southern portions of the study area.
82	43.0%	Hummock grasslands, low tree steppe; snappy gum over *Triodia wiseana*. Extensive across the uplands of the study area.
175	3.3%	Short bunch grassland - savannah/grass plain (Pilbara). Confined to valley areas in the south east portion of the study area.
567	1.9%	Hummock grasslands, shrub steppe; mulga & kanji over soft spinifex and *Triodia basedowii*. Restricted to the north west portion of the study area.

McKenzie et al. (2009) provide a more recent synthesis of the broad patterns of vegetation in the IBRA subregions of the Pilbara bioregion. Relevant findings for the Hamersley subregion are summarised below.

2.6.3.1 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 flowpath 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[1] 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). a series.
- The small flowpaths 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 flowpath 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. *pilbarana*). These are also termed banded mulga formations.

Over the past decade, BHP Billiton Iron Ore has undertaken more detailed vegetation surveys across much of the northern portion of the study area (Figure 2.5). These surveys have generally been conducted in accordance with Environmental Protection Authority (EPA) guidelines for environmental impact assessment (EPA, 2002; EPA, 2004). 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 *Melaleuca argentea*, *Eucalyptus camaldulensis* and *E. victrix*. These species are invariably associated with EHU 8 and in some cases larger flowpath lines feeding into EHU 8.

Populations of the declared rare species *Lepidium catapycnon*, which is listed under State and Commonwealth legislation, have been recorded in upland areas of the Hamersley Range within the study area. Several priority listed flora, as recognised by the Department of Parks and Wildlife (DPaW), 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 (**Cenchrus ciliaris*) is notable due to its propensity to rapidly colonise alluvial surfaces via river systems and displace indigenous shrub and grass cover.

1. a series of coalescing alluvial fans along a mountain front

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 CPR study area, the major habitat types can be characterised as follows:

- Mountainous rugged terrain associated with the Hamersley Range comprising ridges, plateaus, steep hills with free faces and stream channels.
- Rolling hills and foothills associated with the Hamersley Range.
- Mulga woodlands and scrublands of the broad valleys.
- Calcrete plains adjacent to the upper Weeli Wolli Creek.
- The major flowpath systems and floodplains associated with Weeli Wolli Creek and its tributaries, including riparian woodlands.
- Internal drainage basins (e.g. Lake Robinson, Munjina Claypan and the Mt Bruce, Coondewanna and Wanna Munna Flats) including mulga and eucalypt woodlands.

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), and is generally considered to 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). In addition, two microbat species (*Nyctophilus bifax* and *Chalinolobus morio*) are considered to be restricted to productive riparian environments (McKenzie and Bullen, 2009). Within the CPR study area, the valley of Weeli Wolli Spring supports a rich microbat assemblage.

A number of fauna of elevated conservation significance, including those listed under State and Commonwealth legislation, are known from the CPR 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 flowpath systems and lakes. Notable species include Eastern Great Egret (*Ardea modesta*) 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).

While 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), none of these occur within the study area. However Weeli Wolli Spring is known to host a stygofauna community of conservation interest (DEC, 2013; DPaW, 2014).

2.6.6 Ecological Assets

The study area intersects uplands of the Hamersley Range along the eastern fringe of Karijini National Park. The national park comprises a complete north-south traverse section of the Hamersley Range. It contains a representative sample of many of the geological types, plant and animal communities and landscape forms of the central portion of the range. The floors of some gorges contain permanent water sources, which support riverine woodlands and disjunct plant and animal populations (CALM, 1999).

Portions of the study area currently under pastoral management have been proposed for non-renewal and transfer into the conservation estate post-2015 by the DPaW. This includes the Coondewanna Flats and immediate surrounds, and a section of the Hamersley Range along the northern fringe of the study area immediately east of Karijini National Park. Note that current pastoral leases were granted under the now repealed *Land Act 1933* (WA), and all will expire on 30 June 2015 (EDO 2010).

The study area does not contain any Threatened Ecological Communities (TECs) recognised under State and Commonwealth legislative frameworks. However several Priority Ecological Communities (PECs) described by DPaW (2014) occur within or near to the boundaries of the study area, including:

- Weeli Wolli Spring Community (PEC Priority 1) - Weeli Wolli Spring's riparian woodland and forest associations are unusual as a consequence of the composition of the understorey. The sedge and herbfield communities that fringe many of the pools and associated water bodies along the main channels of Weeli Wolli Creek have not been recorded from any other wetland site in the Pilbara. The spring and creekline are also noted for their relatively high diversity of stygofauna and this is probably attributed to the large-scale calcrete and alluvial aquifer system associated with the creek. The valley of Weeli Wolli Spring also supports a very rich microbat assemblage including a threatened species. Representation in the study area includes the major spring zone and Ben's Oasis further up-gradient.
- Coolibah-lignum flats: *Eucalyptus victrix* over *Muehlenbeckia* community - Woodland or forest of Eucalyptus victrix (Western Coolibah) over thicket of *Muehlenbeckia florulenta* (Lignum) on red clays in run-on zones. Associated species include *Eriachne benthamii*, *Themeda triandra*, *Aristida latifolia*, *Eulalia aurea* and *Acacia aneura*. A series of sub-types have been identified:

  - Coolibah woodlands over Lignum over swamp wandiree (Lake Robinson is the only known occurrence) (PEC Priority 1).
  - Coolibah and mulga woodland over lignum and tussock grasses on clay plains (Coondewanna Flats and Wanna Munna Flats) (PEC Priority 3).
- Brockman Iron cracking clay communities of the Hamersley Range (PEC Priority 1) - Rare tussock grassland dominated by *Astrebla lappacea* in the Hamersley Range, on the Newman Land System. Tussock grassland on cracking clays- derived in valley floors, depositional floors. This is a rare community and the landform is rare, with known locations near West Angeles, Newman, Tom Price and the boundary of Hamersley and Brockman Stations. One occurrence in the far south west of the study area (Figure 2.5). Here the cracking clay community overlies an alluvial plain with groundwater likely to be around 20 to 30 m below ground level and believed not to influence the surface cracking clay formation or its surface vegetation.
- The West Angelas cracking clay communities have been classified by the Department of Environment and Conservation as a PEC Priority 1 ecological community and defined as "Open tussock grasslands of *Astrebla pectinata*, *A. elymoids, Aristida latifolia*, in combination with *Astrebla squarrosa* and low scattered shrubs of *Sida fibulifera*, on basalt derived cracking-clay loam depressions and flowlines". Although the West Angelas cracking clay communities occur outside the study area, some of the BHP Billiton Iron Ore orebody areas are located in the upstream catchments of these communities (Figure 2.5) and therefore they warrant mention.

  As the West Angelas cracking clay areas occur outside of the CPR they have not been subject to field investigations by BHP Billiton Iron Ore. Topographical mapping indicates that the cracking clay zones typically occupy relatively flat areas in the landscape and are believed not to be present in the bounding and protruding outcropping zones. Geological mapping indicates that the West Angelas cracking clay communities generally overlie the low permeability Jeerinah Formation which is consistent with the clay being derived from basalt. Groundwater in this formation is believed to be around 15m below ground level, is moderately brackish and is unlikely to influence the surface cracking clay formation or its surface vegetation.

  Moisture replenishment in the West Angelas cracking clay ecological communities (as well as the Brockman Iron cracking clay communities) is believed to be dependent on direct rainfall and possibly surface runoff. Ephemeral water courses pass through the cracking clay zones. Surface runoff would locally replenish soil moisture along the water courses but typically not away from the water courses.

2.7 Water Use

Groundwater abstraction by BHP Billiton Iron Ore in the CPR is illustrated in Figure 2.6.

There are no permanent surface water resources in the CPR and all water use is supported by groundwater abstraction. Historically, there was only small amounts of groundwater abstraction from windmill-equipped pastoral bores and wells through the area. These bores typically targeted shallow aquifers.

Groundwater abstraction to support mining started in 2001 when BHP Billiton Iron Ore began constructing MAC. Early abstraction was for construction purposes and was less than 2,000 kL/d on average. This abstraction occurred from bores drilled into the regional dolomite/Tertiary detrital aquifer. Subsequently, abstraction increased to an average of approximately 5,000 kL/d when mining and ore-processing at C Deposit started.

In 2006, mining commenced at E Deposit and abstraction from the regional aquifer adjacent to E Deposit started, progressively increasing to approximately 4,000 kL/d by 2009.

All of this early abstraction was water demand-driven.

More recently, mining have progressed below the watertable at both C and E Deposits and abstraction has occurred to dewater the ore. This abstraction has occurred from a combination of the orebody aquifers and from the adjacent regional aquifer in proximity to the orebodies. Dewatering abstraction is approximately 6,000 kL/d and 12,000 kL/d at C and E Deposits respectively.

Dewatering abstraction volumes are driven by dewatering requirements, regardless of whether there is a subsequent use for the abstracted water and there have been occasions when there has been a surplus of produced water at the mine. At the beginning, surplus dewatering water has been returned to the groundwater system by disposal into and infiltration from onsite water storage basins (an in-pit lake and ex-pit pond). From 2012, excess water has also been reinjected directly back into the aquifer through a Managed Aquifer Recharge (MAR). MAR to the groundwater system by infiltration and reinjection can be seen as the “negative” flows in Figure 2.6.

In addition to BHP Billiton Iron Ore abstraction, there is substantial dewatering at Hope Downs at the eastern end of the MAC. There are no available data on Hope Downs’s abstractions. However, based on published information in environmental approval documentation, it is believed abstraction rates could be up to 100,000 kL/d.

3. REGIONAL HYDROLOGY

3.1 Surface Water

3.1.1 Setting and Key Features

3.1.1.1 General

The CPR orebodies are located within the Weeli Wolli Spring catchment which drains into the Upper Fortescue River catchment; the Coondewanna catchment which is an internally draining basin located in the Ashburton River Basin; and the Turee Creek East Branch catchment (within the Turee Creek catchment) also located in the Ashburton River Basin. The Wanna Munna catchment which is an internally draining basin located in the Upper Fortescue River catchment is also within the CPR study area (Figure 2.1).

In common with most natural drainage systems in the Pilbara region, the CPR study catchments contain ephemeral drainage systems flowing 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 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. 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 may 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 types, soil depths, 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.

Upland and Lowland Transitional Landscape Units may be 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.

These broad landscape units can generally be identified from the topographical mapping covering the CPR catchment areas. These maps typically show a high density of drainage gullies adjacent to the ridgelines, indicating higher runoff characteristics, discharging into a lower density of drainage channels away from the ridgelines and then draining downstream into larger more mature creek channels on the flatter slopes.

The main creek systems in the CPR study area (Weeli Wolli Creek, Homestead Creek and Turee Creek East Branch) have variable bed gradients. Weeli Wolli Creek has a typical bed gradient approximately 0.3% upstream and downstream from Weeli Wolli Spring, and approximately 1% through the spring zone. Homestead Creek flowing into the Coondewanna Flats is considerably flatter with an average bed gradient approximately 0.1%. Whereas Turee Creek East Branch has a typical bed gradient approximately 0.4% increasing to approximately 0.7% downstream from the orebody areas. The main flow channels of creek systems with reducing bed gradients typically show signs of becoming less defined with distance downstream and developing wider floodplains. These drainage characteristics lower the runoff velocities and spread runoff over a wider area, allowing more time and area for detention and infiltration, thus typically reducing the overall discharge volume progressing downstream.

3.1.1.2 Weeli Wolli Spring Catchment

The majority of the CPR orebodies are within the Weeli Wolli catchment upstream from Weeli Wolli Spring (Figure 2.2). Weeli Wolli Creek is an ephemeral surface water system and Weeli Wolli Spring is a natural surface expression of groundwater flow resulting from hydrogeological features in the creek bed. A typical view of Welli Wooli Spring is shown in Plate 3.1. The surface water catchment upstream from Weeli Wolli Spring has an approximate area of 1,450 km².

Weeli Wolli Creek is one of several large watercourses discharging into the Fortescue Marsh, and Weeli Wolli Spring is located approximately 60 km upstream from the Marsh. The bed elevation at the Weeli Wolli Spring is approximately 550 m AHD whereas the Fortescue Marsh has a bed level of approximately 400 m AHD. Ridgelines around Weeli Wolli Spring rise to over 800 m AHD. Other large watercourses discharging to the Marsh include Marillana/Yandicoogina Creek (via Weeli Wolli Creek) and the Fortescue River. Several tributary creeks enter Weeli Wolli Creek upstream from the spring, including Pebble Mouse Creek.

The CPR orebodies and existing mine areas located in the Weeli Wolli Spring catchment are shown on a topography plan in Figure 3.1. This plan shows details of the catchment and sub-catchment boundaries and flowpaths, in particular the main flow corridors which are located within the orebody outlines. The existing main diversion works within the MAC and at Rio Tinto Iron Ore Hope North are also shown.

Ben’s Oasis is a perennial pool on Weeli Wolli Creek located approximately 20 km upstream from Weeli Wolli Spring and with a catchment area of 418 km^2. The pool is a natural expression of the watertable which has mounded upstream of a dolerite dyke (URS, 2011). Wonmunna Waterhole (Wanna Munna Pool) occurs in a setting similar to Ben’s Oasis (URS, 2012), but approximately 8 km further upstream on a tributary to Weeli Wolli Creek (Figure 3.1).

The natural Weeli Wolli Creek channel and main tributaries are expansive and well defined. The bed slopes are moderately steep which, in conjunction with the flow regime, has resulted in the creek beds dominated by coarse gravels and pebbles. Although the Weeli Wolli Creek main channels are relatively wide and deep, large flood flows tend to overtop the banks.

The gravel bed along Weeli Wolli Creek and its main tributaries is generally clear of vegetation with the exception of occasional eucalypt trees, whereas the creek banks (and some floodplain zones) typically support a continuous ribbon of riparian eucalypts. Melaleuca trees are also present around Weeli Wolli Spring. Away from the creek channel, the vegetation typically changes to spinifex and shrubs. Riparian eucalypts along the creek channels tend to be less dense with distance upstream from Weeli Wolli Spring.

Based on historical streamflow data, Weeli Wolli Creek typically has up to two flow events a year. These events are generally short duration, with little post rainfall flow persistence, although peak discharges are typically generated by longer duration storms which saturate the catchment and streambed, resulting in streamflow. However, following above average wet seasons, the creek can flow for a period of several months. Under natural conditions, Weeli Wolli Spring discharges are continuous through the spring zone and dissipate into the river gravels a few kilometres downstream.

Water quality of Weeli Wolli Creek is circum-neutral to slightly basic. Water is fresh and typically dominated by sodium and bicarbonate. Water quality can vary significantly between the different creek systems in the same catchment, river reach and seasons (WRM, 2010).

With Rio Tinto Iron Ore development of the Hope Downs 1 deposit, mining operations have extended across Pebble Mouse Creek necessitating the creek to be diverted approximately 2 km eastwards from its natural course into the adjacent main Weeli Wolli Creek channel. This diversion is located approximately 3 to 4 km upstream from the natural confluence of the two creeks.

Excess dewatering water from mining operations at the Hope Downs 1 deposit is discharged into the main Weeli Wolli Creek channel just downstream from Weeli Wolli Spring. Small dewatering volumes are also discharged upstream from the spring, to maintain the natural pools and spring flows. The main dewatering discharges are believed to have created a surface expression of the watertable in the creek bed downstream from Weeli Wolli Spring to around its junction with Marillana Creek approximately 15 km downstream.

3.1.1.3 Coondewanna Catchment

Several of the CPR orebodies are located within the Coondewanna catchment, which is an internally draining catchment of approximately 860 km^2 located to the east of the Weeli Wolli Spring catchment (Figure 2.2). Although internally draining, the catchment is located within the Ashburton River Basin. catchment runoff is discharged into an internal depression known as Lake Robinson where water dissipates by seepage and evapotranspiration.

The CPR orebodies and existing mine areas located in the Coondewanna catchment are shown on a topography plan in Figure 3.2. This plan shows details of the catchment and sub-catchment boundaries and flowpaths, in particular the main flow corridors which are located within the orebody outlines. The existing main diversion works within MAC are also shown.

Although the runoff characteristics from ridgelines in the Coondewanna catchment would be typical of Pilbara catchments, topographical mapping shows that the catchment contains numerous large relatively flat areas where runoff would tend to pool and slowly flow downstream. These areas represent the clay-pan and hard-pan landscape units and runoff over many of these flattish areas would discharge as sheetflow. These characteristics indicate that relative runoff volumes would be low compared with a more free-draining catchment, such as the Weeli Wolli Spring catchment.

Lake Robinson is located in the south-eastern sector of Coondewanna catchment and is the lowest area at approximately 687 m AHD. This lake bed elevation is approximately 130 m higher than Weeli Wolli Spring which is located in the adjacent Weeli Wolli Spring catchment. An aerial view of Lake Robinson after the January 2014 flood event is shown in Plate 3.2. The main flowpath discharging to Lake Robinson is Homestead Creek which drains the northern half of the catchment. Where Homestead Creek passes adjacent to Packsaddle Hill, approximately 8 km north from Lake Robinson, the creek has a well-defined single channel and a streamflow gauging site has recently been established (URS, 2012b). The creek bed at this location is described as comprising coarse gravels and sands, approximately 15 m wide with 1 to 2 m high banks. Scattered eucalypt trees are located along the creek bed.

During a high rainfall event, runoff could potentially discharge to Lake Robinson from all sides, with proportionally higher runoff from ridgelines which are in close proximity. However, it is estimated that as runoff from over 50% of the catchment would need to pass through flattish slowly draining areas prior to reaching Lake Robinson, relative runoff volumes to the lake would typically be low for small to medium rainfall events. Significant runoff to Lake Robinson would likely only occur after a large rainfall event. It is estimated that runoff and inundation at the Lake has a return period of approximately once every four years (refer Chapter 4.2).

Two Rio Tinto Iron Ore railway corridors and the main Northwest Highway pass through the Coondewanna catchment, as shown in Figure 3.2. Earthworks associated with these transport corridors interrupt the natural drainage flowpaths, and culverts or bridges (and floodways on roads) are typically located at identified drainage flowpaths to allow runoff to pass downstream. Similarly access tracks may potentially interrupt the natural drainage flowpaths. Although culverts/bridges may have been located on identified drainage flowpaths, sheetflow zones are more difficult to manage. To cater for the sheetflow zones, it is understood that additional culverts have been installed along the railway corridors.

3.1.1.4 Wanna Munna Catchment

The Wanna Munna catchment is an internally draining catchment of approximately 350 km^2 located to the south of the Weeli Wolli Spring catchment (Figure 2.2). Although internally draining, the Wanna Munna catchment is within the Fortescue River Basin. There are no CPR orebodies within the catchment, except for the southeastern corner of Gurinbiddy. Due to the catchment largely comprising a collection of flattish slowly draining basins, some catchment boundaries are difficult to reliably define using published topographical mapping with 10 m contour intervals. Typical drainage basin areas within the catchment have elevations approximately 680 m to 700 m AHD. With the flat nature of the catchment, runoff collects in the poorly drained basins where water would dissipate by seepage and evapotranspiration.

3.1.1.5 Turee Creek East Branch Catchment

The Turee Creek East Branch catchment is located to the south of the Coondewanna catchment, and has a catchment area of approximately 600 km^2 (Figure 2.2). An area of calcrete is located at an elevation approximately 620 m AHD, approximately 70 m lower than Lake Robinson, and is surrounded by ridgelines rising to 900 m AHD. The catchment generally contains well defined flowpaths, except in its far eastern sectors where some flattish poorly drained areas are located.

The CPR orebodies located in the Turee Creek East Branch catchment are shown on a topography plan in Figure 3.3. This plan shows details of the catchment and sub-catchment boundaries and flowpaths, in particular the main flow corridors which are located within the orebody outlines. The Rio Tinto Iron Ore West Angela's mine site is located in this catchment.

3.1.2 Catchment Response to Rainfall

3.1.2.1 CPR rainfall data

Streamflow in the Pilbara region directly correlates to rainfall, and monitoring rainfall enables more reliable streamflow predictions. Rainfall data is also important for hydrogeological assessments. Locations of the existing and historical BOM and DoW rainfall monitoring stations in the general CPR area are shown in Figure 3.4 and listed in Table 3.1. Locations of the BHP Billiton Iron Ore rainfall monitoring stations, which typically have a more recent data record, are also shown. Rainfall monitoring stations are likely to be operating at the Rio Tinto Iron Ore mine sites though no public data are available.

Table 3.1: BOM & DoW Rainfall Monitoring Stations

Site No.	Site Name	Owner	Type	Date Commenced	Date Closed
505004	Munjina	DoW	Continuous	1969	-
505011	Flat Rock	DoW	Continuous	01/03/1970	-
505014	Packsaddle	DoW	Continuous	30/05/1970	03/09/1999
505035	Yandicoogina	DoW	Continuous	12/12/1979	14/04/1986
5009	Marillana	BOM	Daily Continuous	29/11/1936 08/09/1998	- -
505041	Waterloo Bore	DoW	Continuous	08/05/1985	-

Site No.	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	-
5089	Packsaddle Camp	BOM	Daily	1989	21/07/2002
505015	Juna Downs Station	DoW	Daily	1971	1973
505020	Juna Downs	DoW	Continuous	29/09/1973	18/11/1980
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	Jan. 1913	Dec. 1913
7176	Newman Aero	BOM	Continuous	14/12/1996	-
7191	Capricorn Roadhouse	BOM	Daily Continuous	27/02/1975 16/07/1984	- 20/11/2006
5064	Sand Hill	BOM	Daily	29/04/1971	30/07/1984
505038	Poonda	DoW	Continuous	29/11/1984	-

Of the 23 BOM/DoW rainfall monitoring stations listed in Table 3.1 for the CPR area, 10 are still operating. Although many of the rainfall monitoring stations are now closed, their data records are still useful. Several of the DoW rainfall (and streamflow) monitoring stations are believed to be supported by BHP Billiton Iron Ore.

BHP Billiton Iron Ore has installed full weather stations (recording rainfall, temperature, evaporation, humidity, etc.) at most of their operating mine sites including MAC and Yandi. At Jinidi, a rainfall gauging station with data logger has been installed, prior to a full weather station when the mine becomes operational. BHP Billiton Iron Ore has also recently installed rainfall monitoring stations at four sites within the Coondewanna catchment for assessing rainfall variability.

Representative rainfall data for the Weeli Wolli Spring catchment can be obtained by averaging between the Tarina, Wonmunna and Rhodes Ridge rainfall data. Similarly the Packsaddle, Packsaddle Camp, Wonmunna and MAC rainfall data can be used to represent the Coondewanna catchment. However no rainfall data are collected within the Turee Creek East Branch catchment, except for those collected by Rio Tinto Iron Ore at West Angela's.

Generated rainfall data for the CPR study area are also available from the SILO database where SILO is a meteorological dataset managed by the Science Delivery Division of the Department of Science, Information Technology, Innovation and the Arts (DSITIA). SILO is able to provide daily historical weather records 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 in regions were historical data is sparse, the SILO data would be less reliability.

Annual average rainfall recorded for the longer term rainfall monitoring stations in the CPR catchments are provided in Table 3.2. For comparison purposes and to provide a more definitive representation of wet season rainfall totals, these annual data are taken for the July to June water year for the period July 1985 to June 2013, except for Rhodes Ridge where recorded rainfall data after June 2003 are intermittent. SILO data for the centroids of the Weeli Wolli Spring, the

Coondewanna and the Turee Creek East Branch catchments are also shown. Note that due to no available rainfall records within the Turee Creek East Branch catchment, the SILO data is the only source of historical rainfall data which can be referred to.

Table 3.2: Average and Maximum Annual Rainfall (1985 – 2013)

Catchment	Station Name	Average	Maximum	Year of Maximum
Weeli Wolli	Tarina	367 mm	771 mm	2005 – 2006
	Wonmunna	376 mm	970 mm	1999 – 2000
	Rhodes Ridge [1]	421 mm	1,084 mm	1999 – 2000
	SILO Database (119.10°E, 23.05°S)	385 mm	1,001 mm	1999 – 2000
Coondewanna	Coondewanna Hybrid [2]	387 mm	1,036 mm	1999 – 2000
	SILO Database (118.75°E, 22.95°S)	398 mm	1,005 mm	1999 – 2000
Karijini	SILO Database (118.70°E, 23.15°S)	370 mm	739 mm	2005 - 2006

1. Rhodes Ridge Data from July 1985 – June 2003
2. Comprising Packsaddle, Packsaddle Camp, Wonmunna & MAC

As can be seen, the average annual rainfall in the CPR study catchments for the 28 year period (1985 – 2013) is approximately 380 mm (ignoring Rhodes Ridge which has a truncated record). Although there is some variability between the annual average rainfall totals and between the annual maximum rainfall totals, the data appear reasonably consistent.

For comparison purposes, average annual SILO rainfall isohyets across the Pilbara region are shown in Figure 3.5, 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 EPR study area. Average annual rainfall over the study catchments approximately 300 mm (1961–2012) which are slightly lower than the averages given in Table 3.3 (1980–2013), due to an increase in annual rainfalls over recent years.

An assessment of the long term annual rainfall totals for the Coondewanna 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 (it is expected that the Weeli Wolli Spring and Turee Creek East Branch catchments rainfall patterns would be similar). These annual data are shown plotted in Figure 3.6, together with a plot of the 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 plot of the five year moving average annual rainfall where average annual rainfall totals appear to have increased since the 1960s. The assessment shows that the long term average annual rainfall is 328 mm (1900–2013), as compared with an average annual of 385 mm for 1985 to 2013 (Table 3.2). This recent higher rainfall period would likely result in higher catchment runoff and aquifer recharge volumes as compared to the long term average.

CSIRO in partnership with the Western Australian Government Departments of Water and Regional Development, BHP Billiton Iron Ore and the Water Corporation are carrying out a scientific 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 eastern Pilbara since the 1960s.

3.1.2.2 CPR Runoff Data

Three DoW streamflow gauging stations have been located on Weeli Wolli Creek of which two are still operational. The locations of these gauging stations are shown in Figure 3.7 and station details given in Table 3.3. These gauging stations monitor streamflow discharges using DoW derived rating curves. The Tarina station, installed in 1985, is located approximately 4 km downstream from Weeli Wolli Spring and measures streamflow from the catchment above Weeli Wolli Spring (approximately 1,450 km^2), plus from an approximate additional 50 km^2 catchment area between the two stations. Additionally, surface water flows arising from the Rio Tinto Iron Ore dewatering discharge system flow through the gauging station site and are included in the streamflow discharge data. The Weeli Wolli Spring station was installed at a later date (1997) to directly measure the spring discharge which was not recorded at the Tarina site (natural spring surface flows did not extend to Tarina). The Waterloo Bore station, located approximately 20 km downstream from the Tarina station, monitors streamflows from Weeli Wolli, Yandicoogina and Marillana Creeks, but is less relevant to the CPR study area.

Table 3.3: Weeli Wolli Creek DoW Streamflow Gauging Stations

Station Number	Station Name	Location (MGA Z50)	Status	Station Opened	Station Closed
708016	Weeli Wolli Spring	726,831E, 7,464,086N	Closed	08/10/1997	14/07/2008
708014	Tarina	729,240E, 7,467,654N	Open	10/05/1985	-
708013	Waterloo Bore	740,180E, 7,484,344N	Open	30/11/1984	-

Comprehensive daily data are available for all three sites, with the exception of the Weeli Wolli Spring station, which was washed away by runoff from Cyclone John in December 1999. The Cyclone John flood event dramatically altered the Weeli Wolli Creek bed and bank profile rendering the existing gauging site unsuitable. A temporary replacement gauging station, designed to monitor spring discharges only, was installed approximately 600 m downstream of the original site in December 2000. This was never upgraded to a permanent site due to traditional owner concerns, changes to the natural flow regime from dewatering contributions from Hope Downs (from contributions upstream of the gauge), frequent vandalism and flood damage. These factors resulted in the closure of the station in 2008. As such, there is currently no streamflow gauging station available to measure low flows directly at Weeli Wolli Spring. As mentioned above, although the Tarina station cannot measure base flows at the spring, it should provide a reliable measure of the overall catchment discharges, provided a correction factor can be applied to account for the Rio Tinto Iron Ore dewatering discharges.

No DoW streamflow gauging stations have been located within the Coondewanna catchment with the nearest gauges being at Tarina (discussed above) and at Flat Rocks. The DoW Flat Rocks streamflow gauging station (gauge S708001) is located on Marillana Creek, being the next main catchment north from Coondewanna and not part of the CPR study area. The gauging station is located to measure runoff from the upper half of Marillana Creek and has a catchment area of 1,370 km^2 (refer Figure 3.3). This station has been open since September 1967 and has approximately 46 years of mostly unbroken streamflow record. The upper Marillana catchment contains large flat storage areas, in particular the Munjina Claypan, which attenuates catchment runoff. The hydrological characteristics of Coondewanna catchment, with its numerous large relatively flat slow draining areas, are considered to be more akin to those within the upper Marillana catchment (recorded at Flat Rocks gauge) than those within the Weeli Wolli Creek system.

To supplement the DoW streamflow monitoring system, BHP Billiton Iron Ore installed several crest gauges around the Weeli Wolli and Coondewanna catchments in 2011 and 2012. The locations of these monitoring sites are shown in Figure 3.7 and the station details are listed in Table 3.4. These stations have been in operation for one to two wet seasons, but at this stage their data records have not been assessed.

Table 3.4: BHP Billiton Iron Ore Streamflow Gauging Stations

Catchment	Crest Gauge	Location (MGA Z50)	Station Installed
Weeli Wolli	South Flank	699,555E, 7,453,047N	4 Dec 2011
	Jinidi A	728,590E, 7,460,374N	8 Dec 2011
	Jinidi B	731,653E, 7,458,163N	8 Dec 2011
	Ben's Oasis Downstream	722,914E, 7,450,952N	15 Dec 2011
	B Deposit	712,479E, 7,460,901N	16 Dec 2011
Coondewanna	HCF0017	677,928E, 7,462,957N	8 Dec 2011
	HCF0018	687,519E, 7,453,631N	Nov 2012
	HCF0019	685,609E, 7,454,382N	Nov 2012
	HCF0020	682,694E, 7,453,197N	Nov 2012
	HCF0021	682,007E, 7,457,900N	Nov 2012
	HCF0022	680,344E, 7,452,955N	Nov 2012

3.1.2.3 Weeli Wolli Spring Catchment Runoff Volumes

A significant number of the CPR orebodies are located in the 1,500 km^2 catchment area upstream of the Tarina streamflow gauging station. Monthly streamflow volumes at Tarina gauging station (January 1985 to April 2013) are presented in Figure 3.8, together with the corresponding monthly SILO rainfall for the catchment. The Tarina streamflow gauging station also records the surface water flow component of the Rio Tinto Iron Ore dewatering flows which are being discharged to Weeli Wolli Creek just downstream of Weeli Wolli Spring. These discharges commenced in January 2007. Based on the gauged discharges, an approximate estimate of the average surface water component due to dewatering discharges has been abstracted from the recorded data. The adopted dewatering components abstracted are 800 ML/mth for Jan 2007 to June 2008; 2,000 ML/mth for July 2008 to June 2010; and 2,500 ML/mth for July 2010 to April 2013. These Rio Tinto Iron Ore discharges have compromised the Tarina gauging station to reliably measure catchment rainfall runoff volumes since January 2007. However for large individual runoff events, the Rio Tinto Iron Ore discharges would have a relatively minor impact on the peak discharge measurement and total runoff volume.

A comparison of the recorded Weeli Wolli Spring and Tarina streamflow annual volumes (adjusted for estimated Rio Tinto Iron Ore dewatering discharges) is given in Table 3.5 for the period of data availability at the Weeli Wolli Spring gauge, using the July to June water year. To compare just the catchment rainfall runoff, the Weeli Wolli Spring monthly data have also been adjusted to remove the groundwater component (measured baseflow) adopted at 210 ML/mth. As the table data shows, there is considerable variability between the recorded annual flow volumes between the two gauging stations with no discernible pattern. As the replacement Weeli Wolli Spring gauging station was established to monitor spring discharges only (not high streamflows), the reliability of this streamflow gauge to measure large runoff events is questionable. As such, the Tarina gauging station should be used for assessments of the CPR catchment rainfall runoff volumes.

Table 3.5: Tarina and Weeli Wolli Spring – Annual Streamflow Gauging Volumes Comparison

Year	Annual Runoff Volume at Tarina (ML)	Annual Runoff Volume at Weeli Wolli Spring (ML) [1]	Tarina / Weeli Wolli Spring Runoff Volume Ratio
1998 – 1999	17,763	24,783	0.72
1999 – 2000	147,305	Station Damaged	NA
2000 – 2001	9,516	Station Damaged	NA
2001 – 2002	192	0	NA
2002 – 2003	31,224	19,792	0.58

Year	Annual Runoff Volume at Tarina (ML)	Annual Runoff Volume at Weeli Wolli Spring (ML) [1]	Tarina / Weeli Wolli Spring Runoff Volume Ratio
2003 – 2004	3,887	1,312	2.96
2004 – 2005	98	0	NA
2005 – 2006	24,102	9,032	2.67
2006 – 2007	1,685 [2]	7,554	0.22
2007 – 2008	11,891 [2]	20,100	0.59

1. Adjusted to remove Weeli Wolli Spring baseflow (adopted at 210 ML/month)
2. Adjusted to remove Hope Downs dewatering discharge component (adopted at 800 ML/month for Jan. 2007 to June 2008

To assess the annual correlation between rainfall depths and runoff volumes for the Weeli Wolli Spring catchment, the catchment SILO annual rainfall was compared to the Tarina annual discharge volumes for the 28 year period of data availability at the Tarina gauge, using the July to June water year. These annual data are given in Table 3.6 together with the calculated annual runoff percentages. The total catchment runoff over the 28 year period is estimated at 2.4% of the total rainfall (i.e. average 9.3 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 0.95% of annual rainfall (3.0 mm/year) could be considered a more typical runoff characteristic for the catchment and is significantly less than the long term average runoff of 2.4% (9.3 mm/year).

Table 3.6: Tarina Catchment - Annual Rainfall and Runoff (1985 – 2013)

Year	Weeli Wolli Spring Catchment Annual SILO Rainfall (mm)	Tarina Annual Runoff Volume (ML)	Annual Runoff
1985 – 1986	176	0	0.0%
1986 – 1987	281	0	0.0%
1987 – 1988	374	7,403	1.3%
1988 – 1989	318	0	0.0%
1989 – 1990	190	1,771	0.6%
1990 – 1991	208	0	0.0%
1991 – 1992	335	748	0.1%
1992 – 1993	312	1,383	0.3%
1993 – 1994	201	158	0.1%
1994 – 1995	590	26,894	3.0%
1995 – 1996	236	27	0.0%
1996 – 1997	692	18,500	1.8%
1997 – 1998	196	304	0.1%
1998 – 1999	775	17,763	1.5%
1999 – 2000	1001	147,305	9.8%
2000 – 2001	389	9,516	1.6%
2001 – 2002	311	192	0.0%
2002 – 2003	470	31,224	4.4%
2003 – 2004	409.5	3,887	0.6%
2004 – 2005	108.4	98	0.1%
2005 – 2006	718.7	24,102	2.2%
2006 – 2007	328.3	1,685 [1]	0.3%

Year	Weeli Wolli Spring Catchment Annual SILO Rainfall (mm)	Tarina Annual Runoff Volume (ML)	Annual Runoff
2007 – 2008	309.1	11,891 [1]	2.6%
2008 – 2009	338.7	26,138 [2]	5.1%
2009 – 2010	124.3	5,382 [2]	2.9%
2010 – 2011	467	12,267 [3]	1.8%
2011 – 2012	492.2	28,569 [3]	3.9%
2012 - 2013	432.9	14,171 [3]	2.2%
Average	385 mm	13,978 ML	2.4% [4]
Median Value	332 mm	4,635 ML	0.95%

1. Adjusted to remove Hope Downs dewatering (adopted at 800 ML/month)
2. Adjusted to remove Hope Downs dewatering (adopted at 2,000 ML/month)
3. Adjusted to remove Hope Downs dewatering (adopted at 2,500 ML/month)
4. Volume weighed average for 28 year record

Plots of the annual runoff percentage versus annual rainfall (Table 3.6 data) and the monthly runoff percentage versus monthly rainfall for the Weeli Wolli (Tarina) catchment are shown in Figure 3.9. Given the unreliability of the runoff volume data after 2007 (due to Rio Tinto Iron Ore dewatering discharges), these data points were omitted. As expected, the data generally shows that the runoff percentage (of rainfall) increases with rainfall depth. Although relationship trend lines have been plotted in the figure, 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 in the figure (i.e. effectively zero rainfall with high runoff). These data points have been removed from the plot.

Based on the Tarina streamflow annual volume assessment (1985 to 2013), the corresponding average and median runoff volumes for Weeli Wolli Spring catchment (1,450 km^2) and Ben's Oasis catchment (418 km^2) have been estimated, assuming that the runoff volumes are a direct area proportion to those recorded for the Tarina catchment (1,500 km^2). These estimates are given in Table 3.7.

Table 3.7: Weeli Wolli Spring Catchment - Annual Runoff Estimate (1985 – 2013)

	Tarina Catchment Annual Runoff Volume (ML)	Weeli Wolli Spring Catchment Annual Runoff Volume (ML)	Ben's Oasis Catchment Annual Runoff Volume (ML)
Average	13,978	13,510	3,900
Median Value	4,635	4,480	1,290

3.1.2.4 Coondewanna Catchment Runoff Volumes

Although not located in the CPR study area, the runoff characteristics of the upper Marillana Creek catchment, as recorded at the Flat Rocks streamflow gauging station, are believed to better represent the Coondewanna catchment than those recorded at the Tarina streamflow gauging station (on Weeli Wolli Creek). As such, these Flat Rocks data have been used to provide runoff estimates for the Coondewanna catchment.

In a similar manner as undertaken for the Weeli Wolli Creek (Tarina) streamflow volume assessment, an assessment of the annual correlation between rainfall depths and runoff volumes for the upper Marillana catchment has been undertaken. This assessment used the catchment SILO annual rainfall data (for the catchment centroid) and the Flat Rocks annual discharge volumes for the 44 year period of usable data (two years of data not complete) at the gauging station, using the July to June water year. A summary of the assessment results is given in Table 3.8. The total catchment runoff over the 44 year period is estimated at 2.05% of the total rainfall (average 8.3 mm/year). Whereas the median catchment runoff at 0.65% of annual rainfall (2.4 mm/year) could be considered a more typical runoff characteristic for the catchment (50%

AEP) and is significantly less than the long term average runoff which has been distorted by the more extreme flood volume events. Based on a probability assessment for the annual runoff volumes, the long term annual average runoff volume (11,353 ML) represents approximately a 25% AEP (annual exceedance probability) (4 year ARI) event.

Table 3.8: Flat Rocks Catchment - Annual Rainfall and Runoff Summary (1967 – 2013)

	Flat Rocks Catchment Annual SILO Rainfall (mm)	Flat Rocks Annual Runoff Volume (ML)	Annual Runoff	Coondewanna Catchment Annual Runoff Volume (ML)
Average	402	11,353	2.05%	7,130
Median Value	355	3,263	0.65%	2,050

Assuming that the Coondewanna catchment (860 km^2) runoff volumes are a direct area proportion to those recorded for the upper Marillana Creek at Flat Rocks (1,370 km^2), then the predicted corresponding annual runoff volumes for the Coondewanna catchment are shown in Table 3.7 for the period 1967 to 2013. When assessed using the long term SILO annual rainfall data, which are lower than the more recent data, the long term annual volume estimates also are reduced (refer Section 4.2).

3.1.2.5 Turee Creek East Branch Catchment Runoff Volumes

As streamflow gauging is not undertaken in the Turee Creek East Branch catchment, a correlation with a nearby gauged catchment is required to obtain an annual runoff volume estimate. For this correlation, the Tarina gauging data were selected, as the runoff characteristics of the Weeli Wolli Spring catchment, are considered to better represent the Turee Creek East Branch catchment than those recorded at the Flat Rocks streamflow gauging station (Marillana Creek). Both gauging stations are located approximately 50 km away.

Based on the Tarina streamflow annual volume assessment (1985 to 2013), the corresponding average and median runoff volumes for Turee Creek East Branch catchment (600 km^2) have been estimated, assuming that the runoff volumes are a direct area proportion to those recorded for the Tarina catchment (1,500 km^2). These estimates given in Table 3.9 provide an indication of the annual surface water runoff volumes discharging through the Turee Creek East Branch catchment area.

Table 3.9: Turee Creek East Branch Catchment - Annual Runoff Estimate (1985 – 2013)

	Tarina Catchment Annual Runoff Volume (ML)	Turee Creek East Branch Catchment Annual Runoff Volume (ML)
Average	13,978	5,590
Median Value	4,635	1,850

3.1.3 Peak Discharges

Based on the streamflow record available for the Tarina gauging station (DoW Station 708014), a partial series flood frequency analysis of the available monthly peak streamflow data was completed to estimated peak discharges for a range of design AEP flood events. The assessment found that the Log Pearson Type III Distribution, as recommended in Australian Rainfall and Runoff (Institute of Engineers Australia, 2013), provided the best data fit. The design peak discharges estimated by this procedure are given in Table 3.10 and range between 130 m^3/s for the 50% AEP event to 2,320 m^3/s for the 1% AEP event. The peak discharge recorded during the data record was 2,100 m^3/s which resulted from Cyclone John (Dec. 1999) and corresponds to between a 2% and 1% AEP event.

Table 3.10: Peak Discharges at Tarina & Flat Rocks Gauging Stations

Flood Event	Tarina Estimated Peak Discharge (m^3/s) [1]	Flat Rocks Estimated Peak Discharge (m^3/s) [2]	Coondewanna Estimated Peak Discharge (m^3/s) [3]
50% AEP	130	79	57
20% AEP	260	240	170
10% AEP	440	420	300
5% AEP	730	660	480
2% AEP	1,420	1,100	790
1% AEP	2,320	1,500	1,080

[1] Tarina area of 1,500 km^2

[2] Flat Rocks area of 1,370 km^2

[3] Coondewanna area of 860 km^2

For comparison, the design peak discharge estimates for the Flat Rocks gauging station are also given in Table 3.10. These data were derived by Rio Tinto Iron Ore (Rio Tinto Iron Ore, 2010). For the 5%, 10% and 20% AEP events, the design peak discharges for both catchments are similar, whereas for the 50% AEP event and 1% and 2% AEP events, the Flat Rocks design peak discharges are noticeable lower. These lower peak discharges are assumed due to the catchment attenuation in the Flat Rocks catchment.

Assuming that the Coondewanna catchment (860 km^2) peak discharges are a direct proportion to those recorded for the upper Marillana Creek at Flat Rocks (1,370 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 for the Coondewanna catchment are shown in Table 3.10.

3.2 Groundwater

3.2.1 Setting

Broadly, the CPR 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 potential in the CPR area was included in Table 2.3. A generic hydrostratigraphical section is provided in Figure 3.10 to illustrate the hydrogeology of the CPR area.

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. However, even when present, such thrust faulting is quite variable in nature:

- At Hope Downs, thrust faulting has resulted in greatly enhanced permeability within the West Angela Member and movement along the fault is of sufficient extent to have brought Paraburdoo Member into contact with the ore. This has resulted in a very permeable hanging-wall and large inflows to the pit.
- At BHP Billiton Iron Ore's MAC E Deposit, the thrust fault is permeable and has resulted in enhanced permeability through the West Angela Member. However, perhaps because movement has not occurred to the extent that dolomite is in contact with the ore, the resulting inflows are not of the same magnitude as Hope Downs.
- By contrast to E Deposit, the thrust fault at C Deposit has a much more variable permeability and the West Angela Member provides more complete hydraulic isolation of the orebody aquifer.

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

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

Mt Sylvia Formation (Mt Sylvia) and overlying Mt 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. It should be noted that aquifer potential also exists in haloes of submineralised ore (around 40% to 50% Fe) around and between the main orebodies.

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).

No Brockman deposits have been mined in the CPR to date. In the Eastern Pilbara Region, the Brockman orebody aquifer in Orebody 23 and Orebody 25 is in direct hydraulic connection with the Tertiary detritals of the Fortescue River Valley. Dewatering requirements have ranged between10 ML/d to 20 ML/d at these pits.

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 Tertiary sediment, where present, comprises sands silts and pisoliths and is generally 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.

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.

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 margins of the valley, screes may be preserved representing the TD3 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 and form part of a regional aquifer.

3.2.3 Hydrostratigraphic Connectivity

BHP Billiton Iron Ore projects in the CPR area have been grouped into eight mining areas (refer Table 1.1); other mining companies have an additional three mining areas in the CPR. In each case, the mining area comprises are series of orebodies 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). Abstracting 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).

In other cases, the orebodies are juxtaposed against Tertiary detritals which are often in hydraulic connection with aquifers in underlying Paraburdoo Member dolomite. Abstraction from these orebodies will draw water from the regional groundwater system. Operating experience from E Deposit (MAC) or Hope Downs (North Flank Valley) shows the impact of this can be wide ranging and abstraction volumes will be large.

The extensive occurrence of the permeable dolomite (Paraburdoo Member), overlain by saturated and sometimes permeable alluvium, results in lateral connectivity and a regional groundwater flow system throughout the CPR. In places there are low-permeability dykes which can retard groundwater flow in the dolomite, but there remains connectivity throughout the system.

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

3.2.4 Hydraulic Parameters

3.2.4.1 Hydraulic Conductivity

Table 3.11 summarises the range in hydraulic conductivities that have been determined for the major hydrogeological units of the CPR. These estimates comprise both the results of field tests (falling/rising head tests, airlift tests and abstraction tests) and parameters determined through the process of calibrating numerical models.

There is a considerable range in estimates of hydraulic conductivity which reflects both the range in methods of determination and also natural variation within the formations across the Hamersley Basin. Considerable variation will occur on a local scale where the permeability in a formation is secondary and reliant on the development of either solution or structural features. For example, while the Paraburdoo Member is a major regional aquifer in most places, the hydraulic conductivity derived from any test will vary with the degree of karst-development encountered in a specific bore. As such, the estimates that are determined from numerical modelling exercises may provide the most representative averages 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 Aquifers

The major regional aquifer which occurs over a wide area and provides continuity within the regional groundwater system, comprises the Paraburdoo Member dolomite and the overlying Tertiary detritals; notably the calcrete/silcrete and CID/geothitic hardcap of TD2.

Estimates of the hydraulic conductivity of the Dolomite aquifer (from field testing) range between 0.1 m/d to 105 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 (from field testing) 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 lumped into a single hydraulic unit during modelling, masking any difference in hydraulic conductivity between calcrete/silcrete and CID/goethitic 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/goethitic 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 5 and 7 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

*1 – No estimates available from previous work, suggested value only.

3.2.4.3 Aquifers Associated with Geological Structure

Some local aquifers occur associated with specific faults and/or folds and their hydraulic conductivity is site-specific. The Triplets, Bruno's Band and Colonial Chert are prominent chert bands within the Mt Sylvia and the Mt McRae. In tightly folded settings (e.g. in the footwall of some Brockman deposits), these cherts have been broken/brecciated and form local aquifers. Hydraulic conductivities in the order of 10 m/d are commonly reported. 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 (EPR).

Similarly, discontinuous local aquifers caused by fault zones have been reported in the Jeerinah Formation; for example in the West Angela's mine area where the outcrop of Jeerinah is contiguous with the outcrop of Jeerinah at Wanna Munna Flats in the CPR. In this area, discontinuous zones of enhanced permeability are known to occur along 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.

Other than these local-scale features, there is no evidence in the groundwater level data that structural features play a major role in the flow systems in CPR. This is corroborated by a detailed investigation by Solid Geology (2013) that found no evidence of structural influences on dewatering at E Deposit (other than the generally enhanced hanging wall permeability caused by the thrust fault).

3.2.4.4 Aquitards

The BIFs of the Weeli Wolli Formation and unmineralised Marra Mamba and Brockman behave as aquitards with adopted hydraulic conductivity (derived from numerical modelling) ranging between 0.001 m/d and 0.01 m/d. However, it is noted that the very few available data from field tests suggest the hydraulic conductivity is some two or more orders of magnitude higher for these units. Most tests will have taken place during an orebody investigation. It is interpreted that 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 also higher than the limited available field testing data, at 0.8 m/d. This is due to the fact that 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 proximity to an orebody. In such areas, experience 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. Thus, the higher derived estimates of hydraulic conductivity 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 CPR is crossed by several dolerite dykes trending northwest-southeast and northeast-southwest. These orientations cross the predominantly east-west orientated strike valleys (and hence the dolomite of the regional aquifer). The dolerite is low permeability, where oxidised forms clay, and acts as a hydraulic barrier to groundwater flow. Key examples of the effect of low permeability dolerite dykes on the regional aquifer occur between C and E Deposits, between Hope Downs and A Deposit and on the south-east margins of Coondewanna Flats. The dykes do not influence the regional groundwater flow direction. However, in all cases there are large changes in groundwater levels across the dyke. The permeability of dolerite has largely been determined through the calibration of groundwater models and is estimated to be 0.01 m/d.

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 MAC 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 CPR area are shown in Figures 3.11a to 3.11h. The following can be interpreted:

- Hydrographs show a strong seasonal or periodic response in the Coondewanna Flats and Weeli Wolli Spring areas. These are Lowland Receiving Landscape Units and are characterised by relatively shallow depths to watertable.
- Elsewhere the hydrographs show only very muted long term trends. Most of the CPR area is represented by Upland and Transitional Landscape Units which are characterised by deeper groundwater levels.

3.2.5.1 Lowland Receiving Landscape Units

- At Coondewanna Flats and fringes of Weeli Wolli Spring, rises in groundwater levels are observed in 2003 (the record extends this far back only at Weeli Wolli Spring), 2006 and 2012 and relate to larger wet-season rainfalls. Recharge only occurs once soil moisture deficits have been satisfied. Rainfall events large enough to achieve this are estimated to occur once every four years when monthly rainfall totals exceed 180 mm (ref Section 3.1).
- The groundwater level rise following such a large rainfall event at Coondewanna Flats is between 1 m and 3 m.
- In the Weeli Wolli Spring area, groundwater level rises occur on an almost annual basis which suggests significant groundwater recharge is generated most wet seasons due to flows in Weeli Wolli Creek. Recharge at Weeli Wolli Spring will occur more readily than at Coondewanna Flats as water infiltrates directly from the creek into the calcrete across which the creek flows (with little soil moisture deficit to overcome).
- The average groundwater level rise at Weeli Wolli Spring during the wet season is approximately 0.5 m to 1 m.
- Notwithstanding seasonal recharge at Weeli Wolli Spring the hydrographs show an overall declining trend since 2006 when dewatering at Hope Downs commenced.

3.2.5.2 Upland and Transitional Landscape Units

- Hydrographs away from Coondewanna Flats and Weeli Wolli Spring do not show a strong seasonal or periodic response. Hydrographs in the Tandanya mining area show a slight but continuous increasing trend since monitoring started in 2006 and 2010 suggesting they are responding to “slower" processes - perhaps the climatic trend of wetter and drier periods occurring over several years; there is a general trend of wet and dry periods occurring every nine years or so and 1998 to 2006 was significantly wetter than average.
- Groundwater levels between Coondewanna Flats and MAC (HCF001P) rose continuously between 2000 and 2009 without any marked seasonality. It is believed this is a delayed response to increased recharge during the 1998 to 2006 wet period. The slow rise indicates recharge occurred some distance from the area where the bore is located and took time to reach the bore as groundwater throughflow.
- Hydrographs at MAC are affected by abstraction in the North Flank Valley since 2001 and in particular dominated by the effects of dewatering since 2006. However, no seasonal trends are readily discernible superimposed on the overall water level declines.
- In the South Flank Valley, the response in bore HSF0002M, on the eastern margin of Coondewanna Flats, is an extension of the response at Coondewanna. Within the area likely to reflect the hydrological regime of the South Flank Valley, bore HSF0001M is located at the eastern end of the valley and shows no seasonal response. The around this bore is characterised by a depth top water in excess of 30 m and transitional landscape units; a similar environment extends west along the valley towards Mt Robinson and based on depth to water data and the lack of a receiving landscape units along the valley, no strong seasonal trend would be anticipated.

3.2.5.3 Recharge Volume

Groundwater recharge occurs preferentially in the area of Coondewanna Flats and Weeli Wolli Spring. In combination these two areas account for approximately 13,500 kL/d of recharge. Notwithstanding the daily average recharge rate, recharge actually occurs seasonally or periodically resulting from high magnitude low frequency rainfall events; on average recharge occurs annually at Weeli Wolli Spring and every four years at Coondewanna Flats.

Chemical evolution of the groundwater suggests most recharge occurs as direct infiltration through the Tertiary detritals (Dogramacci and Dodson 2009). Correlation of recharge areas in the CPR (i.e the Weeli Wolli and Coondewanna areas from which hydrographs demonstrate a seasonal response) with depth to water suggests this recharge place where the depth to water is less than 30 mbgl and where the catchment is large enough to generate substantial runoff volumes.

Elsewhere, infiltration will occur and will be an important contributor to soil moisture. However, it appears infiltration volumes in other areas are insufficient to result in significant recharge to the groundwater system, rather replenishing soil moisture.

The total catchment water balance indicates total recharge is approximately 15,000 kL/d. The remaining 1,500 kL/d of recharge that does not recharge at Coondewanna Flats or Weeli Wolli Spring probably occurs as diffuse recharge across the catchment in response to subtle changes in soil-moisture between wetter and drier periods. It is likely that this recharge occurs at low rates in the following areas:

- At the valley margins, coarser sediments and colluvium will capture runoff from the hills occurring both as sheet flow and channelised flow.
- Over the orebodies, where the permeable geology at outcrop will allow infiltration of rainfall and runoff occurring both as sheet flow and channelised flow.
- In the main creeks, as seepage from alluvial gravels after flood events.

3.2.5.4 Recharge Processes – Coondewanna Flats

Simplified modelling of the recharge processes at Coondewanna Flats was undertaken with a 1D model. A specific focus was to gain a better understanding of the soil moisture budget for the Clay-Pan and Hard-Pan landscape units and in particular, to review the extent to which capillary rise from the watertable may support soil moisture at Coondewanna Flats.

In addition to this key focus, the model also gave an insight into recharge processes in the other more common Transitional Landscape Units across the CPR that are characterised by greater depths to water. The model showed that in areas where the unsaturated soil profile is deep (greater than around 30 m) and where the availability of recharge water is less (because in Upland and Transitional Landscape Units, the water runs off during a flood event whereas it is retained at Coondewanna Flats), much lower rates of recharge occur - to the extent that recharge would barely be discernible in a hydrograph.

In relation to the preferential recharge zone at Coondewanna Flats, this modelling showed how the volume and attenuation of runoff in the Coondewanna Flats area combined with relatively shallow depths to groundwater causes recharge. During these periodic recharge events, the soil moisture is also replenished and is a key factor in the health of halophytic vegetation. The modelling suggests capillary rise from the groundwater is unlikely to be a major component of the soil moisture budget (ref Chapter 4).

3.2.6 Groundwater Levels and Flow

Groundwater generally flows across the catchment from west to east from the Tandanya and Mudlark mining areas through Coondewanna Flats and along the North and South Flank Valleys (Figure 3.12). Groundwater then flows to the northeast with flow concentrating on Weeli Wolli Spring. Weeli Wolli Spring marks the surface and groundwater outflow from the CPR area. The spring occurs where Weeli Wolli Creek passes through a gorge eroded through the Wildflower Range. Downstream of the gorge, the creek flows through a narrow channel past the confluence with Marillana Creek and ultimately into the Fortescue River Valley.

There is also a component of groundwater flow from south to north originating on Wanna Munna Flats - a plateau of Jeerinah Formation. Flow occurs from here to the north into the Pebble Mouse Creek and Weeli Wolli Creek drainage systems and then to Weeli Wolli Spring.

Groundwater levels are approximately 700 m AHD at the catchment margins (Wanna Munna to the south and the Mt Meharry/Juna Downs area in the west). Groundwater levels fall to 550 m AHD at the spring outflow.

In the west the groundwater gradients from the Tandanya and Mudlark mining areas into Coondewanna Flats are low at approximately 0.001, suggesting little throughflow along these valleys. Gradients from Coondewanna Flats along the North and South Flank valleys are three-times steeper at 0.003. Given the regional aquifer in the North and South Flank Valleys (comprising dolomite and overlying Tertiary detritals) is likely to be comparable with the regional aquifer in the Mudlark and Tandanya mining areas, this suggests much larger volumes of throughflow along the North and South Flank Valleys. This is consistent with a large volume of recharge occurring in Coondewanna Flats (refer Section 3.2.5).

Groundwater levels are high on the plateau of Jeerinah Formation at Wanna Munna Flats in the south and this marks an indistinct groundwater catchment boundary between the headwaters of Weeli Wolli Creek and adjacent Coondiner Creek, Turee Creek and the Fortescue River. Hydraulic gradients indicate a component of flow across strike to the north draining into the Pebble Mouse and Weeli Wolli Creek flow systems. Gradients are very steep which reflects the low-permeability across strike and the low permeability nature of the Jeerinah Formation. However, the majority of groundwater in this area appears to flow to the south and east towards the Fortescue River and Coondiner Creek.

In several areas, low-permeability dolerite dykes cross the regional flow system and act as a barrier (at least in the basement) to groundwater flow, causing groundwater levels to back-up behind them:

- In the MAC Mining area- two dykes occur, at the eastern end of E Deposit and the western end of C Deposit. In both cases, there are locally steep gradients (a groundwater "waterfall") across the dykes.
- The southeast corner of Coondewanna Flats is crossed by a dyke which causes water levels to fall from 660 m AHD to approximately 640 m AHD over short distance.

3.2.7 Groundwater Discharge

3.2.7.1 Natural Discharge

Natural groundwater discharge occurs primarily at Weeli Wolli Spring. The spring is formed by the concentration of groundwater flow into a shallow aquifer constrained laterally through a gorge through the Wildflower Range (a ridge of Brockman); with groundwater being forced to the surface. Groundwater discharge occurs as spring baseflow and as throughflow in the alluvium of the creek valley. Total groundwater flow through the spring is estimated to be approximately 11,000 kL/d (7,000 kL/d baseflow and 4,000 kL/d throughflow).

Additional groundwater discharge occurs as evapotranspiration losses, likely to occur in particular upstream of Weeli Wolli Spring, at Ben's Oasis and possibly Coondewanna Flats (perhaps only when the watertable is highest after recharge). Total evapotranspiration losses from the catchment are estimated to be approximately 4,000 kL/d.

3.2.7.2 Existing Users - Additional Groundwater Discharge

Another important discharge of groundwater from the natural hydrological system is through abstraction to support mining operations. The main sources of abstraction within the CPR area are from the BHP Billiton Iron Ore MAC operations and Rio Tinto Iron Ore's Hope Downs Mining operations.

Water supply abstraction for MAC commenced in 2001 from C Deposit (local Marra Mamba aquifer) and the western end of the North Flank Valley (regional aquifer), with additional temporary abstractions used during construction of the railway line and airstrip. Dewatering commenced from

C Deposit and E Deposit in mid 2010 and early 2011 respectively. Total peak dewatering from C and E Deposits is currently between 12,000 kL/d and 14,000 kL/d and has been predicted to range between 16,000 kL/d and 30,000 kL/d in the future.

Rio Tinto Iron Ore's Hope Downs Mining operations are located within the Northern Flank Valley (North and South Deposits). Rio Tinto Iron Ore estimate dewatering abstraction will range from a maximum of approximately 110,000 kL/d in the early years of mining, decreasing to approximately 80,000 kL/d by the end of the mine life. Dewatering commenced in January 2007 and is proposed to continue until the end of 2025 (i.e. until the end of mining and infilling). This is predicted to have a significant impact on flows at Weeli Wolli Spring and Rio Tinto Iron Ore have committed to artificially support Weeli Wolli Spring until the natural flow returns to within 10% of pre-mining flow rates, potentially up to 20 years after decommissioning (HDMS, 2000).

The current combined abstraction rate from the MAC and Hope Downs operations exceeds 120,000 kL/d which is eight times the estimated recharge (Figures 3.11c, d, e and g and Figure 2.6). Abstraction has been in excess of recharge rate since 2007 when Hope Downs dewatering commenced. The abstraction rate is expected to remain in excess of recharge whilst dewatering at MAC and Hope Downs continues. These rates will result in depletion of aquifer storage and a long-term decline in groundwater levels.

3.2.8 Connectivity with the Environment

The depth to water across the area varies between surface and over 100 mbgl (Figure 3.13). Generally, depth to water is greatest in the Upland and Transitional Landscape Units where runoff is generated and initially flows. Depth to water is shallowest in Lowland 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 increases, so there is a thicker unsaturated soil column which must be wetted before recharge can occur. Thus, depth to water is also an important influence 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 *Eucalyptus rossii* (Snappy Gums), Acacia and hummock grasses; such environments cover much of the CPR. It has been shown that the soil moisture deficit created by such arid-zone riparian vegetation, in the upper 10m or so of the soil profile, is sufficient to prevent significant groundwater recharge (Walvoord et al 2002). 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.

The Lowland Receiving Landscape Units, where depth to water occurs within or close to the root-zone of the riparian vegetation, are characterised by vadophytic and phreatophytic vegetation species such as Coolibahs, Paperbarks and River Red Gums. Where such species are truly phreatophytic, then soil moisture deficits will be less as the trees rely on the groundwater rather than soil water. Even where the trees are vadophytic, the shallow depth to water means a smaller soil moisture deficit to overcome as a precursor to groundwater recharge. Large areas with depth to the watertable at or less than 30 mbgl occur on Coondewanna Flats and also in the area around Weeli Wolli Spring. Hydrographs of groundwater levels in these areas show significant rise and fall and it seems likely that the shallow depth to water (and in both cases, substantial water volumes as a result of large catchment areas) results in enhanced groundwater recharge.

Upstream in the Tandanya mining area, there is an area where depth to water is less than 40 m. However, hydrographs from this area do not show seasonal fluctuations. The surface water catchment is relatively small and it is believed that runoff volumes are not large enough to cause groundwater recharge.

Groundwater levels are also relatively shallow in the Jeerinah Formation along the southern boundary of the project area (Wanna Munna Flats). This is an internally draining basin (a hard-pan and clay-pan Receiving Landscape Unit) and while the catchment area is substantially smaller than that which contributes to Coondewanna Flats, the retention of water in the area may lead to enhanced groundwater recharge; no hydrographs are available to confirm this. Regardless, the predominant flow directions from this area are to the east towards Coondiner Creek and southeast towards the upper-Fortescue River. The area is unlikely to contribute substantially to the Weeli Wolli Spring catchment.

Karijini National Park abuts much of the western boundary of CPR. The full range of Upland and Transitional Landscape Units are represented in the hills and valleys in this area. Characteristic of these landscape units, groundwater levels are relatively deep (in excess of 40 m below ground level cf Figure 3.13). There is unlikely to be any groundwater dependency with the vegetation communities relying on surface water processes.

However, the Alligator South and Alligator Park orebodies are in the south west of the project area and are actually located in the Turee Creek catchment; Alligator Park is within the national park. Seven kilometres south of Alligator South and South Park, Turee Creek East Branch flows from the West Angela's mining area and through a gorge in ridges of outcropping Brockman that are located within the national park. Where surface and groundwater flow are constrained immediately upstream of the gorge, a Receiving Landscape has developed. There is an extensive calcrete deposit which is characteristic of shallow groundwater levels and the interpolated depth to water suggests water levels in this area are less than 20 mbgl. A preliminary review of aerial photographs shows extensive vegetation cover which may be influenced by the shallow watertable and the concentration of surface water flow. The West Angela's Mine used to have a monitoring bore in this area although it is not known if this is still operational. The West Angela's mine water supply was located some 20 km further downstream in Turee Creek East Branch to avoid both the national park and the area of extensive vegetation around this gorge.

3.2.9 Hydrochemistry

Chemical analyses of groundwater samples from the CPR are shown on an expanded Durov plot in Figure 3.14.

Groundwater is generally fresh in the CPR area with total dissolved solids (TDS) ranging between 200 mg/L and 1,000 mg/L. This suggests there is little in the way of evaporative concentration of dissolved solids across the CPR area as a whole. In the area of Weeli Wolli Spring, there is a tendency for higher TDS values (up to 1,000 mg/L) to be associated with areas of potential evapotranspiration and this probably results from the progressive concentration of salts as water is lost through evapotranspiration through the zone of phreatophytic vegetation at the spring.

The groundwater samples generally have no dominant cations. Calcium-rich recharging groundwater will evolve with the dissolution of magnesium from dolomite and magnesite (the latter likely present as a cement within the Tertiary sequence) both during recharge and aquifer residence. Ion-exchange can also occur on clay minerals in the detritals and orebodies which increases sodium concentrations. The result is that no cations dominate.

Anions in the groundwater of CPR are generally dominated by carbonate reflecting the carbonate-rich geology.

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 remains fresh throughout the system and does not evolve to a sodium-chloride type water characteristic of an end-point groundwater. This suggests the role of evapotranspiration in the evolution of groundwater chemistry is restricted to local areas such as Weeli Wolli Spring and indicates little in the way of groundwater-surface water interaction more broadly. These processes are consistent with the majority of the study area comprising Upland and Transitional Landscape Units where surface water processes are most important for the environment.

3.3 Water Balance

The water balance for the CPR area considered surface water flow, groundwater recharge and natural groundwater discharge, other groundwater abstraction and changes in groundwater storage.

The pre-mining groundwater balance for the Weeli Wolli Spring catchment has been developed using both a chloride mass balance, also an assessment of recharge and discharge as outlined above (refer Section 3.2.5 and 3.2.6). The water balance is outlined in Table 3.13.

3.3.1 Chloride Balance - Groundwater Outflow

Chloride is generally considered a conservative element in the natural environment. In the CPR, groundwater is generally fresh and there are no salt pans or salinas; there are no obvious areas of active salinisation. As such, under steady-state (i.e pre-mining) conditions, it is 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 for the CPR were presented by PB (2013). In this work, assumptions were made regarding the concentration of chloride in some flow components for which measured data are actually available. The key components of the balance are summarised below and "assumptions" have been updated with "measured data" where possible:

1. Chloride inflow to the groundwater system as solutes in rainfall over the entire catchment area at an annual average rate of 328 mm/yr. Rainfall is considered over both the Weeli Wolli and Coondewanna catchments (i.e 2307 km^2) as both catchments contribute to the groundwater system. 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 Weeli Wolli Creek (as measured at the Weeli Wolli and Tarina gauges). There is some ambiguity over the quality of gauging data; for example, there is poor correlation between the measurements at Tarina and Weeli Wolli gauges despite their relative proximity. This approach provides an annual average outflow of 13,500 ML/yr. The chloride concentration at Weeli Wolli Creek has not been measured. However, chloride in flood flows through Ethel Gorge (EPR) ranged between 5 and 7 mg/L; 6 mg/L has been adopted for flood flow at Weeli Wolli Creek.
3. Chloride outflow as solutes in spring baseflow measured at the Weeli Wolli gauge between rainfall runoff events. The baseflow estimate includes: the long-term flow of approximately 5,000 kL/d occurring through the dry periods between rainfall runoff events; and increased baseflow component during the spring recession in the months after a flood event. Overall it is estimated that average spring baseflow is 7,000 kL/d. The spring has measured chloride concentration of 75 mg/L.
4. Chloride outflow as solutes in groundwater throughflow along the Weeli Wolli Creek valley. Water chemistry data are available from both the alluvium and basement aquifers in the vicinity of the spring (e.g. from Bores HWW0003M1 (shallow), HWW0003M2 (deep), HWW0004M1 (shallow), HWW0004M2 (deep), HWW0010M1 (shallow) and HWW0010M2 (deep). Water quality is comparable with the spring baseflow (as expected given the spring baseflow is groundwater-fed). Chloride concentrations in the groundwater are approximately 70 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 4,000 kL/d.

3.3.2 Water Balance - Summary of Groundwater Fluxes

In addition to the groundwater outflows described above, there are other components of the water balance that will not contribute to the chloride balance - notably evapotranspiration where water is removed but solutes (including chloride) are not and concentrations in the water simply increase as a result.

The key area of evapotranspiration is the large stand of vegetation in the area around Weeli Wolli Spring. It has been estimated that this area comprises 750 ha of phreatophytic and vadophytic trees and that total evapotranspiration is approximately 2600 kL/d (based on tree sapflow measurements (Hope Downs 2,000). Total solute concentrations in groundwater (TDS) increase from 500 to 1,000 mg/L as a result of evapotranspirative concentration as groundwater flows across this area in shallow aquifers; chloride increases from 40 to 75 mg/L over the same area.

It is likely that vegetation stands at Ben's Oasis and Coondewanna Flats will also contribute to evapotranspiration losses from the catchment. On the basis of depth to water and areas of trees, it is estimated that this could be in the order of 1,000 kL/d for the two areas combined.

Taking into account these additional losses, the overall catchment water balance is outlined in Table 3.13. Total recharge and discharge under steady-state pre-mining conditions are estimated to be 15,000 kL/d.

Table 3.13: CPR 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		75	mg/L	measured HD & MAC EIA
3	Spring baseflow		75	mg/L	measured HD EIA
4	Surface water flood concentration		6	mg/L	measured Ethel Gorge
	Measured Parameters				
5	Catchment area	2307		Km^2	
6	Rainfall	320		mm/yr	
7	Rainfall volume	591,040,000		m^3/yr	6 x 5
8	Surface water outflow	10,000,000		m^3/yr	gauged Weeli Wolli & Tarina
9	Spring baseflow outflow	7,200		m^3/d	gauged Weeli Wolli
	Chloride Movement				
10	Cl inflow from rain		3.691×10^{11}	mg/yr	1 x 5 x 4
11	Cl outflow spring baseflow		1.972×10^{11}	mg/yr	3 x 9
12	Cl outflow – surface water flood		6.0×10^{10}	mg/yr	8 x 4
	Unaccouted for Chloride – groundwater outflow				
13	(Cl rain) – (Cl out through spring)		1.119×10^{11}	mg/yr	10-11-12; balance of Cl flux
	Water Balance				
14	**Calculated GW outflow**	**4,084**		$\mathbf{m^3/d}$	13/2; Volume required to remove (13)Cl at 75mg/L

Steady State Groundwater Balance

Feature	kL/d	Remarks
Groundwater Recharge		
Direct Recharge in Coondewanna	11,000	hydrograph analysis – approx. 5 year return period
Direct Recharge in Weeli Wolli area	2,500	hydrograph analysis– approx. annual
In direct recharge – remainder of catchment	1,500	calculated by difference; 0.3mm/yr background recharge over catchment
Total Groundwater Recharge	**15,000**	**recharge approx. 0.8% of catchment rainfall**
Groundwater Discharge		
Evapotranspiration– Coondewanna / Ben's Oasis	1,000	estimate based on tree-area and "allowance"
Weeli Wolli Area		
Evapotranspiration	3,000	sapflow measurement during HD EIA
Spring Baseflow	7,000	gauged plus baseflow separation
Spring – Groundwater Through Flow	4,000	calculated from chloride balance
Total Groundwater Discharge	**15,000**	

Cl-based calculation of groundwater outflow

3.4 Hydrological Landscape Conceptual Framework

The conceptual hydrological system is outlined in Figure 3.15 and salient features of the integrated surface water, groundwater and landscape system in the CPR area are shown in Figure 3.16 and summarised below.

3.4.1 Geomorphology

- The CPR area comprises alluvial valleys and plains bound by steep hills formed of basement outcrop. It includes EHUs 1 to 9 (excluding EHU5), described in Figures 1.4 and 1.5.
- The hills provide an Upland Landscape of mountain and steep-sloped (colluvial) 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 (EHU6 and restricted occurrences of EHU7).
- The lower reaches of the catchments support a Lowland Receiving Landscape of river channels and alluvial plains (clay-pan and hard-pan) corresponding with EHU8.
- The Lake Robinson basin, although occurring within the Wannamunna Land System (EHU 6), is considered to be an example of EHU9 based on its hydrological characteristics as a drainage terminus.

3.4.2 Hydrology

- Annual average rainfall across the area is 328 mm (since 1900); the average since 1985 is 385 mm indicating a general wetting trend.
- The median annual runoff is 0.65% and 0.95% of annual rainfall for Coondewanna Flats and Weeli Wolli Spring respectively. Average annual runoff is higher at 2.05% and 2.4% indicating the disproportionate influence of high magnitude low-frequency events.
- Runoff is generated in the Upland and Transitional 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 Landscape, this means the watertable is deep (>40 mbgl) and vegetation is xerophytic - the runoff only playing an important role in replenishing shallow soil moisture.
- The key hydrologic process in the Upland Landscape is the generation of sheet flow and direct infiltration to replenish shallow soil moisture periodically.
- In the Transitional Landscapes, 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 Landscape, watertable remain relatively deep (>30 mbgl) but soil moisture is more abundant supporting vadophytic trees such as Coolibahs in addition to xerophytic species.
- Key hydrological processes in the Transitional Landscapes 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.

The key hydrological processes in the Receiving Landscape are the concentration of surface and groundwater flow from upstream and local recharge to support shallow groundwater levels.

3.4.3 Groundwater Recharge

- Groundwater recharge occurs preferentially in the Receiving Landscape at Coondewanna Flats and in the area of calcrete outcrop upstream of Weeli Wolli Spring. Here, the watertable is relatively shallow and vadophytes and phreatophytes rely on both abundant soil moisture and shallow groundwater.
- At Coondewanna Flats, groundwater recharge occurs approximately every four years in response to particularly large runoff events that cause a general saturation of flat lying areas and impoundments at Lake Robinson. The annual average recharge rate is approximately 11,000 kL/d.

- From a surface water perspective, Coondewanna Flats is internally draining where surface water collects over a broad expanse of flat alluvial plains. Larger runoff events result in an area of inundation at Lake Robinson (an ephemeral lake). Coondewanna Flats is contiguous with the regional groundwater system and recharge in this area is a key driver of groundwater throughflow to Weeli Wolli Spring.
- At Weeli Wolli Spring, recharge occurs on an almost annual basis. The annual average recharge rate is 2,500 kL/d.
- Recharge occurs at diffuse low volumes across the remainder of the catchment at an annual average rate of 1,500 kL/d.

3.4.4 Aquifer System

- Flow within the regional groundwater flow system is hosted in valley aquifers of Tertiary detritals, and underlying dolomite. Groundwater flow occurs from the west and south converging on Weeli Wolli Spring in the northeast corner of the catchment.
- Calcrete and pisolite occurring within the detrital profile and karstic zones within the dolomite are the main aquifers. The median value for permeability for these aquifers is 20 m/d and 10 m/d respectively.
- This 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 groundwater system 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 crossed by several dykes that form low-permeability barriers to groundwater flow. The dykes do not actually disrupt the overall flow direction but there are falls in groundwater levels of approximately 20 m to 30 m across them. The median permeability of the dykes is 0.01 m/d.

3.4.5 Groundwater Throughflow and Discharge

- Groundwater discharge occurs predominantly at Weeli Wolli Spring as baseflow (7,000 kL/d), throughflow (4,000 kL/d) and evapotranspiration from the vegetation stands in the area of the spring (3,000 kL/d).
- Evapotranspiration losses also occur in other areas of phreatophytic vegetation - notably Ben's Oasis and possibly Coondewanna Flats. Other losses total approximately 1,000 kL/d.
- Under natural conditions the catchment has a throughput of 15,000 kL/d.
- There is active mining in the North Flank Valley by both BHP Billiton Iron Ore and Rio Tinto Iron Ore. Groundwater abstractions for water and dewatering exceed the natural throughput resulting in the depletion of groundwater storage. Groundwater levels in the area have declined as a result.

Broadly, in Lowland Receiving Landscape Units, the environment is more likely to rely on shallow groundwater and it is the concentration of both surface and groundwater flow that maintains shallow groundwater levels. By contrast, in Upland and Transitional Landscapes, surface water processes dominate environmental support mechanisms through the replenishment of soil moisture by a range of infiltration and runoff processes. However, the hydrological system is a continuum and cannot be viewed in isolation. Deep groundwater throughflow may not directly support the environment in the Transitional Landscape and it could be intersected (through mine dewatering for example) without local consequence. However, such deep throughflow will also contribute to the water balance in a downstream Receiving Landscape where its intersection may well have consequences.

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 CPR study area (Table 4.1; Figure 4.1). Upland areas (EHUs 1 and 2) are principally associated with the Hamersley Ranges. EHU 1 includes mountainous areas with a dendritic network of drainage floors and channels (EHUs 3 and 4). EHU 2 includes sloping country down-gradient from EHU1, which is dissected by ephemeral streams emanating from EHU 1 which further coalesce before feeding into lowland areas.

Lowlands include alluvial plains (EHU 6) principally associated with the Coondewanna and Wanna Munna Flats, and other broad valley systems between the ranges. An area of calcrete plains (EHU 7) abuts the western margins of the upper Weeli Wolli Creek system, near and upstream from Weeli Wolli Spring. Major channel systems (EHU 8) are associated with the Weeli Wolli Creek and lower portions of its major tributaries. This includes the River Land System and an extension of this unit further up-gradient to south of Ben’s Oasis based on aerial photography interpretation of riparian vegetation communities depth to watertable information.

The Lake Robinson basin, although occurring within the Wannamunna Land System (EHU 6), is considered to be an example of EHU 9 based on its hydrological characteristics as a drainage terminus. This area is demarcated by the boundary of the *Eriachne* Tussock Grassland vegetation mapping unit on the Coondewanna Flats (Figure 4.1).

Groundwater flow follows the major valley systems at a macro scale, ultimately exiting through the Weeli Wolli Creek system. The Coondewanna Flats is a zone of concentrated recharge during flood events, with sub-surface connectivity to the groundwater system down-gradient enabling transfer of recharge volumes down gradient toward Weeli Wolli Spring.

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. These include Weeli Wolli Spring, Ben’s Oasis and the Coondewanna Flats including Lake Robinson (Figure 4.1). These are further discussed in later sections.

The intersection of the study area with Karijini National Park includes uplands of the Hamersley Range (EHUs 1 and 2). These areas are considered to have low susceptibility to ecohydrological impacts, due to their functionality as water source areas and the underlying groundwater systems being deep and disconnected from surface ecosystems. Moreover, it is only a very small proportion of the park that is in proximity to the BHP Billiton Iron Ore mining operations. In this broad area, the environment’s lack of hydrological sensitivity, and the very small affected area combine to result in low ecohydrological risk.

However, some of the western portions of the study area lying outside the national park boundary contribute to surface water sub-catchments that extend into the national park. There is one Lowland Receiving Landscape Unit (EHU8) in the southeast of the national park, which although outside of the study area has the potential to be ecohydrologically connected with parts of the study area. This area is in proximity to Alligator South and is a zone of surface and groundwater flow concentration in the East Turee Creek gorge. There is a calcrete deposit which is characteristic of shallow groundwater levels. Depth to water interpolation by RPS suggests water levels in this area are less than 20 mbgl; and a preliminary review of aerial photographs shows dense riparian woodland which may be influenced by the shallow watertable and concentration of surface water flow. The calcrete is indicative of a habitat able to support high stygofauna diversity and abundance. Dewatering of orebodies at Alligator South has the potential to drawdown groundwater levels in this area if facilitated by groundwater system connectivity.

Ecological assets considered to have a low level of connectivity are therefore considered not to be hydroecological receptors, are summarised as follows:

- Flora of conservation significance such as *Lepidium catapycnon* (Declared Rare Flora) and various priority flora taxa recognised by DPaW, which do not occur in Receiving Landscape Units (EHUs 8 and 9). Such flora are considered to be xerophytic (i.e. their water use requirements are met by direct and locally redistributed rainfall).
- Fauna species of conservation significance whose habitat requirements are not strongly dependent on, or otherwise intimately associated with, Receiving Landscape Units (EHUs 8 and 9). Examples include the Australian Bustard, Bilby, Bush Stone-curlew, Mulgara, Northern Quoll and Western Pebble-mound Mouse.
- Brockman Iron cracking clay communities of the Hamersley Range PEC (Priority 1), which occur in a catchment in the far south west of the study area, on the eastern edge of Karijini National Park (Figure 4.1). Groundwater is deep and disconnected from the surface ecosystem in this area. Moisture replenishment in the cracking clay ecological communities is believed to be dependent on direct rainfall and possibly surface runoff. Ephemeral water courses pass through cracking clay zone. Surface runoff would locally replenish soil moisture along the water courses but typically not away from the water courses. As annual surface water runoff volumes are highly variable, small potential changes to runoff volumes due to mining activities in the upstream catchments are unlikely to impact moisture conditions in the cracking-clay ecological communities. However, if mining deposits are developed in close proximity to the cracking clay communities and impact the surface water runoff, then the cracking clay community could potentially be impacted.
- West Angelas cracking clay communities (Priority 1) occur outside of the study area (Figure 4.1), however, some of deposits in the BHP Billiton Iron Ore Gurinbiddy mining area are located in the upstream catchment of these communities. Although the main drainage channel from this mining area passes through the area of cracking clays, it does not intercept the identified communities. As such, any small potential changes to runoff from these areas due to mining activities are unlikely to have an impact on the communities. In addition, the groundwater in the area of the West Angelas cracking clay communities is believed to be around 15 m below ground level and not to influence the surface cracking clay formation or its surface vegetation.

Table 4.1: Summary of EHUs within the CPR Study Area

EHU	Percent project area	Distribution in project area	Component land systems
1	44.5%	The Hamersley Range comprising the uplands of the Study Area (predominantly the Newman Land System). The western margin of the Ophthalmia Range	Newman; Rocklea (major) McKay; Marandoo; Oakover; Robe (minor)
2	27.9%	Northern foot slopes of the Hamersley Range (predominantly the Boolgeeda Land System). Eastern periphery of the Chichester Range (predominantly the Elimunna Land System).	Boolgeeda; Platform (major) Egerton; Elimunna; Paraburdoo (minor)
3	6.4%[1]	Drainage floors within EHUs 1 and 2	Within EHUs 1 and 2
4	3.2%[1]	Major channels within EHUs 1 and 2	
6	17.1%	Intermonate valley areas between the ranges, including Coondewanna and Wanna Munna Flats.	Wannamunna; Spearhole (major) Jamindie; Pindering (minor)
7	0.5%	Abuts western margins of the River Land System, near and upstream from Weeli Wolli Springs.	Calcrete
8	0.3%	Concordant with the river channel and floodplains of the upper Weeli Wolli Creek system.	River
9	0.2%	Lake Robinson - boundary of the *Eriachne* Tussock Grassland vegetation mapping unit.	Lake Robinson separated out from the remainder of the Wannamunna Land System (EHU6).

[1] – Including EHU's 3 and 4

4.2 Coondewanna Flats

4.2.1 Overview

Coondewanna Flats is a broad, flat lying area with clay soils located some 20 km west of the MAC mining area (Figure 4.2). The flats are hosted in an intermontane area bound by hills of Mt Robinson and The Governor to the east and south respectively, and by Packsaddle and Mt Meharry to the north and west respectively.

Surface water flow from the surrounding catchments are focused onto the flats, which form an internally draining basin comprising alluvial plains of the Wannamunna land system and including the Lake Robinson clay pan (ref Chapter 3). As a terminus for surface drainage, the Lake Robinson area is a Lowland Receiving Landscape Unit classified as EHU9 (refer to Section 1.3). It hosts unusual Western Coolibah (*Eucalyptus victrix*) woodland vegetation communities. The surrounding flats, characterised by poorly defined drainage and mulga woodland vegetation communities with scattered Western Coolibah trees, is classified as EHU6.

The depth to groundwater beneath the Coondewanna Flats is approximately 20 m below ground level (mbgl), which gives rise to potential interactions between the groundwater and the terrestrial environment (through both surface water connection and vegetation). It is likely that Eucalyptus woodland communities in particular are dependent on the hydrological regime of the flats.

4.2.2 Previous Work

Several relevant studies have been undertaken at the Coondewanna Flats. Four monitoring bores were installed by Aquaterra (2005) as part of a regional monitoring network for BHP Billiton Iron Ore. Mineral exploration in the area was carried out by UMC (2009) and 45 RC exploration holes were drilled. These two studies provide good geological control and groundwater level data.

URS (2012) and SKM (2012) undertook a hydro-environmental assessment that included additional drilling (11 bores) and the assessment of soil-water and groundwater chemistry, including stable isotope chemistry. These studies aimed to determine the extent of ecosystem groundwater dependence and as part of this work tree-water chemistry and leaf water potential (LWP) were also measured (Astron 2012).

Regular monitoring has been undertaken in the regional monitoring bores installed by Aquaterra since 2004. Data loggers were also installed in six of the bores drilled by URS (2012). In combination, these data sets provide an indication of water level change at Coondewanna Flats.

4.2.3 Ecological Description

Vegetation of the Lake Robinson area includes Western Coolibah woodlands over open shrubland of Lignum (*Muehlenbeckia florulenta*) and tussock grassland of *Eriachne benthamii, Eulalia aurea* and *Themeda triandra*; growing on orange brown loamy clay. This corresponds to the zone of most frequent and prolonged inundation following catchment runoff events.

Vegetation of the slightly more elevated flats surrounding the Lake Robinson area includes open forest of Mulga (*Acacia aptaneura* and closely related taxa) with occasional *E. victrix* over sparse Lignum and tussock grasses growing on red brown clay loam.

The vegetation communities at Coondewanna Flats are regionally unusual, and consequently the area is recognised as hosting two priority ecological communities (DPaW 2014):

- Coolibah woodlands over lignum over swamp wandiree (Priority 1). Lake Robinson (the area prone to inundation on Coondewanna Flats) is the only known occurrence of this community.
- Coolibah and Mulga woodland over lignum and tussock grass on clay plains (Priority 3). Examples of this community have only been identified at Coondewanna Flats and Wannamunna (approximately 40 km to the southeast).

The distribution of Western Coolibah in the Central Pilbara is often correlated with floodplain environments fed by surface inflows and deep, alluvial soils with large soil-moisture storage volumes.

Flooding events are important drivers for ecosystem structure and function in such environments (Eamus et al. 2006). Flood frequency has been correlated with overstorey tree health in semi-arid wetlands in eastern Australia (McGinness et al. 2013); and has also been linked to flowering, seed production, seed germination and seedling recruitment dynamics (Jensen et al. 2008). The long term persistence of floodplain woodland communities requires sufficient recruitment/regeneration to compensate for adult tree mortality.

Understory vegetation including shrubs contributes to habitat structure and complexity. Lignum has a wide geographic range of occurrence in Australia's arid zone wetlands and is recognised as tolerating a wide range of growing conditions. It generally prefers ponding of water for several months every 1–3 years, but is able to tolerate inundation for up to 12 months and dry periods of up to 10 years (Roberts & Marston, 2011). Regeneration is triggered by flooding; the seedlings grow opportunistically in damp but continuously drying conditions associated with flood recession, and are more tolerant of dry conditions than flooded (Capon et al. 2009). The presence of Lignum on the Coondewanna Flats suggests a variable flooding regime with significant interannual variability.

Mulga (*Acacia aneura* and closely related taxa) is considered to have a functional water use strategy based on the exploitation of rainfall, stem flows and interception of overland flow. Mulga is generally shallow-rooted (likely < 5 m depth), can extract water from very dry soils, and is able to maintain very low rates of water use during extended drought to survive (Page & Grierson, 2010).

Lake Robinson waterbody is ephemeral but may persist for several months after large catchment runoff events. Little is known about the water quality or aquatic invertebrate assemblages in the lake when it holds water (Pinder et al. 2009).

4.2.4 Hydrological Processes

4.2.4.1 Surface water

Coondewanna Flats is an internally draining surface water basin with a catchment area of some 866km^2. Surface water flows onto the flats from the north, west and south. Due to internal drainage and no surface water outflow, larger flood events cause the flats to become inundated in the Lake Robinson area. Once on the flats, surface water may pond and evaporate directly or infiltrate to the soil, replenishing soil water in the unsaturated zone and potentially contributing to groundwater recharge. Significant evapotranspiration losses would be expected.

Based on anecdotal information, inundation of Lake Robinson only results from larger rainfall-runoff events. Significant inundation is reported to have occurred in 2006 and 2012, which also corresponded with major aquifer recharge events based on monitoring of groundwater levels in bores located in the Lake Robinson area. The borehole water level data (further discussed below), indicate that the 2006 and 2012 floods correlate with the only significant aquifer recharge events since records began in 2004. Of these the 2012 event corresponded with greater recharge. Extrapolation from groundwater level data for a bore located in the adjacent South Flank valley indicates that an earlier aquifer recharge event is likely to have occurred in 2003.

No historic streamflow gauging data are available for directly assessing the surface water runoff volumes in the Coondewanna catchment. Hence runoff frequency and volume estimates need to be derived from correlations with rainfall and/or correlations with gauged runoff in similar catchments. As discussed in Chapter 3, the runoff characteristics of the upper Marillana Creek catchment, as recorded at the Flat Rocks streamflow gauging station, are believed to be representative of those in the Coondewanna catchment.

Although runoff is directly related to rainfall, the relationship is complex: with runoff dependent upon numerous factors including rainfall intensities, rainfall duration, catchment wetness and catchment vegetation conditions. As demonstrated with the Tarina streamflow data in Figure 3.8, there is poor correlation between monthly catchment rainfall and runoff volume, though reasonable correlation for runoff frequency with the larger events.

4.2.4.2 Recharge Frequency Based on Rainfall Assessment

To investigate the frequency of aquifer recharge events based on rainfall data, monthly SILO rainfall data for the Coondewanna catchment since July 2002 (to cover the recent aquifer recharge events), are shown in Figure 4.3. These data show that the highest monthly rainfalls were in 2002/03, 2005/06 and 2011/12, which coincide with the main aquifer recharge events. To further investigate these rainfall data, plots of daily rainfall together with three day and seven day moving daily totals are also shown in Figure 4.3. Additionally plots of 14 day, 30 day and 60 day moving daily totals are shown in Figure 4.4. This assessment indicates that the monthly rainfall data most likely provides the best indication as to when runoff would be sufficient to cause aquifer recharge to occur.

Based on these SILO monthly rainfall data, a threshold monthly rainfall total of 180 mm has been adopted as the indicative rainfall required to initiate aquifer recharge at the Coondewanna Flats. This rainfall total was selected to capture the 2002/03, 2005/06 and 2011/12 peak rainfall months, and to avoid the 2003/04 and 2010/11 peak rainfall months. Using this 180 mm monthly rainfall total threshold, the monthly SILO rainfall data for the past 100 years (since 1913/14) has been assessed. This monthly data is shown in Figure 4.5.

For the initial 50 years of SILO rainfall data (1913/14 - 1962/63), nine of the 50 years had a 180 mm or greater monthly rainfall event. For the more recent 50 years of data (1963/64 - 2012/13), 12 years had a 180 mm or greater monthly rainfall event. This increase in the number of larger monthly rainfall totals corresponds with the apparent long term increase in annual rainfall for Coondewanna catchment, shown in Figure 3.6. Using this assumption, over the past 50 years, an aquifer recharge event would likely occur on average approximately every four years. In the prior 50 year period, an aquifer recharge event would likely have occurred on average approximately every five years. Note that these recharge frequencies are sensitive to the threshold rainfall total adopted. If a threshold of 200 mm was adopted, the event numbers would become five in 50 years and nine in 50 years respectively, indicating an aquifer recharge event occurrence likely on average approximately every 10 years and six years respectively.

4.2.4.3 Recharge Frequency Based on Streamflow Assessment

To investigate the frequency of aquifer recharge events based on streamflow data, the streamflow data for Weeli Wolli Creek above the Tarina gauging station (1,500 km²) and for Marillana Creek above the Flat Rocks gauging station (1,370 km²) have been assessed. For comparison, monthly surface water runoff volumes for both Tarina and Flat Rocks are shown in Figure 4.6 for the period 1985 to 2013 (being the record period available for the Tarina station). Monthly runoff volumes appear to be proportionally higher for the Tarina catchment, higher than would be expected for an approximately 10% larger catchment area. As previously discussed (Chapter 3), this proportionally lower runoff at Flat Rocks is believed due to the relatively large (natural) flattish storage areas located in the catchment which tend to attenuate catchment runoff. These upper Marillana Creek catchment characteristics are believed to possibly better represent the Coondewanna catchment; making the Flat Rocks gauging data characteristics also likely a better representation of the Coondewanna Flats runoff characteristics, as compared to those recorded at the Tarina streamflow gauging station.

Comparing the corresponding Tarina and Flat Rocks monthly runoff volumes (Figure 4.7), timings for the main runoff events are mainly the same though event magnitudes vary. For Tarina, five runoff events were clearly dominant, namely 1994/95, 1999/2000, 2002/03, 2008/09 and 2011/12, whereas for Flat Rocks the dominant runoff events were 1994/95, 1996/97, 1999/2000 and 2002/03. These differences are attributed to rainfall variations in conjunction with differences in catchment characteristics.

For streamflow data since 2003, the Flat Rocks data shows 2002/03, 2005/06 and 2011/12 as containing the larger monthly runoff events with 2002/03 clearly having the larger runoff month followed by 2011/12 (Figure 4.6). In comparison, the Tarina streamflow data shows 2002/03, 2008/09 and 2011/12 as containing the larger runoff events, again with 2002/03 being the larger event, followed by 2011/12, but runoff in 2005/06 shown as being a less significant event. This data reinforce the assumption that the Flat Rocks gauging data likely better represents runoff patterns in the Coondewanna catchment (as demonstrated by the aquifer recharge events).

The Flat Rocks monthly runoff volumes since records started in August 1967 are shown in Figure 4.7. This record has missing streamflow data during the 1979/80 and 1980/81 wet seasons. Based on these data, and adopting a threshold monthly runoff volume of 5,000 ML to initiate aquifer recharge (chosen to identify 2005/06 and 2011/12 as being recharge years), then 12 of the 44 years had a runoff event sufficient to cause aquifer recharge. (Note that most of these large volume runoff events had volumes significantly greater than the 2005/06 and 2011/12 runoff events). Hence, using these assumptions, an aquifer recharge event would have likely occurred on average approximately every four years (over the available 44 years of data). This frequency of recharge agrees with the estimate derived using the most recent 50 years of SILO monthly rainfall data (1963/64 - 2012/13) with a 180 mm rainfall threshold.

Similarly based on the Flat Rocks monthly data, 11 of the 44 years had zero runoff which represents on average every four years.

4.2.4.4 Estimated Runoff Volumes

The total catchment runoff volume at the Flat Rocks (44 data years) and Tarina (28 data years) streamflow gauging stations are 2.05% and 2.4% of the total catchment rainfall respectively. Adopting an average annual runoff for the Coondewanna Catchment of 2.05% and an average annual SILO rainfall of 328 mm (1900–2013), the average annual runoff to Lake Robinson would be approximately 5.8 GL. However, the Flat Rocks catchment median annual runoff of 0.65% could be considered a more typical runoff characteristic for the catchment (50% AEP) and adopting this for the Coondewanna catchment equates to a median annual runoff of approximately 1.8 GL. This volume is significantly less than the long term average runoff which has been distorted by the more extreme flood volume events. Based on a probability assessment for the annual runoff volumes for the Flat Rocks catchment, the long term annual average runoff volume (5.8 GL) represents approximately a 25% AEP (4 year ARI) event.

On an annual basis, the Coondewanna catchment runoff would be highly variable with some years (July to June) having zero runoff, others possibly approximately 20 GL (pro-rata of Flat Rocks 2002/03 runoff) and a very extreme event could approach 100 GL (pro-rata of Flat Rocks 1975/76 runoff – Cyclone Joan).

Based on Lidar data, Lake Robinson has an approximate area of 30 km² below the 688 m AHD contour. For an assumed typical annual runoff of 1.8 GL (50% AEP), this represents an average inundation depth of 60 mm over the lake bed. Given this relatively low volume, it is likely that most of this water would infiltrate into the base of the drainages and lake bed with just isolated pockets of ponding. Infiltration from these typical annual events, while insufficient to recharge groundwater, would replenish soil moisture; particularly the upper 5 m – the rooting depth of the Mulga, herbaceous understorey and the shallow root zone of mature Western Coolabah trees.

In comparison, the long term estimated average annual runoff of 5.8 GL represents an average inundation depth of approximately 0.2 m over the lake bed and a rather wet year of 20 GL runoff (e.g. 2002/03) would give an average inundation depth of approximately 0.7 m. For an extreme runoff event of 100 GL (e.g. 1975/76 – Cyclone Joan), runoff would give an average inundation depth of approximately 3 m over a 30 km^2 lake area; hence water would pond beyond the confines of the lake into the adjacent lower lying drainage flowpaths. Anecdotal information reports that following Cyclone Joan (Dec 1975), the resulting lake on Coondewanna Flats persisted for many months.

In summary to conceptualise the surface water recharge over Lake Robinson:

- On average, runoff will likely discharge to Lake Robinson in three out of four years, with runoff typically being insufficient to cause groundwater recharge, but would replenish soil moisture in the unsaturated profile.
- Larger events resulting in groundwater recharge are likely to occur on average once every four years, triggered by a monthly rainfall in excess of approximately 180 mm.

4.2.5 Hydrostratigraphy

Coondewanna Flats is bounded by hills of Marra Mamba and Brockman. Preferential weathering of the Wittenoom Formation between these outcrops resulted in a low-lying area which has subsequently been infilled with Tertiary deposits of alluvium and colluvium. The geological sequence comprises an upper Tertiary sequence (TD3) of variable sand, silt and gravel overlying a middle Tertiary sequence (TD2) of variable calcrete and silty gravel overlying shale and dolomite of the Paraburdoo Member. The calcrete lies close to the watertable and the extent to which it is saturated varies with recharge state (up to a 5 m change in groundwater levels has been observed following inundation in Lake Robinson).

Based on drill logs, the calcrete is described as karstic or vuggy and weathered in places, and hard in others. There is likely to be a considerable range in permeability for the calcrete.

There is a steep groundwater gradient across the southeastern part of Coondewanna Flats suggesting a low flow barrier in the otherwise reasonably consistent aquifer system across the flats. Extrapolation from the surrounding outcrop suggests this area is crossed by a SW-NE trending dyke which acts as a partial groundwater flow barrier. Groundwater levels decline from approximately 665 m AHD (approximately 25 mbgl) on the Flats to the north and west of the dyke to 635 m AHD (approximately 55 mbgl) to the south and east. The dyke is likely to act as an effective boundary to the Coondewanna Flats groundwater system by impeding the propagation of hydraulic stress. The increased depth to groundwater downstream of the dyke is likely to reduce the potential for groundwater dependence in the environment.

The geology and hydrogeology of Coondewanna Flats is illustrated on Figure 4.8.

4.2.5.1 Aquifer parameters

The Table 4.2 below compares the range of aquifer parameters estimated for Coondewanna Flats (URS 2012) with the regional values outlined in Chapter 3.

Table 4.2: Hydraulic Conductivity - Coondewanna Flats

Unit k (m/d)	Regional Values			Coondewanna Flats		Remarks
	Min	Max	Med	Min	Max	
TD3	0.0	100.0	0.9	6.8	14.5	Within range; less reliable due to testing in unsaturated zone
Calcrete	2.5	41.4	11.2	1.8	18	Within range
Dolomite	0.1	105.0	10.4	0.7	2.1	Within range for non-karstic dolomite/Bee Gorge
Bee Gorge	1.8	1.8	1.8			

In general, the aquifer parameters within Coondewanna Flats are within the middle of the range of regional values.

The estimated permeability for the dolomite is at the lower end of the regional range which suggests that the dolomite subcrop tested to date is either of less-weathered Paraburdoo Member or it is the lower permeability Bee Gorge or West Angela Members; based on a comparison between drill-log and type section descriptions, unweathered crystalline dolomite of the Paraburdoo Member seems likely.

Estimates for the calcrete appear very typical of the region. Reports of circulation and sample loss during drilling suggest the calcrete is vuggy in places. Estimates for the TD3 detritals are at the higher end of the regional range. Some caution must be exercised as this material at Coondewanna Flats is largely unsaturated which may have affected test results.

No specific estimates of confined or unconfined storage are available for Coondewanna Flats. The adoption of the regional values (cf Chapter 3) is recommended.

4.2.5.2 Groundwater Levels and Flow

Although Coondewanna Flats is an internally draining surface water feature, groundwater levels show it is in connection with the regional groundwater system (Figure 4.8). Groundwater inflow occurs from valleys to the north and west. Groundwater gradients along these valleys are very low and inflow will be small regardless of the permeability of any aquifers underlying the valleys.

Groundwater outflow is eastward into the South and North Flank Valleys. Groundwater levels across the flats are in the range 665 m AHD with groundwater levels in the upper South Flank valleys falling to 635 m AHD in relatively close proximity to Coondewanna Flats; the steep gradient between Coondewanna Flats and the valley being related to the NE/SW trending dyke. The effect of the dyke on water levels is highlighted on Figure 4.8 and shown in section on Figure 4.9.

Over much of the flats, the depth to ground water is approximately 20 mbgl (Figure 4.10), rising to approximately 15 mbgl following major recharge events. South of the dyke, depth to groundwater increases to approximately 50 mbgl. The major stands of Coolibahs are associated with shallower depth to groundwater north and west of the dyke.

Available groundwater level monitoring data for Coondewanna Flats are shown in Figure 4.11. Two significant rises in the watertable (recharge events) can be seen since 2006. The following are interpreted from these hydrographs:

- Watertable rises vary between approximately 1 m and 5 m bringing groundwater levels to within approximately 15 m to 21 m of the surface.
- The rise in groundwater levels is relatively rapid suggesting a relatively rapid recharge process. This is consistent with isotope analysis (URS 2012) that suggests groundwater is not subject to much evaporation prior to recharge.
- Given the rapid rise in response to rainfall and the low groundwater gradients which will drive little inflow into Coondewanna Flats, recharge mainly occurs locally from infiltrating surface water rather than groundwater throughflow from upstream in the catchment.
- The rise in groundwater levels in some bores (e.g. HCF0010M, HSF0002M (BH41) and HCF0012M for the 2011/2012 wet season) is more rapid than in others. This is believed to relate to the location of the bores where flow and/or inundation is concentrated. HCF0010M occurs where water inundates Lake Robinson and is proximal to surface water inflows from the west. HCF0012M and HSF0002M are proximal to surface water runoff from the hills on the eastern side of the flats; in the case of HSF0002M, there may also be water locally retained by the Great Northern Highway road embankment.
- Notwithstanding the rapid rise in water level in HSF0002M, the rise during the 2011/2012 wet season is particularly large and rapid in comparison with that observed during 2006. It is believed the bore may have been flooded during the 2012 event and it seems more likely that the recession from approximately 662 mRL is more representative of groundwater levels.

During the 2011/2012 event, groundwater levels were highest in bores HCF0010M and HCF0011M suggesting a recharge mound related to infiltration of water from flooding of Lake Robinson.

- The decline in groundwater levels in HCF0010M (while groundwater levels in other, distant bores continue to rise) suggests the short term dissipation of the recharge mound under HCF010M with the dissipating groundwater continuing to recharge other areas across the Flats. Figure 4.10 illustrates a groundwater mound at the end of 2011/2012; the mound dissipating with groundwater flow to the north (towards bore HCF0002M (BH37)) and east (towards bores HCF008M/007M). Thus, while groundwater gradients are low across the Flats in general, there is likely to be considerable variation and local flow at a local scale and following rainfall-recharge events.

4.2.5.3 Groundwater Recharge

As noted above (Section 4.2.4.4), groundwater inflow to Coondewanna Flats is likely to be small and recharge to the area will occur primarily on the flats from infiltrating surface water. Based on a chloride balance, URS (2012) estimate groundwater recharge at 3.4 mm/yr over Lake Robinson (approximately 1% of catchment rainfall). This gives an annual recharge volume of 2.8 GL or 7,800 kL/d. Consideration of hydrographs in close proximity to Coondewanna Flats (refer Chapter 3 - CPR Regional hydrogeology) suggests total recharge in the broad Coondewanna Flats area is 4 GL or 11,000 kL/d. By comparison, recharge to the whole Weeli Wolli (groundwater) catchment is approximately 5.5 GL or 15,000 kL/d (refer Water Balance section in Chapter 3) which suggests 70% of catchment recharge occurs from surface water infiltration on Coondewanna Flats.

The groundwater hydrographs (Figure 4.11) show that only two significant watertable rises have occurred over the last six years. It is therefore concluded that while 11,000 kL/d may be an average rate of recharge, actual recharge is variable between years. Correlation of rainfall magnitude with recharge (refer section 4.2.4.1) suggests rainfall events large enough to trigger significant groundwater recharge would have a 1 in 4 year return period. Based on one recharge event every four years, the actual volume recharged per event would be approximately 16 GL. It is estimated the area inundated at Lake Robinson could be up to 24 km^2, which would result in an inundation depth of approximately 0.5 m.

Based on saturated porosity of the Tertiary detritals of 20%, 0.5 m infiltration would result in a 2.5 m rise in the watertable. This is consistent with the range of watertable rises recorded in the available hydrographs.

Coondewanna Flats is likely to be an area of enhanced groundwater recharge due to infiltrating water from the periodic inundation of Lake Robinson; the 1% recharge estimate is reasonable in comparison to the 0.6% estimate of rainfall-recharge for the Weeli Wolli Spring catchment as a whole (cf Chapter 3 - Regional hydrogeology). Infiltration at Lake Robinson specifically appears to account for approximately 50% of catchment recharge while the broader Coondewanna Flats appears to account for approximately 70% of groundwater recharge over the Weeli Wolli Spring catchment.

4.2.5.4 Groundwater Discharge

Groundwater discharge occurs both as outflow to the South and North Flank Valleys (cf Chapter 4.2.4.4) and as evapotranspiration on the Flats, and considerable work has been undertaken in relation to the latter (URS 2012 and SKM 2012). Rio Tinto have also undertaken research into the groundwater-vegetation interactions on Mt Bruce Flats notably pertaining to the Western Coolibah woodlands (Batini 2009, Eamus, 2010, Rio Tinto 2011), an environment analogous to Coondewanna Flats.

The key outcomes from this work are:

- Leaf water potential (pre-dawn) in the Western Coolibahs at Coondewanna Flats range between -4,000 kPa and -2,000 kPa. These measurements were taken in November 2011 at the end of a six year period of no recharge and it would be expected they would be representative of “drought" conditions. (Measurements from Mt Bruce were comparable, ranging up to -4,600 kPa).
- Pre-dawn leaf water potential approximates the matric pressure in the root zone where the tree is sourcing water. The negative pressures show the trees are taking water from the unsaturated zone.
- Matching the isotopic characteristics of tree-water and soil-water shows the trees are taking water from approximately 10 mbgl to 15 mbgl (at least at the end of a prolonged dry period). This compares with approximately 6 mbgl to 11 mbgl estimated for the Western Coolibahs at Mt Bruce. In both cases, depths indicate that tree water originates from the unsaturated zone.
- The estimated deepest rooting depth (15 mbgl) is coincident with the maximum watertable rise observed in the available hydrographs (i.e. following recharge, the watertable has risen to a depth of 15 mbgl). The maximum rise in water levels at Mt Bruce following recharge also brought water levels to around the base of the likely root-zone.
- The hydrological regime may be important for the phenological cycle of the woodland trees, and the long term persistence of the woodland vegetation community.
- A simple soil moisture balance (Table 4.3 below) suggests soil moisture would be sufficient to support the trees at Coondewanna Flats for up to seven years. Moreover, surface water

will reach the Flats three out of four years (ref section 4.2.4.1) and even where this is insufficient to cause recharge, it will replenish soil moisture. Thus, the estimated seven years for which soil moisture could support Western Coolibah trees at Coondewanna Flats is very conservative and would represent a period of extreme drought.

Table 4.3: Illustrative Soil Moisture Balance for Coondewanna Flats - Drought Conditions

Description	**Water Usage/Availability**	
	Published/Estimated Values	**Adopted Value**
A: Estimated Coolibah Consumptive Use (Rio Tinto 2012)	255 to 600 mm/yr	300 mm/yr
B: Soil Moisture Storage (SKM 2012) - based on measured moisture content and estimated porosity	160 mm	160 mm
C: Total available water column from below zone of evaporation to below root depth (15m X B)	2400 mm	2400 mm
D: Total available water assuming only 90% is available - the residual lingering in the soil below PWP (0.9 x C)		2160 mm
Period of Available Supply from Soil Moisture (D/A)		**Approx. 7 years**

note: all water volumes converted to equivalent depths (mm/sq.m)

It is likely that following a major flood event, infiltration wets the soil profile, matric pressure becomes much less negative and downwards-flowing water recharges the groundwater. Progressively, evaporation from the near surface and transpiration from greater depths (up to 15 mbgl in the case of the Western Coolibahs at Coondewanna Flats) reduces moisture content in the soil profile causing matric pressures to become increasingly negative (up to -4000 kPa in the deep root zone at the end of a prolonged dry period).

Simplified modelling of the recharge processes on Coondewanna Flats was undertaken with a 1D model (Hydrus). A specific focus was to better understand the soil moisture budget and in particular to review the extent to which capillary rise from the watertable may support soil moisture at Coondewanna Flats. Salient features of the model were:

- Two soil profiles were considered to represent the range in depth to water observed at Coondewanna Flats: 20 m depth to water and 30m depth to water.
- To facilitate a simplified modelling approach, the depth to water was fixed and did not rise as recharge occurred - rather the process of recharge was noted as a flux through the base of the modelled profile.
- A uniform soil profile was adopted representing a composite of the range in soil materials observed in the profile at Coondewanna Flats. Adopted saturated permeability was 1 m/d (typical of the non-calcrete alluvial sequence at Coondewanna Flats) and unsaturated permeability was derived by the model using typical hysterisis relationships.
- Two root zones were used: 0–5 m representing the shallow root system of the Western Coolibah trees and the primary root zone of the Mulga trees; and 10 m to 15 m representing the deep root zone of the Western Coolibahs (as suggested by the SKM isotope studies).
- Maximum tree-suction pressure in the uppermost soil profile was set at -10,000 kPa to simulate the extreme surficial pressure that maybe generated by the combination of arid conditions and arid-adapted species such as Mulga and Spinifex.
- Maximum tree-suction pressure was set at -3,000 kPa - the average of the range observed at Coondewanna Flats for the deep root zone of the Western Coolibahs.
- The lower boundary was set as a fixed pressure at 0 kPa to simulate the atmospheric pressure that occurs at the watertable in an unconfined aquifer.
- A large recharge flux was applied every four years to represent inundation at Lake Robinson. Intervening smaller events were not simulated to ensure conservatism in the model.
- There are insufficient data to calibrate the model. Rather, the aim was to use the model to investigate the important processes that are occurring rather than accurately quantify those processes.

The results are summarised in Figures 4.12a and 4.12b. Key findings from the model were:

- Soil moisture content increased rapidly within the first day in response to the recharge flux and soil matric pressure approached 0kPa (fully saturated conditions).
- There was a significant increase in flux through the profile (representing the process of infiltration and recharge).
- In the periods following the simulated inundation, both soil matric pressure and flux (recharge) declined.
- The flux through the soil profile declined quickly after 30 days suggesting recharge would occur and stop rapidly, consistent with the rapid rise and shift to recession observed in the hydrographs.
- Soil moisture and matric potential decline as would occur between recharge events. The effects of the two root zones are clearly seen with pressure in the lower zone at 3,000 kPa and moisture content between 10% and 15%, consistent with work of URS (2012c) and SKM (2012) where measured soil moisture ranged between 10% and 20%.
- Although declining to become almost negligible, there remains a flux through the soil profile throughout the entire period, despite the large negative pressures imposed by the deep root zone only some 5 m above the watertable (in the case of the 20 m depth to water scenario). Thus at no point over the four year period between recharge events does groundwater contribute to the soil moisture budget through capillary rise. Moreover, this is considered conservative as the scenarios allow for no replenishment of soil moisture from smaller runoff events that occur more frequently than once every four years.

The available data on tree water use indicate that the Coolibah trees at Coondewanna Flats abstract water from the unsaturated zone at depths up to 15 mbgl. The modelling suggests groundwater contribution to the unsaturated zone through the capillary fringe is unlikely and that recharge from surface water inundation is the major control on soil moisture at Coondewanna Flats. This tends to confirm that periodic soil moisture replenishment from surface water runoff is important (even when the runoff events are not large enough to cause groundwater recharge).

4.2.5.5 Water Quality

Groundwater from bores in the Coondewanna Flats area is typically fresh calcium/magnesium and bicarbonate type water. This is characteristic of recharge water in dolomite-rich terrain. The quality of groundwater is similar to that observed in the South and North Flank Valleys and corroborates continuity in the groundwater system at a regional scale (URS 2012c).

4.2.6 Ecohydrological Conceptual Model

The key features of the ecohydrological conceptualisation of the Coondewanna Flats are depicted in Figures 4.13 and 4.14 and summarised as follows.

4.2.6.1 Surface And Groundwater Systems

- Surface water runoff from the surrounding catchments is attenuated in the internally draining low-relief landscape of the flats, principally accumulating in the Lake Robinson area but extending more widely across the flats in very large and infrequent flood events.
- Beneath the flats is an unconfined aquifer comprising a high permeability calcrete around 10 m thick occurring at a depth of 20–30 mbgl. This overlain by low to moderate permeability Tertiary detritals and underlain by low to high permeability basement of the Wittenoom Formation. Aquifer parameters are within the range of regional estimates.
- Groundwater level gradients across the flats have a general west-east direction. However, gradients are low and little groundwater flows into the area from the west. Consequently recharge derived from ponding of surface water runoff is the major source of groundwater replenishment in Coondewanna Flats.
- Recharge occurs predominantly as infiltration from surface water in the Lake Robinson area. Recharge events have a return period of approximately four years and although recharge is highly variable over time, annual average recharge rates are approximately 2.4 GL at Lake

Robinson and 4 GL over the broader Coondewanna Flats area. The latter represents approximately 75% of total recharge to the down-gradient Weeli Wolli (groundwater) Spring catchment.

- Notwithstanding that recharge occurs every four years on average, surface water flows typically reach Coondewanna Flats three out of every four years and replenish soil moisture in the unsaturated profile, even when groundwater recharge does not occur.
- A southwest-northeast trending dyke acts as a partial (low flow) groundwater flow barrier at the eastern end of Coondewanna Flats; as indicated by a steep groundwater gradient.
- Groundwater discharge occurs as outflow to the South and North Flank Valleys, thus connecting the Coondewanna and Weeli Wolli Spring catchments from a groundwater perspective. Coondewanna Flats is the major source of groundwater throughflow that ultimately reaches Weeli Wolli Spring.

4.2.6.2 Ecosystem Components

- Vegetation of the Lake Robinson area includes Western Coolibah (*Eucalyptus victrix*) woodlands over open shrubland of Lignum (*Muehlenbeckia florulenta*) and tussock grassland of *Eriachne benthamii, Eulalia aurea* and *Themeda triandra*; growing on orange brown loamy clay. This corresponds to the zone of most frequent and prolonged inundation following catchment runoff events.
- Vegetation of the slightly more elevated flats surrounding the Lake Robinson area includes open forest of Mulga (*Acacia aptaneura* and closely related taxa) with occasional *E. victrix* over sparse Lignum and tussock grasses growing on red brown clay loam.
- The Western Coolibah trees on Coondewanna Flats rely on stored soil moisture to meet water requirements. Studies indicate they are able to obtain water for prolonged periods from deeper layers in the unsaturated zone above the watertable (pre-dawn leaf water potentials of at least 4,000 kPa have been measured after prolonged dry conditions). There is no evidence to suggest that they use groundwater. The surface water regime of regular soil water replenishment (around three out of four years) maintains sufficient soil moisture to support these trees.
- The surface water dynamics of Coondewanna Flats are likely to influence Western Coolibah bud-set, flowering, seed production and seedling recruitment. However further investigations are necessary to understand the relationship between flooding regimes and the phenological cycle of the woodland trees.
- Mulga is a shallow rooted species with xerophytic adaptations to drought stress. It is likely that the water use requirements of the Mulga communities are met by soil water in surface layers (up to 5 mbgl), which is replenished by rainfall and runoff.
- The Lake Robinson waterbody is ephemeral but may persist for several months after large catchment runoff events. Little is known about the water quality or aquatic invertebrate assemblages in the lake when it holds water (Pinder et al*.* 2010).

4.2.6.3 Key Indicators

The key indicators for the preservation of ecological values of the Coondewanna Flats are:

- Flood frequency providing soil moisture replenishment in unsaturated profile.
- Frequency of recharge (i.e. frequency of flood events >180 mm monthly rainfall equivalent).
- Depth to watertable range.
- Tree health (Western Coolibahs).

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 4.4.

Table 4.4: Coondewanna Flats - key indicators for the preservation of ecological values

Variable	Coondewanna Flats Vegetation Communities	Variable
	Tolerance	**Observed/modelled range**
Flood frequency providing soil moisture replenishment in unsaturated profile	N/A	Approximately 3 out of 4 years
Frequency of recharge (i.e. frequency of flood events >180 mm monthly rainfall equivalent)	N/A	Approximately 1 out of 4 years
Depth to watertable range (m)	N/A	15 to 20 mbgl
Tree health (Western Coolibahs)	N/A	N/A

4.3 Weeli Wolli Spring (and Ben's Oasis)

4.3.1 Overview

Weeli Wolli Spring marks the surface and groundwater outflow from the Weeli Wolli Spring catchment. The spring occurs where Weeli Wolli Creek passes through a gorge eroded through the Wildflower Range. Groundwater flows are concentrated into the spring by low permeability basement rocks. A shallow groundwater system occurs up-gradient form the spring and is associated with an extensive zone of calcrete. Downstream of the gorge, the creek flows through a narrow channel past the confluence with Marillana Creek and ultimately into the Fortescue River Valley.

The Weeli Wolli Spring area hosts a groundwater dependent PEC. Elements of the Weeli Wolli Spring community PEC also occurs at Ben's Oasis, some 20 km upstream of Weeli Wolli Spring in the Weeli Wolli Spring catchment. At this location, the vegetation is concentrated along a relatively narrow creek channel adjacent to some surface water pools.

Almost all of the mining areas in the CPR are located in the Weeli Wolli Spring catchment. However, Hope Downs, Jinidi, OB10, OB11 and OB12 occur in particularly close proximity to Weeli Wolli Spring, with MAC only some 10 km further away than Jinidi. Since 2007, the spring has been affected by dewatering at Hope Downs (a joint venture between Rio Tinto and Hancock Resources) and to lesser extent MAC, C and (most recently) E Deposits. Dewatering surplus from Hope Downs has been discharged into Weeli Wolli Creek to both dispose of any surplus and to irrigate areas of riparian woodland already affected by dewatering-induced watertable drawdown.

The setting of Weeli Wolli Spring and locations of existing bores are shown in Figure 4.15. The setting of Ben's Oasis is shown in Figure 4.16.

4.3.2 Previous Work

Weeli Wolli Spring has been the focus of numerous previous studies involving surface water gauging and analysis, and hydrogeological drilling investigations and modelling. Surface water analysis has enabled the assessment of flood magnitude and frequency, and the separation of groundwater discharge to the surface at the spring (baseflow) from flood events.

Seven groundwater monitoring bores were installed around the spring by BHP Billiton Iron Ore and Hope Downs (in combination) during the environmental impact assessments (EIAs) for MAC and Hope Downs (Woodward Clyde 1998 and HDMS 2000). Four of these bores were dual piezometers with discrete monitoring intervals in the detrital and basement aquifers. All of these bores have been monitored since this time by Hope Downs. The monitoring results provide data on differences in groundwater levels (and groundwater quality) between the alluvial and basement aquifers, on the response of the groundwater system to flood events and on the effects of dewatering since 2007 (particularly at Hope Downs). The bores in the vicinity of the spring confirmed a shallow watertable and seasonal recharge.

A groundwater model of the spring was developed during the aforementioned EIAs, which has been subject to ongoing calibration by both Hope Downs and BHP Billiton Iron Ore against the effects of dewatering at Hope Downs and the MAC C and E Deposits. The large volumes of abstraction associated with Hope Downs is a significant change to the hydrogeological regime at Weeli Wolli Spring and has provided an opportunity for a robust model calibration. Re-calibration efforts have provided updated aquifer parameters and distilled key elements of the groundwater system (e.g. Aquaterra 2011 and 2013) and refined catchment water balances; notably the outflow through Weeli Wolli Spring which can be corroborated against the gauged data. Recently, Parsons Brinckerhoff (2013) provided a much larger estimate of groundwater outflow through the spring based on a chloride mass balance (refer Chapter 3).

In combination the surface water analysis and groundwater modelling has allowed quantification of water fluxes through Weeli Wolli Spring. Drilling investigations have confirmed the nature and distribution of aquifers.

Vegetation mapping and an assessment of vegetative water use around the spring was undertaken during the Hope Downs EIA using tree sapflow measurements (Hope Downs 1999). This work confirmed the presence and distribution of phreatophytic species over some 750 ha and estimated that evapotranspiration was in the order of 3,000 kL/d.

The extent of previous work and monitoring provides a good understanding of the hydrological regime at Weeli Wolli Spring and the relative importance of key hydrological processes within the system.

4.3.3 Ecological Description

The ecology of the Weeli Wolli Spring area is defined by surface and subsurface inflows, and the presence of a shallow groundwater system associated with Weeli Wolli Creek. This supports riparian vegetation communities, permanent pools and a diverse stygofauna community. The area is recognised to have multiple ecological values that collectively contribute to its status as a Priority 1 Ecological Community (DPaW 2014; DEC 2009). These include:

- Riparian woodland and forest associations with unusual understorey species composition; including an assortment of wattles (*Acacia* spp.), and sedges and herbs that fringe many of the pools and associated water bodies along the main channel. There are several species of conservation interest including a trigger plant named after the spring (*Stylidium weeliwolli*). The woodland trees include the obligate phreatophyte Silver Cadjeput (*Melaleuca argentea*) and facultative phreatophytes River Red Gum (*Eucalyptus camaldulensis*) and Western Coolibah (*E. victrix*).
- An unusual and diverse aquatic fauna assemblage occurs in a series of permanent pools associated with the spring and shallow groundwater system in areas immediately up-gradient from the spring. The permanent, flowing water in the Weeli Wolli Spring area is an uncommon habitat type in the Pilbara (Pinder et al. 2010); and may function as a refuge for mesic adapted fauna.
- A relatively high diversity of stygofauna is associated with the large-scale calcrete and alluvial aquifer system in connection with Weeli Wolli Creek.
- The valley of Weeli Wolli Spring also supports a diverse bird assemblage (over 60 species) and very rich microbat assemblage including the Ghost bat (*Macroderma gigas*), a State and Commonwealth listed species. The permanent pools provide a water source and foraging habitat for microbats.

The phreatophytic vegetation uses shallow groundwater and hence contributes to groundwater discharge. This is likely to occur in areas where the watertable is less than 20 mbgl; however the relative contribution of groundwater to 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; Silver Cadjeput occurs in these areas). In places where the watertable is greater than approximately 10 m it is possible that groundwater is only accessed transiently, during prolonged dry periods where the unsaturated profile dries out. Thus in general terms, a greater reliance on groundwater would be expected as the depth to watertable decreases. 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).

Subterranean habitats in groundwater can be defined by the types of voids and interstitial spaces present and by groundwater chemistry (Halse et al. 2014). In general the habitat requirements of Pilbara stygofauna, including their distributions within heterogeneous groundwater environments and tolerances of differing water qualities, are poorly understood (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 shallow a watertable typically have greater stygofauna diversity, where attenuation of organic matter and oxygen by the overlying unsaturated profile is minimised. Areas with a watertable 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 geology, 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. In the Weeli Wolli Spring area in its natural state, the shallow groundwater system occupied by stygofauna is characterised by low (TDS) and relatively stable water levels.

Ben's Oasis was recently classified by the DPaW as an occurrence of the Weeli Wolli Spring Community PEC located further up-gradient in the Weeli Wolli Creek system. However there is very little documented information about this area.

4.3.4 Hydrological Processes

4.3.4.1 Weeli Wolli Spring Catchment

Weeli Wolli Creek is an ephemeral surface water system and Weeli Wolli Spring is a natural surface expression of groundwater flow resulting from hydrogeological features in the Weeli Wolli Creek bed. The surface water catchment upstream from Weeli Wolli Spring has an approximate area of 1,450 km^2. The Coondewanna and Wanna Munna surface water catchments in the upper reaches of the CPR area are both internally draining (i.e. they do not contribute any surface flows towards Weeli Wolli Spring).

Several tributary creeks enter Weeli Wolli Creek upstream from the spring, including Pebble Mouse Creek. Ben's Oasis is a perennial pool on Weeli Wolli Creek located approximately 20 km upstream from Weeli Wolli Spring with a catchment area of 418 km^2. There is no data on groundwater levels around Ben's Oasis and it is uncertain whether Ben's Oasis is a natural surface expression of groundwater flow (like Weeli Wolli Spring) or whether it is simply an area where surface water flows in the creek pond and form a local water hole perched above the regional groundwater system, supported between flood events by bank-storage in the creek channel alluvium (Innawally Pool near the Jimblebar Mine in the EPR area would be analogous to the latter scenario).

The natural Weeli Wolli Creek channel and main tributaries are expansive and well defined. The bed slopes are moderately steep which, in conjunction with the flow regime, has resulted in the creek beds dominated by coarse gravels and pebbles. Although the Weeli Wolli Creek main channels are relatively wide and deep, large flood flows tend to overtop the banks onto adjacent floodplains.

The gravel beds (active channel) along Weeli Wolli Creek and its main tributaries are generally clear of vegetation with the exception of occasional eucalypt trees, whereas the creek banks (and some floodplain zones) typically support a continuous ribbon of riparian eucalypts. Away from the creek channel, the vegetation typically changes to spinifex and shrubs. Riparian eucalypts along the creek channels tend to be less dense with distance upstream from Weeli Wolli Spring.

Similarly at Ben's Oasis, the main active channel is clear of vegetation while there are dense stands of riparian vegetation along the banks and alluvia terraces. The vegetation rapidly thins both upstream of the surface water pools and with lateral distance from the creek.

Based on historical streamflow data (discussed below), Weeli Wolli Creek typically has up to two flow events a year. These events are generally short duration, with little post-rainfall flow persistence; although peak discharges are typically generated by longer duration storms which saturate the catchment and streambed resulting in streamflow. However, following above average wet seasons, the creek can flow for a period of several months. Under natural conditions, Weeli Wolli Spring discharges (baseflow) are continuous and dissipate into the river gravels a few kilometres downstream of the spring.

Water quality of Weeli Wolli Creek is circum-neutral in pH (slightly alkaline). The water is fresh and typically dominated by sodium and hydrogen bicarbonate (WRM, 2010).

With the development of the Hope Downs 1 deposit, mining operations have extended across Pebble Mouse Creek necessitating the creek to be diverted approximately 2 km eastwards from its natural course into the adjacent main Weeli Wolli Creek channel. This diversion is located approximately 3 to 4 km upstream from the natural confluence of the two creeks.

Excess dewatering water from mining operations at the Hope Downs 1 deposit is discharged into the main Weeli Wolli Creek channel just downstream from Weeli Wolli Spring. Small dewatering volumes are also discharged upstream of the spring, to maintain the natural pools and spring flows. The main dewatering discharges are believed to have created a surface expression of the watertable in the creek bed downstream from Weeli Wolli Spring to around its junction with Marillana Creek, approximately 15 km downstream of the spring.

4.3.4.2 Catchment Runoff Volumes

A detailed discussion of catchment runoff volumes for the Weeli Wolli Spring catchment is provided in Section 3.1.2.3. The estimations of annual runoff estimates for Weeli Wooli Spring and Ben's Oasis and the effects of discharges from the Hope Downs mining operations since 2006 are also discussed in Section 3.1.2.3.

From the available gauging data, the spring baseflow is estimated to be typically 6,900 kL/d. This baseflow represents the long term discharge of groundwater from the catchment through the spring. Seasonal variability in the spring's baseflow has been noted to occur. Baseflow in the spring can increase significantly in response to recharge and rising groundwater levels in the aquifer after a flow event; the peak baseflow varies with the antecedent flow event but is typically up to 10,000 kL/d (higher flows than this through the spring tend to represent surface water runoff). Baseflow recedes from this post-flow peak typically over a period of one year and tends to approximately 5,000 kL/d.

With respect to flood volumes additional to the spring's baseflow, the total catchment runoff is estimated at 2.4% of the total rainfall (i.e. average 9.3 mm/year). However, the median value is somewhat less than this. 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 rainfall and runoff totals represent the 50% AEP (annual exceedance probability) event. The median catchment runoff of 0.95% of annual rainfall (3.0 mm/year) could be considered a more typical runoff characteristic for the catchment and is significantly less than the long term average runoff of 2.4% (9.3 mm/year). It is estimated that flow events typically occur twice each year with only four years over the 30 year record period recording no flow events.

Ben's Oasis has a contributing runoff catchment area of approximately 418 km^2, which is approximately 3.5 times smaller than the Weeli Wolli Spring runoff contributing catchment area (1,450 km^2). Thus the annual runoff volumes at Ben's Oasis are significantly less than the runoff volumes at Weeli Wolli Spring.

Based on median and average runoff percentages, annual runoff volumes at Ben's Oasis and Weeli Wolli Spring are summarised below in Table 4.5.

Table 4.5: Weeli Wolli Spring Catchment - Annual Runoff Estimate (1985 – 2013)

	Weeli Wolli Spring Catchment Annual Runoff Volume (ML)	Ben's Oasis Catchment Annual Runoff Volume (ML)
Average	13,510	3,900
MedianValue	4,480	1,290

As stated in Section 3.1.2, monthly streamflow volumes at Tarina gauging station (January 1985 to April 2013) are presented in Figure 3.8, together with the corresponding monthly SILO rainfall for the Weeli Wolli Spring. Additionally plots of the annual runoff percentage versus annual rainfall and the monthly runoff percentage versus monthly rainfall for the Weeli Wolli (Tarina) catchment are shown in Figure 3.9.

4.3.4.3 Surface Water and the Broader Environment

Weeli Wolli Creek is characterised by relatively regular flow events, typically twice per year. Thus, both Ben's Oasis and the creek channel upstream of the spring are regularly inundated, providing sources of water to replenish soil moisture and bank storage along the flowpath channels and alluvial plains. A seasonal rise in groundwater levels close to Weeli Wolli Spring indicates that some of this water also recharges the shallow groundwater system.

4.3.5 Hydrostratigraphy

4.3.5.1 Setting

As outlined above, the surface water catchment of Weeli Wolli Creek at the spring is 1448 km^2 comprising the sub-catchments of the North Flank Valley, Pebble Mouse Creek and upper Weeli Wolli Creek. The groundwater catchment of Weeli Wolli Spring is larger with an area of 2307 $km^{2,}$ due to groundwater connectivity with the Coondewanna catchment. It is estimated that recharge derived from impounded flood waters on the Coondewanna Flats contributes approximately 75% of total recharge to the Weeli Wolli (groundwater) catchment (refer to Section 4.2).

Weeli Wolli Creek and its tributaries flow along valleys bound by hills of Marra Mamba and Brockman. Preferential weathering of the Wittenoom Formation between these outcrops resulted in a low-lying area which has subsequently been infilled with Tertiary deposits comprising alluvium sourced from the surrounding outcrop and chemically-precipitated calcrete which forms a local aquifer.

4.3.5.2 Basement Aquifers and Aquitards

In the area of Weeli Wolli Spring and the calcrete aquifer immediately upstream, the bedrock comprises:

- Wittenoom Formation (the Paraburdoo Member has a high permeability whereas the Bee Gorge member, stratigraphically higher than the Paraburdoo Member and closer to the spring, is of low permeability). The Wittenoom Formation occurs at depths of between 40 to 70 mbgl - getting shallower closer to the spring as the more weathering resistant Bee Gorge Member subcrops.
- Mount Sylvia Formation (low permeability).
- Mount McRae Shale (low permeability).
- Brockman Iron Formation (unmineralised - low permeability).

The Brockman and Mt McRae are particularly resistant to erosion and form a prominent ridge (Wildflower Range) along the northern extent of the catchment. Weeli Wolli Creek flows through this ridge (across the regional geological strike) along a narrow fault-controlled valley. Under the creek, the erosion-resistant Brockman and Mt McRae rise to shallow subcrop (i.e. they form a rock-bar).

Weeli Wolli Creek downstream of the spring also follows the fault-controlled valley with a NE orientation. However, there is no evidence in available drilling records that the fault has resulted in enhanced permeability in the basement. Even where drill-cuttings have indicated a possible fault zone (e.g. BH18), it is noted that fracturing is weak, infilled with carbonate and well-healed. This is consistent with Keppert (2001) who notes that faults in the North Flank Valley are characteristically less than 30 cm in width with little brecciation, and Solid Geology (2013) who found no evidence of permeability in NE orientated faults in the MAC area.

Thus the basement defines a broad alluvial valley bound to north by scarp slope (Brockman) with a narrow and shallow channel eroded through the scarp as the outflow. All surface and groundwater flow from the upstream catchment is concentrated through this narrow channel into a shallow aquifer.

4.3.5.3 Tertiary Aquifers

The valley immediately upstream of the spring is expansive and flat lying and essentially forms a small sedimentary basin. The Tertiary detritals are up to 75 m in the centre of this basin and thin to 20 m where basement rises to the north. Tertiary deposits include an extensive outcrop of calcrete. It is believed the calcrete was deposited as micritic limestone in a lacustrine environment when, during a wetter climate in the late Tertiary, the flow constraint imposed by the narrow outflow channel resulted in a lake forming upstream of the current spring (pers comm M Kneeshaw)..

The calcrete is underlain by poorly sorted alluvium of clay, sands and gravels with minor pisolite to depths between 10 mbgl and 75 mbgl; the alluvium overlies basement. These Tertiary detritals (TD2) have a varying permeability (based on clay content and degree of cementation).

The outcrop geology around Weeli Wolli Spring is shown on Figure 4.17. A typical hydrogeological cross section is shown on Figure 4.18.

As noted above, the basement formations north of the Paraburdoo Member are low permeability. Thus the main aquifer in proximity to the spring is the Tertiary detritals, particularly the calcrete and most groundwater flow occurs within this alluvial sequence.

4.3.5.4 Aquifers and the Welli Wolli PEC

Figure 4.19 shows the interpreted extent of calcrete around the spring.

The calcrete deposit varies between 0 and 40 m thick and the top of the calcrete occurs from outcrop to depths of up to 25 mbgl. The area of outcrop is concentrated in an inverse fan over an area up to 7 km upstream (south) of the spring. Calcrete extends over an even wider area, occurring in the Tertiary sequence of both the North and South Flank valleys. However, from the upstream edge of the “inverse" fan, the calcrete is covered by increasing amounts of Tertiary detritals. The surface of the calcrete occurs at increasing depths below ground level and it progressively thins and eventually becomes unsaturated approximately 10 km upstream of the spring. The calcrete aquifer is considered likely to support a high abundance of stygofauna; although stygofauna have been discovered over a much wider area around Weeli Wolli Spring and in other (non-calcrete) Tertiary detritals. No boundary is currently available to define the extent of stygofauna habitat.

Where the calcrete occurs as outcrop, it is incised by Weeli Wolli Creek. The incised channel is infilled with Quaternary alluvium that comprises an active creek channel, terraces and flood-plains of gravel, silt and clay. The main vegetation stands occur in these alluvial channels where the silt and sand provides better soil conditions than the calcrete, and where the incision of the channel brings the root zone into close proximity to the watertable. Figure 4.19 also shows the extent of shallow alluvium in proximity to the spring.

4.3.6 Ben’s Oasis

Considerably less is known about Ben’s Oasis than Weeli Wolli Spring as no drilling or investigations have been undertaken in the area. Based on available geological mapping and interpretation from satellite images, Wittenoom Formation (basement) outcrops extensively around Ben’s Oasis. Detrital sediments are confined to the narrow channel of the upper-Weeli Wolli Creek which is incised into the dolomite outcrop.

Where the Wittenoom Formation is permeable, it tends also to be prone to erosion and occurs usually in subcrop. The large area of outcrop around Ben's Oasis tends to suggest the formation would not have undergone the karstification that typically results in increased permeability; it is likely to be low-permeability basement and groundwater flow through the area is likely to be low to moderate. Nevertheless, a flow constraint such as a low-permeability dyke could still restrict what groundwater flow does occur and bring levels close to the surface into the alluvial channel.

However, from the interpretation of available groundwater levels, it is not necessarily the case that Ben's Oasis is in connection with the regional groundwater system (refer Section 4.3.4.1). This interpretation suggests that groundwater levels could be between 20 and 30 mbgl in the area. Furthermore is also possible that low-permeability dolomite prevents deep infiltration and recharge with water being captured in local pools and by infiltration into the shallow alluvium which forms a local perched aquifer. Subsequent seepage from this perched aquifer back into the creek channel supports the pools between flood events that "top up" the system. Under this scenario, the shallow alluvium forms a local perched aquifer in an otherwise low-permeability environment characterised by a deeper regional groundwater level.

Riparian woodland vegetation in the vicinity of Ben's Oasis is concentrated along the narrow creek channel where the alluvium provides better soil conditions. Figure 4.20 shows the setting of Ben's Oasis and schematically presents the two conceptual models for the presence of the pools.

4.3.7 Aquifer Parameters

Table 4.6 below compares the range of aquifer parameters estimated for Weeli Wolli Spring with the regional values outlined in Chapter 3.

Table 4.6: Permeability around Weeli Wolli Spring and Ben's Oasis

Unit	Regional Values			Weeli Wolli Spring		Remarks
k (m/d)	Min	Max	Med	Min	Max	
Alluvium	0.03	100	0.9	0.2	5	Mid-range
TD3	0.03	100.0	0.9	6.8	14.5	Within range; less reliable due to testing in unsaturated zone
Calcrete	2.5	41.4	11.2	20	50	
TD2 (Pisolitic Alluvium)	2.5	41.4	11.2	20	30	Mid-range
Brockman Iron Formation	0.001	0.05	0.002	0.0001	0.001	Mid-range
Mount McRae Shale	0.0001	0.1	0.0121	0.0001	0.0001	At the low-end of regional values
Mount Sylvia formation	0.01	1	0.1	0.1	1	Mid-range
Dolomite	0.1	105.0	10.4	7.0	31.0	Within range for non-karstic dolomite/Bee Gorge
Bee Gorge	1.8	1.8	1.8	0.1	1.0	

No hydraulic tests have been undertaken in the Weeli Wolli Spring area and the parameters are derived from interpretations during drilling, areal extrapolation and model calibration.

In general, the aquifer parameters around Weeli Wolli Spring fall within the middle of the range of regional values.

Estimates of permeability for the calcrete appear very typical of the region.

The basements units that occur in subcrop close to the spring (Mt Sylvia, Mt McRae and Brockman) have low permeability. This low permeability barrier across the groundwater flow path restricts groundwater flow in the basement, driving groundwater flow within the basement up into the alluvium and supporting the spring. However, as discussed below (Pre-mining Groundwater Levels), it is likely there is a weathered/transition zone in at least the first few meters of basement that has an enhanced permeability (this transition zone may relate to the presence of the regional fault). The enhanced permeability in this transition zone is masked by the much higher permeability in the overlying calcrete (and would not be recognisable in drilling yields) and to all intents and purposes, the alluvial aquifer can be considered to incorporate any transition zone at the top of the basement.

No specific estimates of confined or unconfined storage are available for Weeli Wolli Spring. The adoption of the regional values (refer Section 3) is recommended.

4.3.8 Groundwater Levels and Flow

4.3.8.1 Pre-mining Groundwater Levels

Large-scale abstraction close to the spring started in 2006 when dewatering at Hope Downs commenced. Contours of groundwater levels prior to 2006, in the vicinity of Weeli Wolli Spring, are presented in Figure 4.21. Groundwater flow is generally in a northeast direction, converging toward the narrow gap where Weeli Wolli Creek cuts through the Wildflower Range.

At the spring, groundwater levels are approximately 555 m AHD rising to 560 m AHD approximately 1.3 km upstream of the spring. The groundwater level gradient under the spring is steeper, at approximately 0.007. Further upstream, under the extensive area of calcrete, the watertable gradient is much flatter. Water levels are approximately 570 m AHD at HWW0002M (BH15) and rise to only 571.5 m AHD at HWW0001M (BH14), some 2 km away indicating- a gradient of 0.0007 (an order of magnitude less then under the spring). Gradients steepen into the spring as flow is concentrated through the narrowing and shallowing aquifer.

Bores HWW0003M (BH16), BH17, BH18 and BH32 are completed with shallow and deep piezometers and provide water levels from both the shallow alluvial aquifer and the underlying basement. Head differences are less than 1 m and there is no consistent direction to the inter-aquifer gradient (i.e. upwards or downwards). This suggests the alluvial and basement aquifers behave as a single, mixed aquifer unit with the variable gradient resulting from local-scale differences in permeability and aquifer thickness.

No water level data are available for the aquifers around Ben's Oasis. By interpolation from surrounding monitoring bores, it is believed that the water levels in the area of Ben's Oasis are approximately 640 to 650 m AHD and groundwater gradients are relatively flat. Interpolated groundwater contours around Ben's Oasis are shown in Figure 4.22.

4.3.8.2 Groundwater Levels – Changes over Time

Available groundwater level monitoring data for Weeli Wolli Spring are shown in Figure 4.23. There is a declining trend in all groundwater levels since early 2007 which relates to dewatering activities at Hope Downs. Superimposed on this trend of declining groundwater levels, several recharge events can be identified. Excluding the declining trend induced by dewatering, the following are interpreted from these hydrographs:

- Groundwater level rises occur almost annually associated with the summer wet season, although many of these rises are small (approximately 1 m). This suggests some recharge occurs every year; this is consistent with the frequency of flood events estimated from the hydrological analysis.
- Larger recharge events with water level rises of approximately 2 m occur with larger rainfall events - such events can be seen in 2006, 2008, 2009, 2011 and 2012.
- Groundwater level recession from larger recharge events occurs over periods of several months to a year in the bores upstream of the spring (BH14, BH16). Water levels in the bores close to the spring fall much more quickly probably because the spring itself facilitates more rapid groundwater dissipation. The elevated groundwater levels upstream of the spring are likely to contribute to increased spring baseflow throughout the period of recession.
- The greater frequency of recharge events at, and immediately upstream of the spring (than elsewhere in the catchment) and the rapid rise in groundwater levels suggests much of the recharge occurs locally as infiltration from creek flows as floods cross the calcrete outcrop. This is consistent with the results of isotope studies in the area (Dogramaci and Dodson 2009.

The groundwater conditions near Weeli Wolli Spring have changed significantly due to the impacts of mining (primarily dewatering at Hope 1 North (H1N). Contours of groundwater levels (for 2012 conditions) in the vicinity of the spring are presented in Figure 4.24. There is now a groundwater divide which has developed in the vicinity of HWW0003M and BH18 (around halfway between Hope Downs 1 North (H1N) and the spring). Northeast of the divide flow has remained towards the spring. However, southwest of the groundwater divide, groundwater now flows west towards the cone of depression around the H1N pit. Some of the groundwater flow from the south is now diverted towards the H1N cone of depression, while some continues to flow to the spring.

The hydraulic gradient close to the spring remains about the same as that of pre-mining conditions. Groundwater level drawdown of approximately 1 to 2 m at HWW0003M has occurred since pre-mining conditions. Closer to the spring at BH17, BH18, and BH32 groundwater levels remain at pre-mining water levels. The maintenance of throughflow towards the spring and the maintenance of the hydraulic gradient at the spring are likely to be due to increased recharge from the discharge of excess dewatering volumes in this area.

Groundwater levels west of the groundwater divide have exhibited significant drawdown since pre-mining: 45 m at BH14, 23 m at BH31, and over 13 m at BH30 (based on Dec 2012 data), clearly illustrating the impacts of mine dewatering at H1N.

4.3.8.3 Groundwater Levels in the PEC

Under pre-mining conditions, depth to watertable under Weeli Wolli Spring and the calcrete ranges between 0 and 10 mbgl. The watertable progressively deepens away from the spring. The calcrete, while retaining a thickness of at least 5m, becomes unsaturated where the depth to water exceeds approximately 30 mbgl. Thus, the saturated thickness in the calcrete ranges between 0 to 5 m at the periphery of the aquifer to 10 to 30 m in proximity to the spring. Thus, potential stygofauna habitat is maintained over a wide area and is particularly concentrated in the area where the calcrete occurs at outcrop immediately south of the spring (the area of saturated calcrete was shown in detail in Figure 4.19 and its boundaries are also shown in Figure 4.25).

Weeli Wolli Creek is incised into the calcrete outcrop by several meters. Suggesting the depth to water is several meters along the alluvium-filled channel. These channel areas support the riparian vegetation community associated with the spring.

Since 2006, a cone of water level depression has developed around the Hope Downs mine. This has resulted in part of the calcrete becoming unsaturated, presumably with a consequent reduction in stygofauna habitat. The extent of habitat reduction and any associated impacts on stygofauna populations cannot be determined from publicly available information. Groundwater levels have also declined along portions of the Weeli Wolli Creek channel hosting riparian vegetation. However targeted discharge of excess dewatering volumes has been used to maintain the vegetation community in affected areas; although the magnitude of these discharges is not publicly available.

4.3.9 Groundwater Recharge

4.3.9.1 Natural Recharge

Mechanisms of recharge to Weeli Wolli Spring and the calcrete aquifer upstream of the spring include groundwater throughflow from the upstream catchment and infiltration of surface water runoff events. The frequency of recharge events outlined above suggests the calcrete is likely to be an area of enhanced groundwater recharge. This is due to a higher frequency of runoff events in the lower catchment, high permeability calcrete at outcrop and the proximity of the watertable to the surface. Analysis of hydrographs and application of a simple storage accretion model suggests that up to 2500 kL/d of recharge (on average) occurs locally in the vicinity of the spring and calcrete. The post flood peak and recession in baseflow (refer Figure 4.23) represents the drainage of this local recharge.

The balance of recharge to the spring occurs as groundwater throughflow originating as recharge over the rest of the catchment. It is believed that up to 125,000 kL/d of recharge occurs over the remainder of the catchment, collecting and transmitting through the major valley systems to the spring-area. A large proportion of this recharge originates from the Coondewanna catchment, which is hydraulically connected to down-gradient groundwater systems (refer to Section 4.2).

Regional recharge is unlikely to contribute to short term variations in spring flow or indeed be seen in hydrograph response near the spring on a short term basis. Rather its effect will be subdued due to the damping effect of the aquifer and because it occurs at considerable distance from the spring. Regional recharge will affect long term trends in the amount of groundwater flowing into and thus groundwater levels (storage) in the alluvial sedimentary basin above the spring.

No hydrographs are available from aquifers around Ben's Oasis.

4.3.9.2 Additional Recharge – Current Regime

Recharge has increased since 2006 as surplus water from dewatering at Hope Downs has been discharged to the spring. This additional recharge has two components:

- Irrigation into Weeli Wolli Creek channel to maintain riparian vegetation and pools above the spring. Irrigation occurs at several points along the channel above the spring. This water results in both surface water runoff (which has increased continuous flow through the gauging station) and infiltration into the soil moisture and shallow alluvial aquifer where it supports the vegetation.
- Discharge into Weeli Wolli Creek downstream of the main spring. This water results in surface water runoff downstream and has extended the zone of permanent surface water further downstream than occurred under natural spring discharge only. The discharge infiltrates into the alluvial aquifer as it flows downstream.

The total or relative proportion of these discharges is not available. However, anecdotally, most water is discharged downstream of the spring (and thus, most of this discharge does not affect the water balance of the calcrete aquifer or PEC).

4.3.10 Groundwater Discharge

4.3.10.1 Natural Discharge

Groundwater discharge at Weeli Wolli Spring represents the main discharge from the entire Weeli Wolli Spring catchment. In summary, groundwater discharge comprises:

- Base flow to the spring (where groundwater reports to the surface). Average groundwater contribution to the spring flow measured at the Weeli Wolli gauge is approximately 6900 kL/d.
- Groundwater throughflow in the alluvial (and transition zone basement) aquifer underlying the Creek of approximately 4,000 kL/d.
- Evapotranspiration from vegetation around the spring has been estimated at approximately 3,000 kL/d. The area of riparian vegetation was estimated at 750 ha during the Hope Downs EIA giving an annual tree-water use of approximately 150 mm/yr (this is at the lower end of the anticipated range of tree-water use). However, it is believed the surveyed area extended downstream of the spring and the value of 750 ha used in the calculation is an overestimate of effective area.

The Silver Cadjeputs at the spring rely on a depth to groundwater of less than 5 mbgl and their contribution to evapotranspiration losses is unresolved. The River Red Gums and Western Coolibahs have greater rooting depths (up to 20 mbgl) and are facultative (i.e. opportunistic or periodic) phreatophytes and vadophytes. It is likely that they will contribute to evapotranspiration to varying degrees over a wider area.

There is little data available of the distribution or area of phreatophytic vegetation at Ben's Oasis, which has not been surveyed by BHP Billiton Iron Ore. Aerial photography interpretation suggests that the extent of riparian woodland vegetation is limited to tens of hectares. However, based on the regional water balance outlined in Chapter 3, it is estimated that evapotranspirative discharge from the area could be up to 1,000 kL/d.

4.3.10.2 Existing users

Since 2006 and the start of dewatering at Hope Downs, the largest discharge from the system in proximity to Weeli Wolli Spring has been dewatering abstraction. This is believed to be in the order of 100,000 L/d (based on original predictions presented in the Hope Downs EIA - Hope Downs 2000). The effects of dewatering abstraction in BHP Billiton Iron Ore's MAC mining also extend towards the spring. Neither of these discharges affect the short term processes at the spring associated with seasonal floods and recharge. Rather, they represent a long-term depletion of the groundwater storage that is maintained by recharge across the broader catchment and throughflow into the spring area.

4.3.10.3 Groundwater quality

Figure 4.26 illustrates groundwater quality for the Weeli Wolli Spring area from alluvial, basement aquifers and the spring itself.

Groundwater from bores in the Weeli Wolli Spring area is typically fresh calcium/magnesium and bicarbonate type water. This is characteristic of any water in carbonate (and particularly dolomite) rich terrain. The quality of groundwater in spring baseflow, the alluvial aquifer and the basement aquifer are all very similar suggesting a mixed groundwater system essentially functioning as a single aquifer unit.

There is an increase in salinity as groundwater flows towards the spring. The salinity in bores HWW0001M and HWW0002M is approximately 500 uS/cm and increases to approximately 1000 uS/cm in bores BH17 and BH18. This is largely due to evapotranspirative concentration of salts.

No data are available for groundwater quality at Ben's Oasis.

4.3.11 Ecohydrological Conceptual Model

The key features of the ecohydrological conceptualisation of the Weeli Wolli Spring area are depicted in Figure 4.27 and 4.28 and summarised as follows.

4.3.11.1 Surface and Groundwater Systems

- Surface flow at Weeli Wolli Spring is a combination of spring baseflow supported by groundwater and seasonal surface water floods.
- On average, there are two surface water flow events each year. There is local infiltration from these surface water flows resulting in recharge to the shallow groundwater system.
- The groundwater system comprises an unconfined aquifer sequence which comprises high permeability calcrete, moderate permeability Tertiary alluvium and moderate permeability transition zone underlain by low to high permeability basement.
- Groundwater levels range between 0 and 20 mbgl with watertable depths becoming shallower towards the spring. The aquifer thins and narrows towards Weeli Wolli Spring, concentrating groundwater flow, causing gradients to steepen and groundwater to report to the surface as baseflow.
- Recharge to the spring area occurs as direct infiltration from streamflow events on an almost annual basis; recharge is 2500 kL/d (when averaged over the year). Throughflow from the catchment upstream is approximately 11,000 kL/d.
- Discharge occurs as spring base-flow (approximately 7,000 kL/d), evapotranspiration (approximately 2,600 kL/d) and groundwater throughflow in the shallow aquifer (approximately 4,000 kL/d).
- There is no evidence (nor indeed a water balance requirement) for outflow in a deep (fault-controlled) aquifer through the gorge through Wildflower Range. There may be a zone of slightly enhanced permeability in the transition zone at the top of the otherwise low permeability basement at the spring. This transition zone, however, is in hydraulic connection and effectively acts as a single aquifer system with the overlying alluvium.

- Aquifer parameters are within the range of regional estimates and the system is driven by the high permeability in the calcrete and alluvium and low permeability in the basement in proximity to the spring.

4.3.11.2 Ecosystem Components

- The Weeli Wolli Spring area hosts a Priority Ecological Community including groundwater dependent vegetation, permanent pools supporting a range of fauna and a diverse stygofauna community.
- The riparian woodlands include the obligate phreatophyte Silver Cadjeput and the facultative phreatophytes River Red Gum and Western Coolibah. These access shallow groundwater and contribute to groundwater discharge via evapotranspiration. Woodland transpiration is likely to occur from areas where the watertable is less than 20 mbgl (albeit at a declining rate as the watertable depth increases). 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).
- The base of the calcrete is such that there is up to 30 m of saturated calcrete across a broad area. This provides the main stygofauna habitat, although data sources suggest that stygofauna do occur in other alluvial deposits over a wider area.
- A number of permanent pools occur in the calcrete formation upgradient from Weeli Wolli Spring, which are sustained by the shallow groundwater regime. These provide aquatic habitat and a permanent water source for terrestrial fauna and avifauna. The valley of Weeli Wolli Spring is known to support a very rich microbat assemblage.

4.3.11.3 Ben's Oasis

No information is available regarding groundwater levels or seasonal variation at Ben's Oasis. No drilling has occurred in the area and the stratigraphy is poorly characterised. As such, there is insufficient information to formulate a conceptual ecohydrological model for Ben's Oasis at the present time. Based on general knowledge of the area and extrapolation from elsewhere, it is postulated that the groundwater system may comprise either:

- A perched-alluvial aquifer confined to a shallow channel incised through low-permeability basement. Bank-storage and seepage from this perched aquifer would replenish local rock-pools between surface runoff events. Perched groundwater in this shallow aquifer would also support riparian vegetation; or
- A deeper regional groundwater flow system, that is diverted up to the surface by a (currently undefined) flow constraint.

Surface flow at Ben's Oasis is likely to have a similar frequency to the Weeli Wolli Spring area (i.e. on average two surface water flow events each year) but the magnitude will be substantially less in proportion to the much smaller contributing catchment area. On the basis of the regional water balance, total discharge from Ben's Oasis attributable to evapotranspiration is estimated to be up to 1,000 kL/d.

4.3.11.4 Key Indicators

The key indicators for the preservation of the ecological values of the Weeli Wolli Spring Community PEC are:

- Surface water expression.
- Surface water quality.
- Average depth to watertable.
- Groundwater quality.
- Rate of watertable decline (in response to dewatering stressors).
- Extent of permanently saturated 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: Weeli Wolli Spring Community PEC - key indicators for the preservation of ecological values

Variable	Groundwater Dependent Vegetation		Surface waterbodies		Stygobiont Community	
	Tolerance	**Observed/ modelled range**	**Tolerance**	**Tolerance**	**Observed/ modelled range**	**Tolerance**
Surface water expression (ha)	Not applicable	Not applicable	*No data*	*???*	Not applicable	Not applicable
Surface water quality (TDS)	*No data*	*???*	*No data*	<2,000 mg/L	Not applicable	Not applicable
Average depth to watertable (mbgl)	*No data*	0 to 20m	Not applicable	Not applicable	*No data*	0 to 30m
Groundwater quality (TDS)	*No data*	<2,000 mg/L	Not applicable	Not applicable	*No data*	<2,000 mg/L
Rate of watertable decline (adaptability and natural recession)	*No data*	*???*	Not applicable	Not applicable	*No data*	*???*
Extent of permanently saturated habitat for stygofauna	Not applicable	Not applicable	Not applicable	Not applicable	*No data*	???

5. STRESSORS

5.1 Introduction

As outlined in Chapter 1.1.2, there are 41 designated orebodies in the CPR, 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 CPR 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 5.9) include a summary of the hydrogeological investigations completed to date, the key hydrogeological interactions that will influence Wolli Spring and/or Coondewanna Flats.

The contents of Tables 5.1 to 5.9 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 CPR the orebody types include 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 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 flowpaths and possible sourcing of water resources (either surface water or groundwater) to meet water requirements.

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 unmineralised West Angela Member. Dewatering will be required for the removal of stored groundwater within the orebody aquifer. Inflows to the pit will be generally be (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 connected mine types pose low potential impact risk on the regional aquifer and associated receptors; however, monitoring is recommended to demonstrate water level response.

C Deposit in MAC 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 marginal connectivity with the regional groundwater system, it will be 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 generally 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.

E Deposit in MAC is an example of current mining in this category. Many of the future Marra Mamba pits the CPR could also 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 generally 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.

Rio Tinto's Hope Downs is the only example of such an orebody mined to date in the CPR. In the future, the Railway Deposit, among others, could be similar.

5.2 Jinidi

The Jinidi – OB10, OB11, OB12 mining area (hereafter referred to collectively as Jinidi) is located 70 km to the northwest of Newman at the eastern margin of the CPR study area, 10 km to the east of Rio Tinto's Hope Downs project, and approximately 20 km east of the MAC mining area. The Jinidi mining area is adjacent to Weeli Wolli Spring (Figure 5.2).

There are eight orebodies (OB10 OB11, OB12, OB13, OB14/15, OB16 and OB41) in the Jinidi mining area, which are all Brockman deposits and planned to be mined below the watertable.

There have been extensive groundwater and surface water investigations completed in the overall Weeli Wolli Spring catchment, commencing in the 1970s, by Goldsworthy Mining and BHP Billiton Iron Ore at MAC and Packsaddle, and Hancock Prospecting and Rio Tinto at Hope Downs. In the Jinidi mining area, specific hydrological investigations have been underway since 2009, focused on OB13 and OB41. The investigations completed (at Jinidi and elsewhere in the CPR region), and operational experience gained from existing mines, provide a high level of confidence in the local hydrology of the Jinidi mining area.

An overview of the key hydrological features of each orebody is listed in Table 5.1.

5.2.1 Jinidi Conceptual Model

The main surface water flowpath in the area of the Jinidi mining area is Weeli Wolli Creek which drains from south to north, towards Weeli Wolli Spring (Figure 5.1). The Jinidi mining area itself is drained by two tributaries of Weeli Wolli Creek. The northern tributary system drains the area to the south of OB10, OB11, OB12 OB13, OB14/15 and OB41 area, draining north-westwards to Weeli Wolli Creek at Weeli Wolli Spring. The southern tributary is much longer and drains the full length of OB16 in a northwesterly direction to a confluence with Weeli Wolli Creek some 10 km upstream of Weeli Wolli Spring.

Groundwater outflow from OB13, OB14/15, OB16 and OB41 occurs to the northwest and west towards Weeli Wolli Creek, and then converges around the dewatering drawdown cone of depression that has developed around the Hope Downs mine. Groundwater outflow from OB10, OB11 and OB12 is to the south and southwest towards Weeli Wolli Creek upstream of Weeli Wolli Spring, and to the west and north towards downstream sections of Weeli Wolli Creek (downstream of Weeli Wolli Spring).

The Brockman orebodies are all mostly surrounded by low permeability unmineralised BIF and shales/siltstones and, in most cases, dewatering should simply require desaturation of the orebody aquifers followed by minor maintenance abstraction to handle low rate ongoing inflows from the surrounding aquitards. However, OB13 mineralisation has been interpreted to extend beneath Tertiary detritals and there could be enhanced hydraulic connection between the orebody and the regional aquifer regardless of whether the pit intersects the Tertiary detritals or not.

A series of northeast–southwest and east–west faults have also been interpreted which could further enhance hydraulic connection between OB13 and the regional aquifer. These faults may also enhance hydraulic connection between OB14/15 and the regional aquifer. Depending on the degree of hydraulic connection, dewatering of these pits may not only require desaturation of the orebody aquifers, but also higher rates of abstraction to intercept inflows from the regional aquifer. Longer term dewatering requirements could be similar to initial dewatering requirements.

The conceptual hydrological model is shown schematically on Figure 5.3.

Table 5.1: Orebody Overview – Jinidi

Orebody	Orebody 10, 11, 12	Orebody 14, 15	Orebody 13	Orebody 41	Orebody 16
Ore Type	Brockman	Brockman	Brockman	Brockman	Brockman
Current Status[1]	Proposed (AWT) mining No drilling	Proposed mining Moderate drilling	Proposed mining Extensive drilling	Proposed mining Extensive drilling	Proposed mining Moderate drilling
Previous Hydrogeological Studies[2]	Nil	Nil	Drilling and testing: - DW, EIA Modeling: - DW, MAR, EIA (numerical)	Drilling and testing: - DW, EIA Modeling: - DW, MAR, EIA (numerical)	Nil
Ore Below Watertable (BWT)[3]	5%	5%	48%	4%	38%
Max saturated thickness [4]**(m)**	20	60	200	100	140
Strike Length (m)	2,000	4,000	2,500	5,000	3,000
Generic Type[5]	BIF - Connected	BIF – Partially Connected	BIF - Connected	BIF – Isolated or Disconnected	BIF – Isolated or Disconnected
Dewatering Requirements (and basis[6]**)**	MOD – 2 to 10 ML/d	MOD – 2 to 10 ML/d	HIGH– 14 to 25 ML/d	LOW to MOD– 0.6 to 3 ML/d	MOD – 2 to 10 ML/d
Key Dewatering Drivers[7]	Storage TD connection	Storage TD connection (possible)	Storage TD connection	Storage	Storage
Interaction with Weeli Wolli Spring	Close to receptor Possible interception of GW throughflow to receptor Possible reversal of GW flow from receptor Potential 0.1% reduction in runoff to Weeli Wolli Spring	Close to receptor Possible interception of GW throughflow to receptor Possible reversal of GW flow from receptor Potential 0.2% reduction in runoff to Weeli Wolli Spring	Close to receptor Possible interception of GW throughflow to receptor Possible reversal of GW flow from receptor Potential 0.4% reduction in runoff to Weeli Wolli Spring	Close to receptor Possible interception of GW throughflow to receptor Possible reversal of GW flow from receptor Potential 0.8% reduction in runoff to Weeli Wolli Spring	Distant from receptor Possible interception of GW throughflow to receptor Potential 0.4% reduction in runoff to Weeli Wolli Spring

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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

5.3 MAC

MAC is located approximately 100 km northwest of Newman (Figure 5.4). The MAC mining area is bound to the east by Rio Tinto's Hope Downs mine, to the south by the South Flank mining area, to the north by the Wildflower Range, and to the west by Coondewanna Flats and the Great Northern Highway.

Within the MAC mining area, there are eight designated Marra Mamba orebodies with seven extending below the watertable; eleven Brockman orebodies with four extending below the watertable; and a Tertiary detritals deposit being above the watertable. Construction of the mine started in 2001, mining started in 2003 and dewatering at two Marra Mamba orebodies (C and E Deposits) started in 2010.

Groundwater abstraction in the mining area commenced in 2001 (construction water supplies) and gradually increased to around 6 ML/d by 2004 after above watertable mining commenced. Dewatering abstraction commenced in 2010 and currently ranges up to 30 ML/d. Dewatering at the nearby Hope Downs mine commenced in 2006 and has been in excess of 70 ML/d since this time.

There is a long history of investigations, operating experience and monitoring dating back to water supply investigations for a proposed town and mine in the 1970s and more detailed investigations for the current orebodies since 1997. The more recent hydrological investigations have supported environmental approvals, water supply development, dewatering design and development and ongoing groundwater and surface water management, and have included comprehensible groundwater modelling of the region, including taking into account the impacts of Hope Downs dewatering. The extensive and detailed investigations completed to date provide a high degree of confidence in the hydrogeological system in the MAC mining area.

An overview of the status and key hydrological features of each orebody is listed in Tables 5.2, 5.3 and 5.4.

5.3.1 MAC Conceptual Model

The orebodies are mostly located in the Weeli Wolli Spring catchment, with three orebodies at the western end of the mining area (Packsaddle West, Packsaddle 1 and Dead End) being partly within the Coondewanna catchment and the northern parts of the Packsaddle 3, 4, 5, 6 orebodies also extending northwards over the catchment divide into the Yandicoogina Creek catchment. However, the main surface water flowpath in the MAC mining area is the unnamed northern tributary of Weeli Wolli Creek which flows from Coondewanna to Weeli Wolli Spring (Figure 5.4). At the western end of the mining area, within the Coondewanna catchment, surface water run-off flows westwards, into Lake Robinson.

Groundwater flows from west to east from Coondewanna Flats through MAC (predominantly through the regional aquifer) to discharge through Weeli Wolli Spring. There are some minor groundwater flow pathways to the northwest, west and southwest from the extreme western orebodies which eventually flow south into Coondewanna Flats and then eastwards through MAC There are also some minor northwards groundwater flows from some of the Packsaddle orebodies towards Yandicoogina Creek.

The Brockman orebodies along the northern side of MAC on the Packsaddle Range are completely surrounded by low permeability unmineralised BIF and shale. In these orebodies pit dewatering will simply require desaturation of the orebody aquifer and then minor maintenance abstraction to accommodate low rate ongoing inflows from the surrounding aquitards. If there is any enhanced connection to the regional aquifer via local faults then longer term pit inflows might be a bit 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.

Most of the ore in the MAC mining area is hosted in Marra Mamba orebodies (A, B, C, D, E, R and Dead End Deposits). While the main orebodies (and orebody aquifers) are distinct, there can be some connection along strike via low-grade mineralisation (40%-50% Fe) halos around each orebody. In all of these orebodies, the hanging walls of the pits will likely intersect sections of Tertiary detritals and will be in hydraulic connection with the regional aquifer. A major thrust fault, associated with the geological structure of the orebodies, also provides hydraulic connection between the orebodies and the regional aquifer. As such, dewatering not only requires desaturation of the orebody aquifers, but also sustained high rate abstraction to intercept or accommodate inflows from the regional aquifer through the hanging wall. Overall dewatering requirements have been substantial for existing operations and will likely remain so for future pits.

The conceptual hydrogeological model is shown schematically in Figures 5.5a to 5.5d.

Table 5.2: Orebody Overview – MAC

Orebody	**Dead End**	**R Deposit**	**E Deposit**	**D Deposit**	**C Deposit**	**B Deposit**	**A Deposit**	**F Deposit**
Ore Type	Marra Mamba	Marra Mamba	Marra Mamba	Marra Mamba	Marra Mamba	Marra Mamba	Marra Mamba	Marra Mamba
Current Status[1]	Proposed mining Moderate drilling	Proposed mining Moderate drilling	Current BWT mining Extensive drilling	Mining complete Extensive drilling	Current BWT mining Extensive drilling	Proposed mining Extensive drilling	Proposed mining Extensive drilling	Proposed mining Extensive drilling
Previous Hydrogeological Studies[2]	Nil	Drilling and testing: - DW, EIA	Drilling and testing: - DW, WS, EIA Moisture Content Investigations - DW Modelling - DW,SW, EIA	Desk-top: -DW, EIA	Drilling and testing: - DW, WS, EIA Modelling -DW, SW, EIA	Desk-top: - DW, EIA	Drilling and testing: - DW, EIA Modelling: -DW, EIA	Desk-top: - DW, EIA Modelling: - DW, EIA
Ore Below Watertable (BWT)[3]	17%	8 to 25%	26%	1%	29%	10%	20%	0%
Max saturated thickness (m)	87	138	124	–	171	48	103	–
Strike Length (m)	Unknown	6,500	6,000	1,500	4,500	9,500	5,500	2,500
Generic Type[4]	BIF – Partially Connected	BIF - Connected	BIF - Connected	BIF – Isolated or Disconnected	BIF – Partially Connected	BIF - Connected	BIF – Fully Connected	BIF – Isolated or Disconnected
Dewatering Requirements (and basis[5])	MOD – 2 to 10L/d (empirical model)	HIGH >10 ML/d (empirical)	HIGH – 18 ML/d (numerical model)	LOW – 0.1 ML/d (numerical model)	HIGH – 13 ML/d (numerical model)	LOW <2 ML/d (numerical model)	HIGH – 5 ML/d[a] (numerical model)	LOW –0.1 ML/d (generic model)
Key Dewatering Drivers[6]	Storage TD connection	Storage TD connection	Storage TD connection	Storage TD connection	Storage TD connection	Storage TD connection	Storage TD connection	NA
Interaction with Weeli Wolli Spring and Coondewanna Flats	Distant from Weeli Wolli Spring Possible interception of throughflow to Weeli Wolli Spring Minor drawdown extending into Coondewanna Flats Potential 1.2%reduction in runoff to Coondewanna Flats	Close to Weeli Wolli Spring Possible interception of throughflow to Weeli Wolli Spring Potential 1.1% reduction in runoff to Weeli Wolli Spring	Distant from Weeli Wolli Spring Possible interception of throughflow to Weeli Wolli Spring Potential 0.2% reduction in runoff to Lake Robinson Potential 0.4% reduction in runoff to Weeli Wolli Spring	Distant from Weeli Wolli Spring Possible interception of throughflow to Weeli Wolli Spring Potential 0.1% reduction in runoff to Weeli Wolli Spring	Close to Weeli Wolli Spring Possible interception of throughflow to Weeli Wolli Spring Potential 0.4% reduction in runoff to Weeli Wolli Spring	Close to Weeli Wolli Spring Possible interception of throughflow to Weeli Wolli Spring Potential 0.6% reduction in runoff to Weeli Wolli Spring	Close to Weeli Wolli Spring Possible interception of throughflow to Weeli Wolli Spring Potential 0.5% reduction in runoff to Weeli Wolli Spring	Close to Weeli Wolli Spring Potential 0.2% reduction in runoff to Lake Robinson <0.1% reduction in runoff to Weeli Wolli Spring

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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

a Dewatering at A Deposit is reduced due to interference effects from antecedent dewatering at C Deposit and Hope Downs

Table 5.3: Orebody Overview – Packsaddle and Packsaddle West

Orebody	Packsaddle West	Packsaddle 1 (P1)	Packsaddle 2 (P2)	Packsaddle 3 (P3)	Packsaddle 4 (P4)	Packsaddle 5 (P5)	Packsaddle 6 (P6)	Packsaddle Range Detritals
Ore Type	Brockman	Brockman	Brockman	Brockman	Brockman	Brockman	Brockman	Tertiary Detrital
Current Status[1]	Proposed mining Limited drilling	Proposed mining Extensive drilling	Proposed AWT mining Limited drilling	Mining Extensive drilling	Proposed AWT mining Moderate drilling	Proposed mining Moderate drilling	Proposed AWT mining Extensive drilling	Proposed AWT mining Extensive drilling
Previous Hydrogeological Studies[2]	Nil	Modelling - DW, EIA	Nil	Modelling - DW, EIA	Nil	Nil	Nil	Nil
Ore Below Watertable (BWT)[3]	10%	6%	0%	1%	0%	1%	0%	0%
Max saturated thickness[4] **(m)**	*30*	4	–	90	–	–	–	–
Strike Length (m)	9,500	10,000	Unknown	3,000	3,000	3,000	3,500	Unknown
Generic Type[5]	BIF – Isolated or Disconnected	BIF – Isolated or Disconnected	BIF – Above Watertable	BIF – Isolated or Disconnected	BIF – Above Watertable	BIF – Isolated or Disconnected	BIF – Above Watertable	BIF – Above Watertable
Dewatering Requirements (and basis[6]**)**	MOD – 2 to10 ML/d (generic model)	LOW - 1.3 ML/d (numerical model)	Nil	LOW – 2 ML/d (numerical model)	Nil	LOW < 2ML/d (empirical)	Nil	Nil
Key Dewatering Drivers[7]	Storage	Storage	NA	Storage	NA	NA	NA	NA
Interaction with Weeli Wolli Spring and Coondewanna Flats	Close to Coondewanna Flats Possible interception of GW throughflow to receptor Potential 1.2% reduction in runoff to Lake Robinson	Distant from Weeli Wolli but close to Coondewanna Flats. Little to no impact on groundwater throughflow to receptors Potential 0.9% reduction in runoff to Lake Robinson Potential 0.3% reduction in runoff to Weeli Wolli Spring	Potential 0.3% reduction in runoff to Weeli Wolli Spring	Distant from Weeli Wolli and Coondewanna Flats. Little to no impact on groundwater throughflow to receptors Potential 0.2% reduction in runoff to Weeli Wolli Spring	Potential 0.1% reduction in runoff to Weeli Wolli Spring	Potential 0.2% reduction in runoff to Weeli Wolli Spring	Potential 0.3% reduction in runoff to Weeli Wolli Spring	Potential 0.3% reduction in runoff to Weeli Wolli Spring

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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

8 Data gaps referred to in this table relate to understanding of conceptual hydrogeology/hydrology and interaction with key receptor. Other data gaps related to dewatering volumes and other mining issues are referred to in the main text

Table 5.4: Orebody Overview Eastern Packsaddle (Orebody 6, 7, 8 and 9)

Orebody	Orebody 6	Orebody 7	Orebody 8	Orebody 9
Ore Type	Brockman	Brockman	Brockman	Brockman
Current Status[1]	Proposed AWT mining Limited drilling	Proposed AWT mining Limited drilling	Proposed AWT mining Limited drilling	Proposed AWT mining Limited drilling
Previous Hydrogeological Studies[2]	Nil	Nil	Nil	Nil
Ore Below Watertable (BWT)[3]	0%	0%	0%	0%
Max saturated thickness[4] (m)	–	–	–	–
Strike Length (m)				
Generic Type[5]	BIF – Isolated or Disconnected	BIF – Above Watertable	BIF – Above Watertable	BIF – Above Watertable
Dewatering Requirements (and basis[6])	Nil	Nil	Nil	Nil
Key Dewatering Drivers[7]	NA	NA	NA	NA
Interaction with Interaction with Weeli Wolli Spring and Coondewanna Flats	Potential 0.2% reduction in runoff to Weeli Wolli Spring	<0.1% reduction in runoff to Weeli Wolli Spring	<0.1% reduction in runoff to Weeli Wolli Spring	<0.1% reduction in runoff to Weeli Wolli Spring

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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

5.4 South Flank

The South Flank mining area is located immediately south of the MAC mining area, east of the main Mudlark Well mining area and north of the Mount Robinson part of the Mudlark Well mining area. It comprises Marra Mamba orebodies that extend along a strike length of approximately 26 km in an approximate east–west orientation. The mining area is approximately 85 km west northwest of Newman and is shown in Figure 5.6.

The South Flank mining area has been subdivided into the three broad orebody zones: Highway, Grand Central and Vista Oriental. Within these broad orebodies, there are two sets of elongated and semi continuous orebodies, a northern and a southern set which will be mined by a series of (often interconnected) pits currently referred to as Phases 1 to 21. Many of these pits will be mined below watertable.

No mining development has taken place at South Flank to date. There have been extensive groundwater and surface water investigations completed in the Weeli Wolli Spring catchment, dating back to the 1970s. In the South Flank mining area, specific hydrological investigations have been underway since 2011. The investigations completed at South Flank mining area (and elsewhere in the CPR region), and operational experience gained from existing mines, provide a moderate level of confidence.

An overview of the status and key hydrogeological features of the South Flank mining area is listed in Table 5.4.

5.4.1 South Flank Conceptual Model

The South Flank mining area marginally extends over the catchment divide between the Coondewanna catchment to the west and the Weeli Wolli Spring catchment to the east. The main surface water flowpath in the South Flank mining area is Pebble Mound Creek (a tributary of Weeli Wolli Creek) which flows from Coondewanna eastwards along the southern margin of the mining area and then northwards towards its confluence with Weeli Wolli Creek just upstream of Weeli Wolli Spring (Figure 5.6). The southern part of the mining area (the area which comprises the known orebodies and the planned Phases 1 to 21 pits) drains to the east via Pebble Mound Creek. The northern part of the mining area (in which there are no know orebodies) drains northwards into the North Flank Valley. The extreme western end of the mining area drains westwards towards Lake Robinson in the Coondewanna catchment.

Groundwater throughflow is mostly from west to east, through the regional aquifer along the South Flank Valley and ultimately towards Weeli Wolli Spring. There is also some outflow to the north and east towards MAC and then to Weeli Wolli Spring.

The northern Marra Mamba orebodies are likely to be completely surrounded by low permeability unmineralised BIF. In these cases, dewatering (in those pits that will be mined below the watertable) will only require desaturation of the orebody aquifers, followed by minor maintenance abstraction to handle low rate ongoing inflows from the surrounding low permeability aquitards. Local normal faulting and regional thrust faulting may provide some hydraulic connection between the northern and southern pits and dewatering of pits in either might intercept groundwater storage in the other pits resulting in higher long term dewatering rates, but also resulting in some advanced dewatering of the other pits.

The southern Marra Mamba orebodies are surrounded by low permeability BIF along strike and to the north, but there may be some local fault connection with the northern series of orebodies. The southern pit walls will intersect Tertiary detritals and where these are saturated, high inflows are possible. Where the pit walls intersect the West Angela Member below the watertable, groundwater inflows will be minimal, unless local faulting through, or mineralisation within the West Angela Member provides enhanced hydraulic connection.

The conceptual hydrogeological model is shown schematically in Figures 5.7a, 5.7b and 5.7c.

Table 5.5: Orebody Overview – South Flank

Orebody	South Flank (covers Highway, Grand Central and Vista Oriental orebody areas and Phases 1 to 21 Pits)
Ore Type	Marra Mamba
Current Status[1]	Proposed BWT mining Proposed AWT mining
Previous Hydrogeological Studies[2]	Drilling and monitoring: - DW, WS, EIA Modelling: - DW, WS, EIA (numerical)
Ore Below Watertable (BWT)[3]	1 to 35%
Max saturated thickness[4] **(m)**	*70*
Strike Length (m)	27,000
Generic Type[5]	Northern Pits: BIF – Isolated or Disconnected Southern Pits: BIF - Connected
Dewatering Requirements (and basis[6]**)**	HIGH - up to 16 ML/d (numerical model)
Key Dewatering Drivers[7]	Storage TD connection?
Interaction with Weeli Wolli Spring and Coondewanna Flats	Modelling of whole site: Coondewanna Flats will be impacted, (10 to 41m drawdown). Weeli Wolli Spring area will have some impact with 0.5m drawdown at spring and 2.3m upstream at BH17 Potential 3.0% reduction in runoff to Lake Robinson Potential 4.1% reduction in runoff to Weeli Wolli Spring

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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

5.5 South Parmelia

5.5.1 Overview

The South Parmelia mining area is located 70 km to the northwest of Newman. It is at the eastern margin of the CPR study area immediately to the south of the Jinidi mining area and 10 km to the southeast of the South Flank mining area (Figure 5.8). Rio Tinto's Rhodes Ridge project is located 5 km to the east of the mining area.

There are three mapped Brockman orebodies (OB4, OB5 and OB27), although these are lumped together and referred to as the South Parmelia orebody which is planned to be mined below watertable.

There has been no mining at South Parmelia to date. There have been extensive groundwater and surface water investigations in the Weeli Wolli Spring catchment commencing in the 1970s (refer MAC – Section 5.2) although there have been no specific hydrological investigations completed to date at South Parmelia. Notwithstanding this, the investigations completed elsewhere in the CPR region, and operational experience gained from existing mines, provide a moderate level of confidence in the local hydrology in the South Parmelia mining area.

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

5.5.2 South Parmelia Conceptual Model

The main surface water flowpaths in the South Parmelia mining area are the main channel of Weeli Wolli Creek, which drains the western end (OB4) of the area, and which flows to the north towards Weeli Wolli Spring, and an unnamed tributary of Weeli Wolli Creek (Figure 5.8). This tributary flows from east to west and drains the northern part of the mining area. The southern part of the mining area (around OB5 and OB27) is drained by a minor tributary of the main northern tributary which flows from west to east before joining the main tributary. Ben's Oasis is located on the Weeli Wolli Creek main channel to the west of the mining area.

The Brockman orebodies are surrounded by low permeability unmineralised BIF and shales/siltstones. There also does not appear to be any direct hydraulic connection with the regional aquifer which is over 5 km downstream of the mining area, although there might be some minor hydraulic connection to the west of Orebody 4 via fault/fracture zones and to the northwest of Orebody 5 via a fault. However, it would appear that these structures do not extend far from the orebody aquifers (if at all). As such dewatering should simply require desaturation of the orebody aquifers followed by minor maintenance abstraction to handle low rate ongoing inflows from the surrounding aquitards.

Figure 5.9 shows the influence of the conceptual hydrogeology on dewatering requirements.

Table 5.6: Orebody Overview – South Parmelia

Orebody	South Parmelia
Ore Type	Brockman
Current Status[1]	Proposed BWT mining Limited drilling
Previous Hydrogeological Studies[2]	Nil
Ore Below Watertable (BWT)[3]	40%
Max saturated thickness[4] **(m)**	44
Strike Length (m)	8,000
Generic Type[5]	BIF – Isolated to Disconnected
Dewatering Requirements (and basis[6]**)**	High - >10 ML/d (generic model – based on extensive strike length of multiple orebodies)
Key Dewatering Drivers[7]	Storage
Interaction with Weeli Wolli Spring	Close to receptors, but limited hydraulic connection. Potential 0.2% reduction in runoff volume to Weeli Wolli Spring

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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

5.6 Mudlark

The Mudlark mining area is located approximately 120 km northwest of Newman and 40 km southwest of BHP Billiton Iron Ore's operational hub at MAC (Figure 5.10). The mining area is bound to the east by the Great Northern Highway and the South Flank mining area, to the north by the Tandanya mining area, to the west by Karijini National Park, and to the south by Rio Tinto's West Angelas mine. The West Angelas rail line passes through the Mudlark mining area. Coondewanna Flats are located in the northeast part of the Mudlark mining area.

There are thirteen designated orebodies within the Mudlark mining area, seven of which extend below the watertable including six Marra Mamba deposits and one Brockman deposit.

There has been no mining in the Mudlark mining area to date. There have been only minor hydrogeological investigations completed in the Mudlark area. These include the installation of monitoring bores at Coondewanna Flats and Boundary Ridge (and ongoing water level monitoring) and two water supply bores on the alluvial plain between Alligator Jaws, Boundary Ridge and Governor Range during construction of the West Angelas Railway. Mineral drilling records also provide some information on cavernous ground conditions and excess water produced during RC drilling. However, together with work completed in other mining areas (in particular, at MAC and Tandanya and anecdotal information from West Angelas), these background data allow for a moderate level of confidence in the conceptual hydrogeological model.

An overview of the key hydrological features related to each orebody is listed in Table 5.6.

5.6.1 Mudlark Conceptual Model

The orebodies in the Mudlark mining area are located mainly within the Coondewanna catchment with some areas extending into the adjacent Weeli Wolli and Turee Creek catchments (Figure 5.10). The main surface water flowpaths in the mining area flow from the west and north towards Coondewanna Flats and Lake Robinson. Some of the flowpath corridors flowing towards Lake Robinson are relatively well defined but there are also many large relatively flat areas where runoff would tend to pool and slowly drain downstream or discharge as sheetflow over a wide flow zone. Run-off from the Alligator South orebody drains south into Turee Creek East Branch, while run-off from eastern parts of the Southeast Corner orebody drains eastwards into Pebble Mound Creek (a tributary of Weeli Wolli Creek) through well defined flowpaths.

Groundwater flows into the mining area from the north and west (into the Coondewanna Flats area). Most groundwater discharges from the mining area is to the east into the upper reaches of Pebble Mouse Creek. Some groundwater discharges to the south into the Turee Creek East Branch catchment.

The one below watertable Brockman orebody (Governor Range) is completely surrounded by low permeability unmineralised BIF and shale. In this orebody, pit dewatering will only require desaturation of the orebody aquifer and then minor maintenance abstraction to accommodate low rate ongoing inflows from the surrounding aquitards. If there is any enhanced connection to the regional aquifer via local faults then longer term pit inflows might be somewhat 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.

Most of the ore in the Mudlark mining area is hosted in Marra Mamba orebodies (Alligator Jaws, Alligator South, Alligator North, Boundary Ridge, Parallel Ridge and Southeast Corner). In all of these orebodies, the hanging walls of the pits will likely intersect Tertiary detritals (including calcrete) and/or dolomite of the regional aquifer. As such, dewatering will not only require desaturation of the orebody aquifers, but also sustained high rate abstraction to intercept or accommodate inflows from these aquifers. Overall dewatering requirements are likely to be large.

Figures 5.11a to 5.11e show the influence of the conceptual hydrogeology on dewatering requirements.

Table 5.7: Orebody Overview – Mudlark

Orebody	Alligator South	Parallel Ridge	Alligator Jaws	Governor Range	SE Corner	Alligator North	Boundary Ridge
Ore Type	Marra Mamba	Marra Mamba	Marra Mamba	Brockman	Marra Mamba	Marra Mamba	Marra Mamba
Current Status[1]	Proposed BWT mining Moderate drilling	Proposed BWT mining Moderate drilling	Proposed BWT mining Extensive drilling	Proposed BWT mining Moderate drilling	Proposed BWT mining Limited drilling	Proposed BWT mining No drilling	Proposed BWT mining Limited drilling
Previous Hydrogeological Studies[2]	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Ore Below Watertable (BWT)[3]	26%	25%	31%	10%	25%	35%	35%
Max saturated thickness[4] (m)	124	–	*20*	*28*	*88*	*90*	90
Strike Length (m)	7,500	11,000	5,000	13,000	12,500	7,000	9,500
Generic Type[5]	BIF – Fully Connected	BIF - Connected	BIF – Fully Connected	BIF – Isolated or Disconnected	BIF – Connected	BIF - Connected	BIF – Connected
Dewatering Requirements (and basis[6])	High – >10 ML/d (generic model)	High – >10 ML/d (generic model)	High –>10 ML/d (generic model)	Low <5 ML/d (experience)	High – >10 ML/d (generic model)	High – >10 ML/d (generic model)	High – >10 ML/d (generic model)
Key Dewatering Drivers[7]	Storage TD connection Wittenoom Formation connection	Storage TD connection Wittenoom Formation connection	Storage TD connection Wittenoom Formation connection	Storage	Storage TD connection Wittenoom Formation connection	Storage TD connection Wittenoom Formation connection	Storage TD connection Wittenoom Formation connection
Interaction with Coondewanna Flats	Close to Karijini 8kms to dense vegetation in National Park	Proximal to Coondewanna Flats Possible reversal of GW flow from receptor Potential 1.6% reduction in runoff to Lake Robinson	15 km to Coondewanna Flats on major trib valley Potential 0.9% reduction in runoff to Lake Robinson	Distant and downstream of Coondewanna Flats Potential 1.2% reduction in runoff to Lake Robinson	Distant from all receptors Potential 1.1% reduction in runoff to Weeli Wolli Spring	15 km to Coondewanna Flats on major tributary valley Potential 0.9% reduction in runoff to Lake Robinson	Proximal to Coondewanna Flats Possible reversal of GW flow from receptor Potential 1.3% reduction in runoff to Lake Robinson

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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

5.7 Tandanya

5.7.1 Overview

The Tandanya mining area is located approximately 120 km northwest of Newman and 30 km west of MAC (Figure 5.12). The mining area is bound to the east by the Great Northern Highway and the Packsaddle mining area, to the north by the Wildflower Range, to the west and southwest by Karijini National Park, and to the south by the Mudlark mining area. Rio Tinto's West Angelas and Yandicoogina rail lines traverse the mining area.

There are eleven orebodies within the Tandanya mining area, comprising both Marra Mamba and Brockman deposits, all of which will be mined below watertable. Several of the orebodies have been combined into broad orebodies referred to as Tandanya Marra Mamba and Tandanya Brockman.

There has been no mining at Tandanya to date. Hydrogeological investigations date back to the 1970's and include groundwater supply investigations at Packsaddle and Camp Hill, railway construction water supply investigations (by Rio Tinto) for the Yandicoogina and West Angelas rail projects, modelling studies of the regional impacts of water supply abstraction, detailed dewatering investigations and a surface water management plan at the Railway orebody. Investigations completed to date together with experience gained in other mining areas (e.g. MAC), allow for a moderate to high level of confidence in the conceptual hydrogeological model.

An overview of the status and key hydrological features of each orebody is listed in Table 5.7.

5.7.2 Tandanya Conceptual Model

The main surface water flowpath in the Tandanya mining area is Homestead Creek (Figure 5.12) which flows from the northeast corner of the mining area and into Lake Robinson to the southwest of the mining area. Homestead Creek drains along a broad floodplain through the Milli Downs / Jocelyn / Railway orebodies and continues southwards through a narrow gap between Hill 65 and Packsaddle ridge towards Lake Robinson. The main channel appears to have a gravelly sand bed with an average gradient of approximately 0.25%, although the bed gradient flattens between the Camp Hill and Packsaddle ridgelines due the constriction created by the Packsaddle ridgeline. Downstream from the Packsaddle ridgeline, the Homestead Creek gradient locally steepens and has a gravelly sand bed containing scattered eucalypt trees before flattening where it discharges into Coondewanna Flats and the main channel widens into a dispersed wide shallow flow zone.

There is also an unnamed tributary which drains the western parts of Camp Hill and Hill 65 and the southern part of Fork North. The Tyler Bore orebody and parts of the Sweet View, The Noose and Flood Plain orebodies drain to the north and into the Marillana Creek catchment.

Most groundwater discharge from the mining area is to the north and into the Marillana Creek catchment system, although there may also be some minor groundwater flow southwards through the Hill 65 ridge (beneath the existing gorge) towards Coondewanna Flats.

Some of the Brockman orebodies are surrounded by low permeability unmineralised BIF and dewatering will simply require 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 the regional aquifer via local faults then pit inflows might be a bit 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.

In some lower lying Brockman orebodies and the Marra Mamba orebodies, the hanging walls of the pits will likely intersect sections of Tertiary detritals (including calcrete) and/or dolomite of the regional aquifer. As such, dewatering will not only require desaturation of the orebody aquifers, but also sustained high rate abstraction to intercept or accommodate inflows from these aquifers.

Figures 5.13a, 5.13b and 5.13c shows the conceptual hydrogeology.

Table 5.8: Orebody Overview – Tandanya

Orebody	**Camp Hill**	**Hill 65**	**Fork North**	**Railway**	**Tandanya MM (Railway East, Rail Link, Jocelyn, Milli Downs)**	**Tandanya BRK (Sweet View, Taylor Bore)**	**Floodplain**	**The Noose**
Ore Type	Marra Mamba	Brockman	Brockman	Marra Mamba	Marra Mamba	Brockman	Brockman	Brockman
Current Status [1]	Proposed mining Limited drilling	Proposed mining Limited drilling	Proposed mining Limited drilling	Proposed mining Extensive drilling	Proposed mining Limited drilling	Proposed mining Limited drilling	Proposed mining Limited drilling	Proposed mining Limited drilling
Previous Hydrogeological Studies[2]	Drilling and testing: - WS Modelling: - WS, EIA			Drilling and testing: - DW Modelling: - DW				
Ore Below Watertable (BWT)[3]	50%	15%	15%	85%	35%	35%	25%	25%
Max saturated thickness[4] (m)	*80*	*80*	*80*	*90*	–	–	*40*	*50*
Strike Length (m)	8,000	9,000	6,000	2,000	11,000	15,000	4,000	4,000
Generic Type[5]	BIF - Connected	BIF – Partially Connected	BIF – Partially Connected	BIF – Fully Connected	BIF – Fully Connected	BIF – Partially Connected	BIF - Connected	BIF - Connected
Dewatering Requirements (and basis[6])	HIGH >10 ML/d (generic model)	MOD - 2 to 10 ML/d (empirical model)	MOD - 2 to 10 ML/d (empirical model)	HIGH ≤ 22 ML/d (numerical model)	HIGH >10 ML/d (generic model)	MOD -2 to 10 ML/d (empirical model)	HIGH >10 ML/d (generic model)	HIGH >10 ML/d (generic model)
Key Dewatering Drivers[7]	Storage TD connection	Storage	Storage	Storage TD connection	Storage TD connection	Storage	Storage TD connection	Storage TD connection
Interaction with Coondewanna Flats	Distant Possible interception of throughflow to receptor Possible reversal of GW flow from receptor Potential 1.9% reduction in runoff	Distant Hydraulically isolated Potential 1.5% reduction in runoff	Distant Hydraulically isolated Potential 3.1% reduction in runoff	Distant Possible interception of throughflow to receptor Possible reversal of GW flow from receptor Potential 1% reduction in runoff	Distant Possible interception of throughflow to receptor Possible reversal of GW flow from receptor Potential 0.4% reduction in runoff	Distant Hydraulically isolated Potential 2.8% reduction in runoff	Distant Possible interception of throughflow to receptor Possible reversal of GW flow from receptor Potential 1.2% reduction in runoff	Distant Possible interception of throughflow to receptor Possible reversal of GW flow from receptor Potential 0.6% 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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

5.8 Gurinbiddy

The Gurinbiddy mining area is located approximately 90 km northwest of Newman (Figure 5.14) and 30 km south of the South Flank mining area and 15 km southeast of the West Angelas mine (operated by Rio Tinto).

There are two designated orebodies within the Gurinbiddy mining area: OB40 comprising Marra Mamba deposits and Gurinbiddy comprising Brockman deposits.

Only limited mineral exploration drilling has been undertaken in the mining area and there has been no mining to date. There have been no hydrological investigations undertaken to date and confidence in the conceptual hydrological model can only be considered low. However, based on available mineral exploration bore logs, geological maps and knowledge of similar orebodies in the region, the conceptual hydrogeology is moderately well understood.

An overview of the status and key hydrological features of the two orebodies is listed in Table 5.8.

5.8.1 Gurinbiddy Conceptual Model

The orebodies are located in the southwest corner of the Weeli Wolli Spring catchment and also extend across the Turee Creek, Spearhole Creek, Angelo River and Wanna Munna catchments (Figure 5.14). The majority of the northern portion of the Gurinbiddy drains to the north via numerous well-defined flowpaths into the upper Weeli Wolli Creek. Drainage from the southeast part of the Gurinbiddy orebody area is to the southeast into Wanna Munna and Spearhole catchments, although the divide between the two catchments is poorly defined. The western part of the Gurinbiddy orebody drains in a westerly direction into the Turee Creek East Branch.

OB40 is located in the upstream reaches of the Angelo River catchment in a relatively flat floodplain area. Runoff collects into a relatively flat valley and flows in a southwest direction from the orebody.

Groundwater outflows from the mining area is predominantly to the northeast, southeast, southwest and west within (beneath) main surface water catchments.

At OB40, where the Marra Mamba orebody appears to be overlain by unsaturated alluvium and flanked by the West Angela Member in the hanging wall, dewatering may only require desaturation of the orebody aquifer followed by low rate maintenance abstraction to accommodate ongoing minor inflows from the surrounding aquitards. However, if the regional aquifer (Tertiary detritals and/or dolomite) has developed to the north of the orebody then there might be some hydraulic connection to the orebody aquifer, either via local faulting in the West Angela Member or direct connection if the Tertiary detritals are intersected by the pit walls. In this case, longer term pit inflows and dewatering requirements could remain relatively high over the life of mine.

At Gurinbiddy, where the orebody aquifer is surrounded by low permeability unmineralised BIF and siltstones/shales, dewatering will simply require desaturation of the orebody aquifer with longer term, lower rate maintenance abstraction to accommodate minor long term inflows from the surrounding aquitards.

The conceptual hydrogeology of the Gurinbiddy mining area is shown on Figures 5.15a and 5.15b.

.

Table 5.9: Orebody Overview – Gurinbiddy

Orebody	**Gurinbiddy**	**Orebody 40**
Ore Type	Brockman	Marra Mamba
Current Status[1]	Proposed Mining Very limited drilling	Proposed Mining Moderate drilling
Previous Hydrogeological Studies[2]	None	None
Ore Below Watertable (BWT)[3]	70%	54%
Max saturated thickness[4] **(m)**	*55*	156
Strike Length (m)	15,000	7,000
Generic Type[5]	BIF – Isolated or Disconnected	BIF – Connected
Dewatering Requirements (and basis[6]**)**	MOD - up to 10 ML/d (generic model – based on extensive strike length)	VERY HIGH – 50 ML/d (generic model – based on extensive strike length)
Key Dewatering Drivers[7]	Aquifer storage	Aquifer storage Potential TD/dolomite connection
Interaction with Key Receptor	Potential 1.5% reduction in runoff volume to Weeli Wolli Spring Potential 0.2% reduction in run-off volume to Turee Creek East Branch in Karijini National Park	None

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 drill hole section data only.

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

6 Generic model - BHP Billiton 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 regional aquifer.

5.9 Third Parties

5.9.1 Hope Downs 1

The Hope Downs 1 mine is located approximately 75 km northwest of Newman and 11 km east of the MAC mining area (Figure 5.16). The mine is owned as a 50:50 joint venture between Hope Downs Iron Ore, (a subsidiary of Hancock Prospecting Pty Ltd), and Rio Tinto Iron Ore. The mine is operated by Rio Tinto Iron Ore and commenced production in November 2007. The Hope Downs 1 mine comprises two major iron ore deposits; the Hope North and Hope South orebodies. Both orebodies consist of mineralised Marra Mamba.

There has been a significant amount of hydrogeological investigation undertaken by Hancock Prospecting and Rio Tinto Iron Ore in the Hope Downs area related to the assessment, design and implementation of pit dewatering and environmental impact assessment. Work completed by BHP Billiton Iron Ore in the area includes groundwater investigations in MAC and at Weeli Wolli Spring to support the environmental impact assessment for MAC, and ongoing modelling to assess the local and regional impacts of various water management strategies at MAC (and other BHP Billiton Iron mining areas) and at Hope Downs. Some of this work was completed in conjunction with Hope Downs Management Services.

5.9.1.1 Hope Downs Conceptual Model

The main surface water flowpaths through Hope Downs are the Weeli Wolli Creek tributary which drains the MAC mining area and the northern part of Hope Downs and which flows west to east towards Weeli Wolli Spring, and the Pebble Mound and Weeli Wolli Creeks which drain the eastern end of Hope Downs and which flow south to north towards Weeli Wolli Spring.

Pre-mining groundwater flow was mostly via the regional aquifer system through MAC and beneath the Pebble Mound and Weeli Wolli Creeks. However, mine dewatering has created a large groundwater cone of depression which intercepts most groundwater through the Hope Downs mining area.

The Hope North orebody is in direct hydraulic connection with the regional aquifer through direct contact with the Tertiary detrital sequence and shear/fault contact through the West Angela Member. Consequently, pit dewatering does (and will continue to) require both desaturation of the orebody aquifer and interception of groundwater flows from the regional system. Dewatering rates are, and will continue to be very high (>70 ML/d).

Figure 5.17 presents a schematic cross section through the Hope Downs orebodies.

5.9.2 West Angelas

West Angelas is located approximately 130 km west of Newman and 30 km southwest of BHP Billiton Iron Ore's MAC mining area (see Figure 1.1). The mine is owned by a Rio Tinto-led joint venture and operated by Rio Tinto Iron Ore. Operations at West Angelas began in 2002, with the ore being processed on site and railed to the coast via the Hamersley and Robe River Railway. The West Angelas mine comprises eight Marra Mamba orebodies, Deposits A to H, (refer Figure 5.18) with a combined mineral resource of approximately 1014 Mt (Ecologia, 1998). Deposits A and B contain the main areas of mineralisation, with a measured iron resource of 458 and 236 Mt respectively. Rio Tinto Iron Ore lists the current production capacity of the overall mine as being 29.5 Mt/a.

Hydrogeological investigations have been undertaken in the West Angelas area related to the assessment, design and implementation of pit dewatering and environmental impact assessment, however, the associated reports are not publically available.

5.9.2.1 West Angelas Conceptual Model

The West Angelas deposits occur along the northern and southern limbs of the east-west trending, Wonmunna Anticline, which plunges to the west. The core of the anticline is exposed as a low-lying plateau of Jeerinah Formation flanked by low-lying hills of the Marra Mamba to the north and south. The Jeerinah area is drained by a series of ephemeral creeks which flow generally to the northwest into the valley which flanks the northern side of the anticline. Both the valleys to the north and south of the anticline drain to the west before coalescing to form part of the Turee Creek East drainage system.

Documentation on which of the orebodies extend below the watertable is limited. It is reported that both Deposits A and B occur below the watertable with approximately 15% of the Deposit A orebody being saturated (i.e. below watertable). Despite Deposit A being bound by low-permeability bedrock, the presence of a thrust fault (refer Figure 5.19) may provide hydraulic connection with the regional groundwater system. Consequently, pit dewatering will require both desaturation of the orebody aquifer and interception of groundwater flows from the regional aquifer.

There is no public documentation regarding the required dewatering rates for the West Angelas deposits or the predicted extent of drawdown. However, it is assumed that low to moderate rates of dewatering would be required for Deposits A and B dependent on the hydraulic connection with the regional groundwater system and the extent of the orebody below the watertable at Deposit B. The extent of drawdown would therefore be assumed to be fairly limited. As Deposits C and D are in close proximity to the calcrete deposit within the Karijini National Park, careful management would be required if mining was to proceed below the watertable.

Figure 5.19 and 5.20 present schematic cross sections through the West Angelas Deposit A and B orebodies.

6. CONCLUSIONS

6.1 Approach

A ecohydrological conceptualisation has been developed to consider the local and regional hydrology within in 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.

Detailed conceptual ecohydrological understandings were developed for Weeli Wolli Spring and Coondewanna Flats, as the two main identified receptors. These conceptualisations identify and quantify the main hydrological processes that sustain the environment at both receptors. Another representation of the Weeli Wolli Spring ecological community has recently been identified at Ben's Oasis. However, there are insufficient data to develop a reliable conceptual hydrological model for Ben's Oasis.

Conceptual ecohydrological understandings were then developed for each specific mining area. These were used to understand the influence of hydrological change on the two main receptors.

6.2 Regional Ecohydrological Conceptualisation

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

- The main aquifers are the Brockman and Marra Mamba orebodies, a regional aquifer system associated with Tertiary detritals and, in places, underlying Paraburdoo Member dolomite. Thus, the regional aquifer system is aligned with the main surface water system. The orebody aquifers are associated with mineralised (hematinic) BIF within the Brockman and Marra Mamba and sometimes with mineralised footwall or hanging wall units. Permeability also occurs at a lower iron content than that required for economic ore and so there can be aquifer potential beyond pit-shells in subgrade material.
- The regional aquifer system comprises Tertiary to Recent aged detrital (alluvial) deposits (comprising mostly sand, gravel and calcrete within mixed sequences of sediments including clay). This is typically underlain by weathered and karstic dolomite.
- Beneath the confluence of MAC and the South Flank Valley upstream of Weeli Wolli Spring, the Tertiary detritals comprise an extensive shallow permeable calcrete deposit (from surface down to up to 30 m below watertable underlain by poorly sorted alluvium of clay, sands and gravels with minor pisolite with variable permeability.
- Beneath Coondewanna Flats, the regional aquifer comprises an upper Tertiary sequence of variable sand, silt and gravel overlying a middle Tertiary sequence of variable calcrete and silty gravel overlying shale and dolomite of the Wittenoom Formation.
- The orebody aquifers tend to be surrounded on most sides by aquitards although 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 system 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 system, where the paleovalleys have been eroded down to result in the saturated Tertiary deposits being immediately 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 occurs at Coondewanna Flats during periods of inundation in Lake Robinson, and in the area immediately upstream of Weeli Wolli Spring. The majority of natural groundwater discharge from the overall catchment occurs as baseflow to Weeli Wolli Spring and evapotranspiration from dense vegetation at, and upstream of the Spring.
- Since the commencement of mining at Rio Tinto Iron Ore's Hope Downs 1, located to the east of the MAC mining area, excess mine water discharge to the Weeli Wolli Spring area has enhanced groundwater and surface water flows to the Spring.

6.3 Ecohydrological Landscapes

As part of the overall assessment process, 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 flowpath 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.

Most of the CPR study area is neither ecohydrologically unique nor critically dependant on unique hydrological conditions. The study area comprises Upland and Transitional Landscape Units which are not unique environments being characterised by deep watertable (greater than 30 m depth to groundwater), and a topography with surface water running off and exiting the area. As such there is little in the way of water dependency, although it is possible that Ben's Oasis, located in a Transitional Landscape Unit, might be supported by elevated watertables held up behind a groundwater flow barrier.

Lowland Landscape Units comprise a smaller proportion of the study area and it is only in these areas where the environments are closely integrated with the hydrological system. The two key lowland ecohydrological environments are Weeli Wolli Spring and Coondewanna Flats. Key ecohydrological characteristics of the two key lowland areas are as follows:

6.3.1 Weeli Wolli Spring

- 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 landscapes have adapted to greater environmental water availability.
- Watertable is shallower (ranging from less than 1 m up to 30 m depth to groundwater), accessible to phreatophytic vegetation, and maintains a saturated habitat for stygofauna.

6.3.2 Coondewanna Flats

- Similar hydrological characteristics (as in the first three points for Weeli Wolli Spring listed above) relating to surface water flow, recharge to soil moisture and groundwater and adaption of landscapes to water availability.
- The watertable is much deeper than for the above, but periodic inundation and replenishment of the soil moisture store supports non-phreatophytic vegetation.

6.4 Key Ecohydrological Receptors

6.4.1 Weeli Wolli Spring

Weeli Wolli Spring occurs where Weeli Wolli Creek flows through the Wildflower Range. Downstream of the Spring, the river flows in a narrow channel immediately to the north, past the confluence with Marillana Creek (and Rio Tinto's Yandicoogina mine) and into the Fortescue Marsh.

The spring occurs upstream of the creek entrance into the gorge, and is designated a Priority 1 Ecological Community (DEC 2012) because of the following rare flora and fauna communities:

- Fringing forest of Melaleuca argentea (Paperbark) and Eucalyptus camaldulensis (River Red Gum) over trees of Eucalyptus victrix (Coolibah) and a dense shrub layer dominated by an assortment of wattles, in particular Acacia citrinoviridis (Black Mulga). In addition, the spring is characterised by an unusual composition of understory vegetation, including sedges and herbs that fringe many of the pools and associated water bodies along the main channel.

- The shallow aquifer in proximity to the spring hosts a large diversity of stygofauna.

Surface and groundwater flows from most of the CPR catchments (all except flows from the western edge of the Mudlark mining area and the southern edge of the Gurinbiddy mining area) are focused into Weeli Wolli Spring and, from a landscape context, the Gorge area can be characterised as a receiving environment, comprising channels, floodplains and calcrete of the River and Calcrete Land Systems. The Weeli Wolli Spring area is characterised by groundwater levels of less than 5 m below ground level (mbgl) in the immediate area of the Spring which gives rise to potential interactions between the groundwater and terrestrial environments (through both surface water connection and vegetation). The key environmental features of the area have evolved as a result of this shallow groundwater. 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 use the shallow groundwater.

A PEC has been identified at Weeli Wolli Spring based on the presence of multiple species of stygofauna and the presence of some uncommon communities of dense riparian and woodland vegetation within the major flowpath lines and floodplains.

The key features of the conceptual hydrological model for Weeli Wolli Spring area and key receptor are as follows:

- The Weeli Wolli Spring groundwater system is recharged by a combination of groundwater throughflow from up-catchment and infiltration of rainfall runoff (streamflow) beneath local flowpath lines upstream of the Spring.
- The water balance shows the following average inputs:
  - Infiltration of runoff along stream channels of approximately 2,500 kL/d.
  - Groundwater throughflow of approximately 11,000 kL/d.
- Discharge from the Weeli Wolli Spring groundwater system is dominated by baseflow to Weeli Wolli Spring and groundwater throughflow. The water balance shows the following average outputs (for pre-mine dewatering conditions):
  - Base flow to the Spring of approximately 7,000 kL/d.
  - Groundwater throughflow in the alluvial (and transition zone basement) aquifer underlying the Creek of approximately 4,000 kL/d.
  - Evapotranspiration from vegetation around the spring of approximately 2,600 kL/d.
- Groundwater levels in the shallow aquifer that hosts the PEC have historically fluctuated through a narrow range (in the order of 1 to 2 m); mostly related to climatic cycles of wetter and drier periods.
- Dewatering abstraction at Hope Downs (since 2006) has resulted in significant drawdown around the pit and extending into the regional aquifer system. Drawdown in the regional aquifer system in excess of 40 m have been recorded at up to 1 km from the pit. However, as a result of the Hope Downs excess water discharge to Weeli Wolli Creek, there have only been minor drawdown in some parts of the Weeli Wolli Spring area. Drawdown of 1 to 2 m have been recorded 1 km upstream of the Spring, but groundwater levels closer to the Spring remain at pre-mining levels.

Overall, the key hydrological processes that maintain the shallow groundwater conditions and support the PEC are groundwater throughflow from up-catchment and infiltration of surface water low through stream channels close to the Spring (which, since 2007, has included excess water discharge from Hope Downs).

6.4.2 Coondewanna Flats

Coondewanna Flats is an internally-draining, surface water wetland feature located upstream of Weeli Wolli Spring. Surface water runoff from the western half of the CPR catchment lows onto the flats from the north, west and south. Due to internal drainage and no surface water outflow, larger flood events cause the flats to become inundated in an area known as Lake Robinson. Once on the Flats, surface water either infiltrates to the soil and groundwater or is lost to evapotranspiration from ponded surface water bodies and vegetation.

Coondewanna Flats hosts two PECs:

- Coolibah woodlands over lignum over swamp wandiree. Lake Robinson (the area prone to inundation on Coondewanna Flats) is the only known occurrence of this community and it is designated Priority 1.
- Coolibah and Mulga woodland over lignum and tussock grass on clay plains. Examples of this community have only been identified at Coondewanna and Wannamunna Flats and it is designated Priority 3.

Surface water flows from the surrounding catchments are focussed onto the Flats which form an internally draining basin comprising clay pans and alluvial plains of the Wannamunna land system. The Flats are characterised as a receiving environment, with relatively shallow groundwater levels (generally less than 30 m below ground level (mbgl)) which gives rise to potential interactions between the groundwater and terrestrial environments (through both surface water connection and vegetation). While neither Coolibah or Mulga rely on permanent groundwater in their root-zones, it is likely the hydrological environment at Coondewanna Flats plays a key role in supporting these vegetation communities through soil moisture replenishment through periodic inundation and infiltration.

The key features of the conceptual hydrological model for Coondewanna Flats are as follows:

- Long-term average runoff to Coondewanna Flats is approximately 5.8 GL/yr, although this average is distorted by some peak flood events (e.g. 100 GL after Cyclone Joan in 1975/76), and it is considered that the 50% annual exceedance probability runoff of approximately 1.8 GL/yr is more appropriate.
- Runoff to Coondewanna Flats occurs in three out of four years on average, but runoff sufficient to cause inundation (ie Lake Robinson) and groundwater recharge, occurs in one out of four years on average.
- The Coondewanna Flats groundwater system is recharged predominantly by infiltration of water from Lake Robinson and the broader Coondewanna Flats when it is inundated.

  The groundwater balance shows the infiltration of surface water over the broader Coondewanna Flats area of approximately 11,000 KL/d on average.
- Discharge from Coondewanna Flats is by evapotranspirative losses from the unsaturated zone and groundwater throughflow to the Weeli Wolli Spring catchment. The water balance shows the following average groundwater outputs:
  - Groundwater throughflow to the North Flank and South Flank Valleys of approximately 11,000 KL/d.
- Groundwater levels have historically fluctuated by approximately 5 m in response to recharge events, although this fluctuation has no impact on the PECs as the vegetation is reliant on soil moisture in the unsaturated zone.

Overall, the key hydrological processes that support the PEC at Coondewanna Flats are surface water runoff from up-catchment and replenishment of soil moisture by the infiltration of surface water into the unsaturated zone.

7. REFERENCES

Aquaterra (2005) Area C Water Supply and Dewatering Hydrogeological Impact Assessment. MPDJV (reference 442/C5/118b)

Astron (2012) Coondewanna Flats Ecohydrological Study. Prepared for BHP Billiton Iron Ore by Astron Environmental Services

Austin AT, Yahdjian L, Stark JM, Belnap J, Porporato A, Norton U, Ravetta DA, Schaeffer SM 2004, "Water pulses and biogeochemical cycles in arid and semiarid ecosystems", *Oecologia*, vol. 141(2), pp: 221–235, DOI:10.1007/s00442-004-1519-1

Beard JS 1975, Vegetation Survey of Western Australia. 1:1 000 000 Vegetation Series sheet 5 – Pilbara. Map and explanatory notes, University of Western Australia Press: Nedlands, Western Australia

Beard JS 1990, *Plant Life of Western Australia*, Kangaroo Press, Kenthurst, NSW

Bennelongia 2013. *Ethel Gorge Threatened Environmental Communities.* PowerPoint presentation prepared for BHP Billiton Iron Ore.

Bonacci O, Pipan T & Culver DC 2008, "A framework for karst ecohydrology", *Environ. Geol.*, vol. 56, pp: 891–900

Boulton AJ, Findlay S, Marmonier P, Stanley EH & Valett HM 1998, "The functional significance of the hyporheic zone in streams and rivers", *Ann Rev Ecol Syst*, vol. 29, pp: 59–81

Boulton AJ 2000, "River ecosystem health down under: assessing ecological condition in riverine groundwater zones in Australia", *Ecosys. Health*, vol. 6, pp: 108–118

Boulton AJ & Jenkins KM 1998, "Flood regimes and invertebrate communities in flood plain wetlands" (pp. 137–148). In: Williams WD (ed.), *Wetlands in a dry land: understanding for management*, Environment Australia, Canberra

Boulton AJ, Humphreys WF & Eberhard SM 2003, "*Imperilled subsurface waters in Australia: Biodiversity, threatening processes and conservation"*, Aquatic Ecosystem Health & Management, vol. 6, pp: 41-54

Boulton AJ & Lloyd LN 1992, "Flooding frequency and invertebrate emergence from dry flood plain sediments of the River Murray, Australia", *Regulated Rivers: Research and Management*, vol. 7, pp: 137-51

Bradbury JH 2000. "*Western Australian stygobiont amphipods (Crustacea: Paramelitidae) from the Mt Newman and Millstream regions"*, Rec. West. Aust. Mus. Suppl., Vol. 60, pp:1–102

Bromley J, Brouwer J, Barker AP, Gaze SR and Valentin C 1997, "The role of surface water redistribution in an area of patterned vegetation in a semi-arid environment, south-west Niger", *Journal of Hydrology*, vol. 198, pp: 1-29

Burbidge AH, Johnstone RE & Pearson DJ 2010, "Birds in a vast arid upland: avian biogeographical patterns in the Pilbara region of Western Australia", *Records of the Western Australian Museum*, Supplement 78, pp: 247–270.

CALM 1999, *Karijini National Park Management Plan 1999-2009*, prepared by the Department of Conservation and Land Management for the National Parks and Nature Conservation Authority, Perth

Capon SJ, James C, Williams I & Quinn G 2009, "Responses to flooding and drying in seedlings of a common Australian desert floodplain shrub: *Muehlenbeckia florulenta* Meisn. (Tangled lignum)", *Environmental and Experimental Botany*, vol 66, pp: 178–185.

Charles et al June 2013. "Hydroclimate of the Pilbara: past, present and future." CSIRO Land and Water Perth Publication.

Davis J, Pavlova A, Thompson R & Sunnucks P 2013, “Evolutionary refugia and ecological refuges: key concepts for conserving Australian arid zone freshwater biodiversity under climate change”, *Global Change Biology*, vol. 19, pp: 1970–1984, DOI: 10.1111/gcb.12203

DEC 2013. *List of Threatened Ecological Communities* endorsed by the Western Australian Minister for the Environment. https://www.dec.wa.gov.au/content/view/174/849/

Department of Agriculture (DOAg) 2013. Soil – Landscape Systems for mapping.

Department of Agriculture 1987. *Evaporation Data for Western Australia*. Resource Management Technical Report No. 65.

Department of Water 2013. *Ecological water requirements of the Yule River aquifer*, Environmental water report series, Report no. 24, September 2013, Department of Water, Perth

Dogramaci S, Dodson W 2009, “The Use of Stable Isotopes of Oxygen and Carbon to Understand Groundwater Dynamics in the Hamersley Basin, Western Pilbara Region, Northwest Australia”, paper presented at *Water in Mining Conference*, Perth, WA, 15-17 September 2009.

Doughty P, Rolfe JK, Burbidge AH, Pearson DJ and Kendrick PG 2011, “Herpetological assemblages of the Pilbara biogeographic region, Western Australia: ecological associations, biogeographic patterns and conservation”, *Records of the Western Australian Museum*, Supplement 78, pp: 315-341.

DPaW, 2014. http://www.dpaw.wa.gov.au/

EDO 2010, *Pastoral Land Management, Fact Sheet 34*, Updated December 2010, Environmental Defenders Office of Western Austral (Inc), Perth

Ellis TW & Hatton TJ 2008, “Relating leaf area index of natural eucalypt vegetation to climate variables in southern Australia”, *Agr. Water Manage.*, vol 95, pp: 743–747

Ecologia 1997. *Vegetation Assessment as part of an Unpublished Environmental Impact Assessment* for BHP Billiton Iron Ore

Ecologia 1998. West Angelas Iron Ore Project Vertebrate Assessment Survey. An unpublished report for Robe River Iron Associates.

Geoscience 2010. Hydrogeological – Landscapes System: a framework for managing water resources. http://www.ga.gov.au/ausgeonews/ausgeonews201003/hydro.jsp

GHD 2009, Report for Railway Prospect – Bore Installation and Testing Report. Prepared for United Mineral s Corporation

Gibson LA & McKenzie NL 2009, “Environmental associations of small ground-dwelling mammals in the Pilbara region, Western Australia”, *Records of the Western Australian Museum*, Supplement 78, pp: 91-122.

Guzik MT, Austin AD, Cooper SJB, Harvey MS, Humphreys WF, Bradford T, Eberhard SM, King RA, Leys R., Muirhead KA and Tomlinson M 2010, “Is the Australian subterranean fauna uniquely diverse?”, *Invertebrate Systematics*, vol. 24, pp: 407–418

Halse SA, Scanlon MD, Cocking JS, Barron HJ, Richardson JB and Eberhard SM 2014, “Pilbara stygofauna: deep groundwater of an arid landscape contains globally significant radiation of biodiversity”, *Records of the Western Australian Museum*, Supplement 78, pp: 443-483.

Hahn HJ & Fuchs A 2009, “Distribution patterns of groundwater communities across aquifer types in south-western Germany”, *Freshwater Biology*, vol.54, pp: 848–860.

Hancock PJ, Boulton AJ & Humphreys WF 2005, “Aquifers and hyporheic zones: Towards an ecological understanding of groundwater”, *Hydrogeology Journal*, vol. 13, pp: 98-111

Hancock PJ & Boulton AJ 2008, *Stygofauna biodiversity and endemism in four alluvial aquifers in eastern Australia*, Invertebrate Systematics, vol. 22, pp: 117-126.

Hope Downs Management Services (HDMS) 2000. *Hope Downs Iron Ore Project – Public Environment Report / Public Environment Review.*

Humphreys WF 2001, “Groundwater calcrete aquifers in the Australia arid zone: the context to an unfolding plethora of stygal biodiversity”, *Records of the Western Australian Museum,* Supplement 64, pp: 63-83

Humphreys WF 2006, “Groundwater fauna” paper prepared for the 2006 Australian State of the Environment Committee, Department of the Environment and Heritage, Canberra, <http://www.deh.gov.au/soe/2006/emerging/fauna/index.html>.

Jaeger KL & Olden JD 2012, “Electrical resistance sensor arrays as a means to quantify longitudinal connectivity of rivers”, *River Res. Applic.*, vol. 28, pp: 1843–1852, DOI:10.1002/rra.1554

Jasinska EJ, Knott B & McComb AR 1996, *Root mats in ground water: a fauna-rich cave habitat*, Journal of the North American Benthological Society, vol. 15, pp: 508–519.

Jensen AE, Walker KF & Paton DC 2008, “The role of seedbanks in restoration of floodplain woodlands. *River Research and Applications*, vol. 24, pp: 632–649

Junk WJ, Bayley PB & Sparks RE 1989, “The flood pulse concept in river-flood plain systems”, In: *Proceedings of the international large river symposium* (Ed. Dodge DP) pp. 110-27. Canadian Special Publication on Fisheries and Aquatic Sciences, No. 106

Kepert, D.A. 2001. The mapped stratigraphy and structure of the mining area C region (the Black Monolith) An eclectic synthesis of geological mapping by BHPBIO Exploration 1994-2001. Internal BHP Billiton Iron Ore report.

Mann AW & Horwitz RC 1979, “Groundwater calcrete deposits in Australia: some observations from Western Australia”, *Journal of the Geological Society of Australia*, vol. 26, pp: 293-303

Maurice L & Bloomfield J 2012, “Stygobitic invertebrates in groundwater – a review from a hydrogeological perspective”, *Freshwater Reviews*, vol. 5, pp: 51–71.

McGinness HM, Arthur AD, Davies M & McIntyre S 2013, “Floodplain woodland structure and condition: the relative influence of flood history and surrounding irrigation land use intensity in contrasting regions of a dryland river”, *Ecohydrol.*, vol. 6, pp: 201–213

McKenzie NL, van Leeuwen S & Pinder AM 2009, “Introduction to the Pilbara biodiversity survey 2002–2007”, *Records of the Western Australian Museum*, Supplement 78, pp: 3–89.

McKenzie NL and Bullen RD 2009, “The echolocation calls, habitat relationships, foraging niches and communities of Pilbara microbats”, *Records of the Western Australian Museum*, Supplement 78, pp: 123-155.

McKenzie NL, May JE and McKenna S 2003, *Bioregional Summary of the 2002 Biodiversity Audit for Western Australia*, Department of Conservation and Land Management, Perth.

Moreno-Gutierrez C, Dawson TE, Nicola´s E and Querejeta JI 2012, “Isotopes reveal contrasting water use strategies among coexisting plant species in a Mediterranean ecosystem”, *New Phytologist*, vol. 196, pp: 489–496

Neumann NN 2013, *The ecohydrology of coupled surface water – groundwater systems*, PhD Thesis, University of British Columbia, Vancouver

Nuttle WK 2002, “Is ecohydrology one idea or many?”, *Hydrol. ci. J.*, vol 47, pp: 805–807

NWC 2012. Australian National Groundwater Modelling Guidelines. www.nwc.gov.au

Ogle K and Reynolds JF 2004, “Plant responses to precipitation in desert ecosystems: integrating functional types, pulses, thresholds, and delays”, *Oecologia*, vol. 141, pp: 282–294.

O’Grady CM 2004, A historical geography of the pastoral occupation of six major river basins in the north-west of Western Australia, PhD thesis, Curtin University of Technology, Perth

O’Grady AP, Carter JL and Bruce J 2011, “Can we predict groundwater discharge from terrestrial ecosystems using Ecohydrological principals?”, *Hydrol. Earth Syst. Sci. Discuss.*, vol. 8, pp: 8231–8253

Page G & Grierson P 2010, "*Review of State of Knowledge - Ecological Water Requirements of Mulga in Pilbara*", Unpublished report for Fortescue Metals Group, University of Western Australia, Perth

Parsons Brinkerhoff 2012. What is a Representative Pan Factor Value for the Eastern Pilbara. International Mine Water Association. Annual Conference 2012. Aditya Jha.

Parsons Brinkerhoff June 2013. *Analysis of Groundwater Responses to Rainfalls.* Progress Report prepared for BHP Billiton Iron Ore.

Pepper M, Doughty P and Keogh JS 2013, "Geodiversity and endemism in the iconic Australian Pilbara region: a review of landscape evolution and biotic response in an ancient refugium", *J. Biogeogr.*, vol. 40, pp: 1225-1239, DOI:10.1111/jbi.12080

Pinder AM, Halse SA, Shiel RJ and McRae JM 2010, "An arid zone awash with diversity: patterns in the distribution of aquatic invertebrates in the Pilbara region of Western Australia", *Records of the Western Australian Museum*, Supplement 78, pp: 205–246

Reeves JM, De Deckker P and Halse SA 2007, "Groundwater Ostracods from the arid Pilbara region of north-western Australia: distribution and water chemistry", *Hydrobiologia*, vol. 585, pp: 99-118, DOI 10.1007/s10750-007-0632-7

Roberts J & Marston F 2011, *Water regime for wetland and floodplain plants: a source book for the Murray–Darling Basin*, National Water Commission, Canberra

RPS 2013; *Hydrogeological Assessment for Mining Area C. Report to BHPBIO*, November 2013 (Updated from 2011).

Rio Tinto Iron Ore, 2010. *Marillana Creek Regional Flow Balance and Catchment Hydrology* (Publically Available)

Sheldon F, Boulton AJ & Puckridge JT 2002, "Conservation value of variable habitat connectivity: aquatic invertebrate assemblages of channel and flood plain habitats of a central Australian arid-zone river, Cooper Creek", *Biological Conservation*, vol. 103, pp: 13–31.

SKM 2012. Coondewanna Flats ecohydrological study – Phase 2 – field investigations for characterisation of ecosystem groundwater reliance. Prepared for BHP Billiton Iron Ore

Solid Geology 2013. "Evaluation of Structural Controls on Groundwater Flow at Mining Area C, Western Australia", Unpublished report to BHP Billiton Iron Ore).

Stumpp C & Hose GC 2013, *The Impact of Water table Drawdown and Drying on Subterranean Aquatic Fauna in In-Vitro Experiments*, PLoS ONE, vol. 8(11),e78502, doi: 10. 371/ journal. pone.0078502

Thomas FM 2014,"Ecology of Phreatophytes", In: Lüttge U, Beyschlag W & Cushman J (Eds.), Progress in Botany, Vol. 75, Springer, pp: 335-375. ISBN: 978-3-642-38796-8 (Print) 978-3-642-38797-5 (Online)

URS 2011, Ben's Oasis Spring – Discussion Notes

URS 2012a, Surface Water and Groundwater Study for the Proposed Jinidi Iron Ore Mine. Prepared for BHP Billiton Iron Ore

URS 2012b, 42907863 – Crest Gauge Network Expansion Project – Coondewanna Flats

URS 2012c. Coondewanna Groundwater Level Monitoring – 2011-2012 Wet Season. Memorandum prepared for BHP Billiton Iron Ore.

Van Vreeswyk A, Payne A, Leighton K and Hennig P 2004, *An inventory and condition survey of the Pilbara Region*, Western Australia, Technical Bulletin No. 92, Department of Agriculture, Perth

Verboom WH & Pate JS 2006, "Bioengineering of soil profiles in semiarid ecosystems: the "phytotarium" concept" A review", *Plant Soil*, vol 289, pp :71–102

Walvoord. MA, Plummer, MA and Phillips FM 2002, Deep arid system hydrodynamics 1. Equalibrium state and response times in thick desert vadose zones. *Water Resources Research*, vol 38, No.12

Wang L, D'Odorico P, Manzoni S, Porporato A, Macko S 2009, "Soil carbon and nitrogen dynamics in southern African savannas: the effect of vegetation-induced patch-scale heterogeneities and large scale rainfall gradients", *Climatic Change*, vol. 94(1–2), pp: 63–76, DOI:10.1007/s10584-009-9548-8

Wilcox BP, Taucer PI, Munster CL, Owens MK, Mohanty BP, Sorenson JR and Bazan R 2008, "Subsurface stormflow is important in semiarid karst shrublands", *Geophysical Research Letters*, vol. 35, L10403, DOI:10.1029/2008GL033696

Woodward Clyde 1998. Addendum to the Mining Area C Hydrogeological Investigations Report. Water Supply Bores and Additional Drilling. Report to BHPBIO, May 1998.

WRM 2010, Cumulative Impacts of RTIO Mining on the Weeli Wolli Creek System, Dry 08 and Wet 09 Sampling (Publically Available).

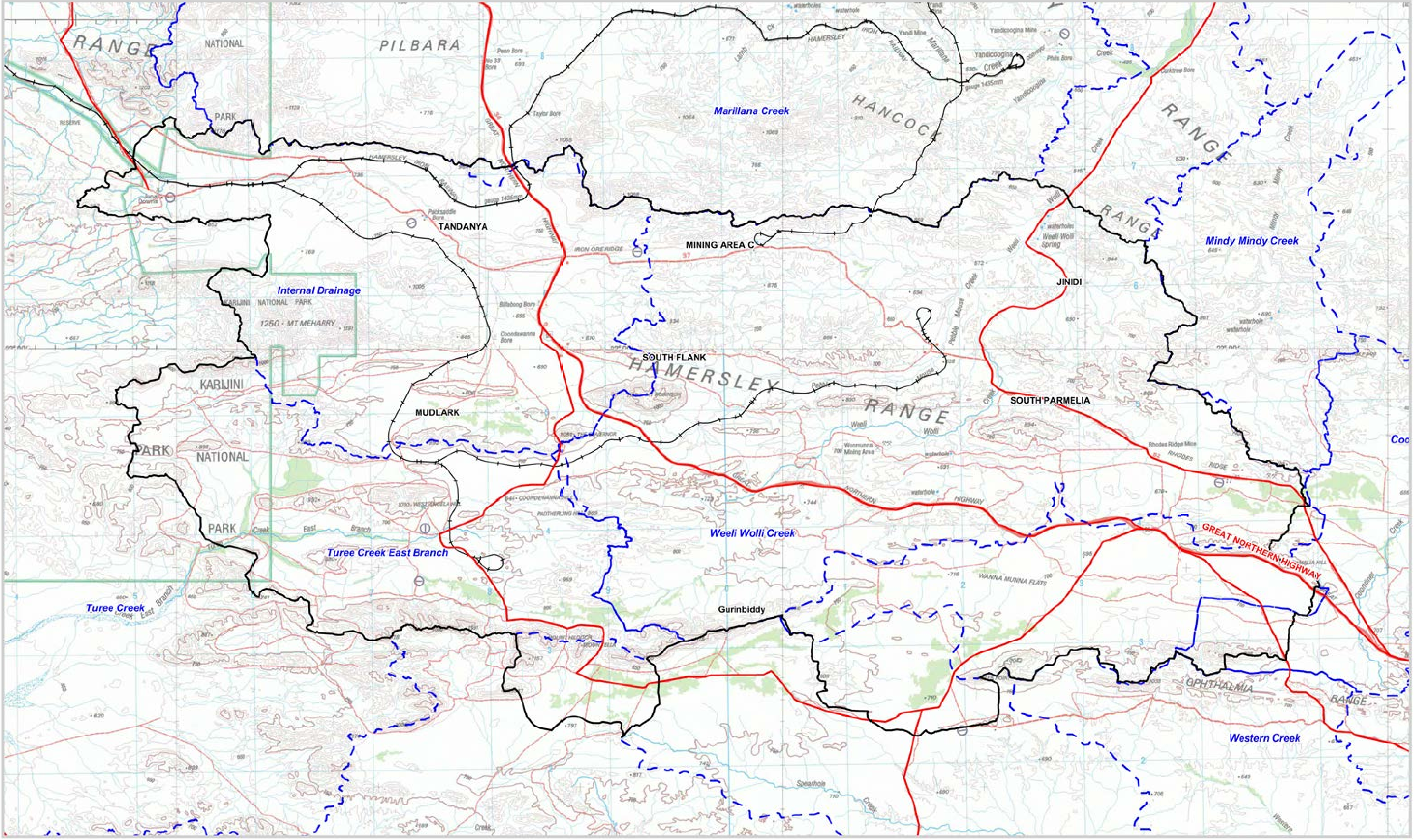
This page is intentionally blank.

PLATES

Weeli Wolli Spring **Plate 3.1**

Lake Robinson **Plate 3.2**

FIGURES



N

0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

Location: F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\275a\275a Figure 1.1 - central Pilbara Hub Location Map_updated

LEGEND

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

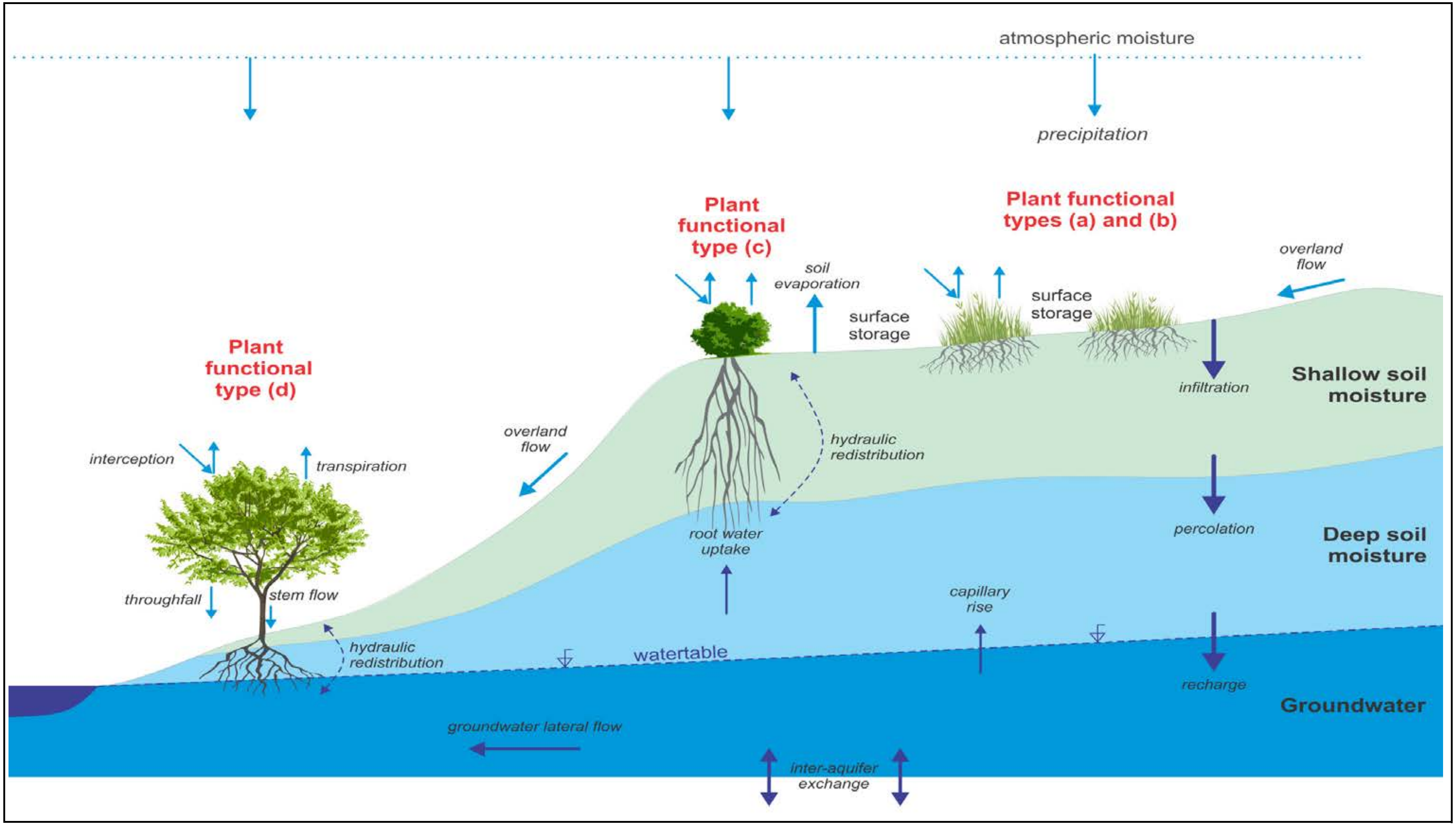
DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 1.1

LOCATION MAP
CENTRAL PILBARA REGION

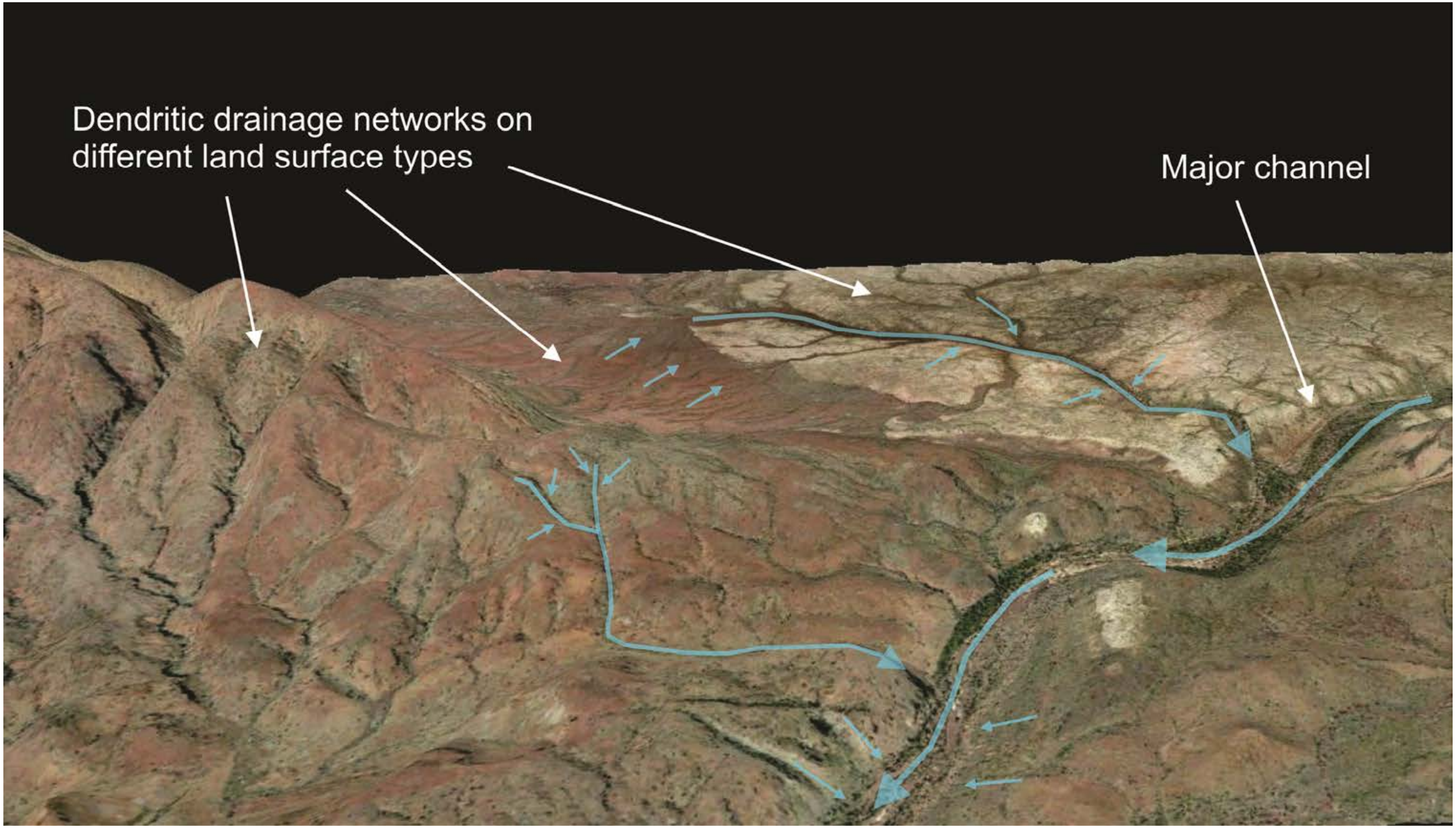
"The content of this map is conceptual only, of a general nature and does not purport to contain all information relevant to future project development associated with the Project. This map has been prepared solely for the purposes of informing environmental impact assessment pursuant to the Environmental 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

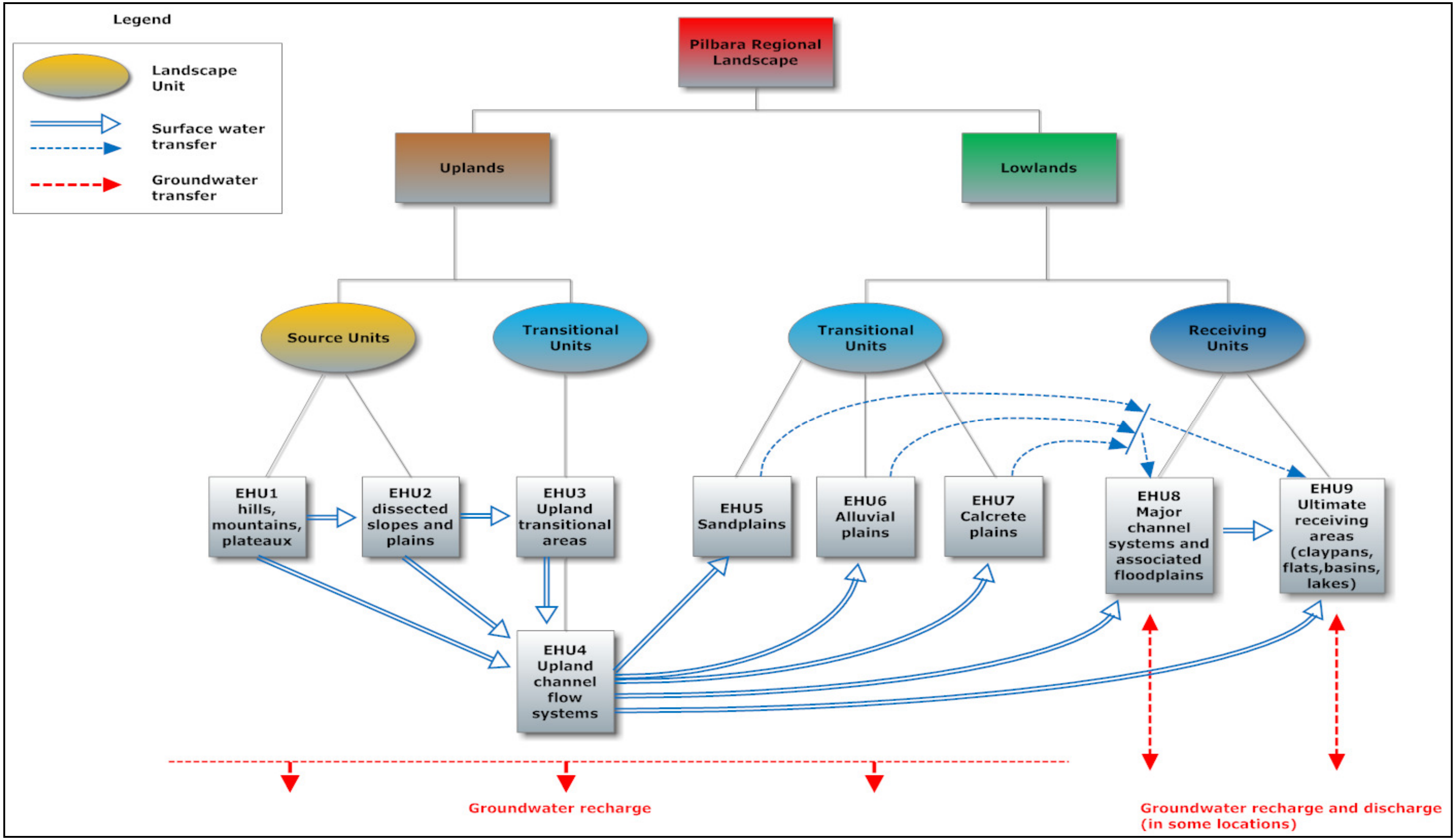
F:\Jobs\1549B\Spatial_Data\Deliverables\Report_Figures\275c\[275c Figure 1.2_1.3_1.4_1.5.xlsx]Figure 1.2



RPS

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

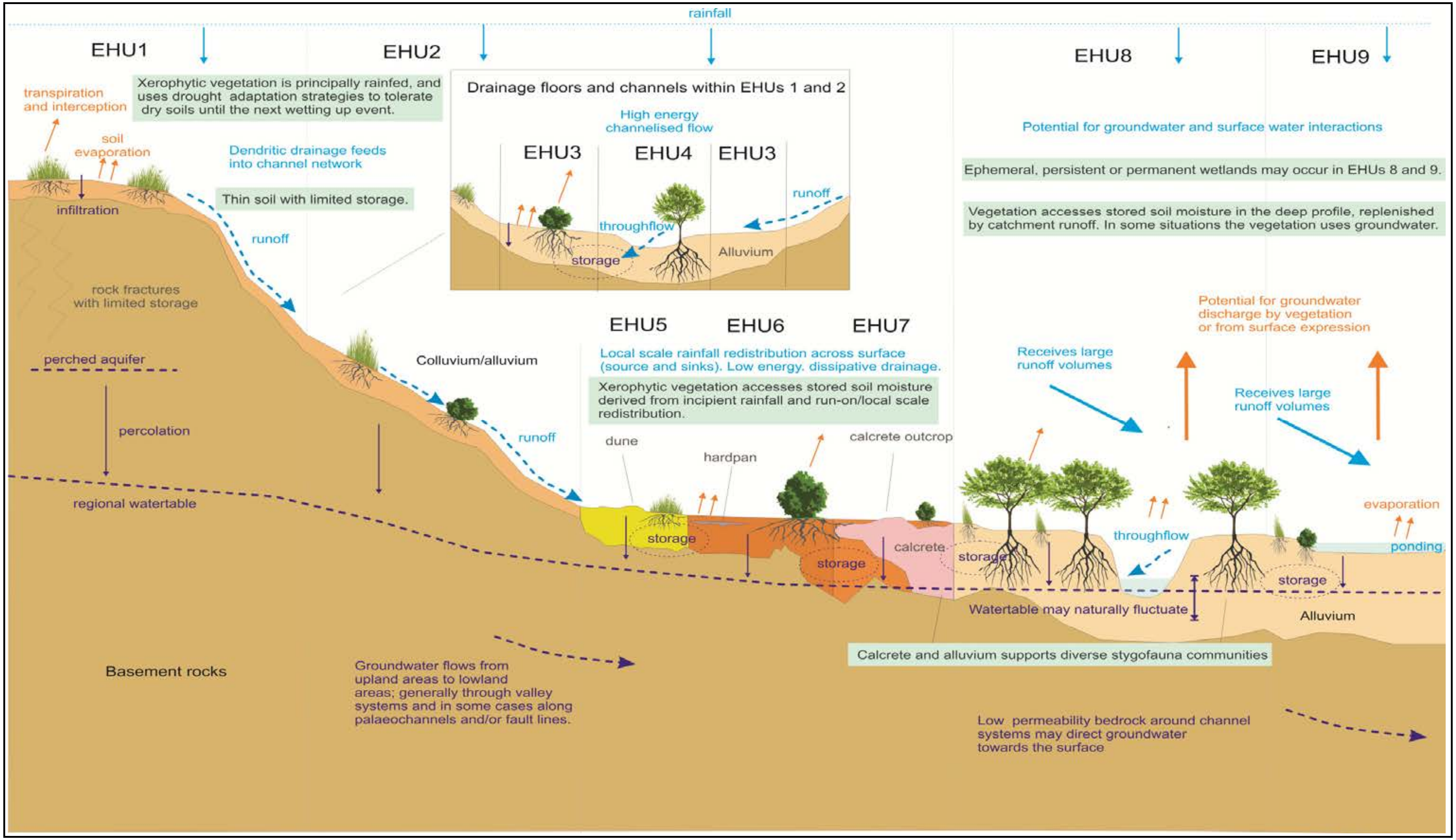
F:\Jobs\1549B\Spatial_Data\Deliverables\Report_Figures\275c\[275c Figure 1.2_1.3_1.4_1.5.xlsx]Figure 1.3



RPS

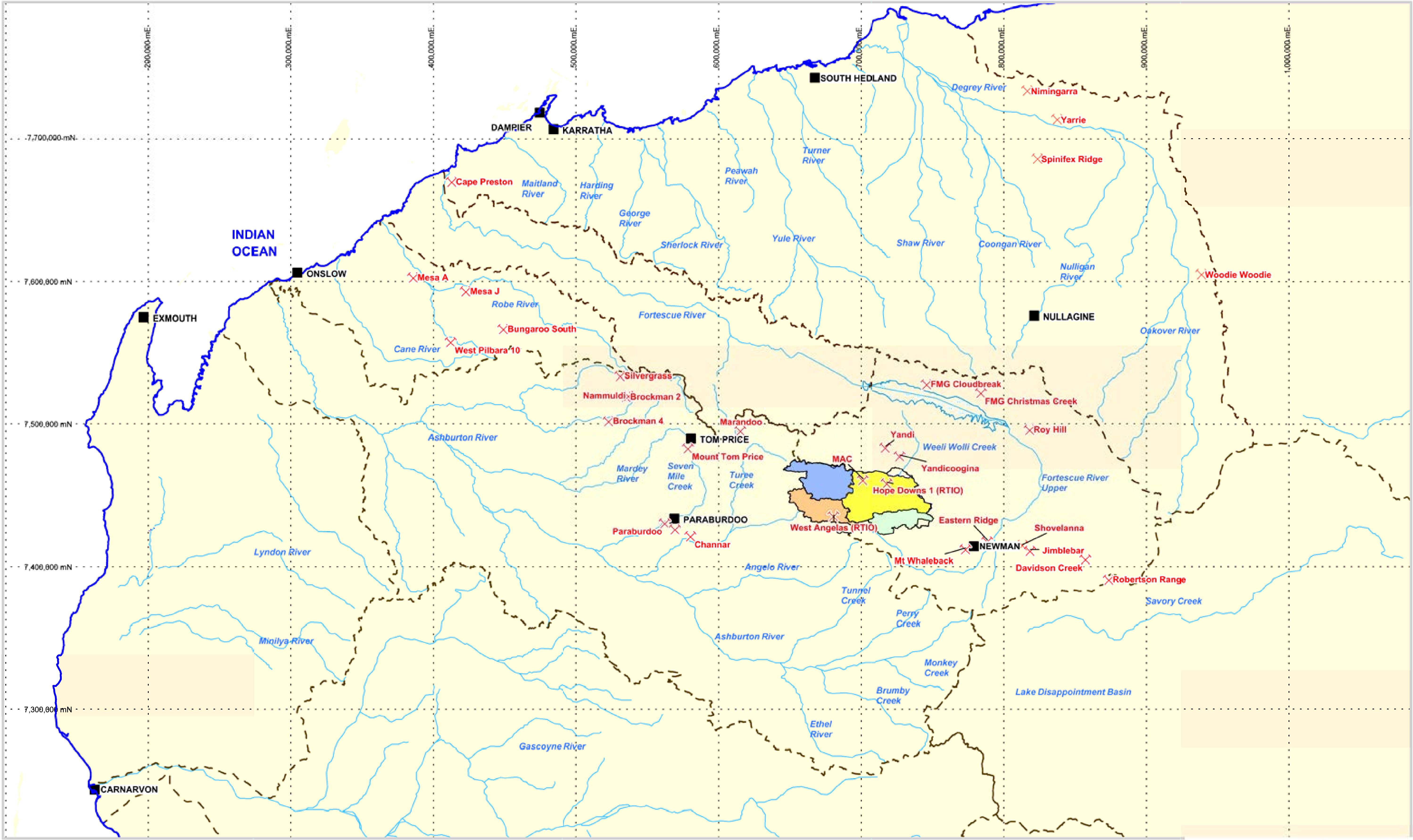
Landscape hierarchy of EHUs and major water flow connectivity FIGURE 1.4

F:\Jobs\1549B\Spatial_Data\Deliverables\Report_Figures\275c\[275c Figure 1.2_1.3_1.4_1.5.xlsx]Figure 1.4



EHUs Landscape Overview FIGURE 1.5

F:\Jobs\1549B\Spatial_Data\Deliverables\Report_Figures\275c\[275c Figure 1.2_1.3_1.4_1.5.xlsx]Figure 1.5



N

50 0 50

Kilometres

Scale: 1:2,500,000 @A3

GDA 1994 Zone 50

AUTHOR: LC	REPORT NO: 275
DRAWN: MR	REVISION: f
DATE: 01/09/2015	JOB NO: 1549B

LEGEND

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

Catchment Areas

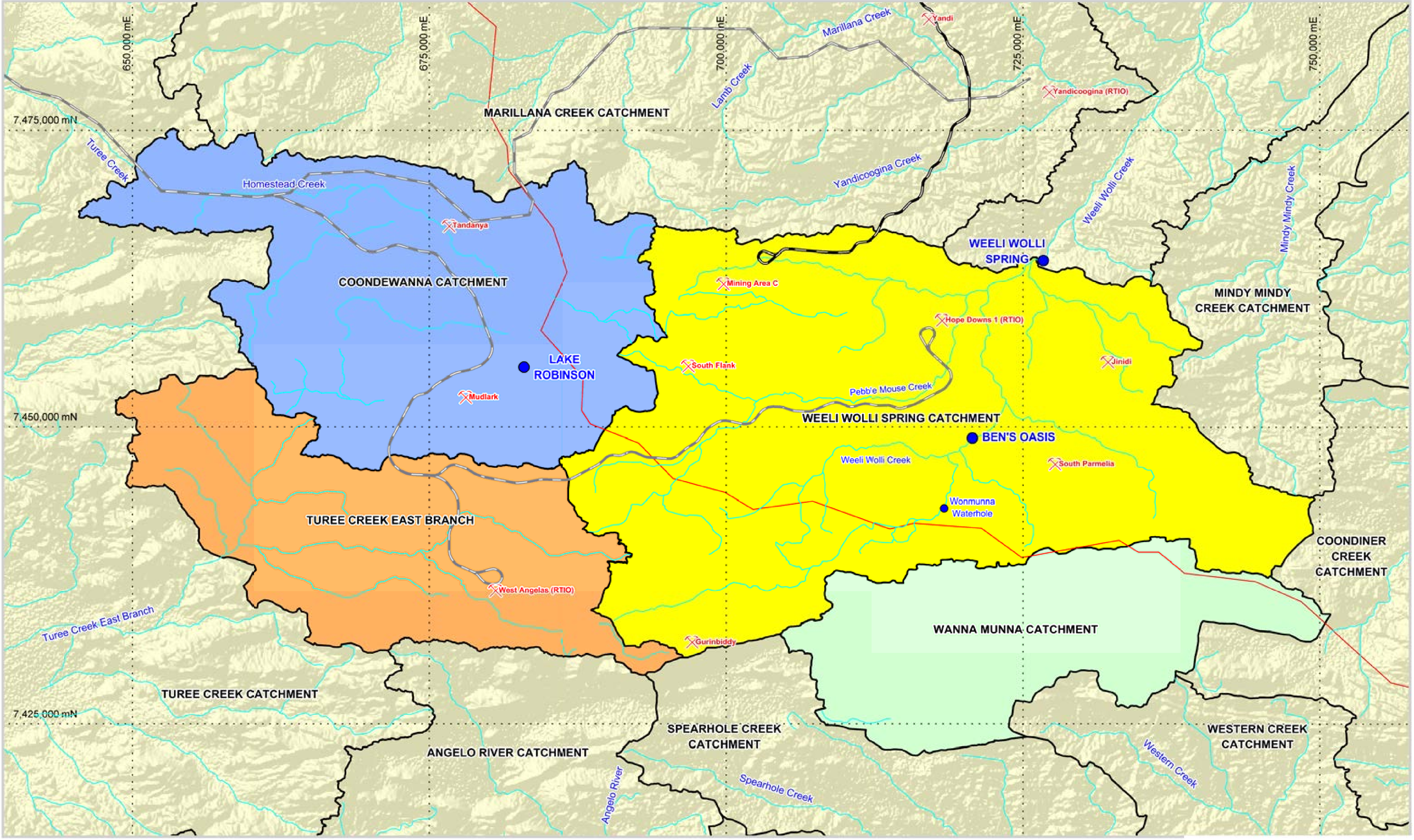
- Coondewanna
- Weeli Wolli Spring
- Wanna Munna
- Turee Creek East Branch

RPS

FIGURE 2.1

CENTRAL PILBARA REGIONAL CATCHMENTS

Location: F:\Jobs\1549C\Spatial_Data\MapInfo\Workspaces\020 Figure 2.1 Rev B.wor



LOCATION MAP

N

0 5 10 15

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR: LC	REPORT NO: 275
DRAWN: MR	REVISION: f
DATE: 01/09/2015	JOB NO: 1549B

LEGEND

- Mining Area
- Creek
- Surface Water Feature
- Catchment Boundary
- Railway
- Major Road/ Highway

Catchment Areas

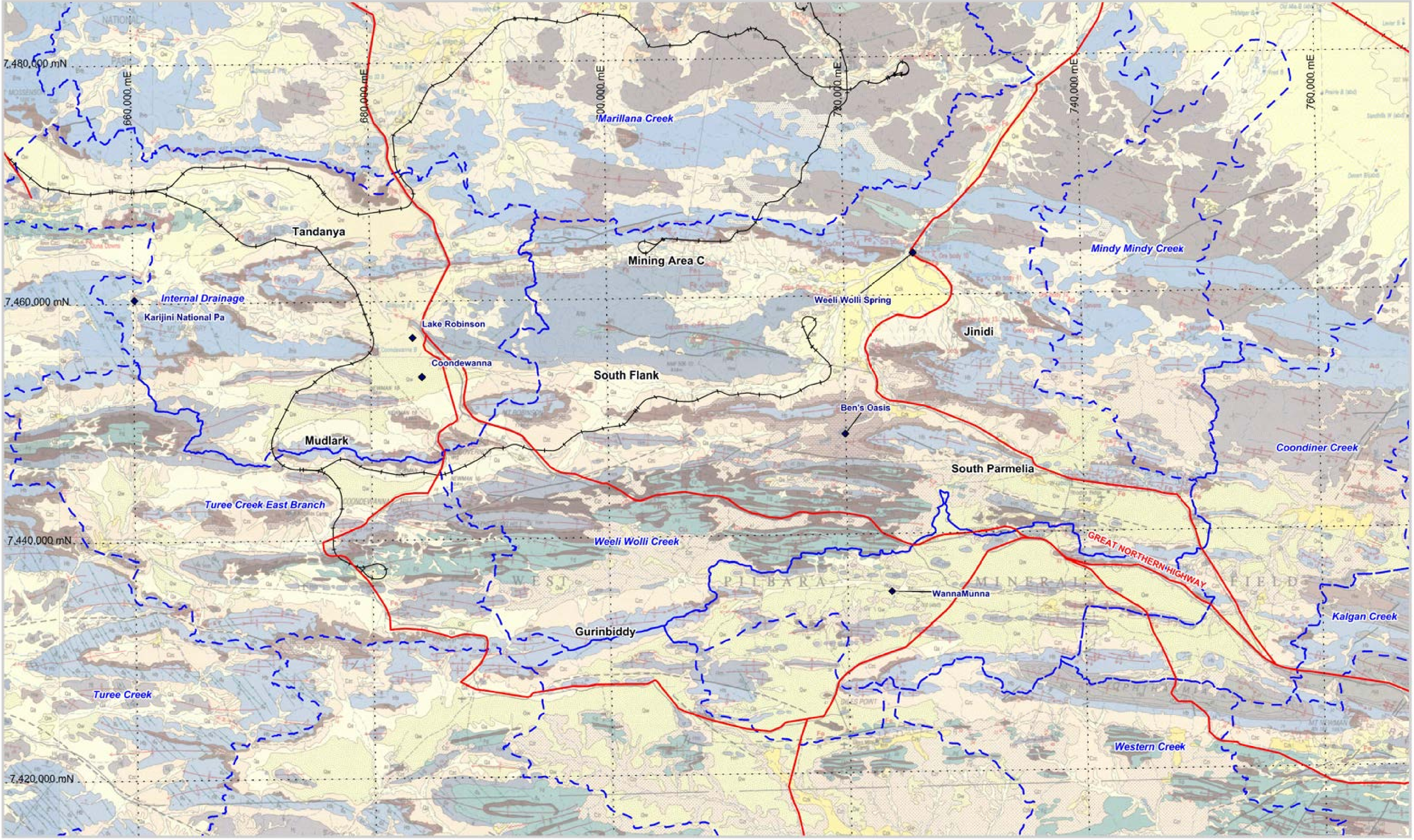
- Coondewanna
- Weeli Wolli Spring
- Wanna Munna
- Turee Creek East Branch

RPS

FIGURE 2.2

CENTRAL PILBARA STUDY CATCHMENT AREAS

Location: F:\Jobs\1549C\Spatial_Data\MapInfo\Workspaces\020a Figure 2.2 - Central Pilbara Catchment Areas Rev B.wor



N

0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

Location: F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a Figure 2.3 - Central Pilbara Hub Geological Map

LEGEND

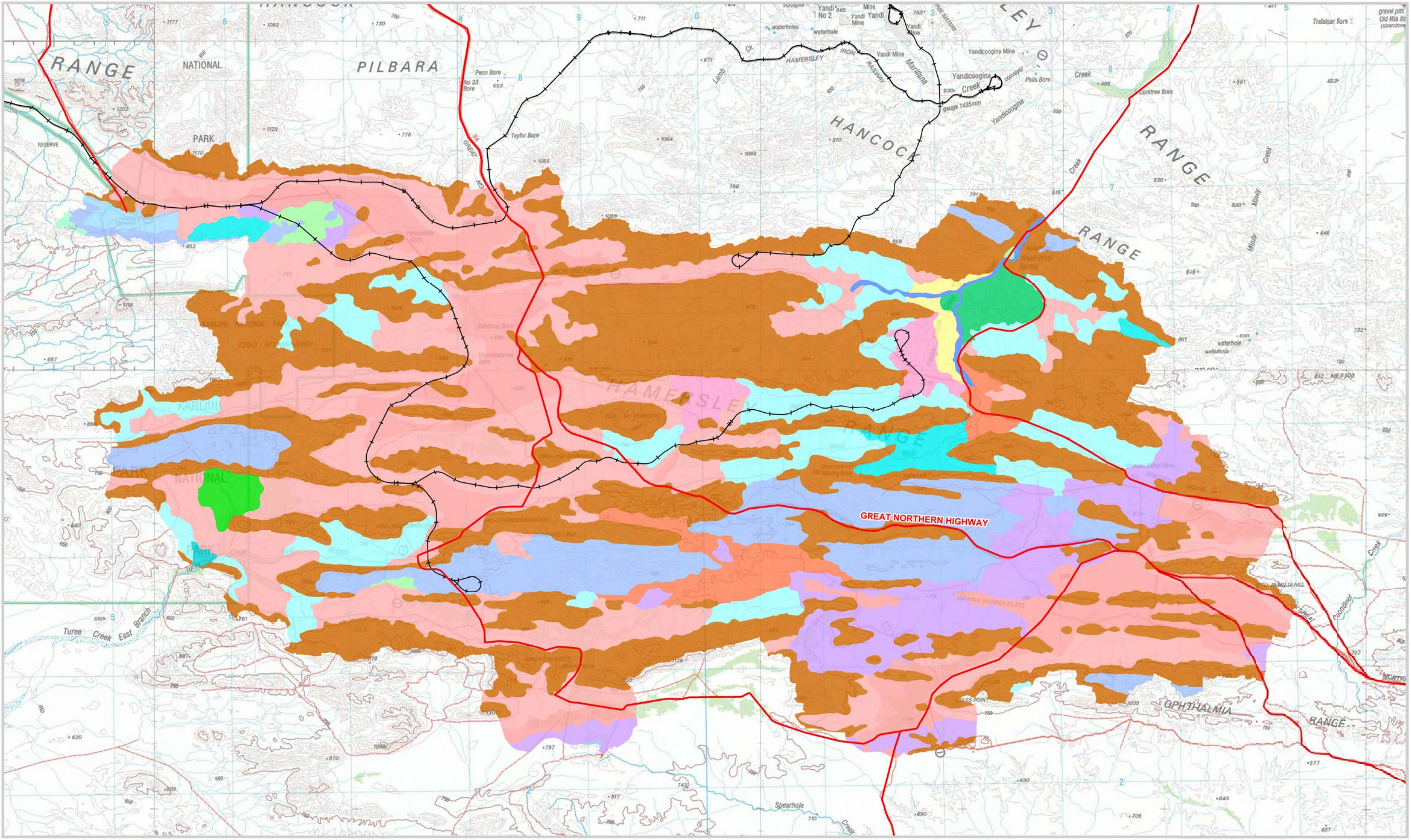
- Environmental Receptors
- Road
- Rail
- Surface Water Catchment

DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 2.3

GEOLOGICAL MAP
CENTRAL PILBARA REGION



0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR: JP	REPORT NO: 275
DRAWN: MR	REVISION: c
DATE: 17/10/2014	JOB NO: 1549B

LEGEND

Road

Rail

Land Systems

- Boolgeeda Land System
- Calcrete Land System
- Egerton Land System
- Elimunna Land System
- Jamindie Land System
- Marandoo Land System
- McKay Land System
- Newman Land System
- Oakover Land System
- Paraburdoo Land System
- Pindering Land System
- Platform Land System
- River Land System
- Robe Land System
- Rocklea Land System
- Spearhole Land System
- Table Land System
- Wannamunna Land System

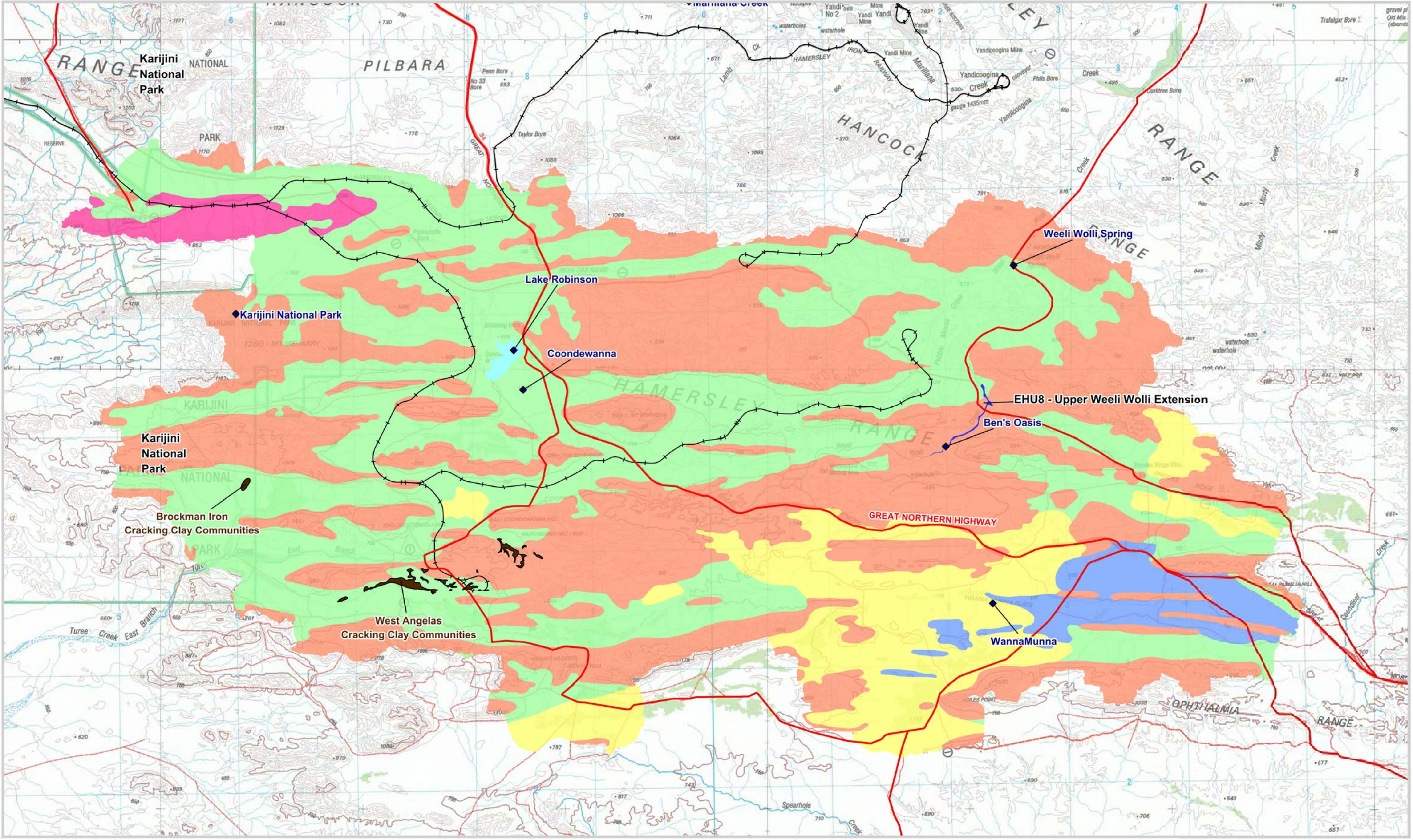
DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 2.4

LAND SYSTEMS IN THE CPR STUDY AREA

Location: F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a Figure 2.4 - Land systems in the CPH Study Area



N

0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	17/10/2013	JOB NO:	1549B

Location: F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a Figure 2.5 - Beard Vegetation

LEGEND

- Road
- Rail
- Environmental Receptor
- Cracking Clay Communities

Vegetation Association Code (Beard 1975)

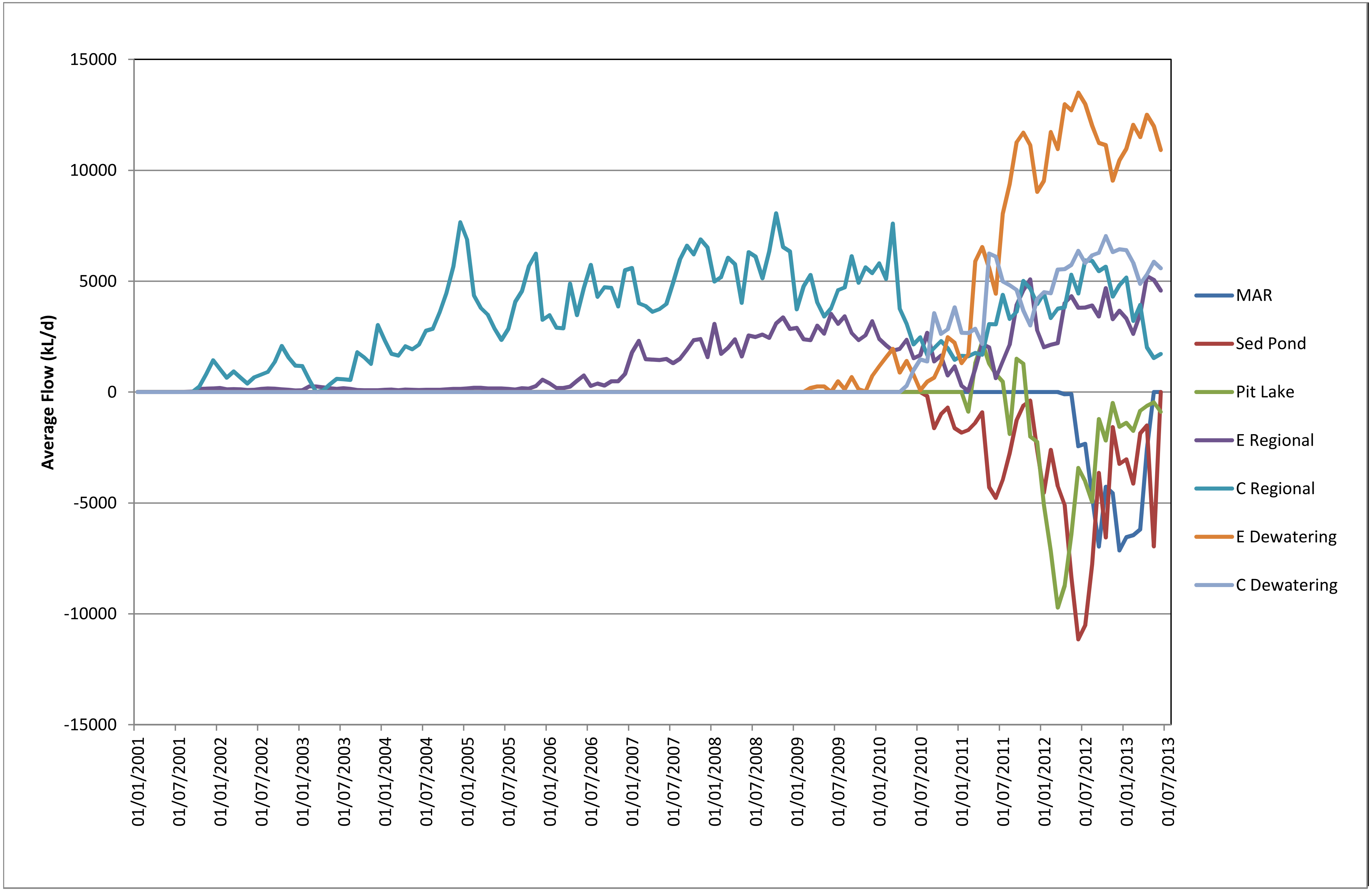
- 18
- 29
- 82
- 175
- 567

DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 2.5

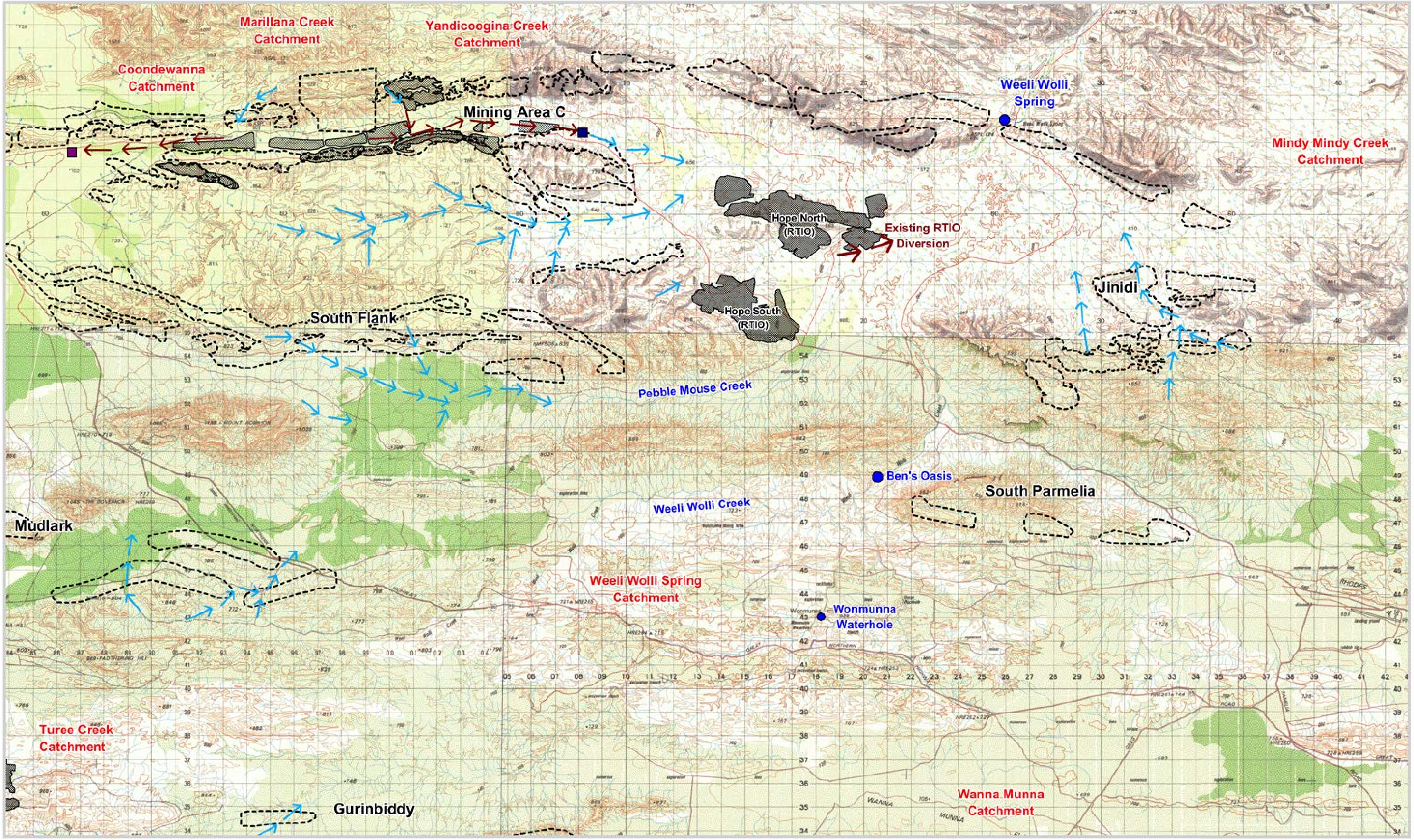
VEGETATION ASSOCIATION MAPPED BY BEARD (1975) IN THE CPR STUDY AREA (INCLUDING LOCATIONS OF KEY ECOHYDROLOGICAL RECEPTORS)



RPS

GROUNDWATER ABSTRACTION/DISPOSAL BY BHPB IN CPR AREA FIGURE 2.6

F:\Jobs\1549B\300\CPR\[264a_Water Use CPR.xlsx]Chart kLd



N

0 2 4 6

Kilometres

Scale: 1:150,000 @A3

GDA 1994 Zone 50

AUTHOR: LC	REPORT NO: 275
DRAWN: LC	REVISION: f
DATE: 01/09/2015	JOB NO: 1549C

Location: F:\Jobs\1549C\Spatial_Data\MapInfo\Workspaces\020a Figure 3.1 Rev C.wor

LEGEND

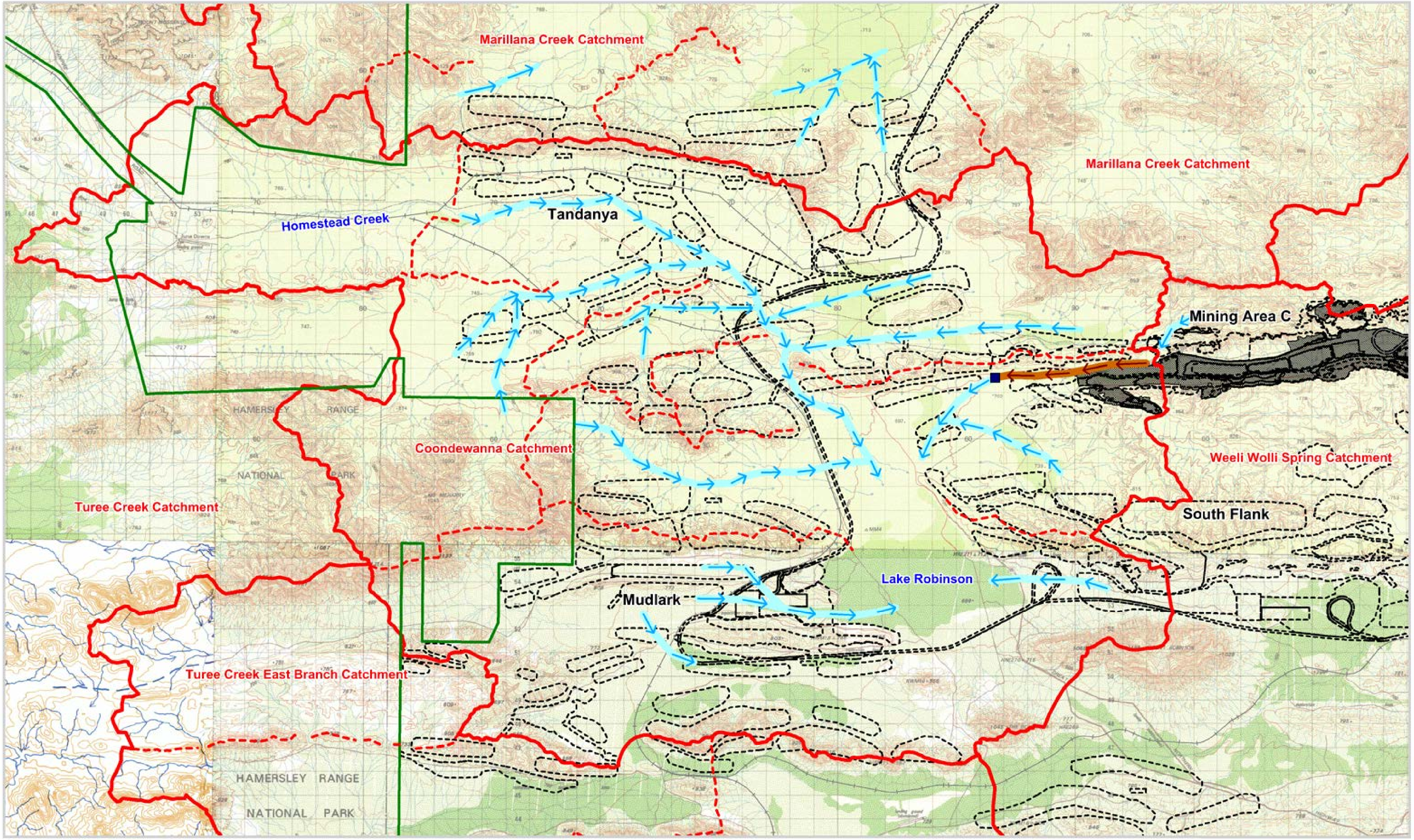
- Main Catchment Boundary
- Sub-Catchment Boundary
- Main Drainage Corridors Within Orebody Area
- Existing Diversion
- Railway
- Existing BHP Billiton Iron Ore Disturbance
- Indicative BHP Billiton Iron Ore Disturbance
- Sediment Basin
- Existing Third Party Disturbance

DATA SOURCES:
1:100,000 Topography Maps

RPS

FIGURE 3.1

WEELI WOLLI SPRING CATCHMENT CPR DISTURBANCE AREAS



0 2 4 6
Kilometres
Scale: 1:150,000 @A3
GDA 1994 Zone 50

AUTHOR:	LC	REPORT NO:	275
DRAWN:	LC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549C

Location: F:\Jobs\1549F\Spatial_Data\MapInfo\Workspaces\020a Figure 3.2 Rev B.wor

LEGEND

- Main Catchment Boundary
- Sub-Catchment Boundary
- Existing Flow Paths
- Existing Diversion
- National Park Boundary
- Indicative BHP Billiton Iron Ore Disturbance
- Existing BHP Billiton Iron Ore Distrurbance
- Sediment Basin
- Rail

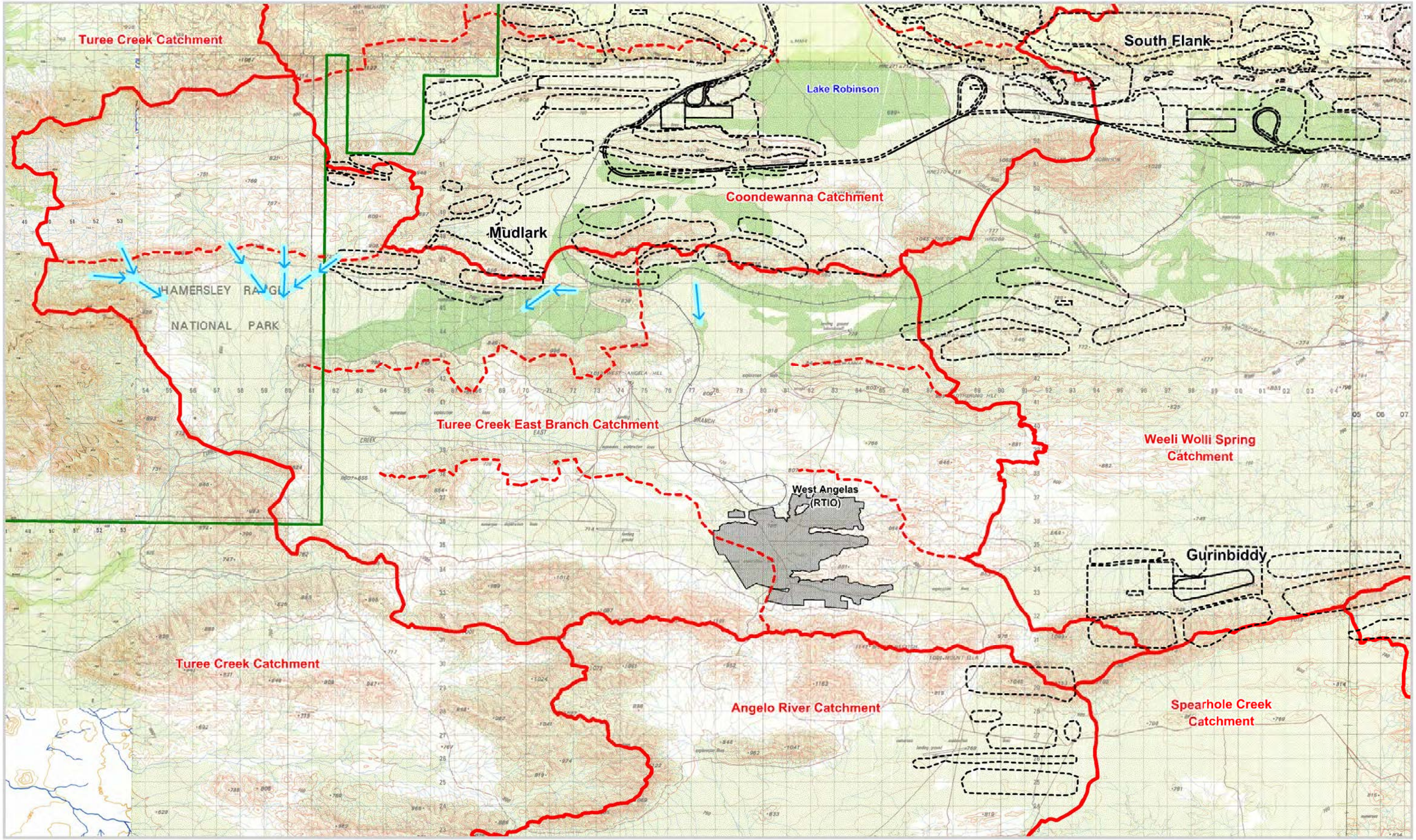
DATA SOURCES:
1:100,000 Topography Maps

RPS

FIGURE 3.2

COONDEWANNA CATCHMENT
CPR OREBODY 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



N

0 2 4 6

Kilometres

Scale: 1:150,000 @A3

GDA 1994 Zone 50

AUTHOR: LC	REPORT NO: 275
DRAWN: LC	REVISION: f
DATE: 01/09/2015	JOB NO: 1549C

Location: F:\Jobs\1549F\Spatial_Data\MapInfo\Workspaces\020a Figure 3.3.wor

LEGEND

- Main Catchment Boundary
- Sub-Catchment Boundary
- Main Drainage Corridor Within Orebody Area
- Existing Diversion
- National Park Boundary
- Rail
- Indicative BHP Billiton Iron Ore Disturbance
- Existing Third Party Disturbance

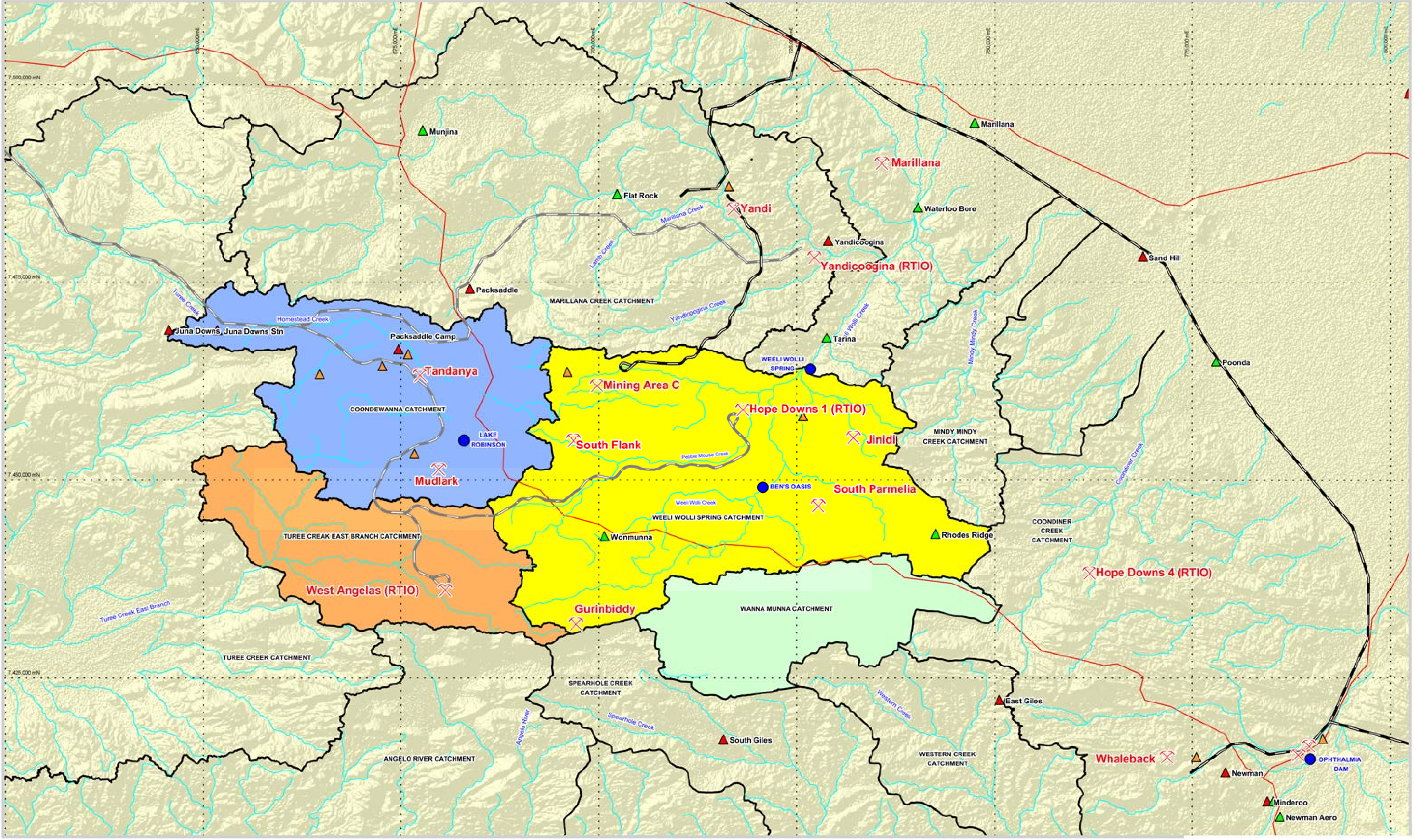
DATA SOURCES:
1:100,000 Topography Maps

RPS

FIGURE 3.3

TUREE CREEK EAST BRANCH CATCHMENT
CPR OREBODY 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 MAP

DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY

N

0 10 20

Kilometres

Scale: 1:450,000 @A3

GDA 1994 Zone 50

AUTHOR: LC	REPORT NO: 275
DRAWN: JT	REVISION: f
DATE: 01/09/2015	JOB NO: 1549C

LEGEND

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

Catchment Areas

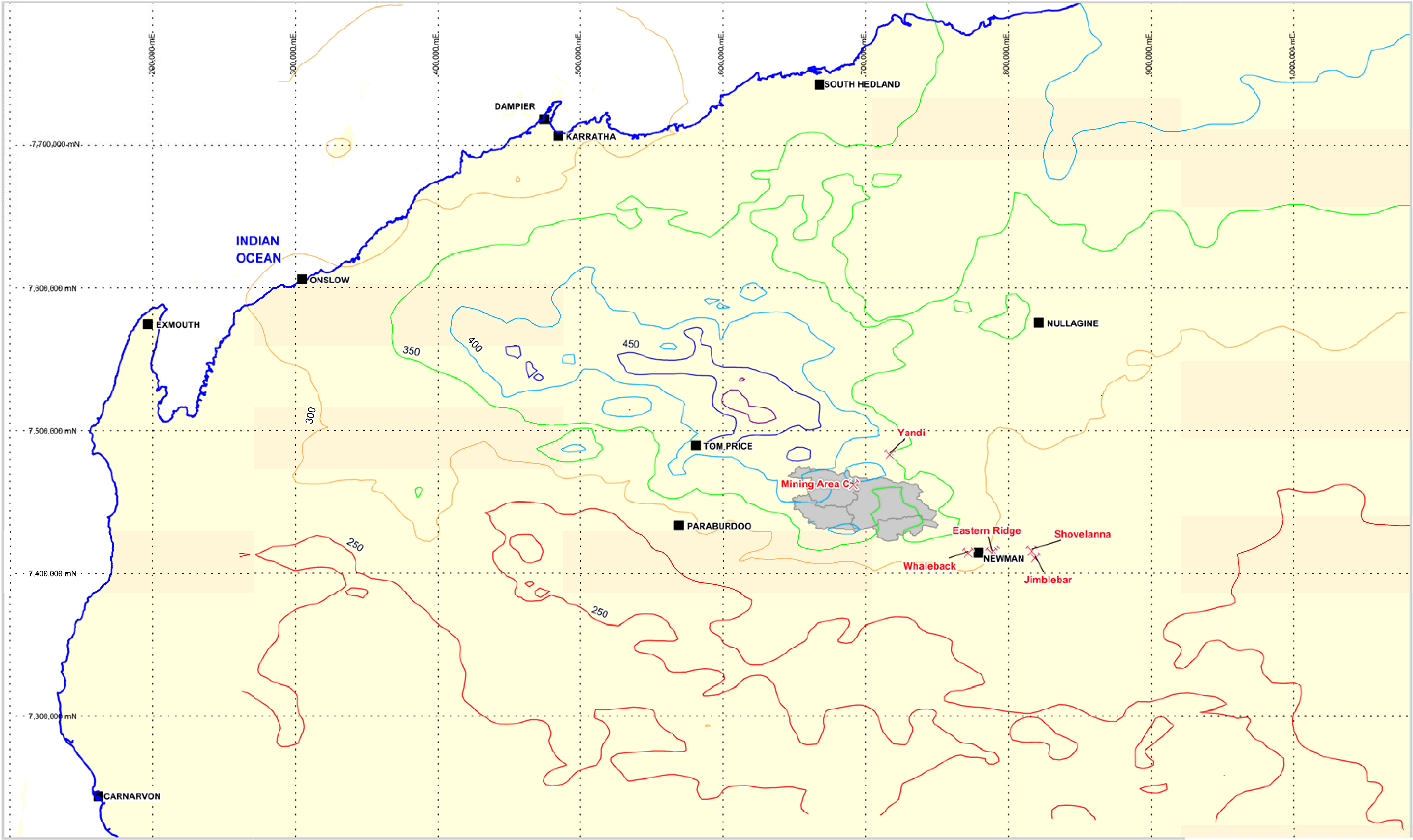
- Coondewanna
- Weeli Wolli Spring
- Wanna Munna
- Turee Creek East Branch

RPS

FIGURE 3.4

EXISTING AND HISTORICAL RAINFALL MONITORING SITES

Location: F:\Jobs\1549C\Spatial_Data\MapInfo\Workspaces\020a Figure 3.4 - Central Pilbara Rainfall Monitoring Sites Rev B.wor



LOCATION MAP

N

50 0 50

Kilometres

Scale: 1:2,500,000 @A3

GDA 1994 Zone 50

AUTHOR: LC	REPORT NO: 275
DRAWN: LC	REVISION: f
DATE: 01/09/2015	JOB NO: 1549C

LEGEND

- Major Town
- BHP Billiton Iron Ore Mine Site
- Average Annual Rainfall 50mm Contours
- Central Pilbara Region Study Catchment Areas

Average Annual Rainfall 50mm Contours

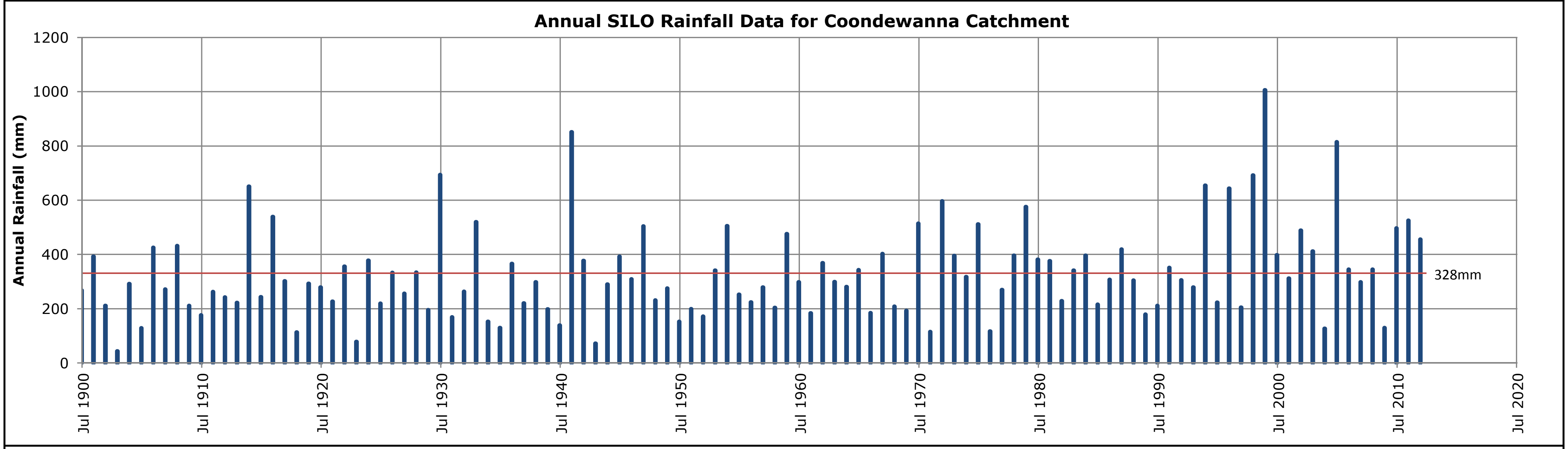
- 250mm
- 300mm
- 350mm
- 400mm
- 450mm
- 500mm

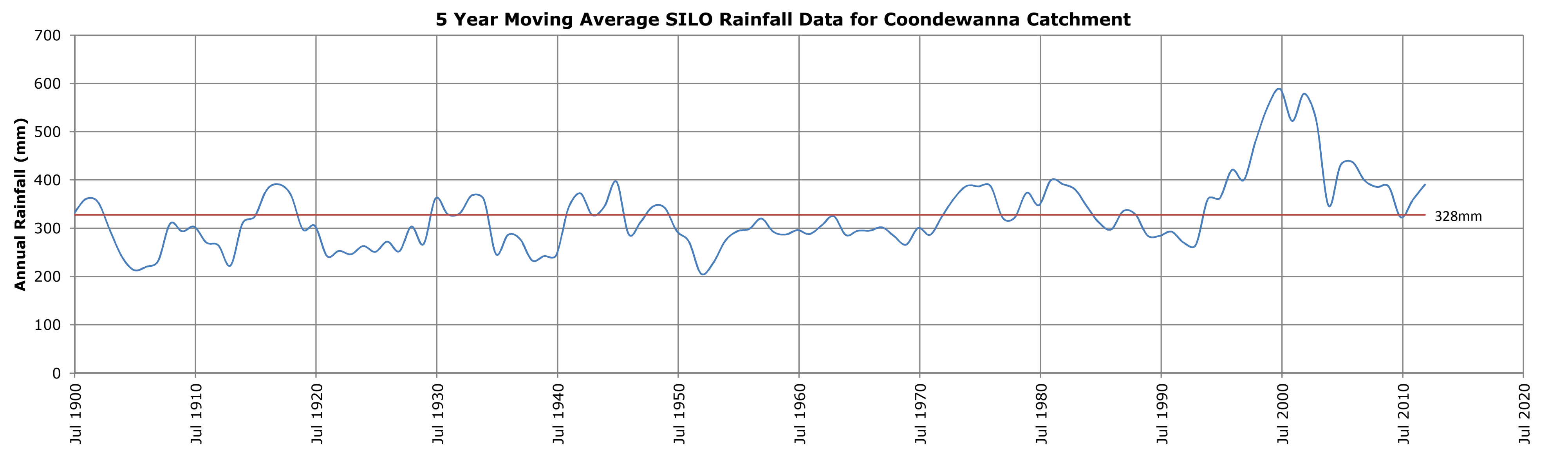
RPS

FIGURE 3.5

AVERAGE ANNUAL SILO RAINFALL DISTRIBUTION (1961 - 2012)

Location: F:\Jobs\1549C\Spatial_Data\MapInfo\Workspaces\020 Figure 3.5 Ave Annual Rainfall.wor





RPS

Coondewanna Catchment Annual Rainfall Data FIGURE 3.6

F:\Jobs\1549C\300\Rain and Streamflow Data\[SILO Data - Coond Flats Catchment Centroid.xls]020a Fig 3.6

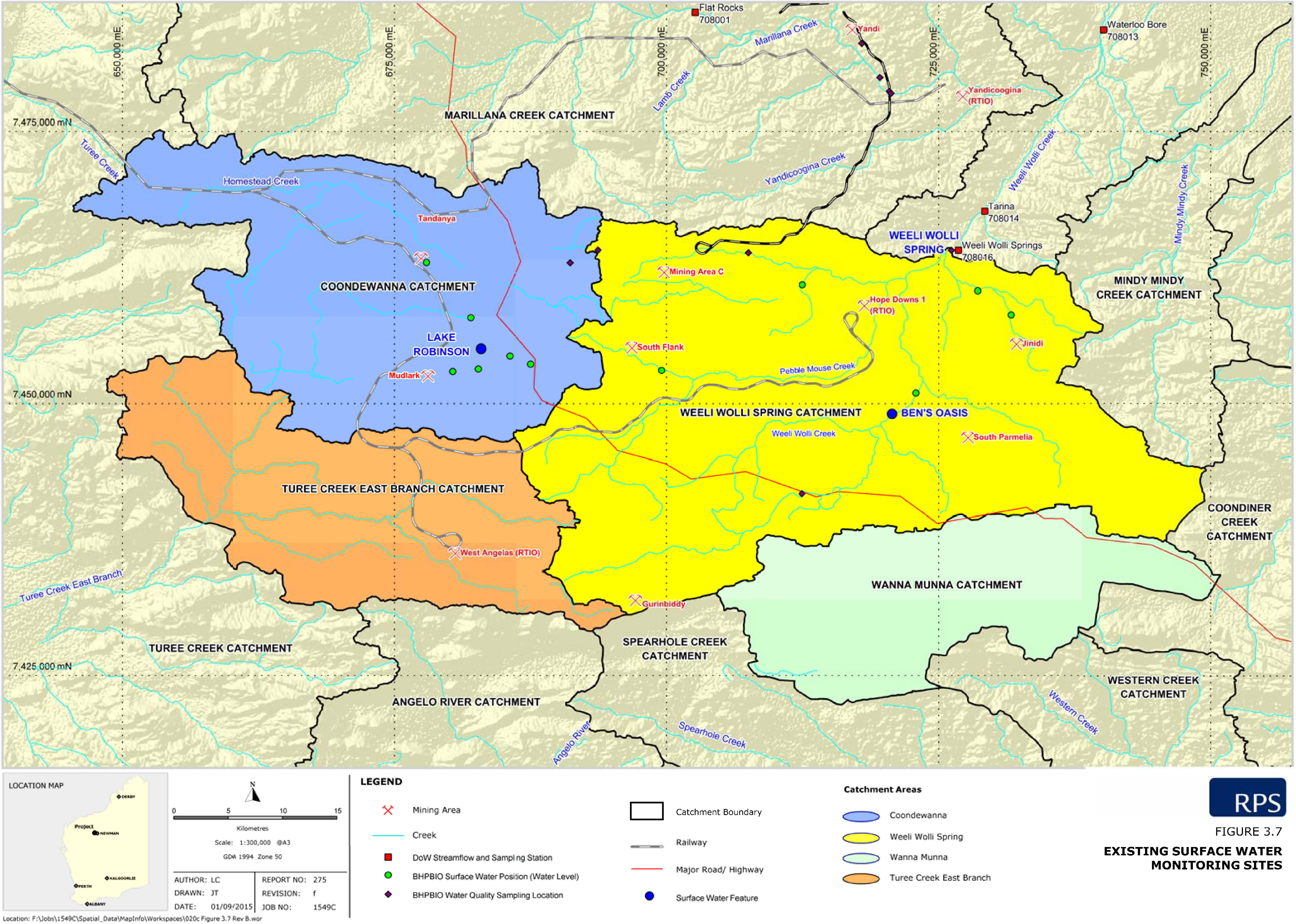
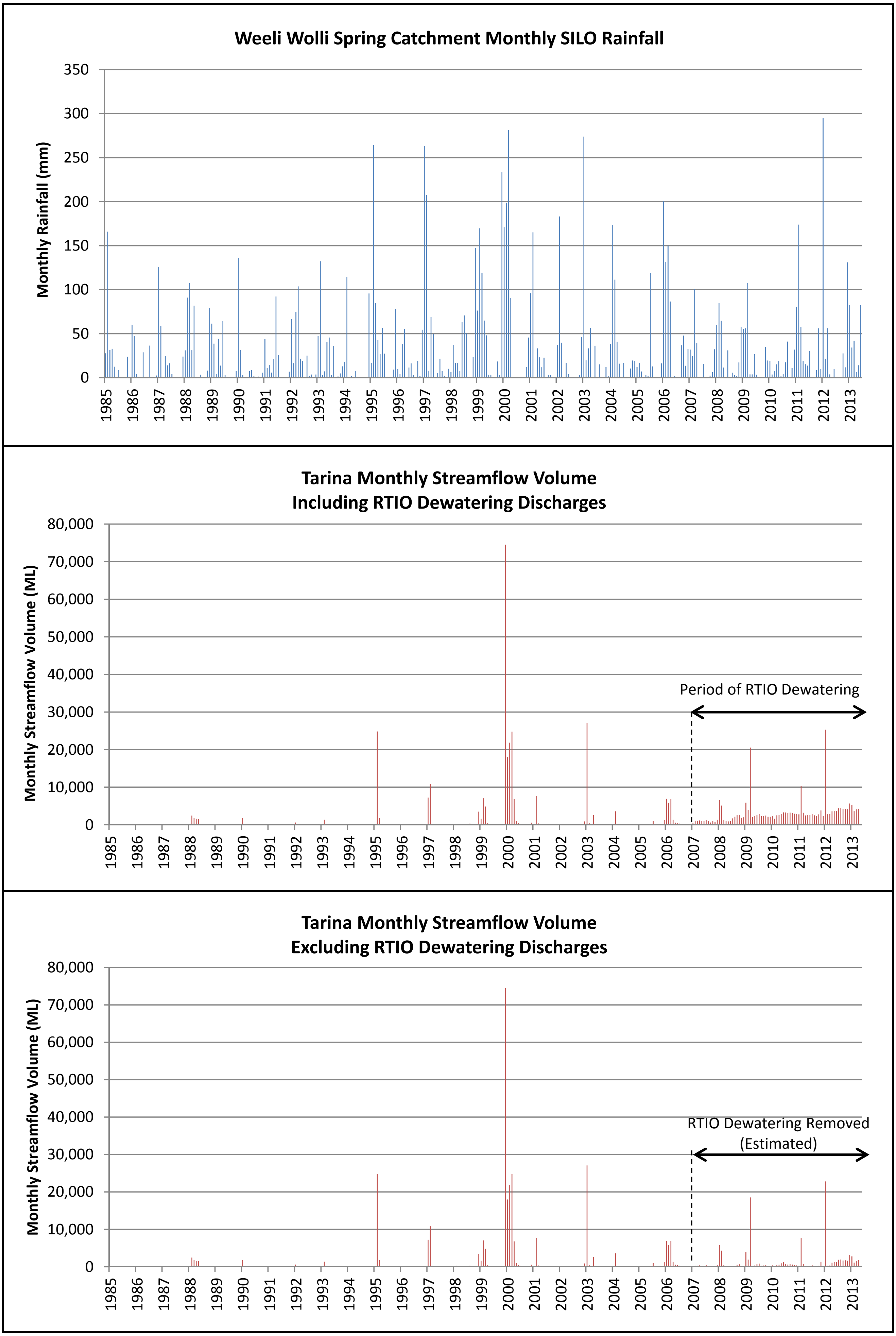


FIGURE 3.7

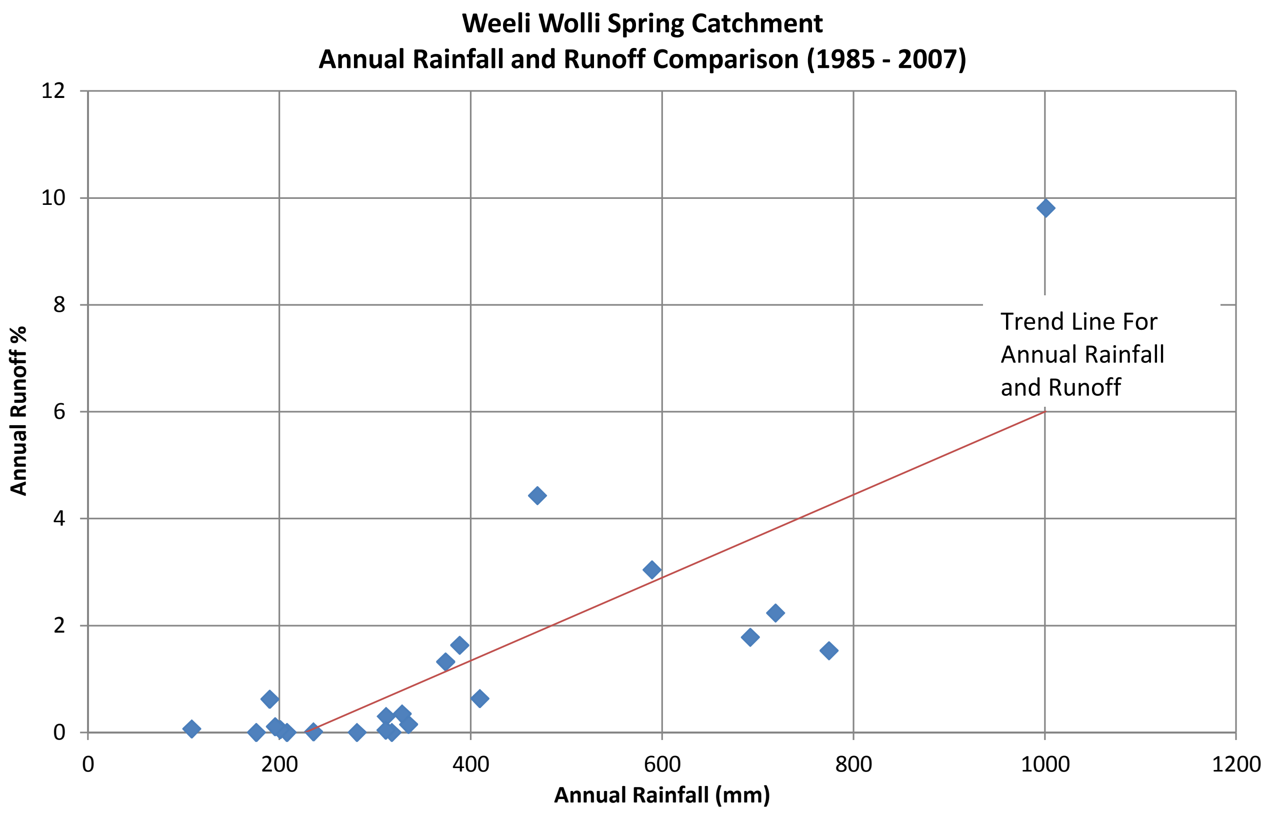
EXISTING SURFACE WATER MONITORING SITES

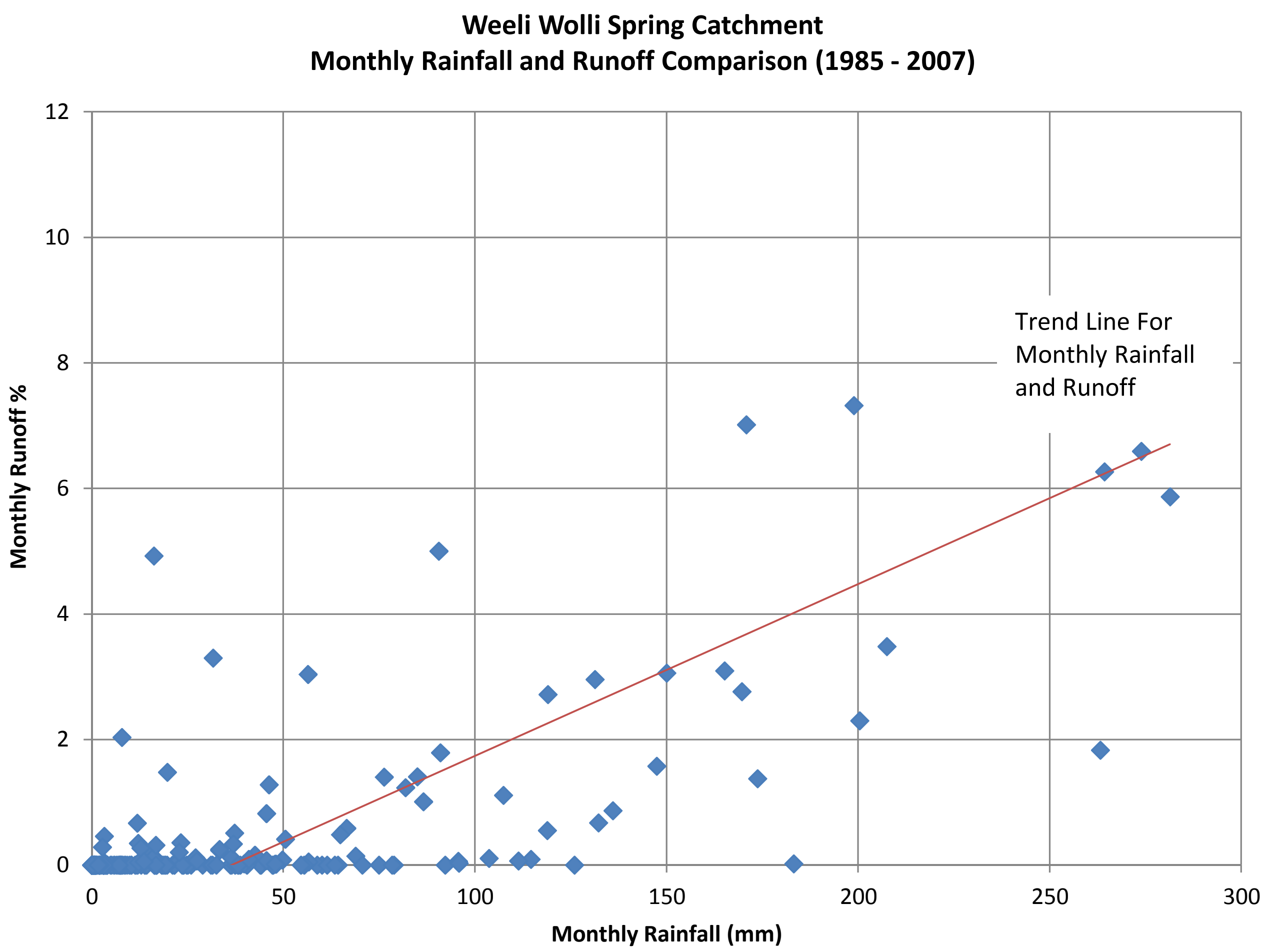


RPS

Weeli Wolli Spring Catchment Rainfall and Tarina Runoff FIGURE 3.8

F:\Jobs\1549C\300\Rain and Streamflow Data\[020a Fig 3.8.xlsx]020a Fig 3.8

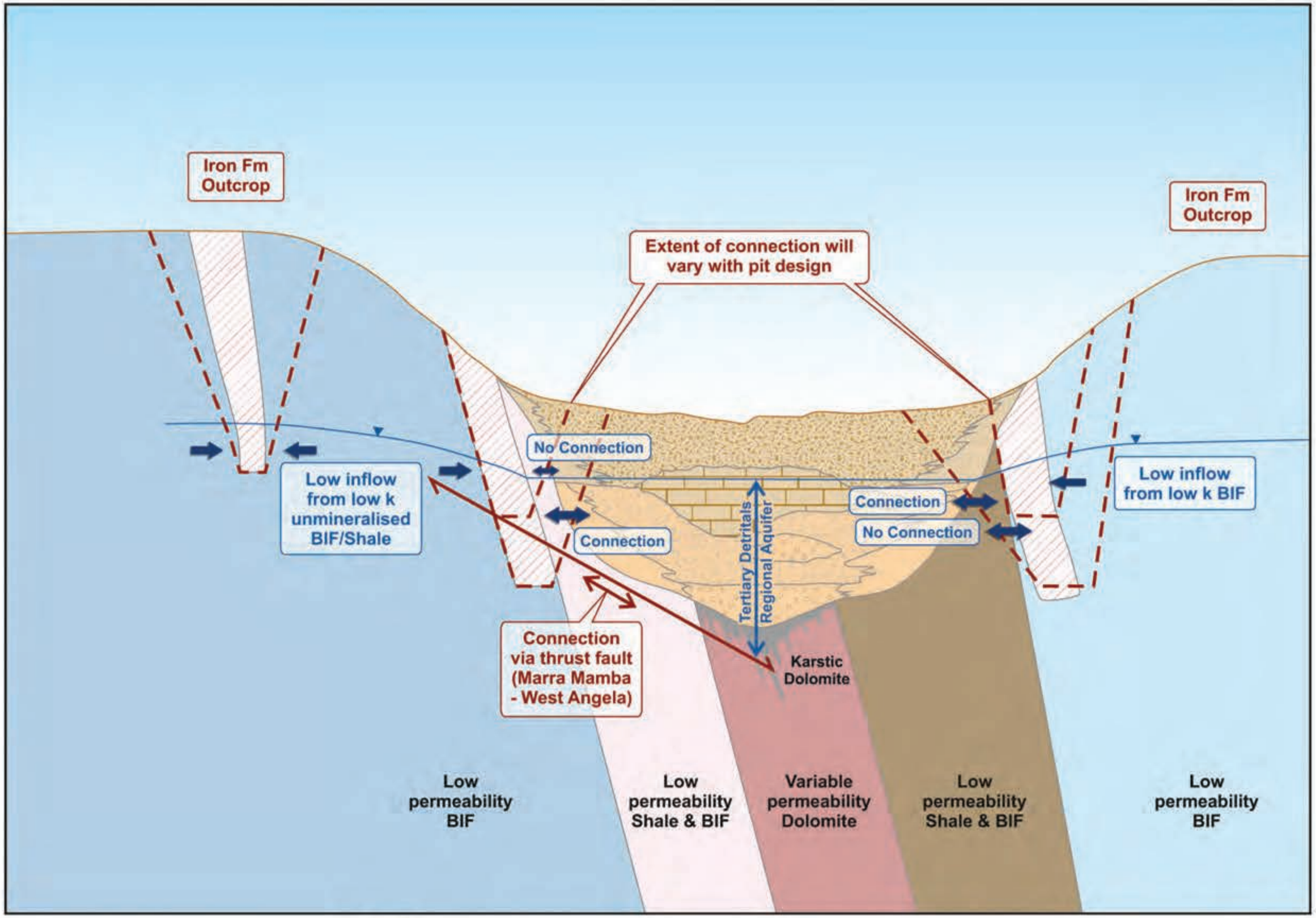


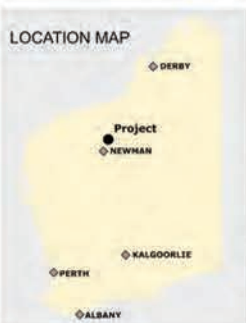


RPS

Weeli Wolli Spring Catchment Rainfall and Runoff Comparisons FIGURE 3.9

F:\Jobs\1549C\300\Rain and Streamflow Data\[Average Rainfall.xlsx]020a Fig 3.9





Location: XXXX

NOT TO SCALE

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	c
DATE:	23/06/2014	JOB NO:	1549B

LEGEND

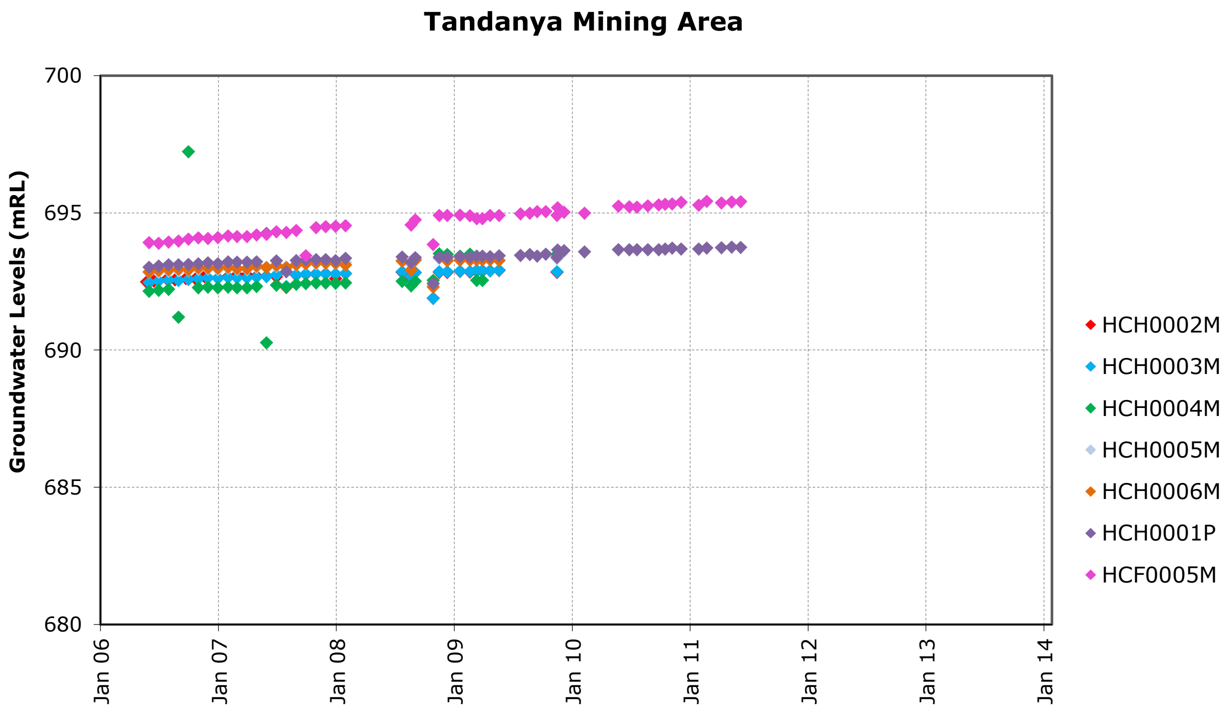
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

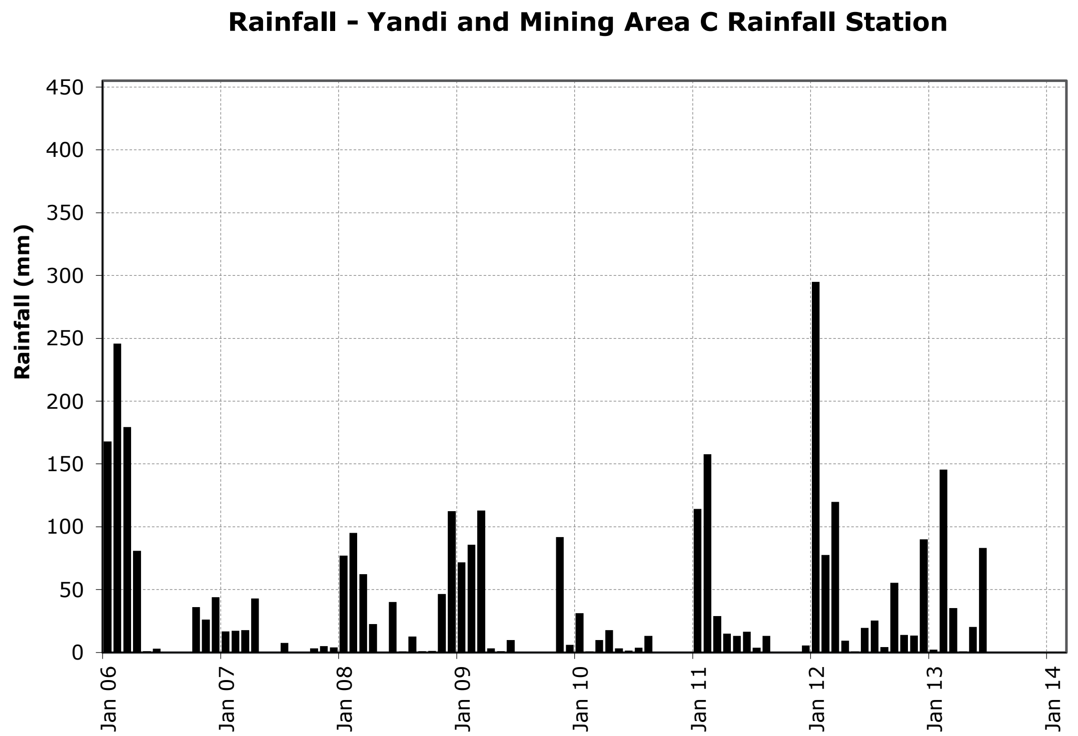
RPS

FIGURE 3.10

GENERIC HYDROGEOLOGICAL CROSS SECTION CENTRAL PILBARA REGION

DATA SOURCES: Input data source here



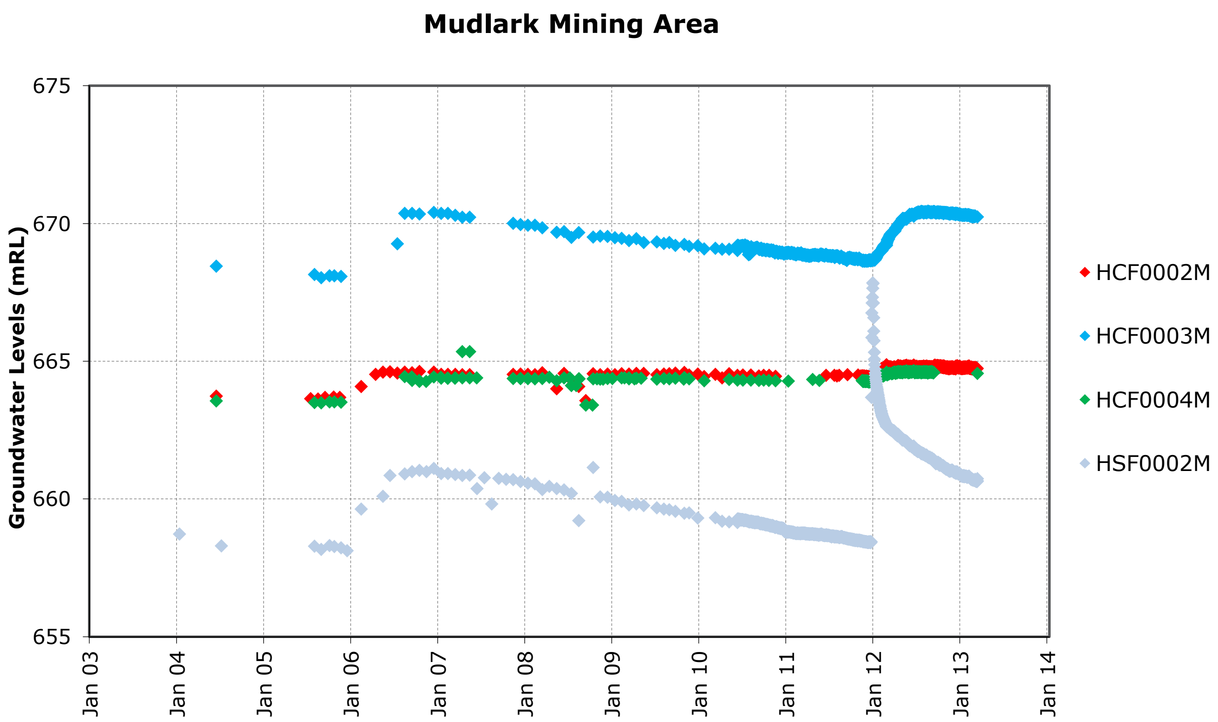


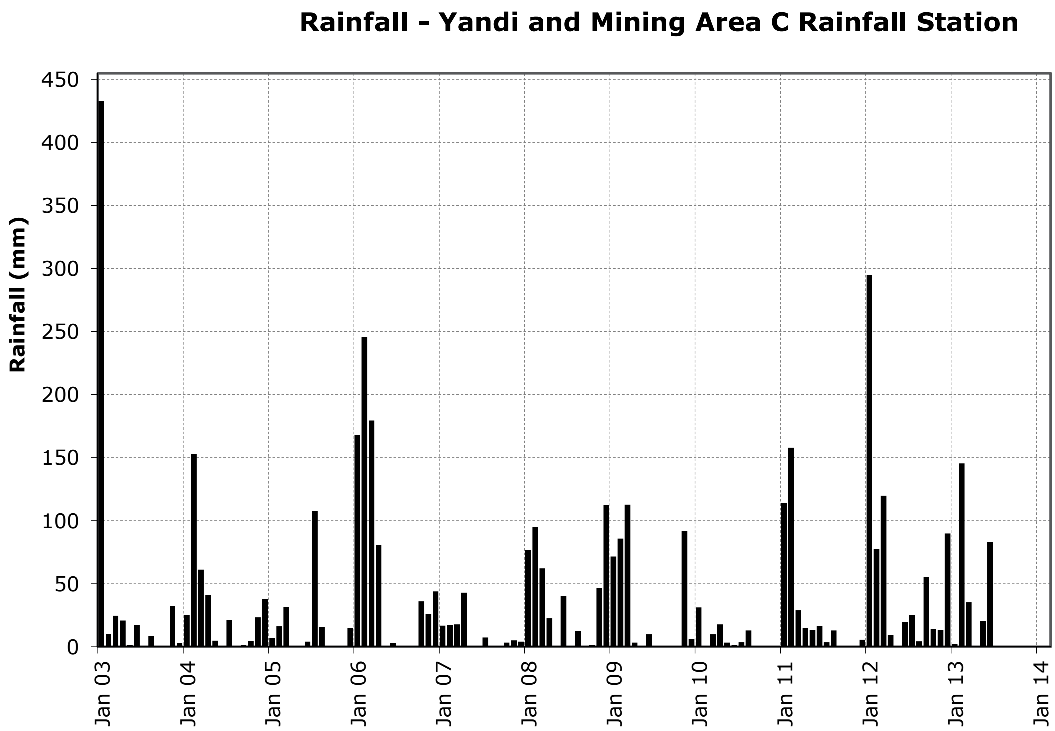
Rainfall data from Yandi - April 1998 to May 2003
Rainfall data from MAC - June 2003 to Present

RPS

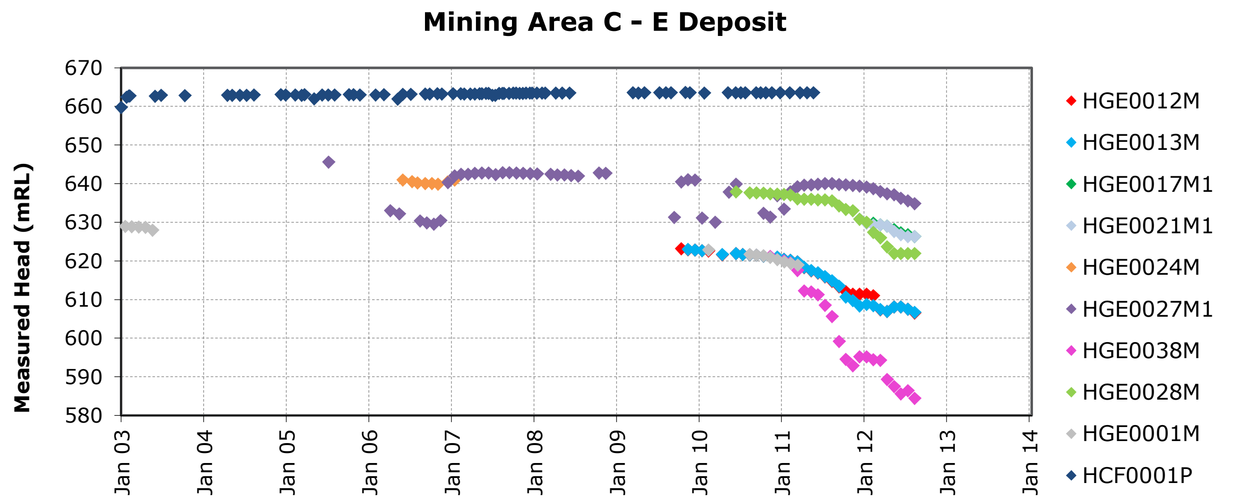
TANDANYA MINING AREA HYDROGRAPHS FIGURE 3.11a

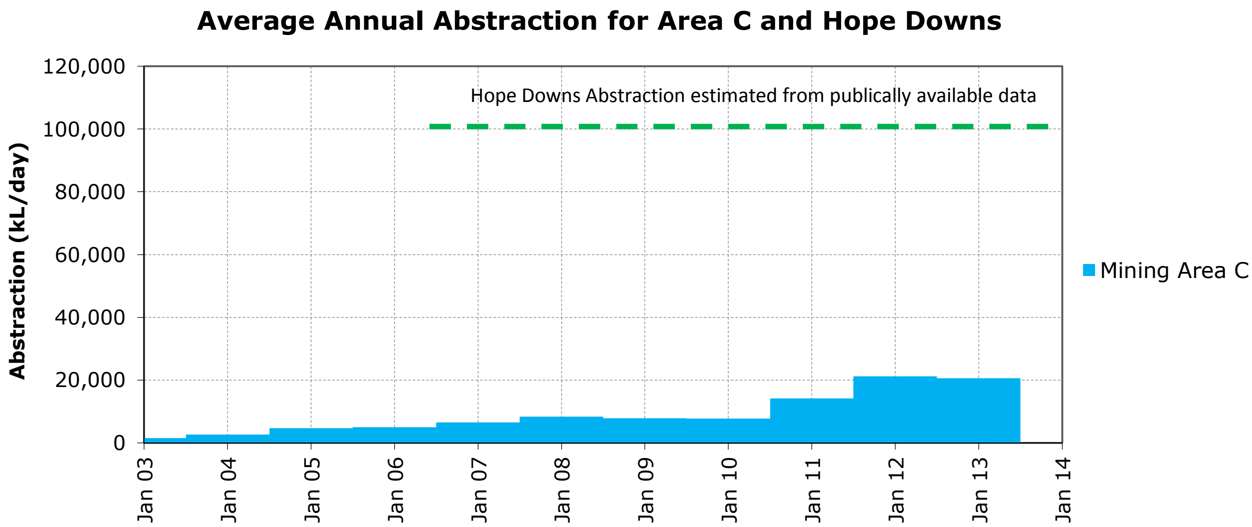
F:\Jobs\1549B\300\CPR\[196d all CPR hydrographs.xlsx]Tandanya

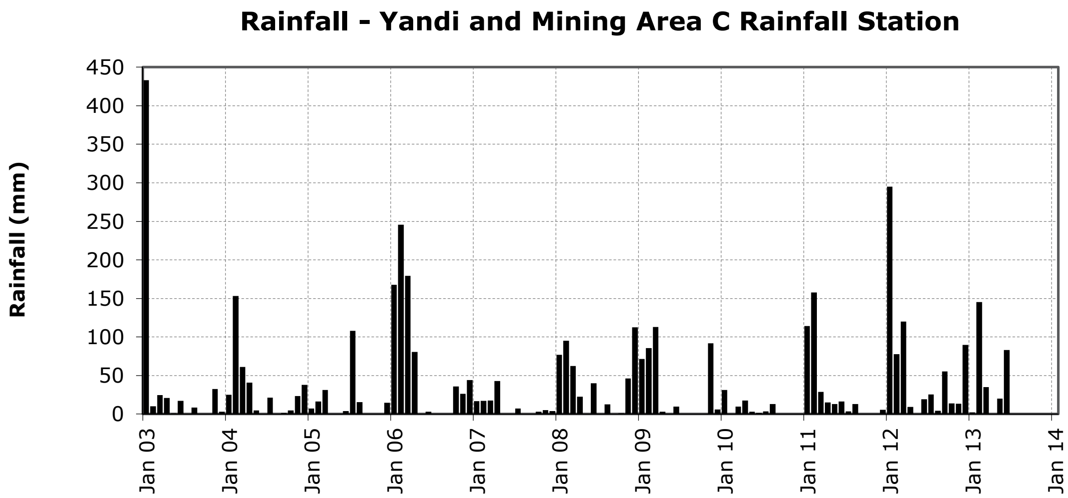




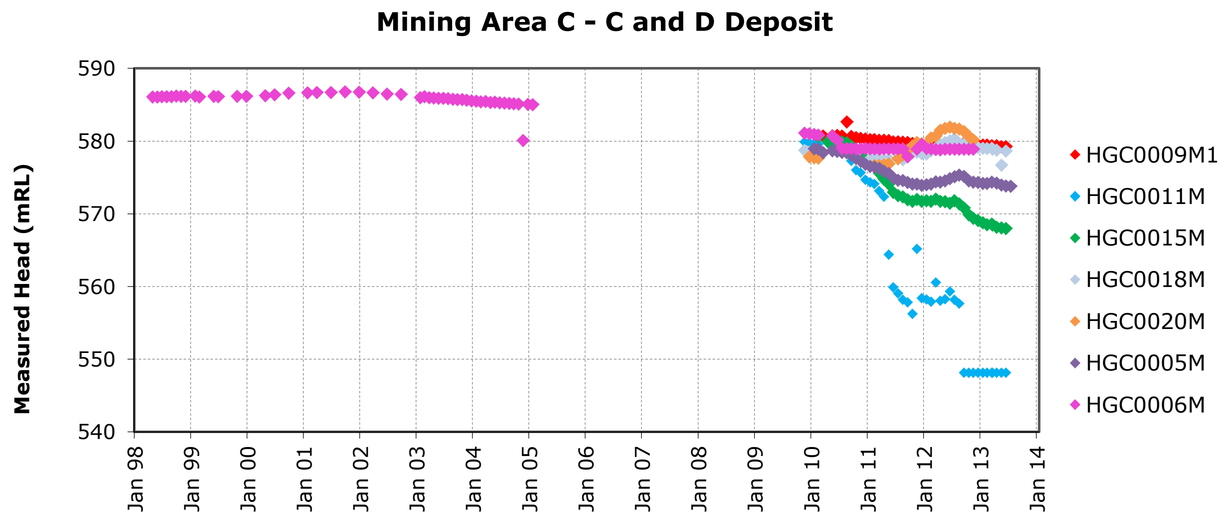
Rainfall data from Yandi - April 1998 to May 2003
Rainfall data from MAC - June 2003 to Present

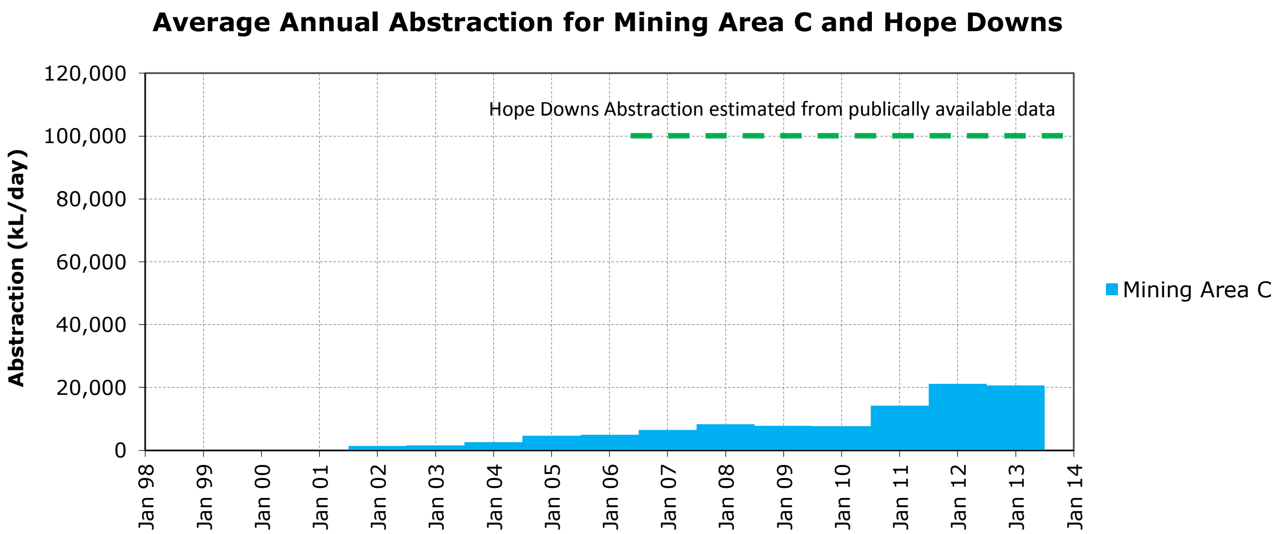


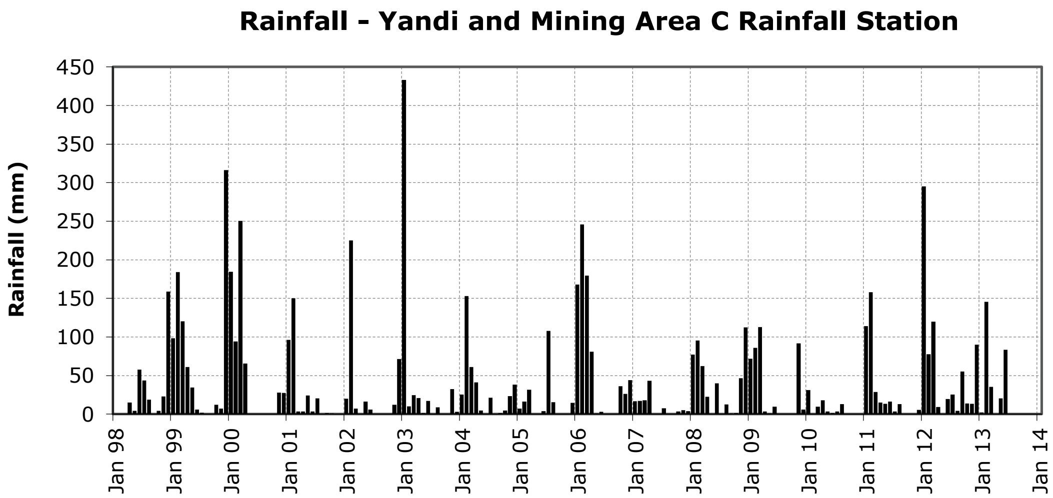




Rainfall data from Yandi - April 1998 to May 2003
Rainfall data from MAC - June 2003 to Present





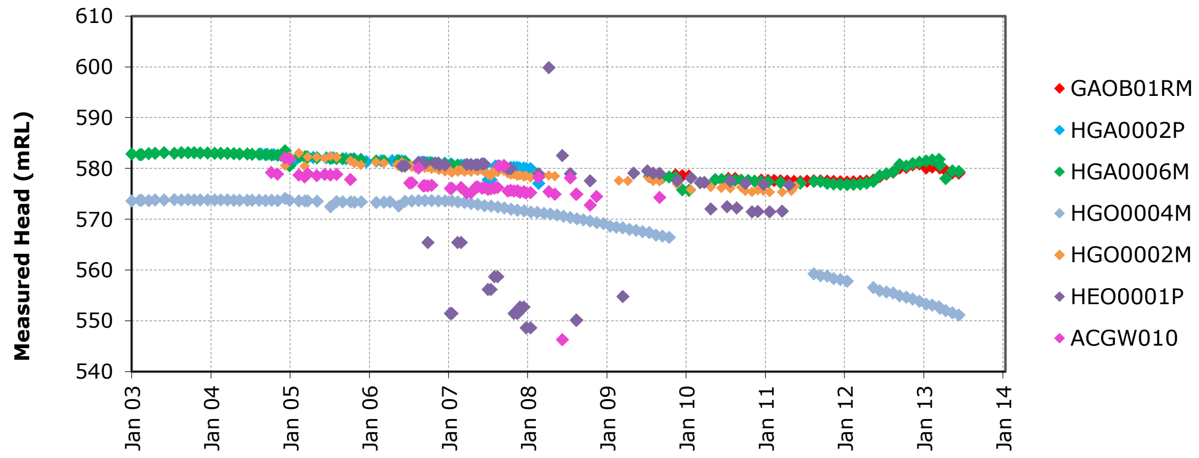


Rainfall data from Yandi - April 1998 to May 2003
Rainfall data from MAC - June 2003 to Present

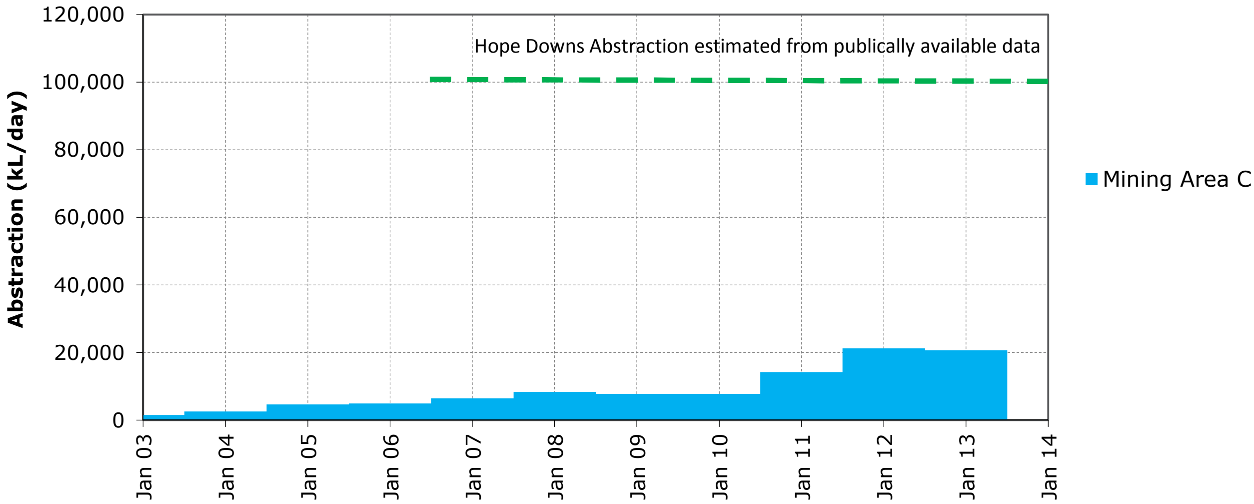
D AND C DEPOSIT MINING AREA HYDROGRAPHS FIGURE 3.11d

F:\Jobs\1549B\300\CPR\[196d all CPR hydrographs.xlsx]D and C Deposit

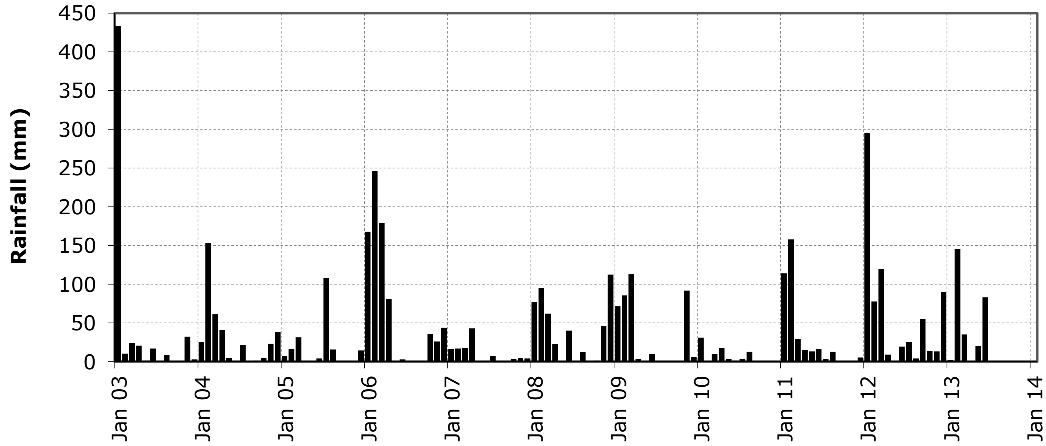
A, B and R Deposit Production and Monitoring Bores



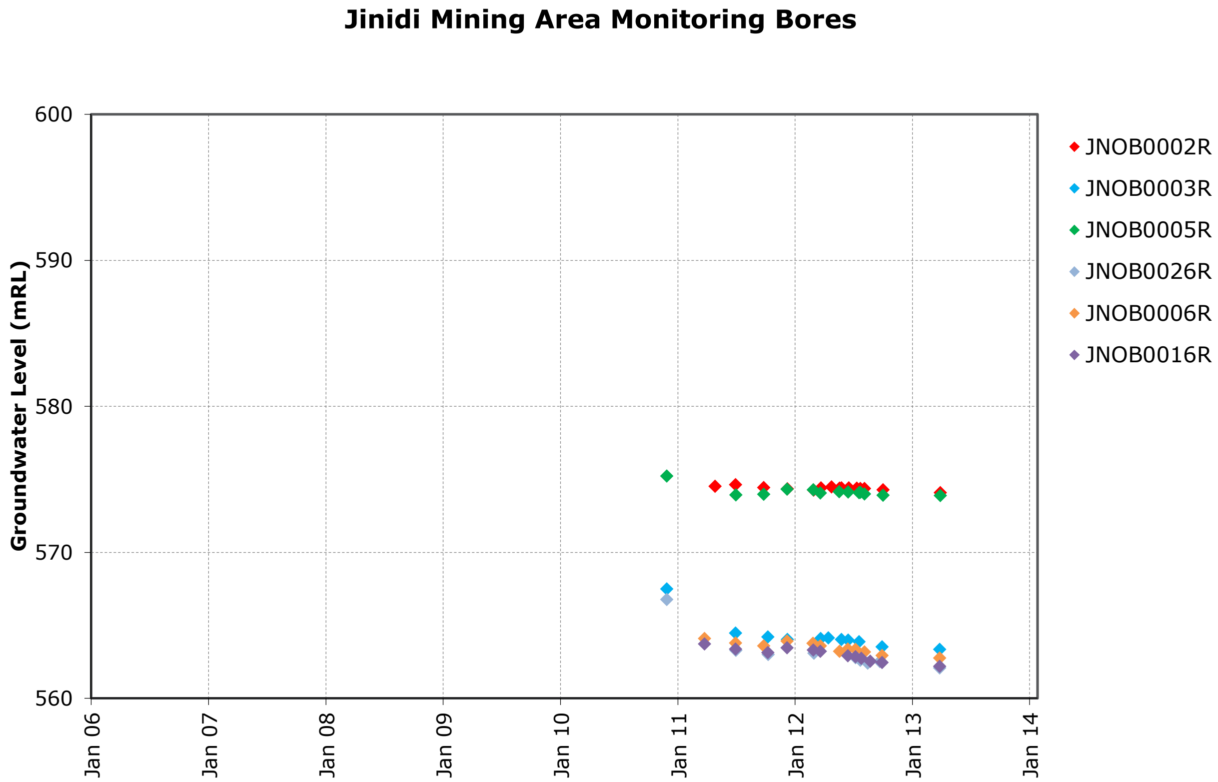
Average Annual Abstraction for Area C and Hope Downs

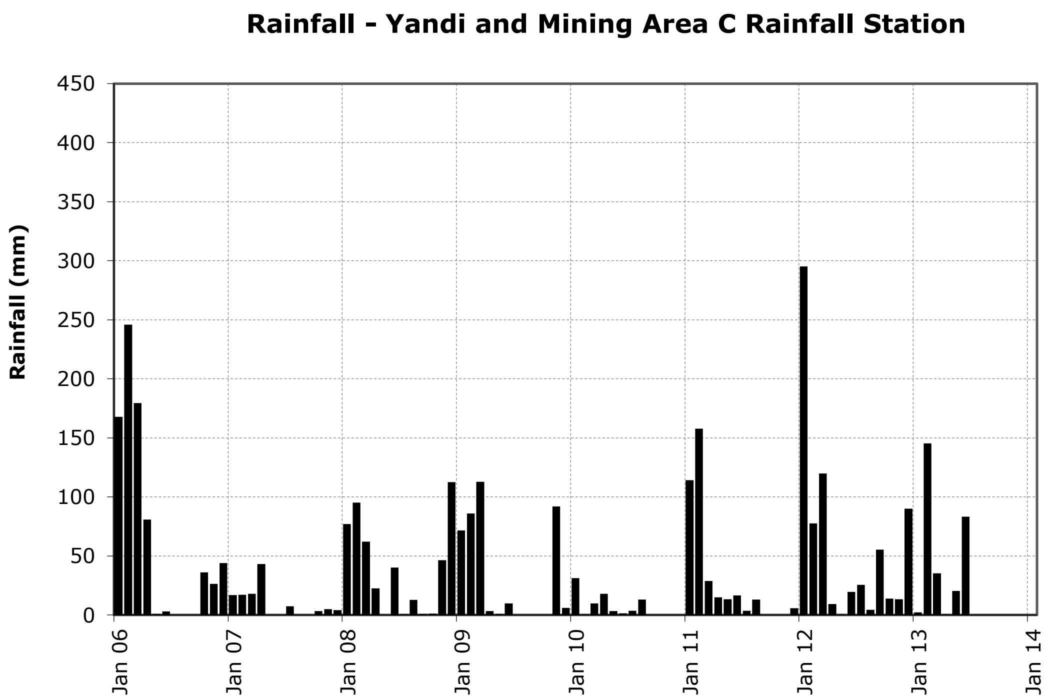


Rainfall - Yandi and Mining Area C Rainfall Station



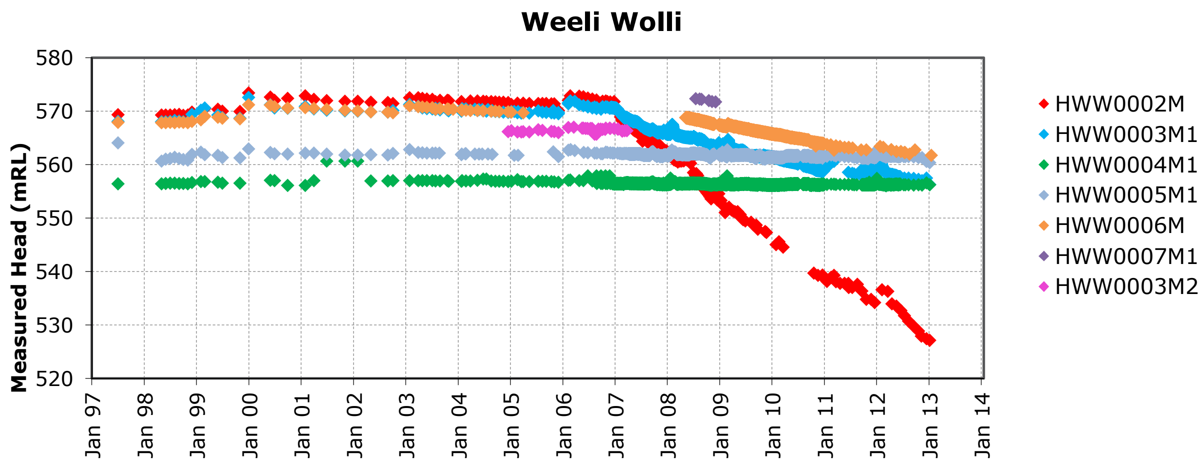
Rainfall data from Yandi - April 1998 to May 2003
Rainfall data from MAC - June 2003 to Present

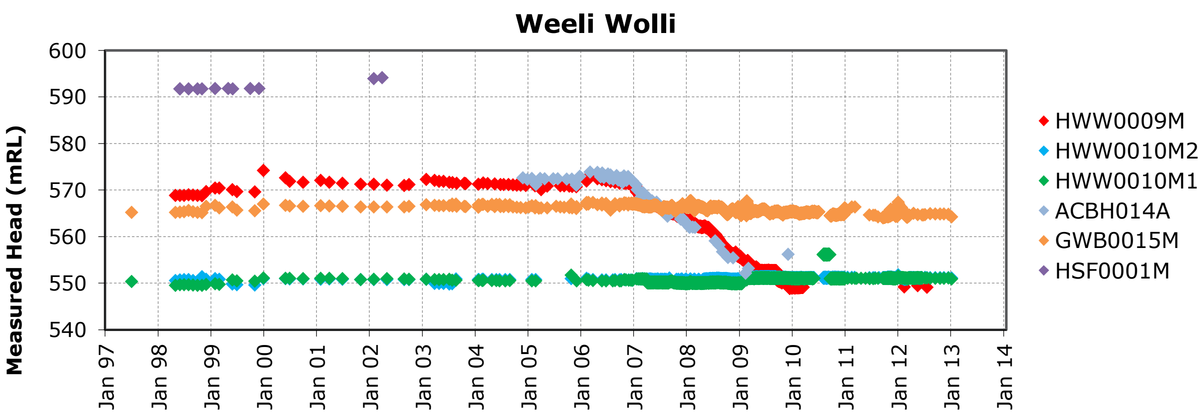


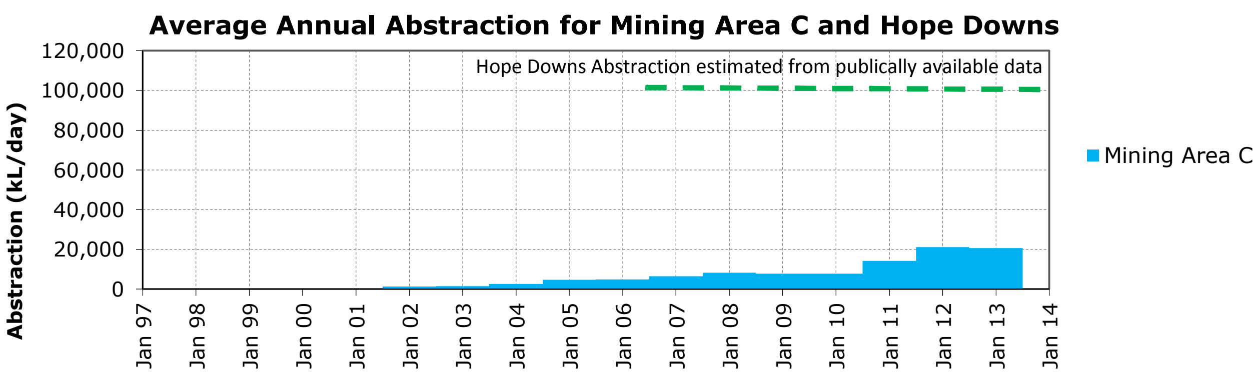


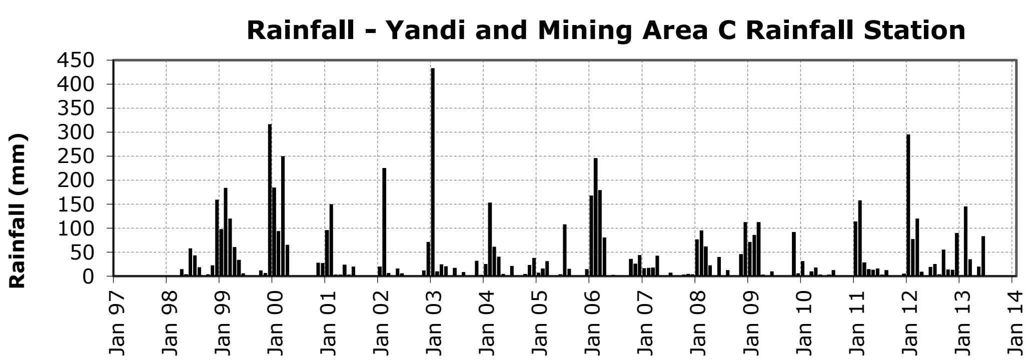
Rainfall data from Yandi - April 1998 to May 2003
Rainfall data from MAC - June 2003 to Present

JINIDI MINING AREA HYDROGRAPHS FIGURE 3.11f

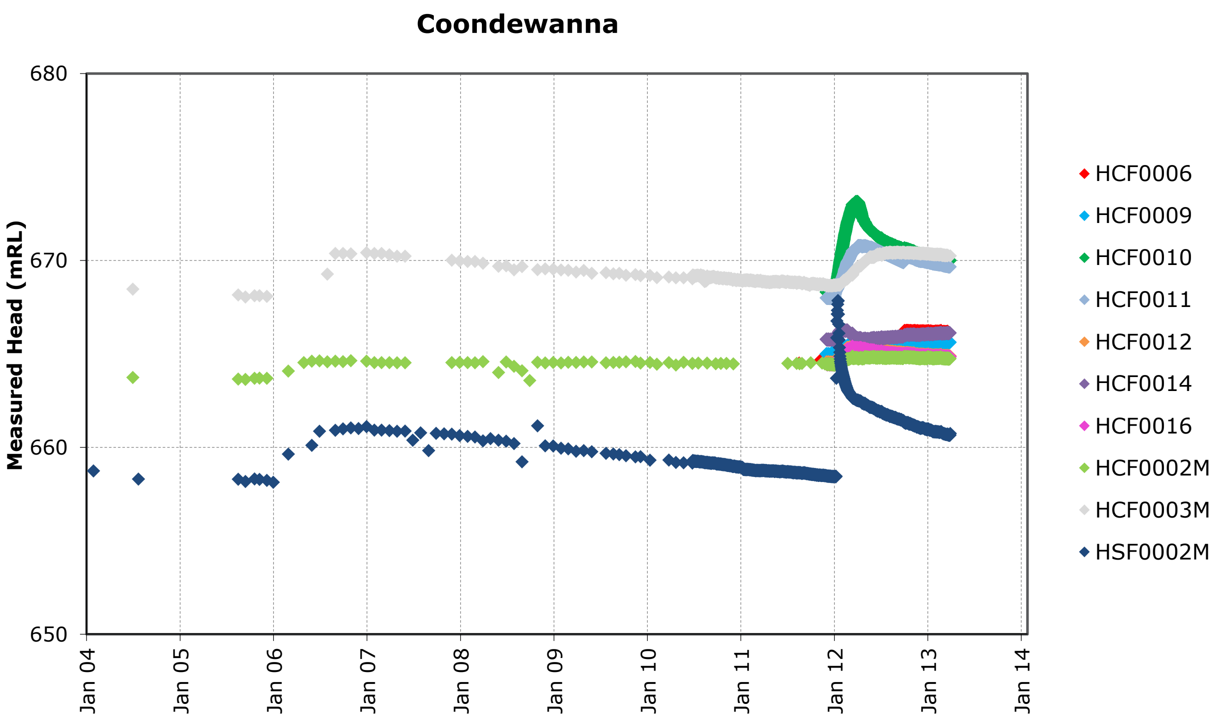


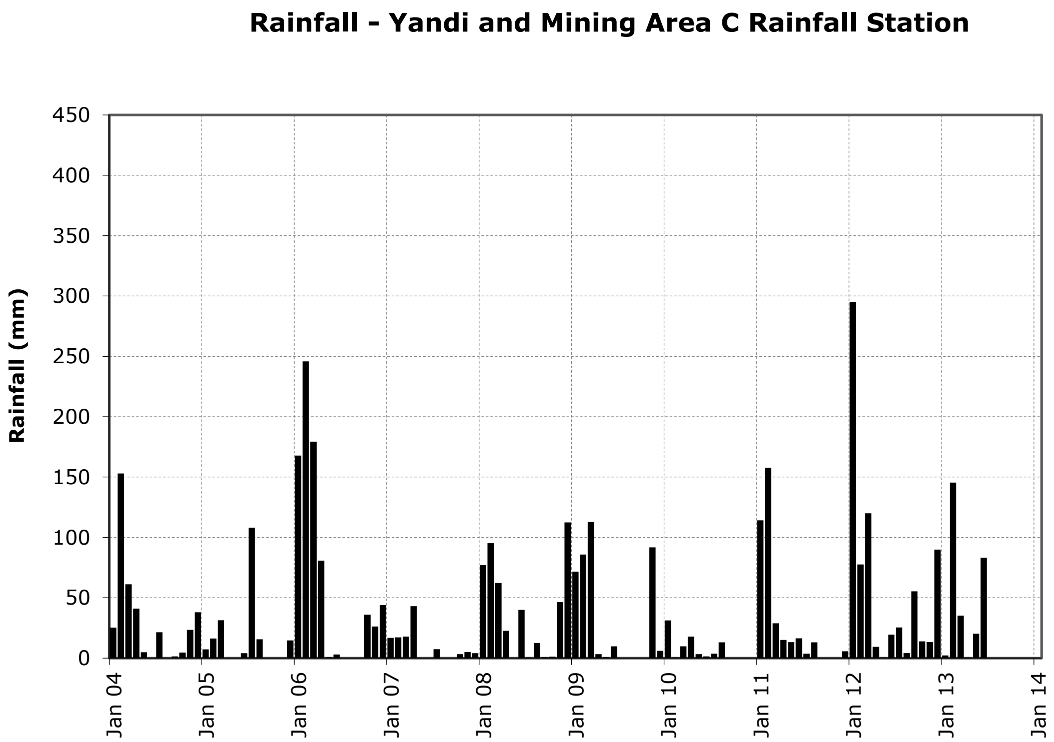




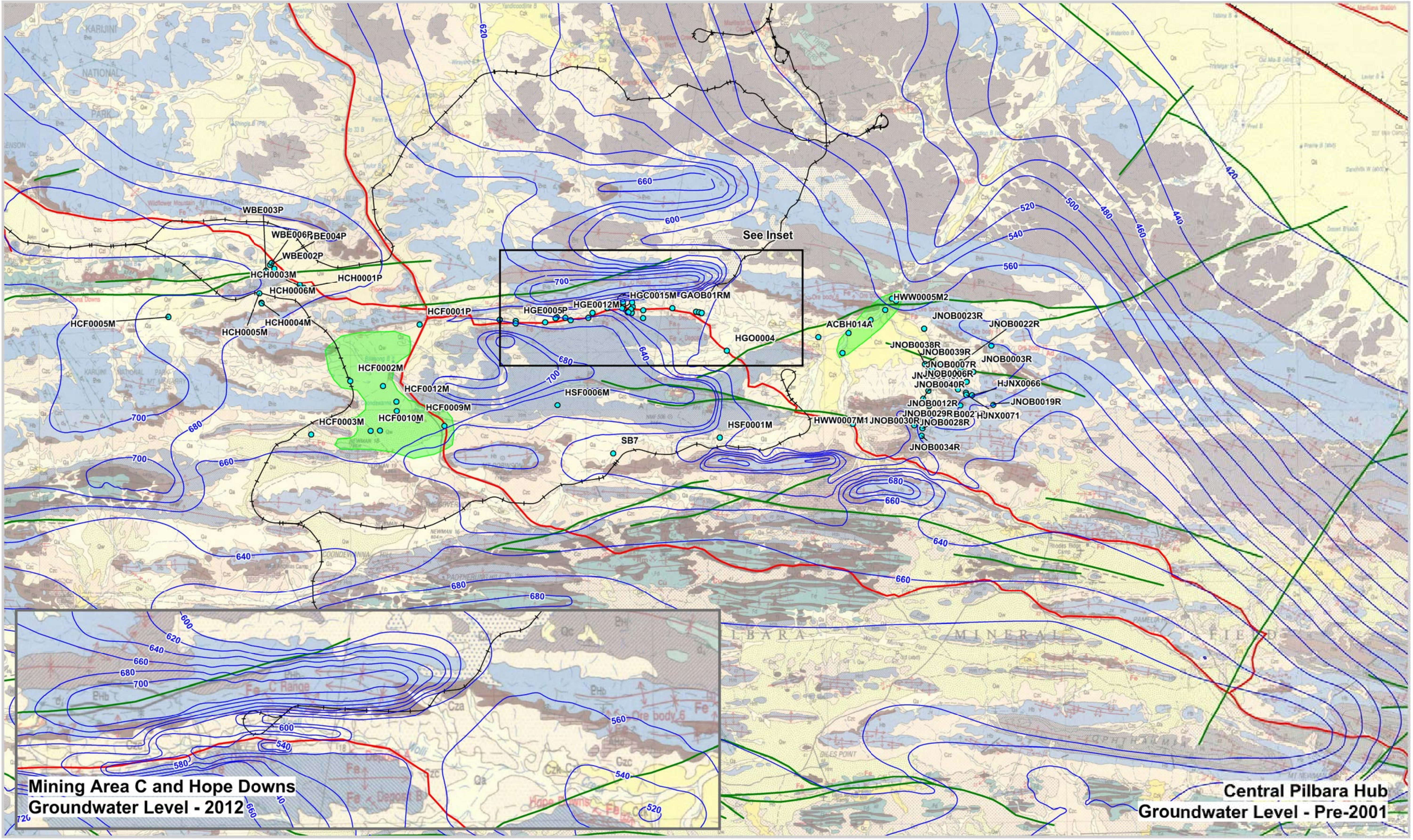


Rainfall data from Yandi - April 1998 to May 2003
Rainfall data from MAC - June 2003 to Present





Rainfall data from Yandi - April 1998 to May 2003
Rainfall data from MAC - June 2003 to Present



N

0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	16/08/13	JOB NO:	1549B

LEGEND

- Key Bore
- CPH Regional Contours (mRL)
- Dyke
- Road
- Rail
- Recharge Location
- Hope Downs Area

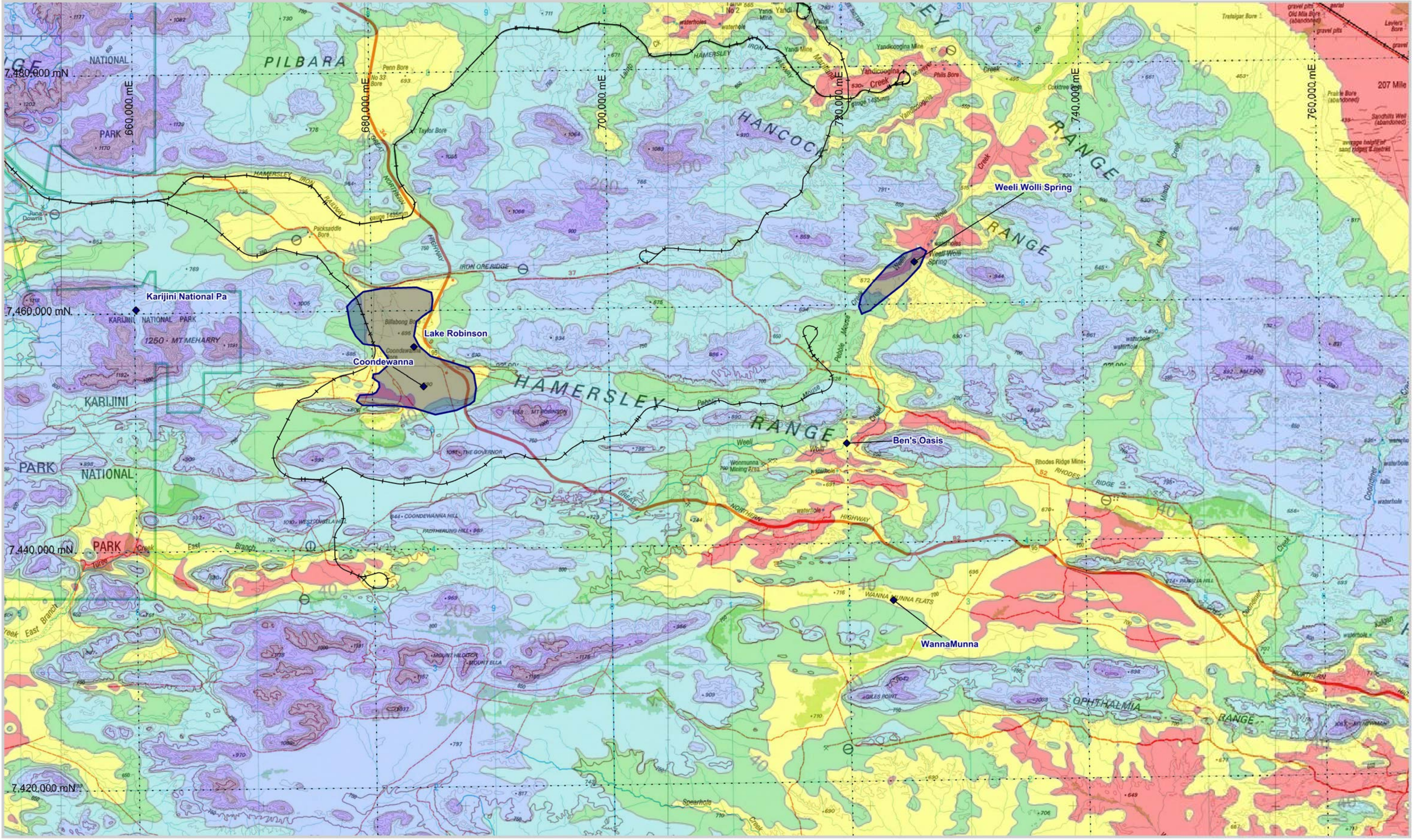
DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 3.12

GROUNDWATER LEVEL CONTOURS PRIOR TO DEWATERING (2001) AND CURRENT (2012) CENTRAL PILBARA REGION

Location: F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a\020a Figure 3.9 - Groundwater Level Contours Prior to Dewatering and Current (2012) CPH



N

0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR: JP	REPORT NO: 275
DRAWN: MR	REVISION: c
DATE: 31/07/2014	JOB NO: 1549B

Location: F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020c Figure 3.13 - Depth to Water CPH

LEGEND

Environmental Receptor

Rail

Recharge Location

DATA SOURCES:
BHPB Iron Ore

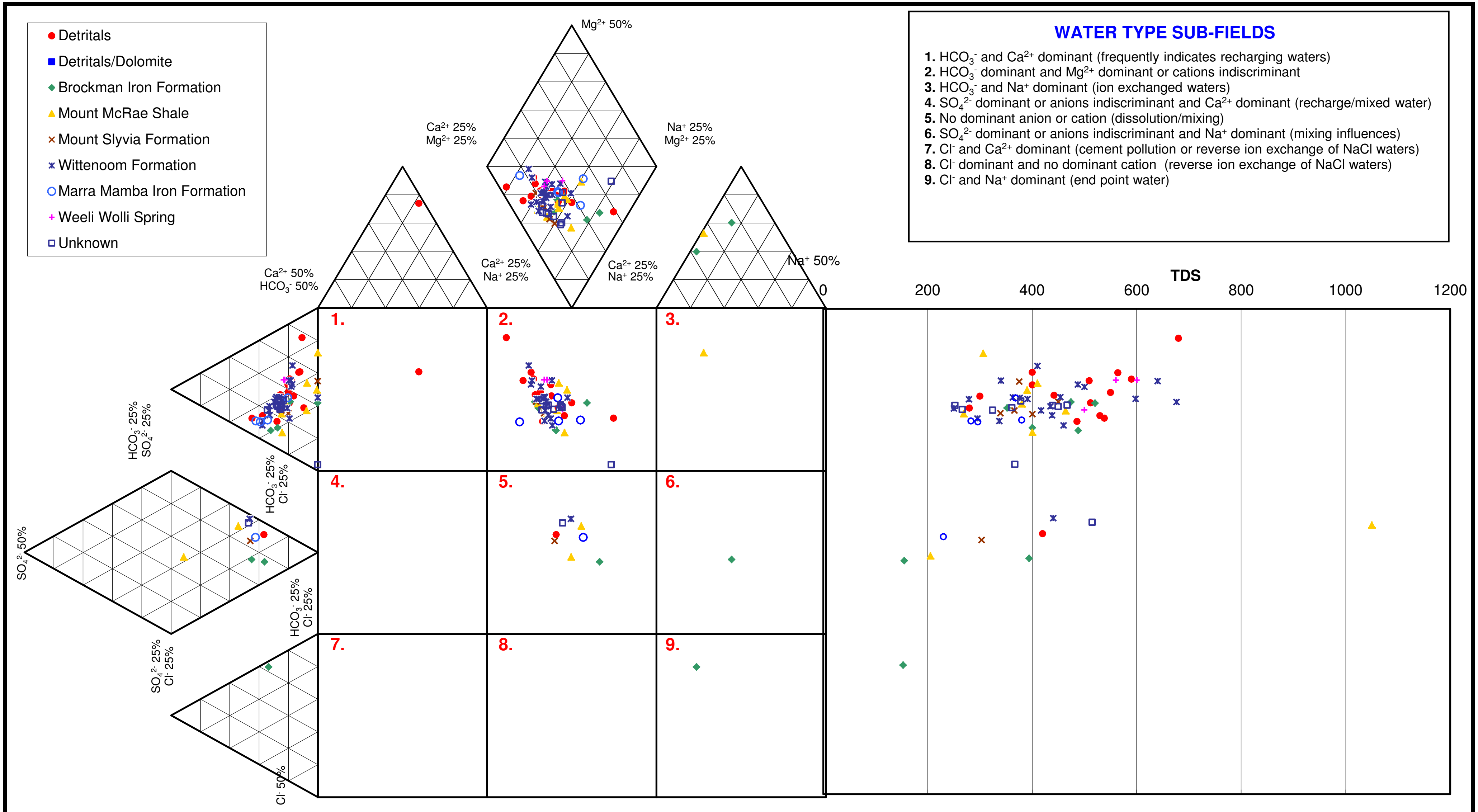
Depth to Water (m)

500
300
200
100
60
40
20
0

RPS

FIGURE 3.13

DEPTH TO WATER
CENTRAL PILBARA REGION



RPS

Expanded Durov Diagram

Figure 3.14

Date: 13/10/14

F:\Jobs\1549B\300\CPR\[200a All CPH Bores HydroCHEM2.0 sorted by geology.xls]Project Information

Project: CPR Conceptual Model
Project No: 1549B

Description: CPR Hydrochemistry
Client: BHP Billiton Iron Ore

HydroCHEM 2.0

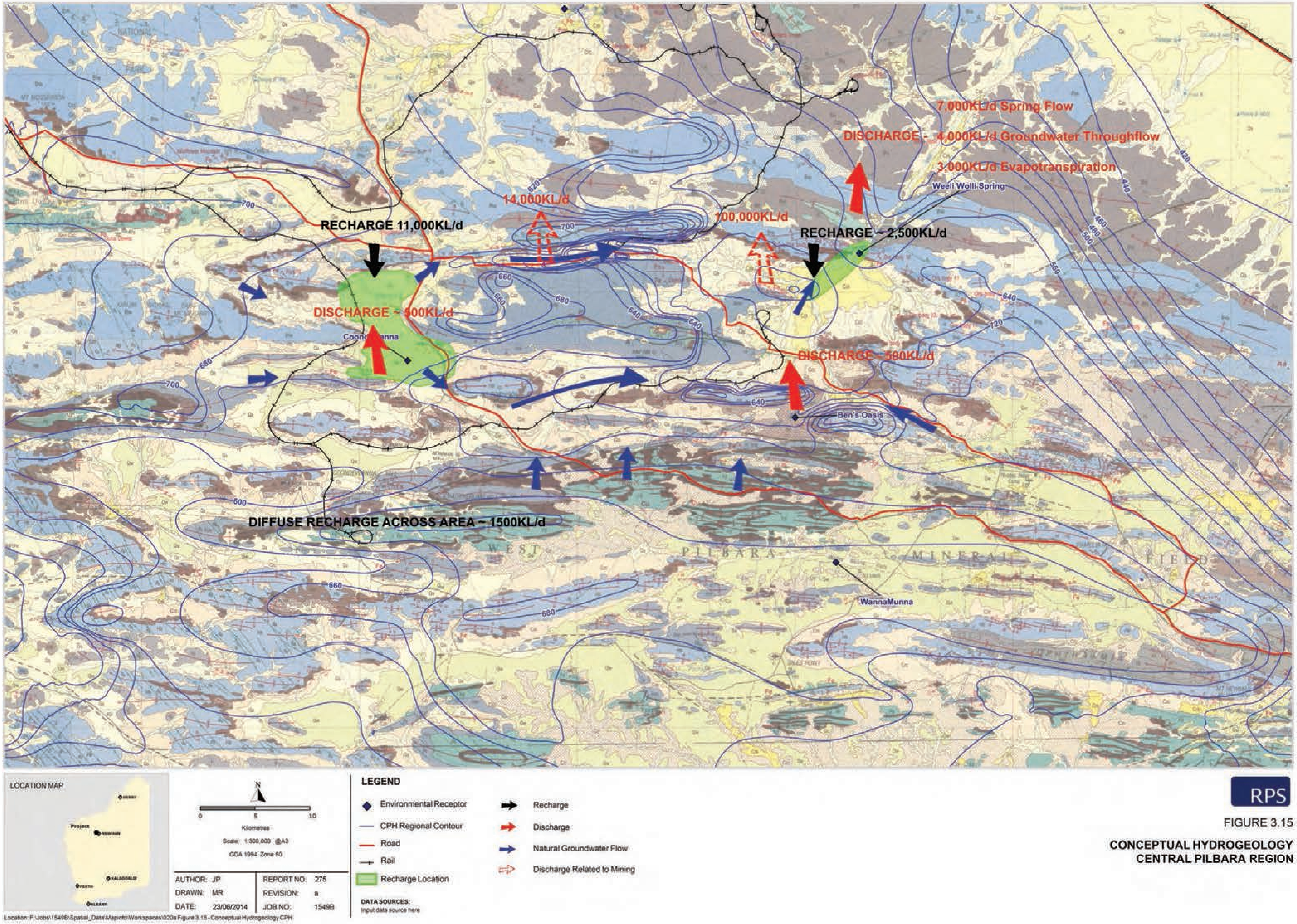
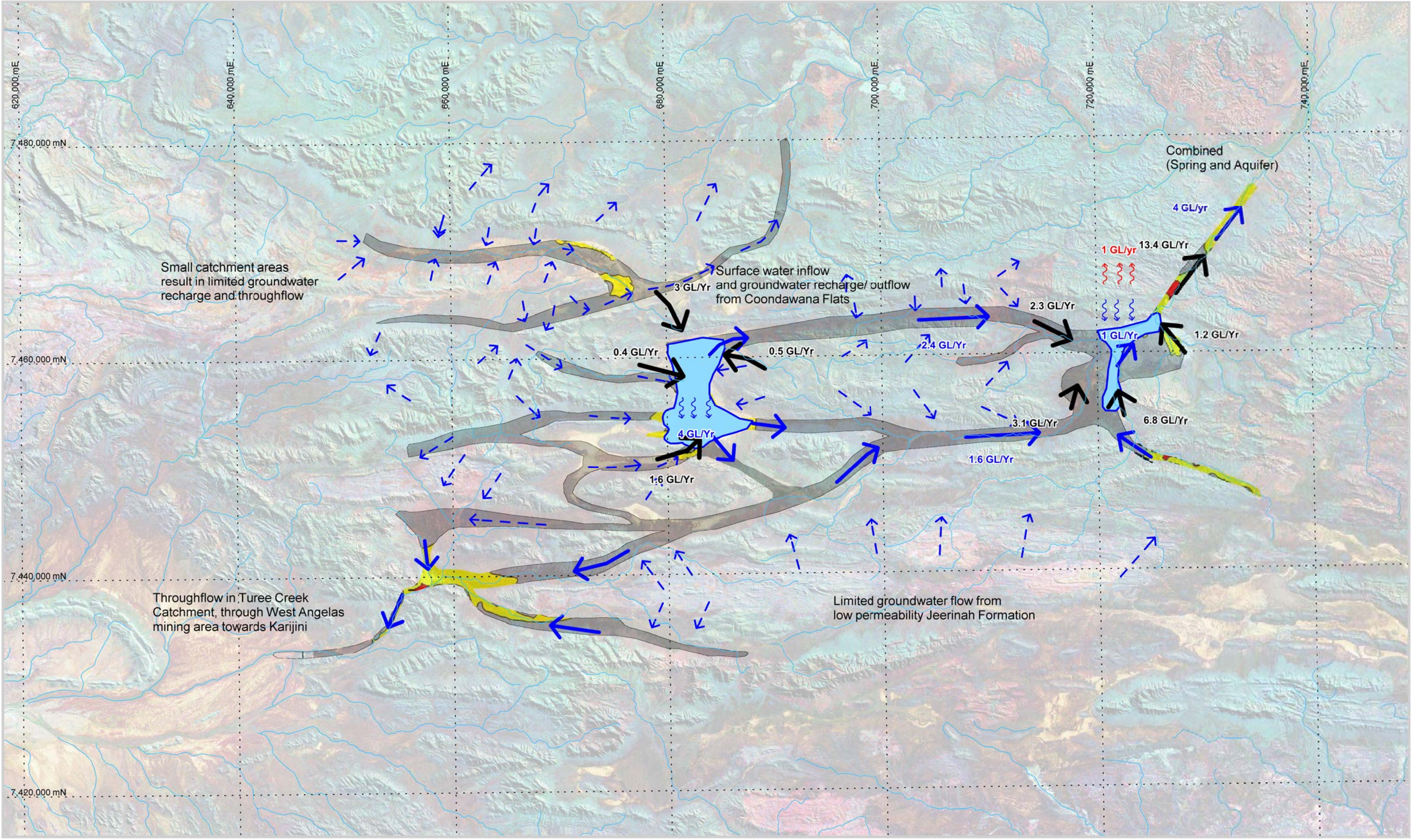


FIGURE 3.15

CONCEPTUAL HYDROGEOLOGY CENTRAL PILBARA REGION



LOCATION MAP

DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY

N

0 5 10

Kilometres

Scale: 1:325,000 @A3

GDA 1994 Zone 50

AUTHOR:	DS	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	28/06/2014	JOB NO:	1549B

Location: F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\020a\020a Figure 3.16

LEGEND

1.4 GL/Yr Major Groundwater (With Flux)

Minor Groundwater flow

0.4 GL/Yr Major Surface Water Flow (With Flux)

Groundwater Recharge Flux

Evapotranspiration Flux

Area of Groundwater/ Surface Water Interaction

DATA SOURCES:
Input data source here

Depth to Water

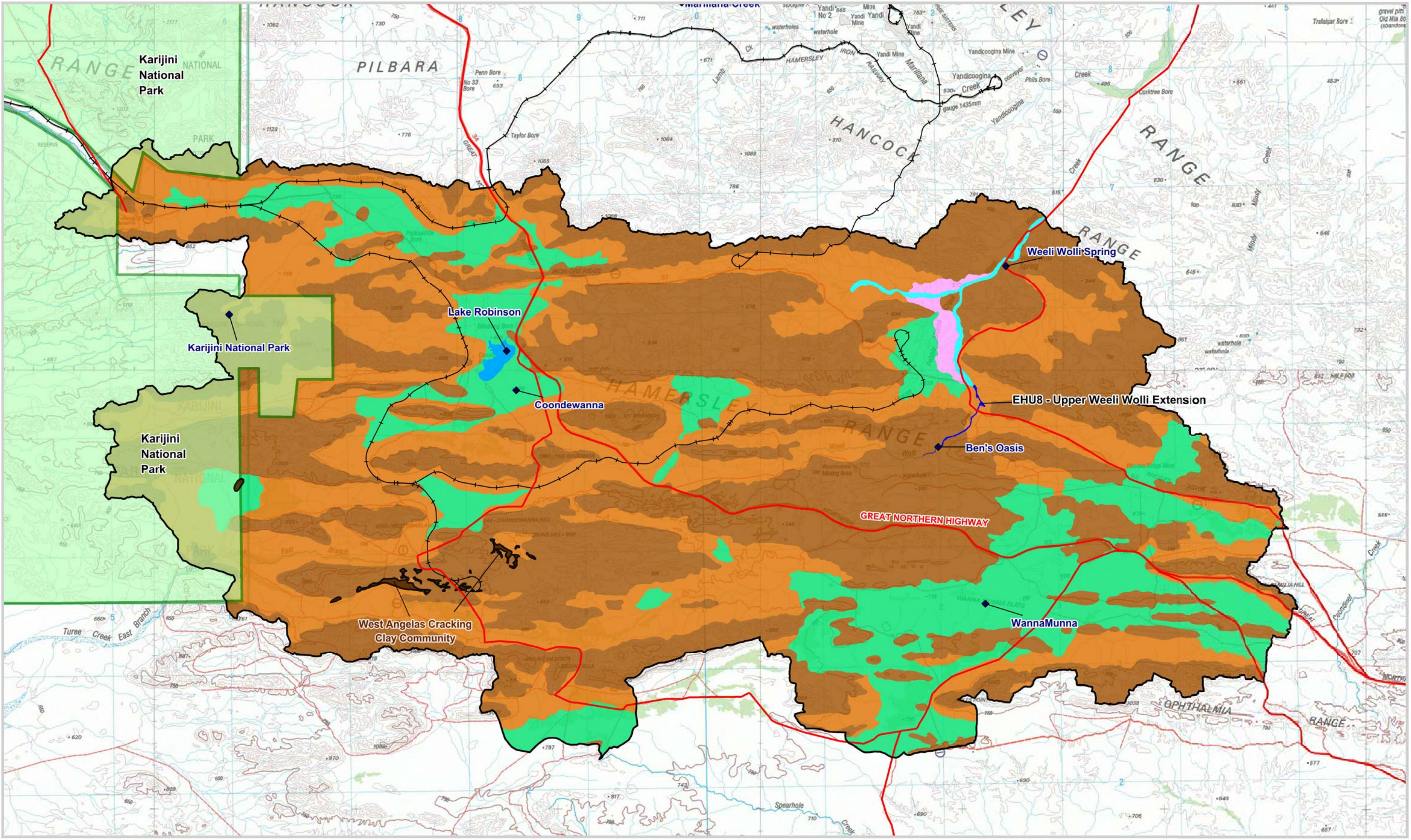
Main Aquifers

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

RPS

FIGURE 3.16

CENTRAL PILBARA REGION ECO-HYDROLOGICAL SYSTEM



LOCATION MAP

0 5 10

Kilometres

Scale: 1:300,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	17/10/2013	JOB NO:	1549B

Location: F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a Figure 4.1 - EHUs in the CPH Study Area

LEGEND

- Key Receptor
- Road
- Rail
- Cracking Clay Community
- CPR Study Area

DATA SOURCES:
BHPB Iron Ore

EHU's

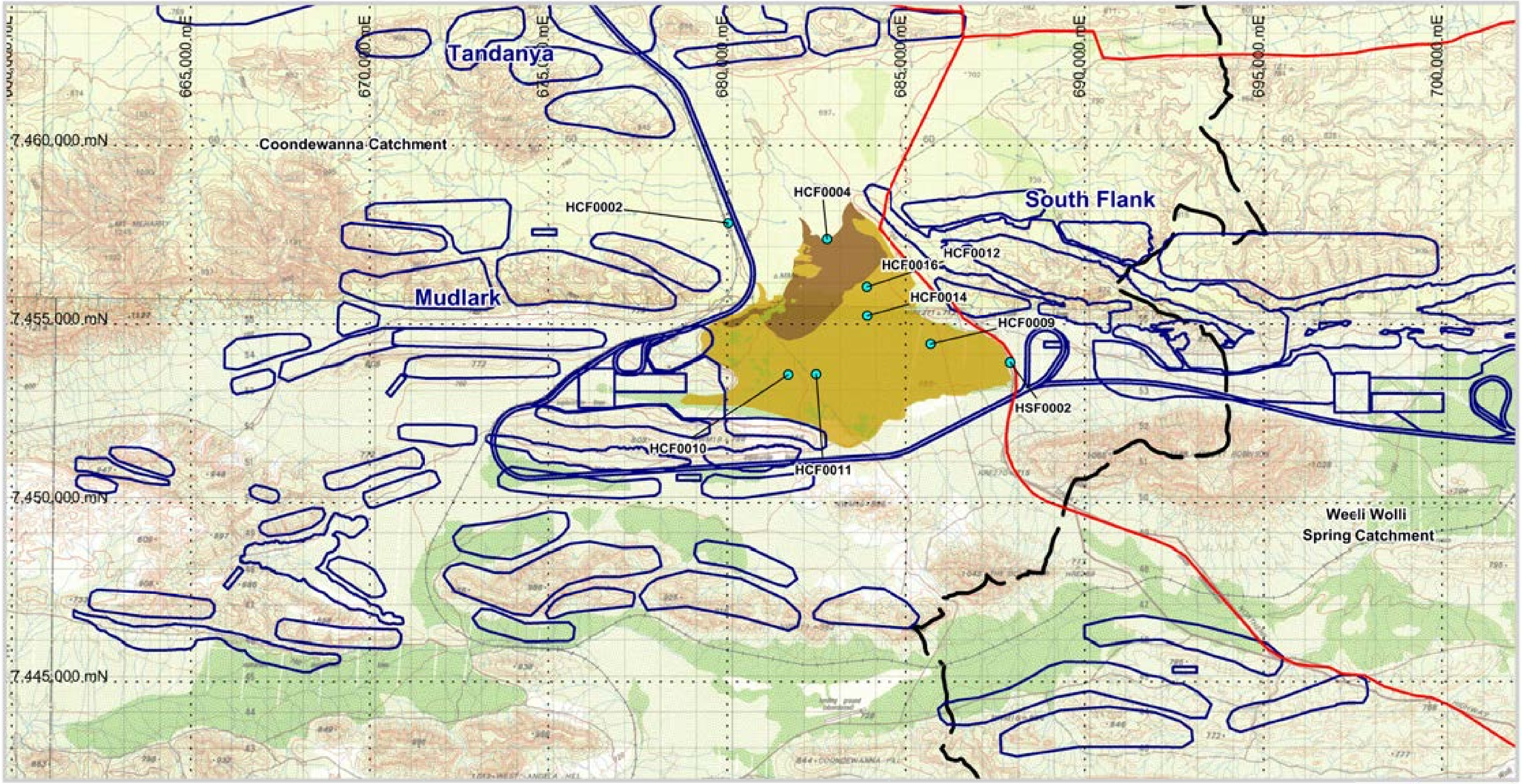
- EHU 1*
- EHU 2*
- EHU 6
- EHU 7
- EHU 8
- EHU 8 (Extension)
- EHU 9 (Lake Robinson)

(* EHU's 3 and 4 occur within EHU's 1 and 2)

RPS

FIGURE 4.1

SPATIAL DISTRIBUTION OF EHUS IN THE CPR STUDY AREA (INCLUDING LOCATIONS OF KEY ECOHYDROLOGICAL RECEPTORS)



N

0 4 8

Kilometres

Scale: 1:180,000 @A4

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

F:\Jobs\1549F\Spatial_Data\Mapinfo\Workspaces\Coondewanna\020a Figure 4.2 Coondewanna Flats Mining Area Loc

LEGEND

- Key Bore
- Road
- Rail
- Catchment Boundary
- Indicative BHP Billiton Iron Ore Disturbance

Coondewanna Vegetation

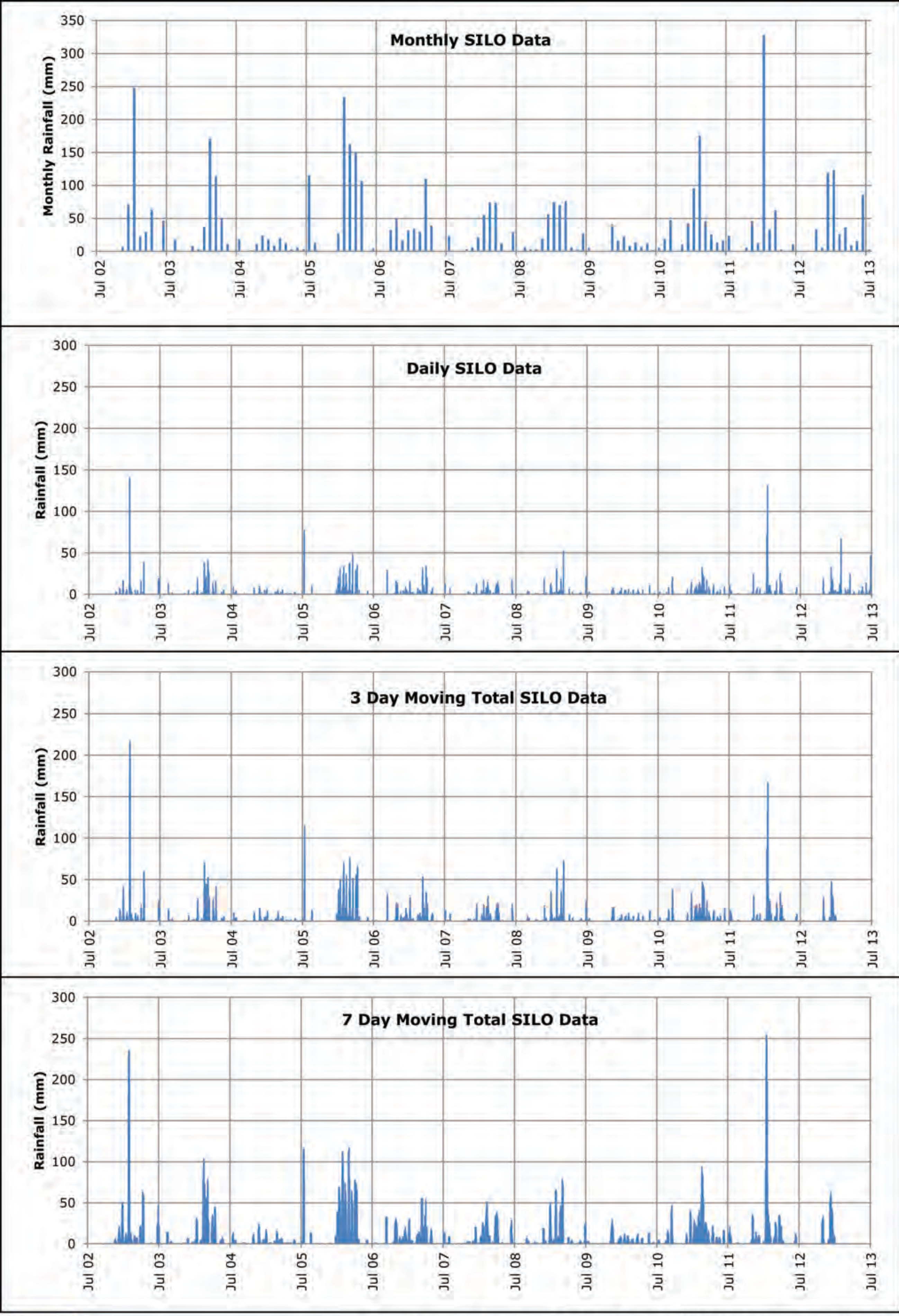
- Coolibah Lignum Thickets
- Lake Robinson
- Mulga Woodlands Sparse Lignum

DATA SOURCES:
BHPB Iron Ore

RPS

Figure 4.2

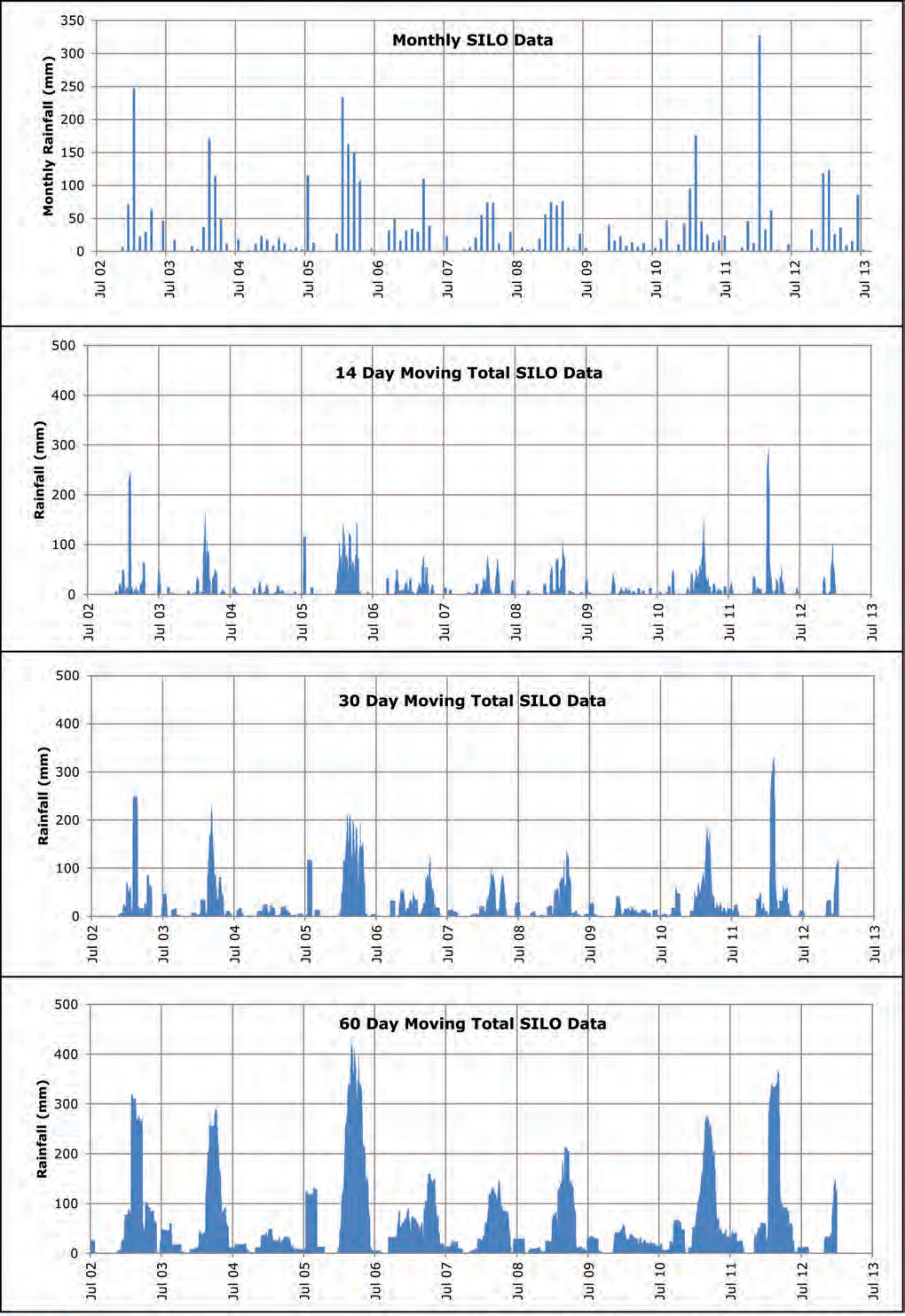
LOCATION PLAN COONDEWANNA FLATS



RPS

Coondewanna Catchment Rainfall Totals 2002 - 2013 Sheet 1 FIGURE 4.3

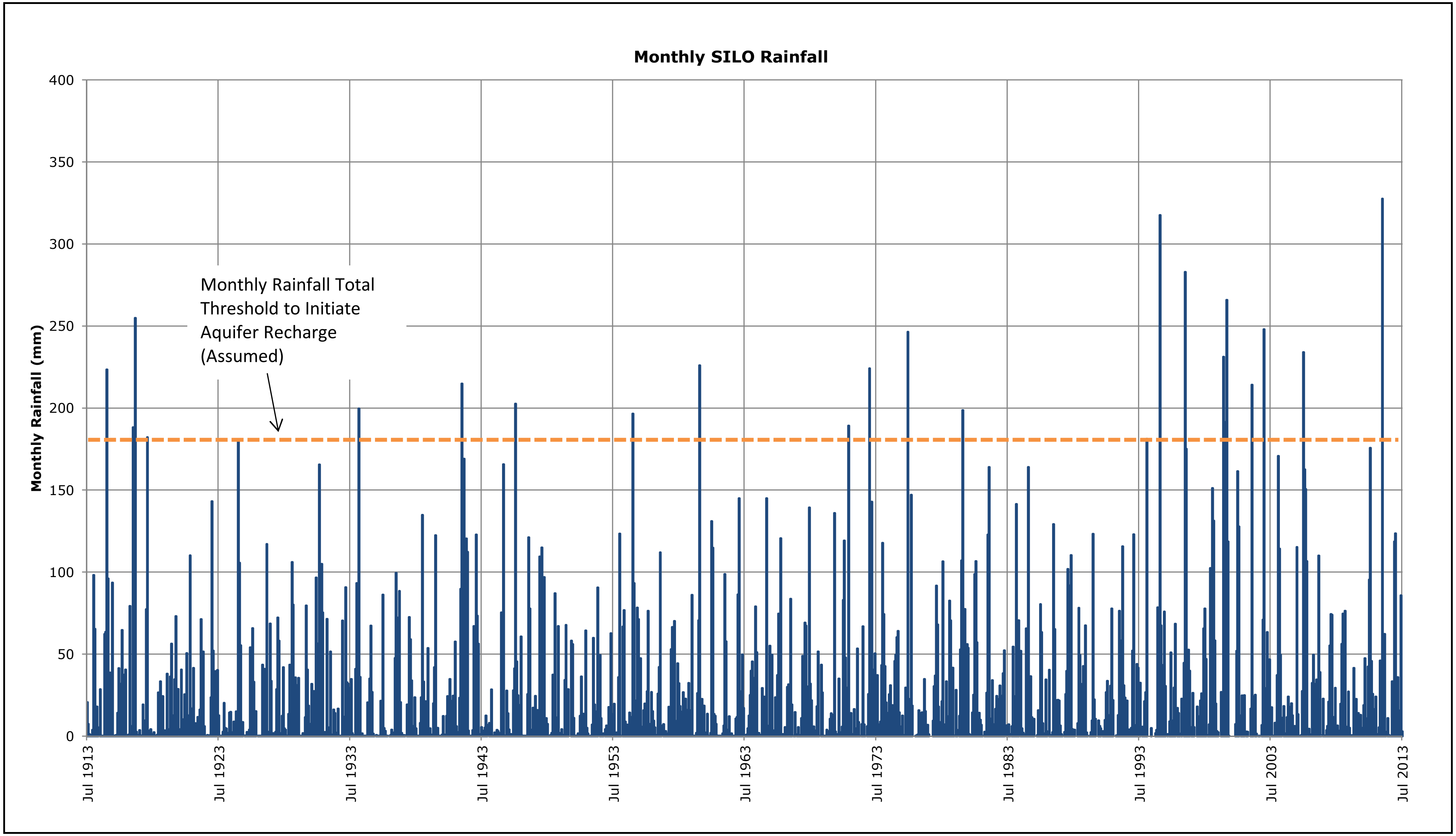
F:\Jobs\1549C\300\Rain and Streamflow Data\[SILO Data - Coond Flats Catchment Centroid.xls]020 Fig 4.3



RPS

Coondewanna Catchment Rainfall Totals 2002 - 2013 Sheet 2 FIGURE 4.4

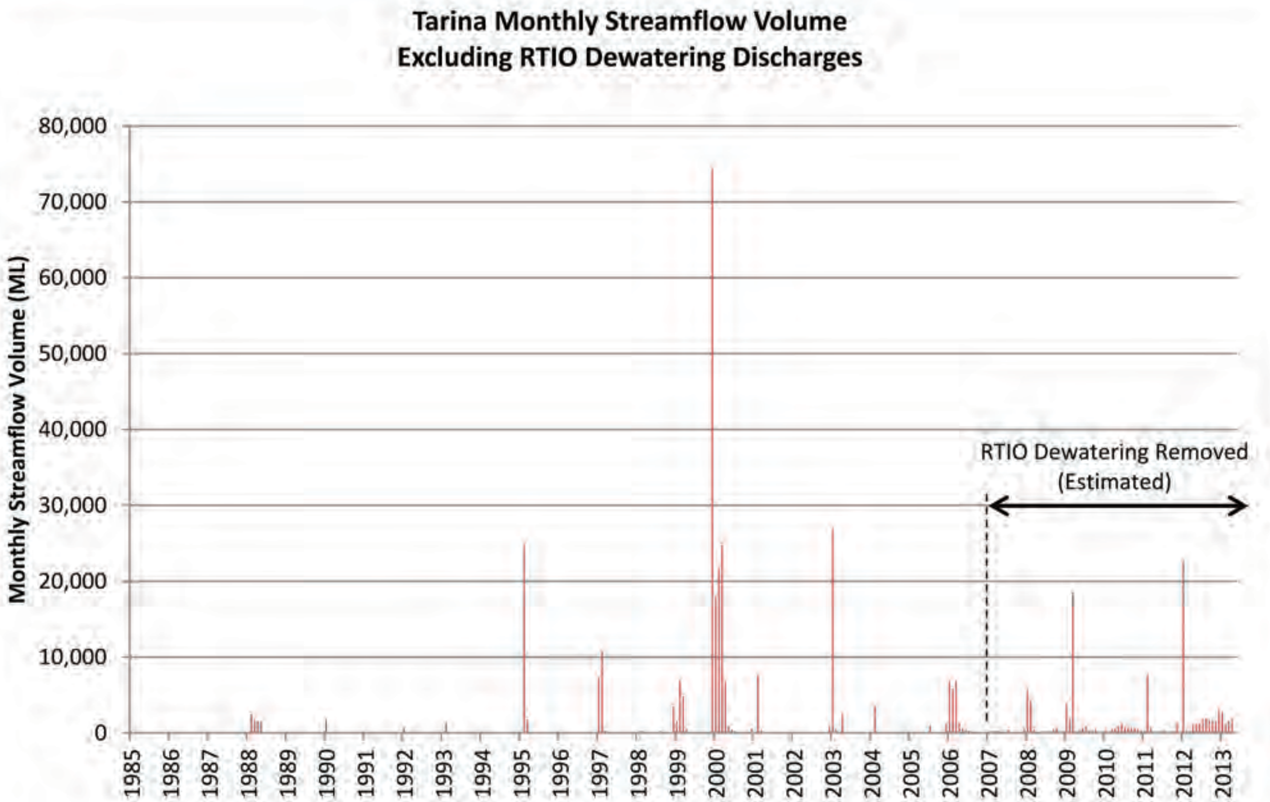
F:\Jobs\1549C\300\Rain and Streamflow Data\[SILO Data - Coond Flats Catchment Centroid.xls]020 Fig 4.4

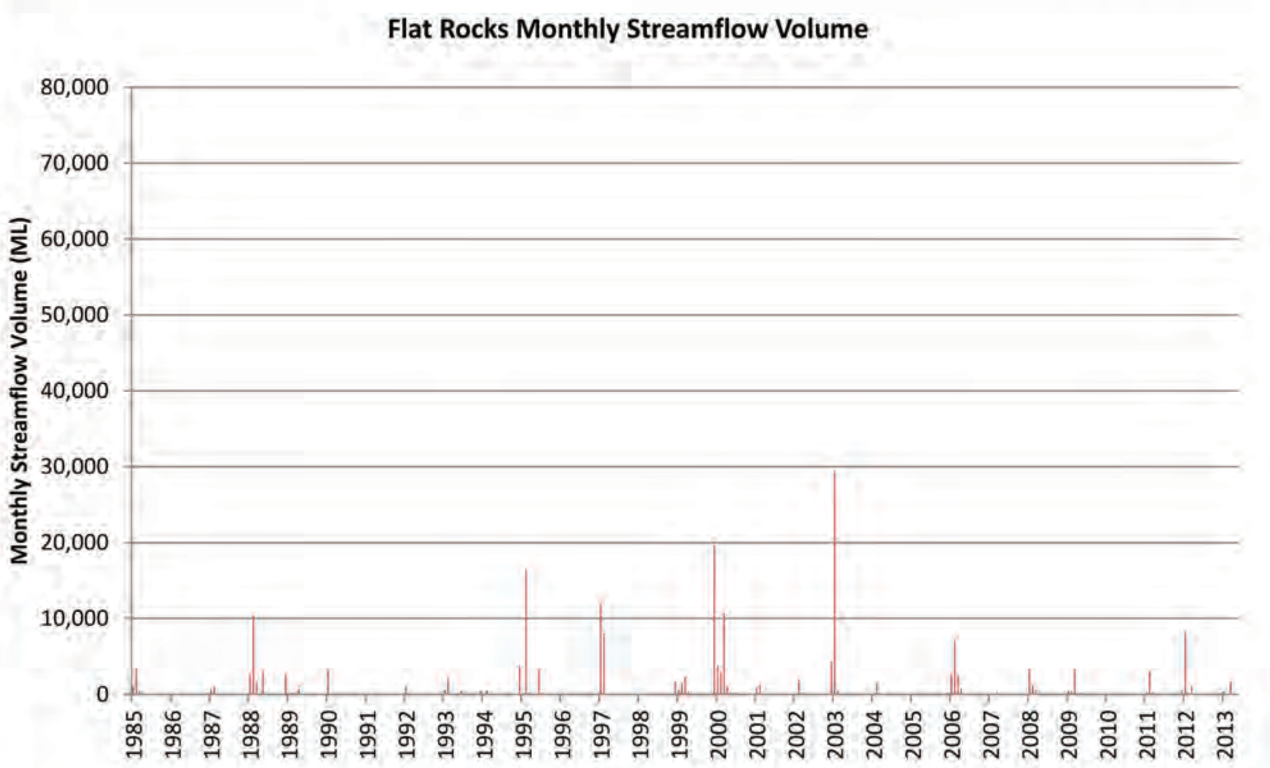


RPS

Coondewanna Catchment Monthly Rainfall 1900 - 2013 FIGURE 4.5

F:\Jobs\1549C\300\Rain and Streamflow Data\[SILO Data - Coond Flats Catchment Centroid.xls]020 Fig 4.5

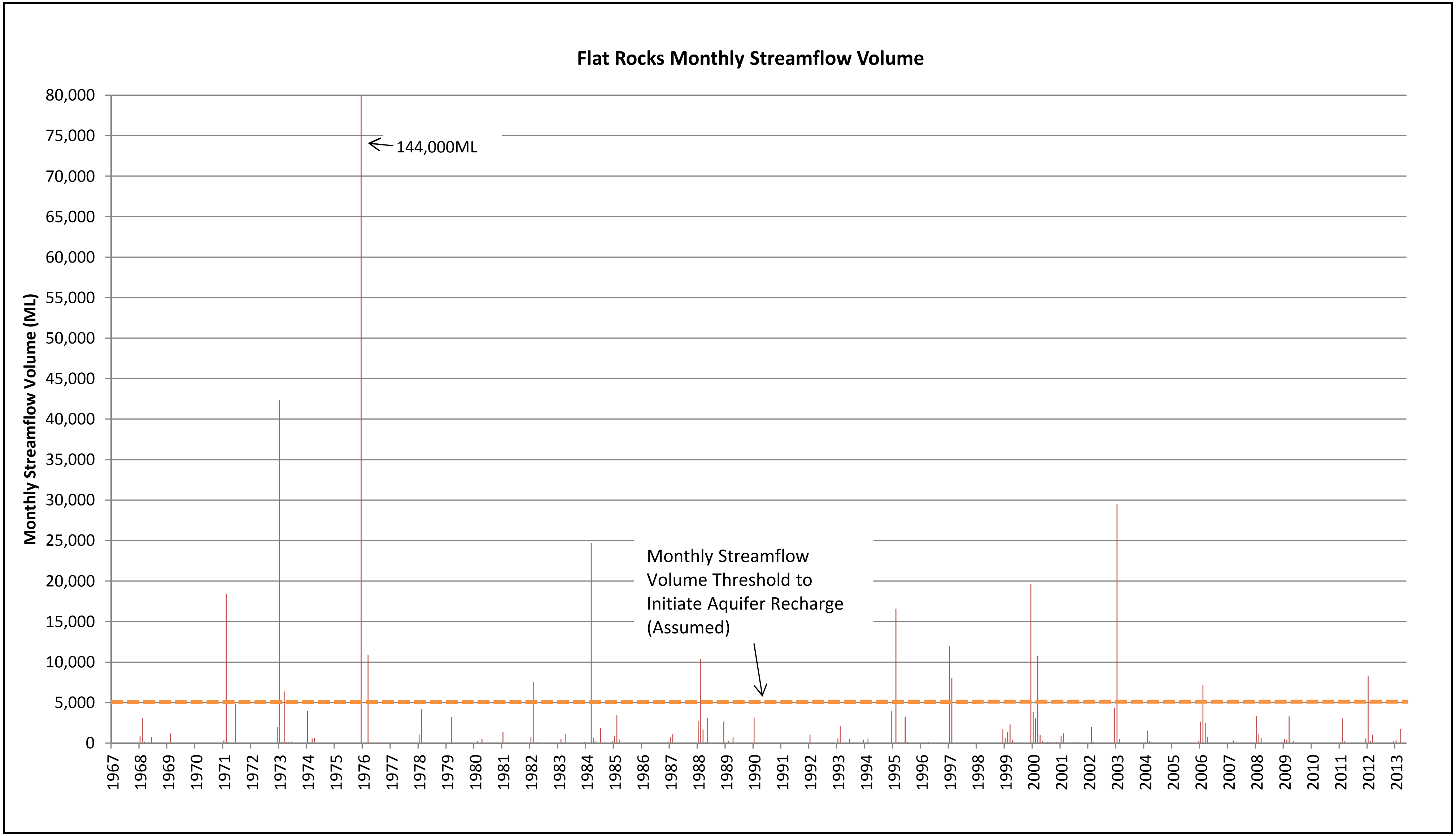




RPS

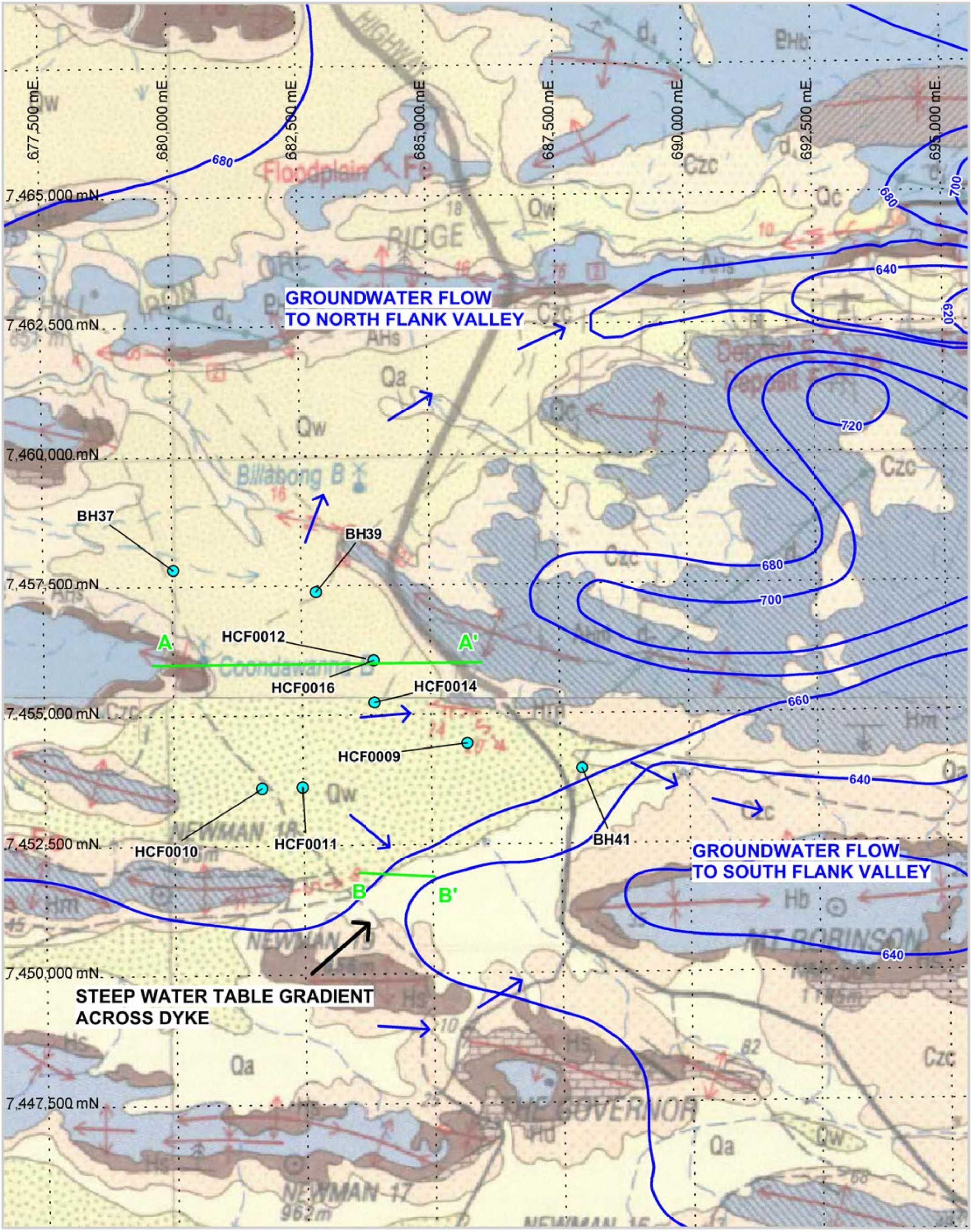
Tarina and Flat Rocks Monthly Runoff 1985 - 2013 FIGURE 4.6

F:\Jobs\1549C\300\Rain and Streamflow Data\[Flat Rocks Streamflow.xlsx]020a Fig 4.6



Flat Rocks Monthly Runoff 1967 - 2013 FIGURE 4.7

F:\Jobs\1549C\300\Rain and Streamflow Data\[Flat Rocks Streamflow.xlsx]020a Fig 4.7



N

0 1.5 3

Kilometers

Scale: 1:100,000 @A4

GDA 1994 Zone 50

AUTHOR:	DVB	REPORT NO:	275
DRAWN:	LP	REVISION:	c
DATE:	13/10/2014	JOB NO:	1549B

LEGEND

- Key Bores
- Cross Sections Lines
- Dolerite Dyke
- 645 Regional Water Level Contour
- Direction of Flow

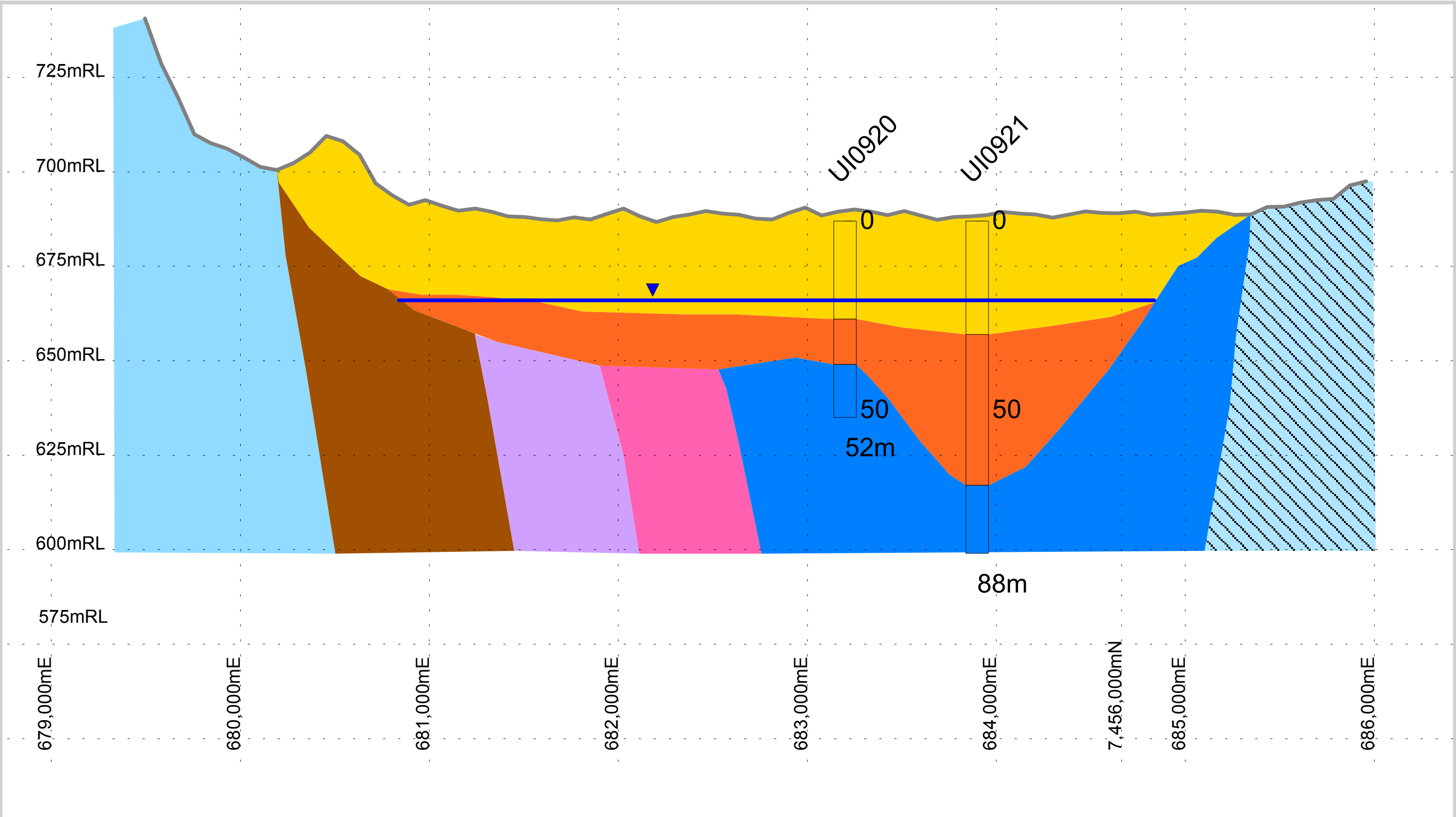
DATA SOURCES:
Input data source here

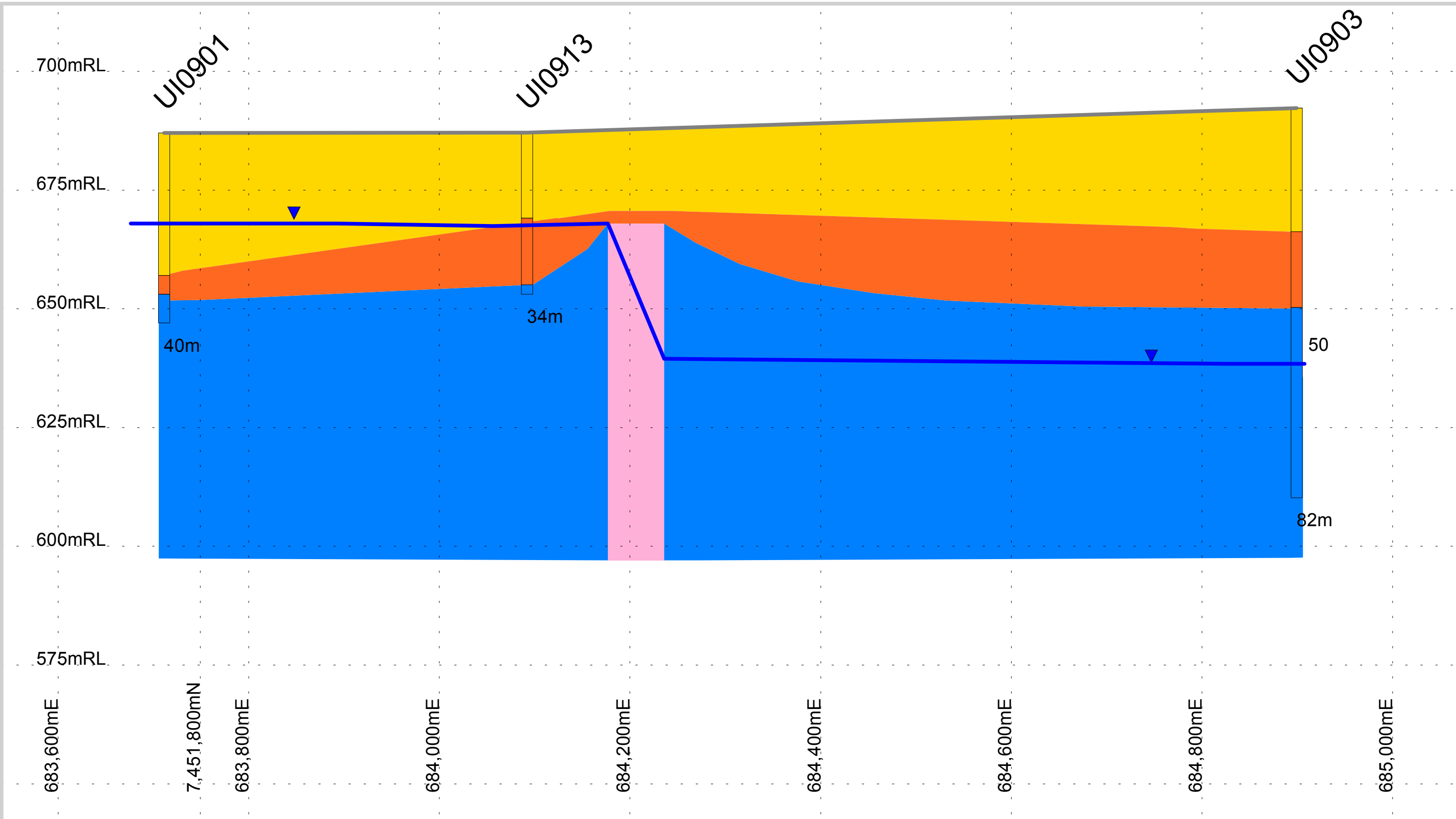
RPS

FIGURE 4.8

GEOLOGY AND HYDROGEOLOGY COONDEWANNA FLATS

Location: F:Jobs\1549B\Spatial_Data\MapInfo\Workspaces\020a\Coondewanna\020a Figure 4.8 Geology and Hydrogeology - Coopondewanna Flats.wor





LEGEND

- TD3
- TD2
- West Angela Shale
- Brockman Iron Formation
- Mt. Sylvia/ Mt. McRae
- Bee Gorge
- Paraburdoo
- Marra Mamba Iron Formation
- Dolerite

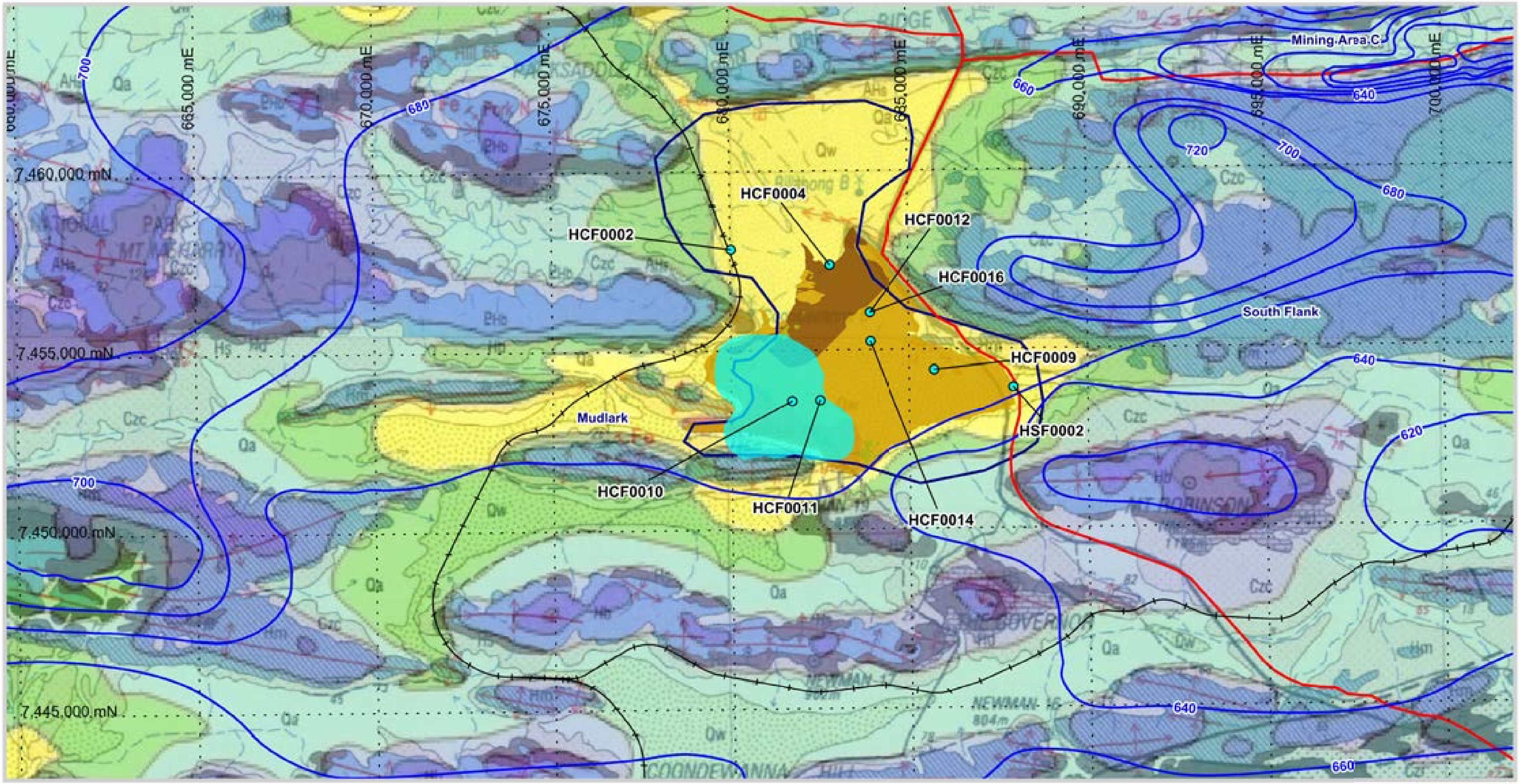
AUTHOR:	DVB	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	04/07/2013	JOB NO:	1549B

DATA SOURCES:
Input data source here

RPS

FIGURE 4.9
CONCEPTUAL CROSS SECTIONS
COONDEWANNA FLATS

Location: F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\020a\Coondewanna\020a Figure 4.9 Conceptual Cross Sections.wor



0 5 10
Kilometres
Scale: 1:150,000 @A4
GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a\Coondewanna\020a Figure 4.10 Coondewanna Flats Mining Area Loc

LEGEND

- Key Bore
- Road
- Rail
- Recharge Location
- Recharge Mound

Coondewanna Vegetation

- Coolibah Lignum Thickets
- Lake Robinson
- Mulga Woodlands Sparse Lignum

DATA SOURCES:
BHPB Iron Ore

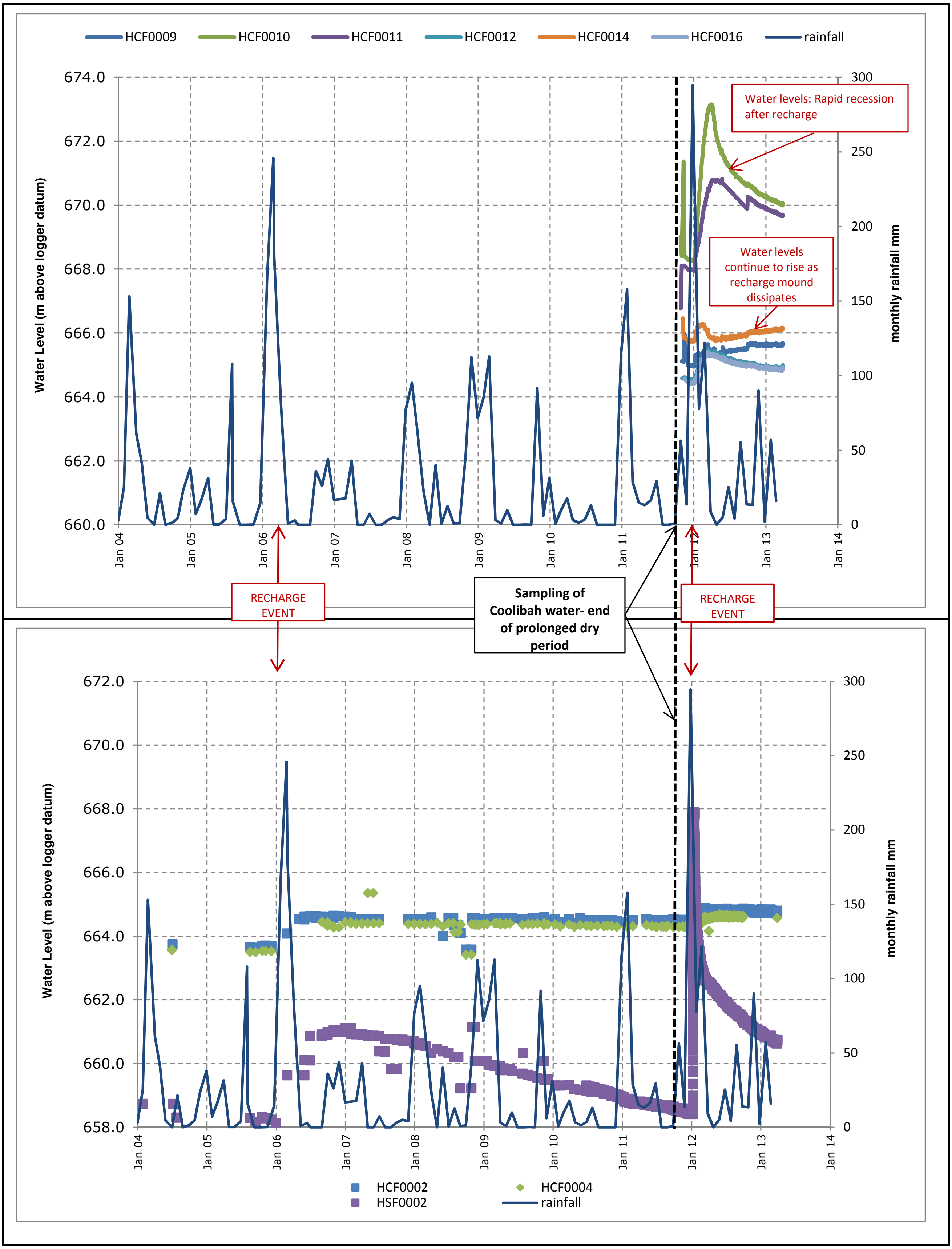
Depth to Water (m)

500
300
200
100
60
40
20

RPS

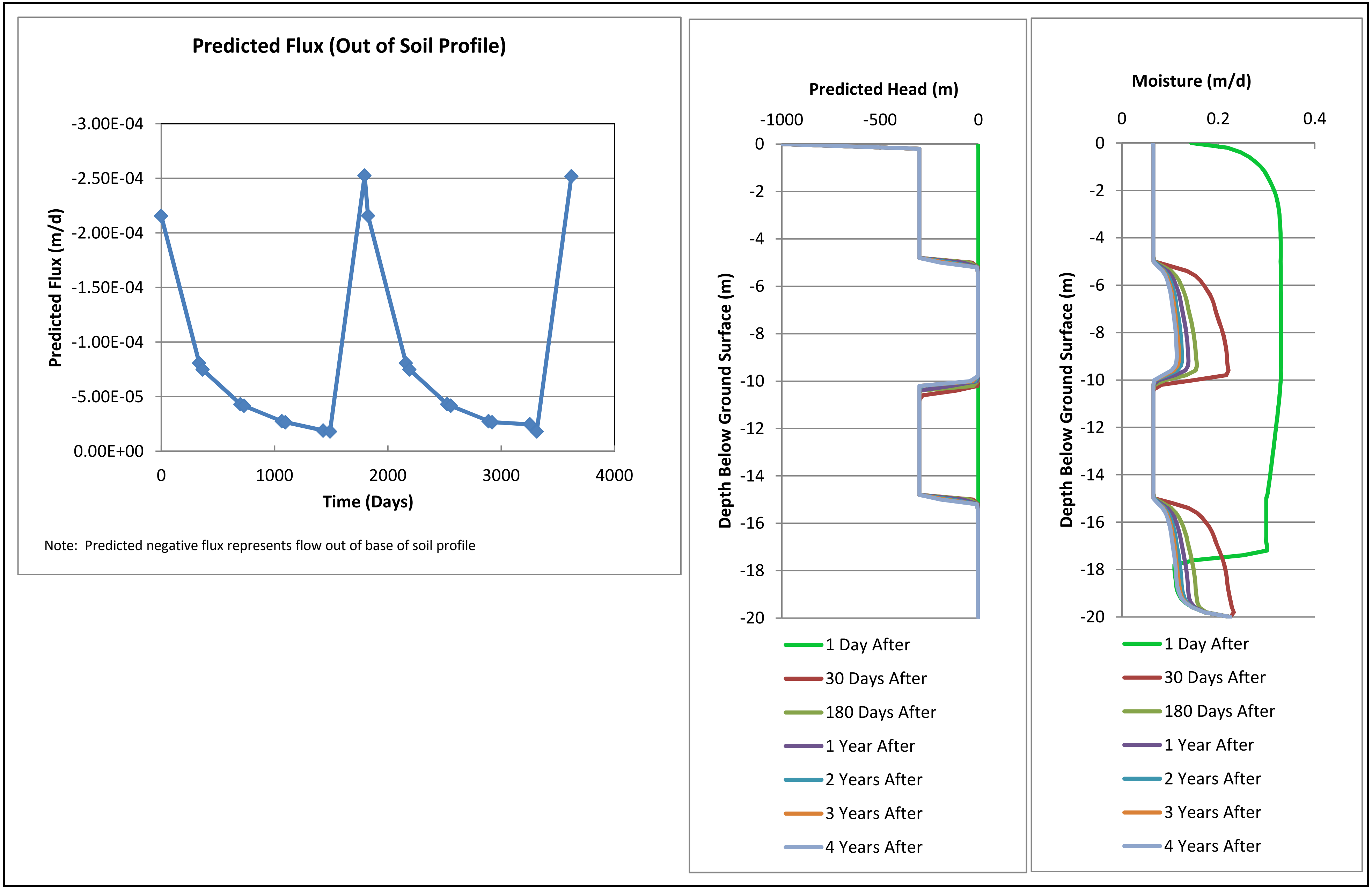
Figure 4.10

GROUNDWATER CONTOURS AND DEPTH TO WATER



GROUNDWATER HYDROGRAPHS - COONDEWANNA FLATS FIGURE 4.11

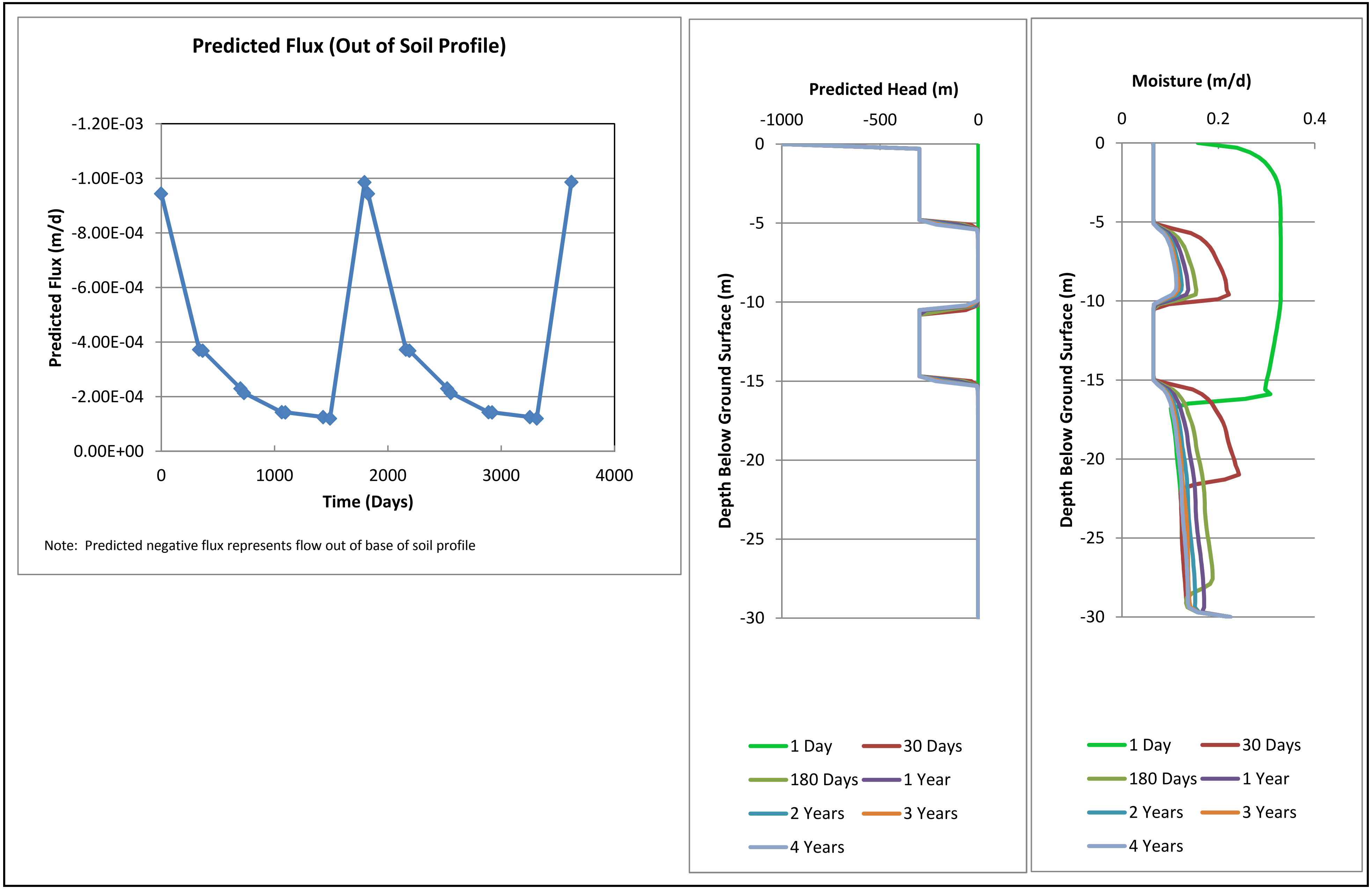
F:\Jobs\1549B\300\Receptors\Coondewanna Flats\[0154a charts HCF0009-16 BH37-39-39.xlsx]2graphs



RPS

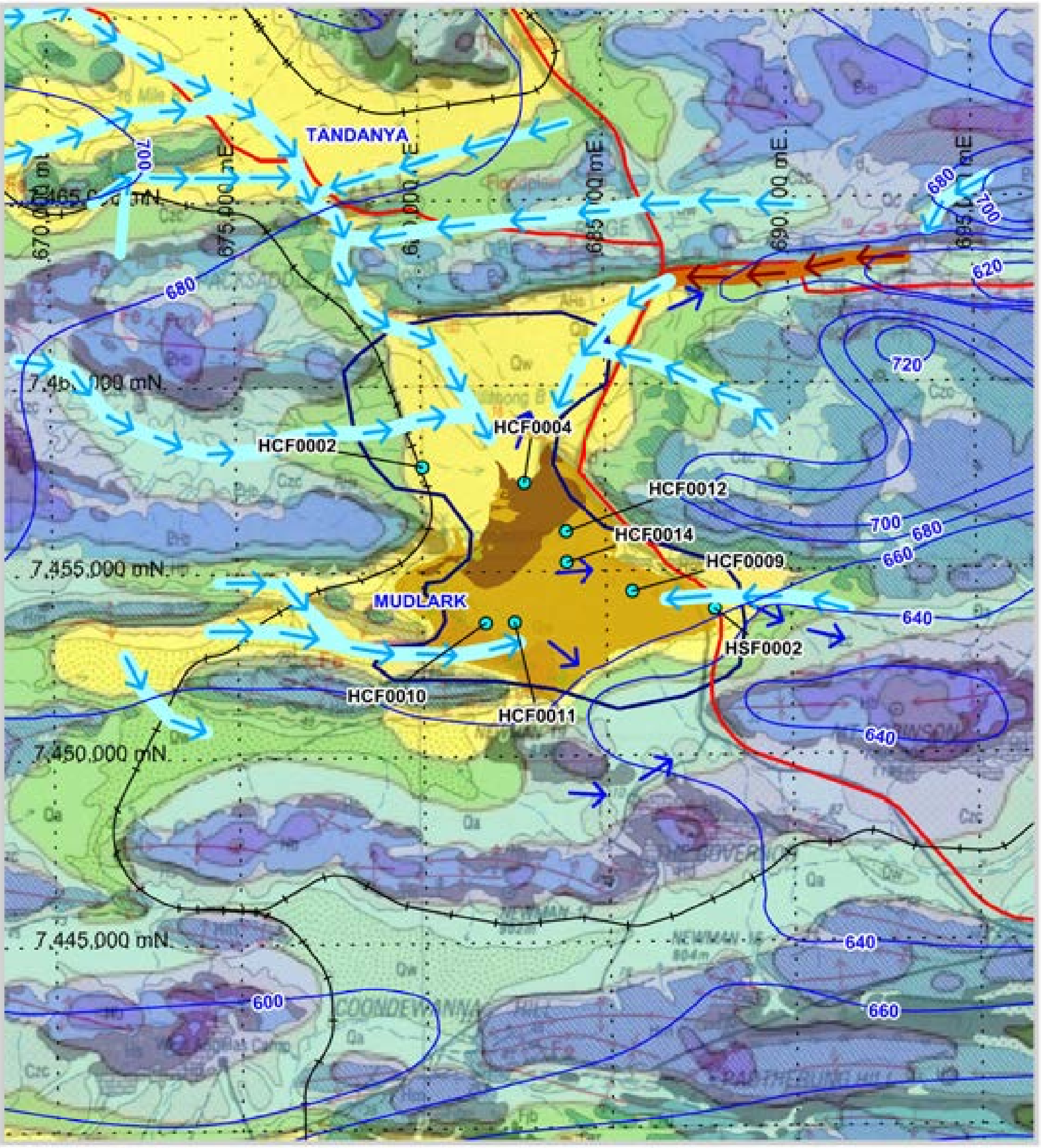
20m PROFILE FIGURE 4.12a

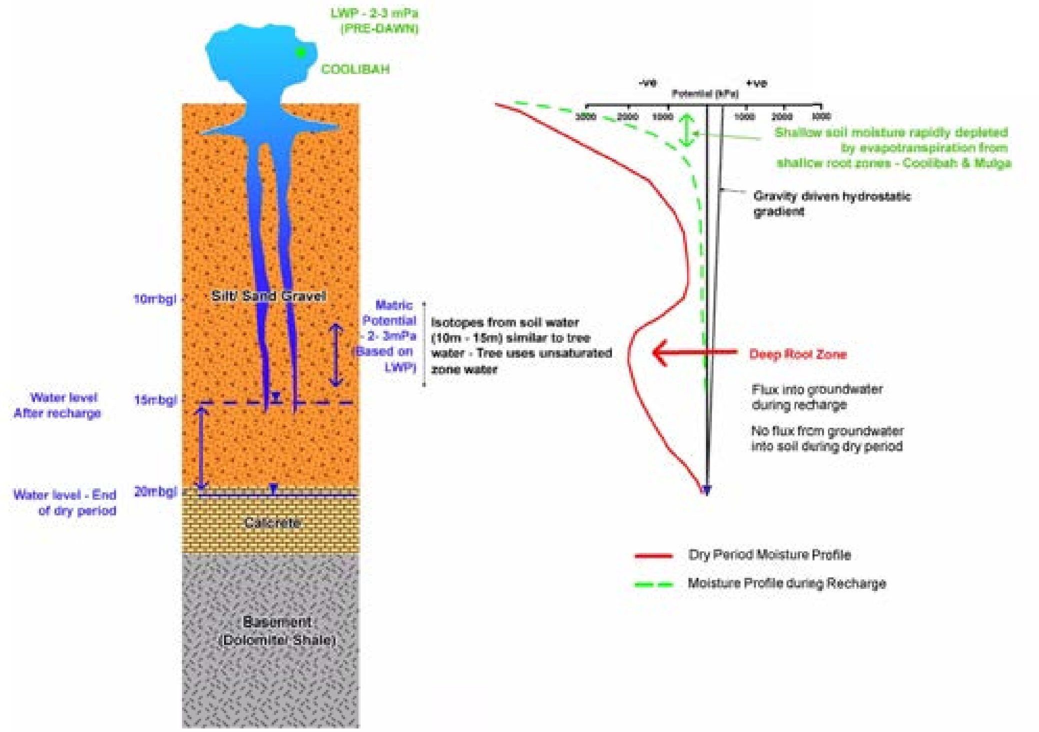
F:\Jobs\1549B\300\Mudlark Well\Hydrus\hydrus modelling\[final results.xlsx]20m chart



30m PROFILE FIGURE 4.12b

F:\Jobs\1549B\300\Mudlark Well\Hydrus\hydrus modelling\[final results.xlsx]30m chart





LOCATION MAP

N

0 4 8

Kilometres

Scale: 1:200,000 @A4

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a Figure 4.12 Coondewanna Flats Mining Area Loc

LEGEND

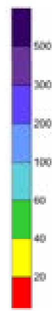
- Key Bore
- Road
- Rail
- Water Level Contour(m)
- Regional Recharge Zone
- Groundwater Flow
- Surface Water Flow
- Existing Surface Water Diversion

DATA SOURCES:
BHPB Iron Ore

Coondewanna Vegetation

- Coolibah Lignum Thickets
- Lake Robinson
- Mulga Woodlands Sparse Lignum

Depth to Water (m)

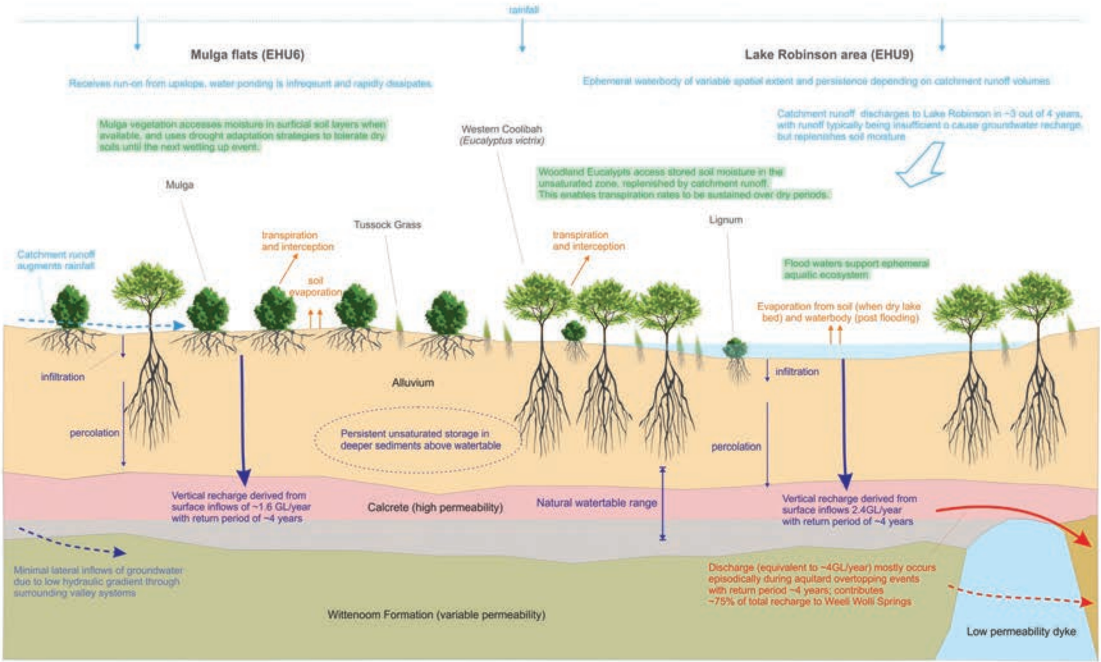


RPS

Figure 4.13

GROUNDWATER AND SURFACE WATER INTERACTION

Coondewanna Flats conceptual ecohydrological model



LOCATION MAP

Not to Scale

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	08/11/2013	JOB NO:	1549B

LEGEND

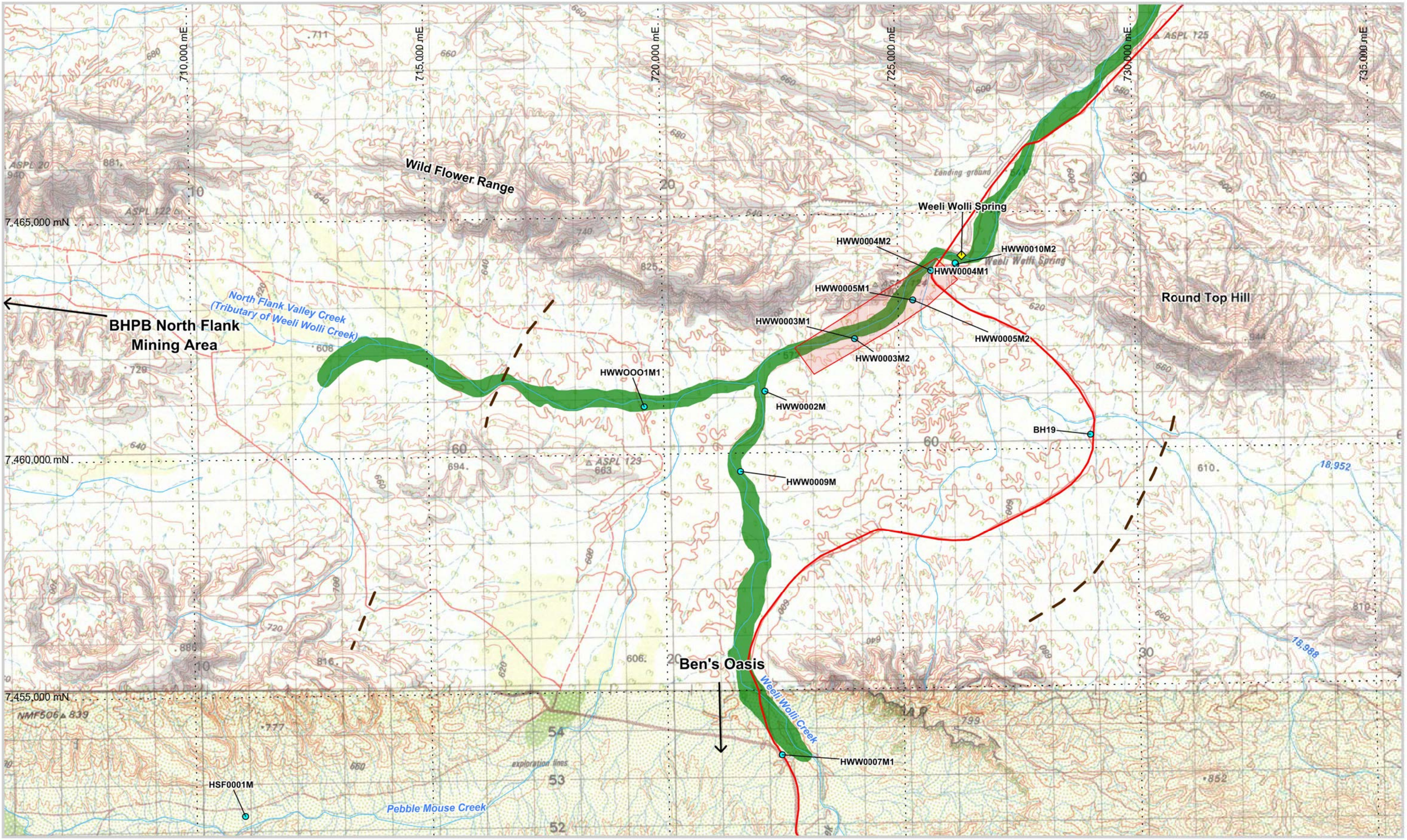
DATA SOURCES:
BHPB Iron Ore

RPS

Figure 4.14

ECO-CONCEPTUAL MODEL

F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a\Coondewanna\020a Figure 4.14 Eco Conceptual Model



N

0 1 2

kilometres

Scale: 1:50,000 @A3

GDA 1994 Zone 50

AUTHOR:	PR	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	13/10/2014	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\129a\Weeli Wolli\020a Fig 4.15 location map.WOR

LEGEND

- Key Bore
- Receptor
- Appoximate Extent of Main Calcrete Aquifer (Key Stygofauna Habitat)
- Important Vegetation Community
- Area of Hope Downs Dewatering Discharge

DATA SOURCES:
Input data source here

RPS

FIGURE 4.15

LOCATION PLAN
WEELI WOLLI SPRING

N

0 1 2

kilometres

Scale: 1:50,000 @A3

GDA 1994 Zone 50

AUTHOR:	PR	REPORT NO:	75
DRAWN:	MR	REVISION:	C
DATE:		JOB NO:	1606B

F:\Jobs\1549\Spatial_Data\MapInfo\Workspaces\129a\Weeli Wolli\020a Fig 5.2 location map.WOR

LEGEND

Key Bore

Receptor

Appoximate Extent of Main Calcrete Aquifer (Key Stygofauna Habitat)

Important Vegetation Community

Area of Hope Downs Dewatering Discharge

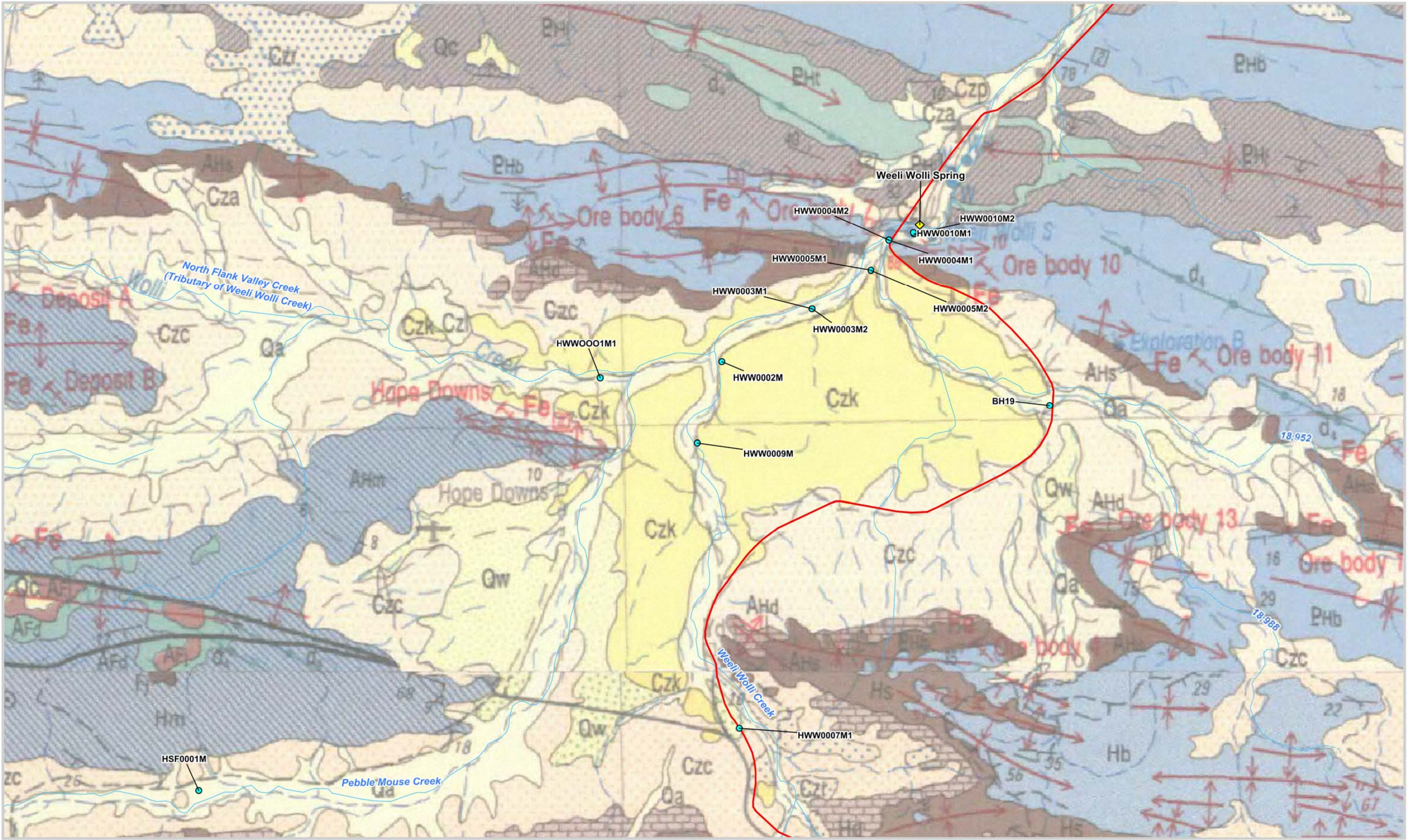
Extent of Surface Water Pools

DATA SOURCES:
Input data source here

RPS

FIGURE 4.16

LOCATION PLAN
BEN'S OASIS



N

0 2.5

kilometres

Scale: 1:75,000 @A3

GDA 1994 Zone 50

AUTHOR:	PR	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	03/02/2014	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\020a\Weeli Wolli\020a Fig 5.3 Bedrock Outcrop.WOR

LEGEND

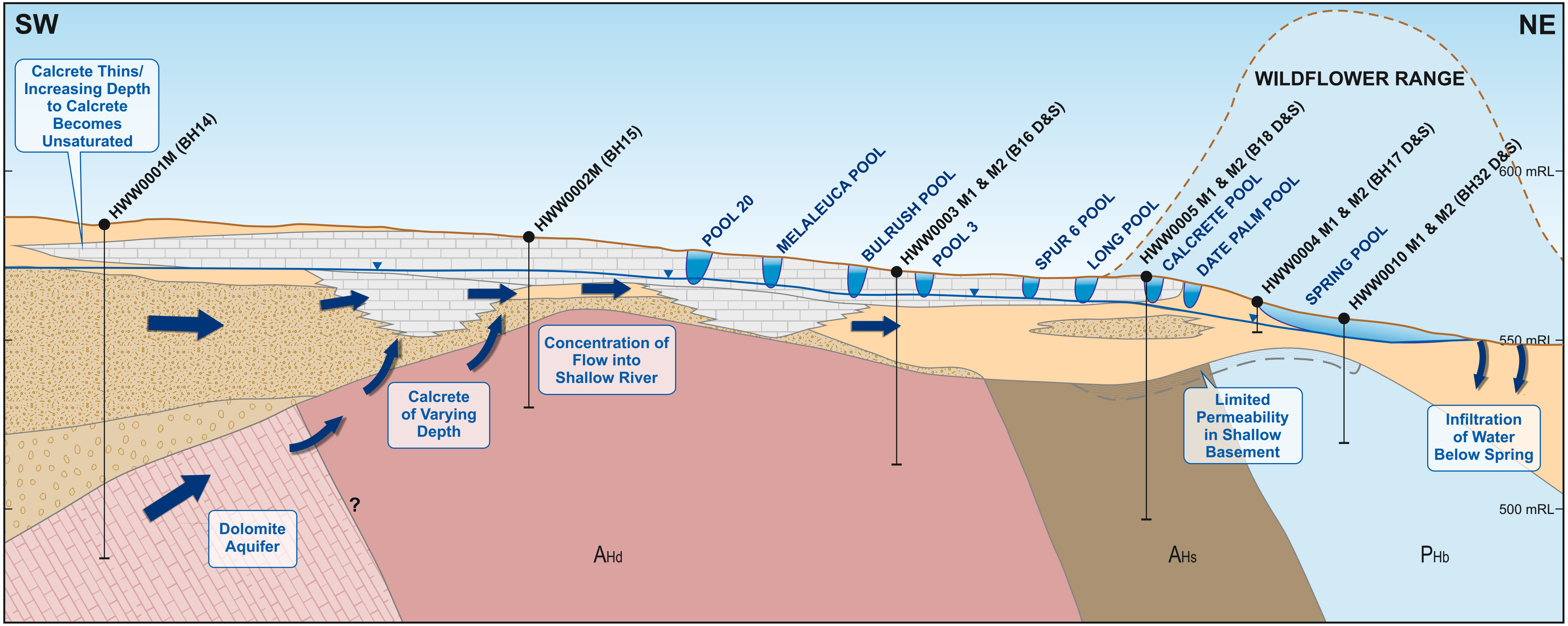
Key Bore

Receptor

DATA SOURCES:
Input data source here

FIGURE 4.17

OUTCROP GEOLOGY
WEELI WOLLI



Location: XXXX

0 0.5 1
Kilometres

AUTHOR:	...	REPORT NO:	...
DRAWN:	PICTOGRAPH	REVISION:	...
DATE:	...	JOB NO:	...

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
- 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 Mount Newman Member

Jeerinah Fm
- AFj

Granitoid Complex
- Ag
- Ore

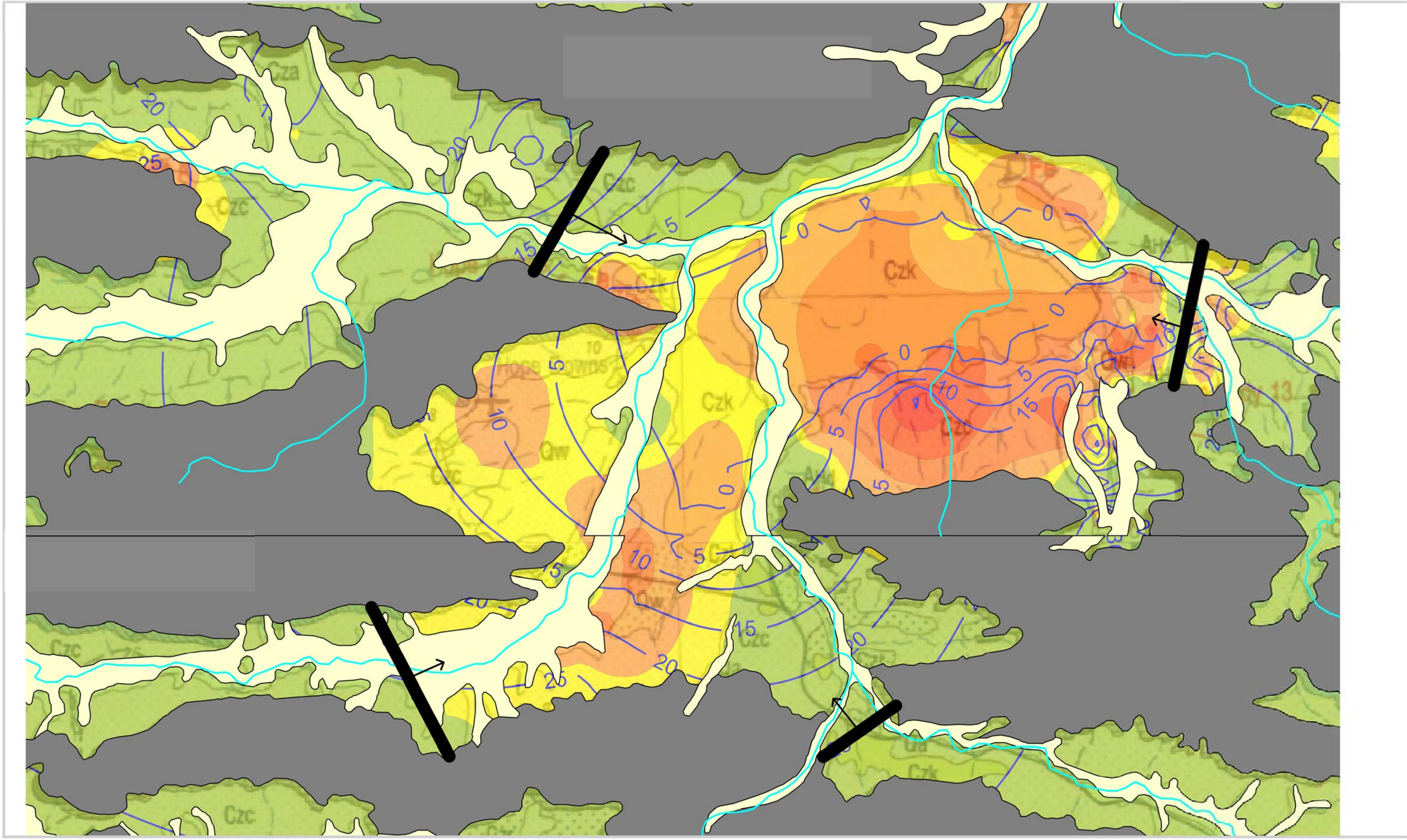
- Surface Water Pool (elevation approximate)
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 4.18

CROSS SECTION WEELI WOLLI SPRING MINING AREA

DATA SOURCES:
Input data source here



N
0 10
Kilometres
Scale: 1:75000@A3
GDA 1994 Zone 50

AUTHOR:	PR	REPORT NO:	275
DRAWN:	PR	REVISION:	c
DATE:	18/11/2013	JOB NO:	1549b

\\rpsperfs02\at1\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\020a\Weeli Wolli\020a Figure 4.19 - Calcrete thickness map.wor

LEGEND

10 Depth to top of Calcrete (mbgl)

River/ Stream

Bedrock outcrop

Alluvium Filled Channel

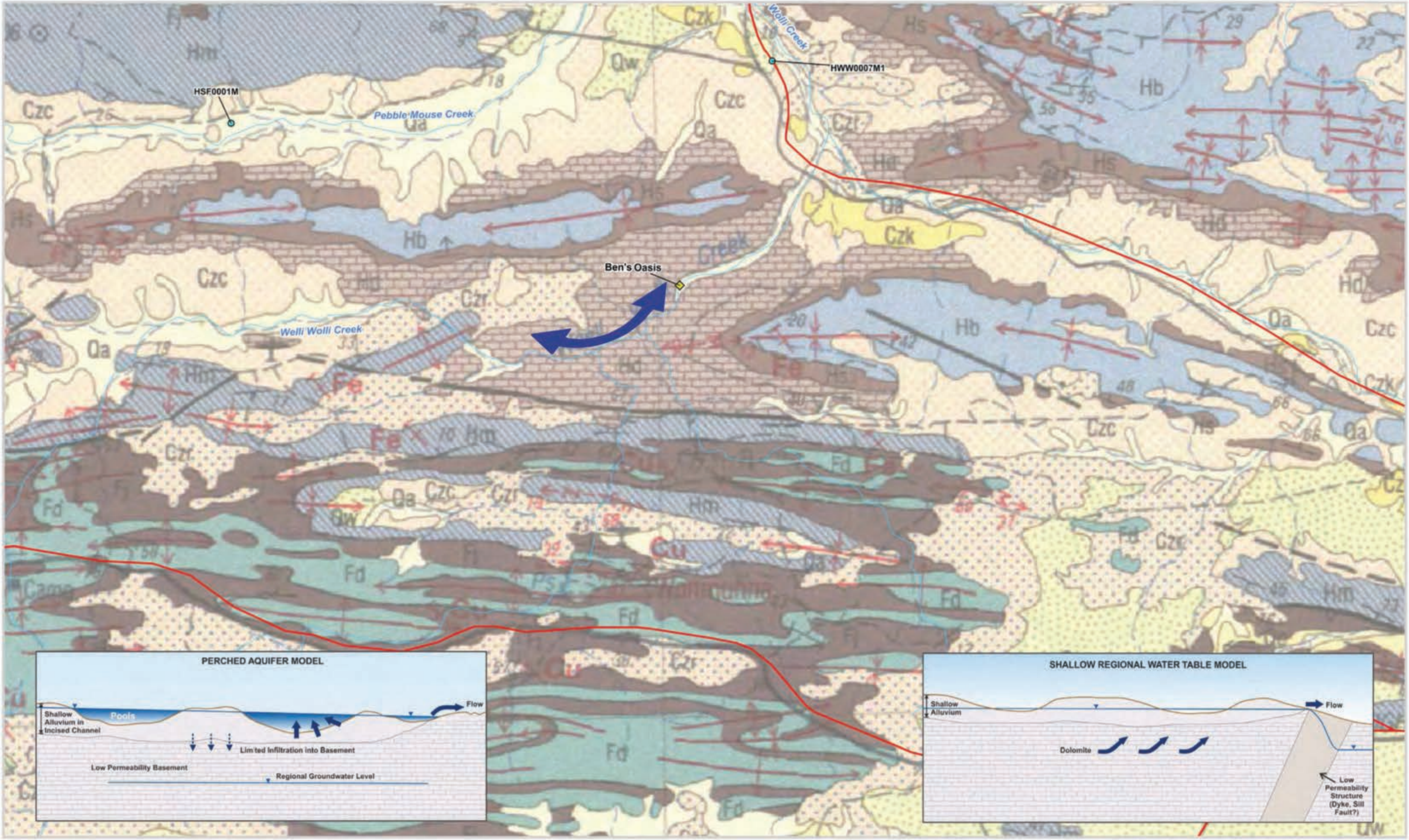
Unsaturated
Saturated
Extent of Saturated Calcrete

40
30
20
10
5
Calcreter thickness contours (m)

RPS

FIGURE 4.19

CALCRETE THICKNESS AND DEPTH



0 1 2

kilometres

Scale: 1:50,000 @A3

GDA 1994 Zone 50

AUTHOR:	PR	REPORT NO:	275
DRAWN:	MR	REVISION:	C
DATE:	23/06/2014	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\020a\Weeli Wolli\020a Fig 5.6 Bedrock Outcrop.WOR

LEGEND

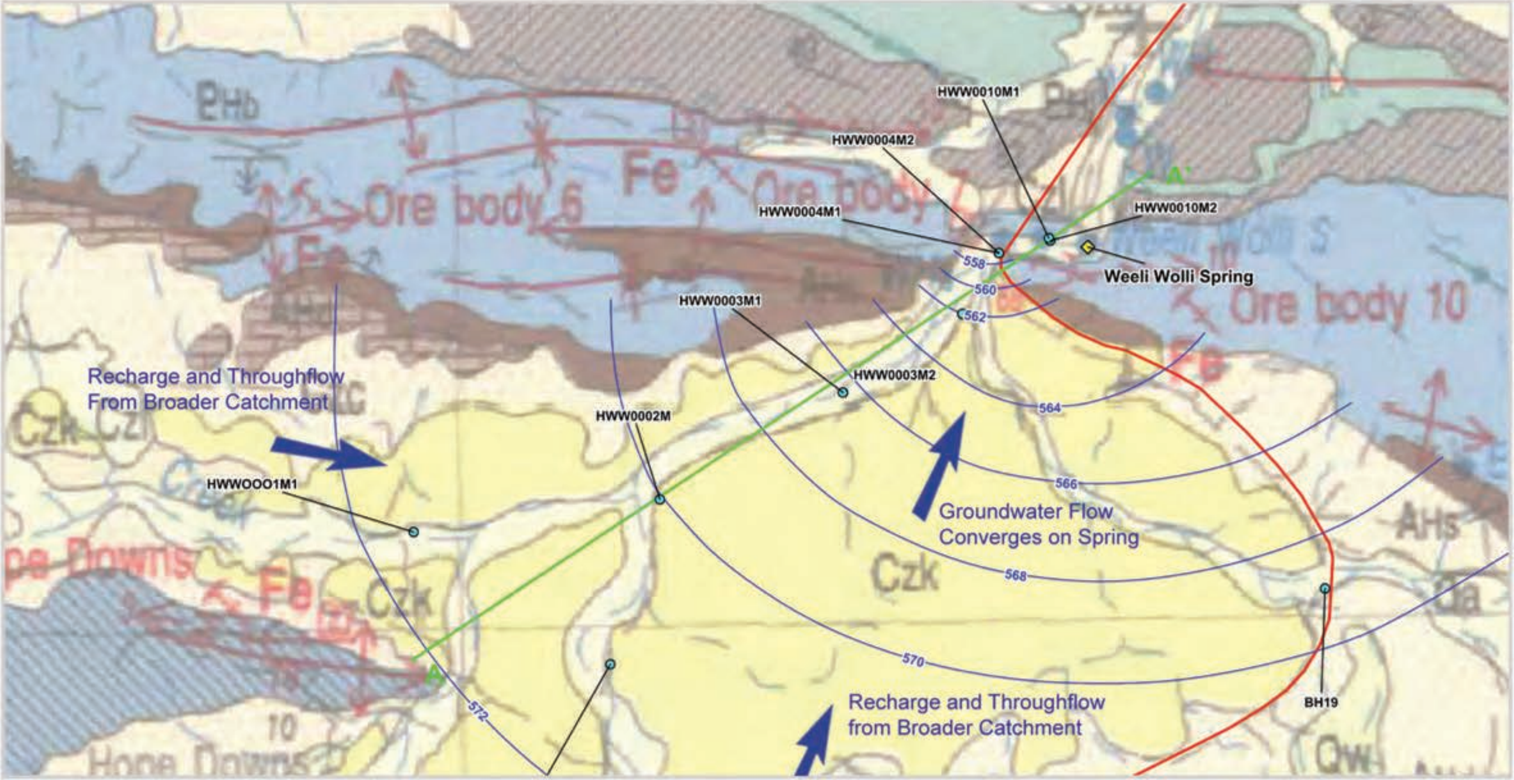
- Key Bore
- Receptor
- Extent of Surface Water Pools

DATA SOURCES:
Input data source here

RPS

FIGURE 4.20

OUTCROP GEOLOGY
BEN'S OASIS



N

0 1 2

Kilometres

Scale: 1:50,000 @A4

GDA 1994 Zone 50

AUTHOR: JP	REPORT NO: 275
DRAWN: RS	REVISION: C
DATE: 23/06/2014	JOB NO: 1549B

F:\Jobs\1549B\Spatial_Data\Working\MapInfo\Workspaces\020a\020a Figure 5.7 - Weeli Wolli GWL Contours

LEGEND

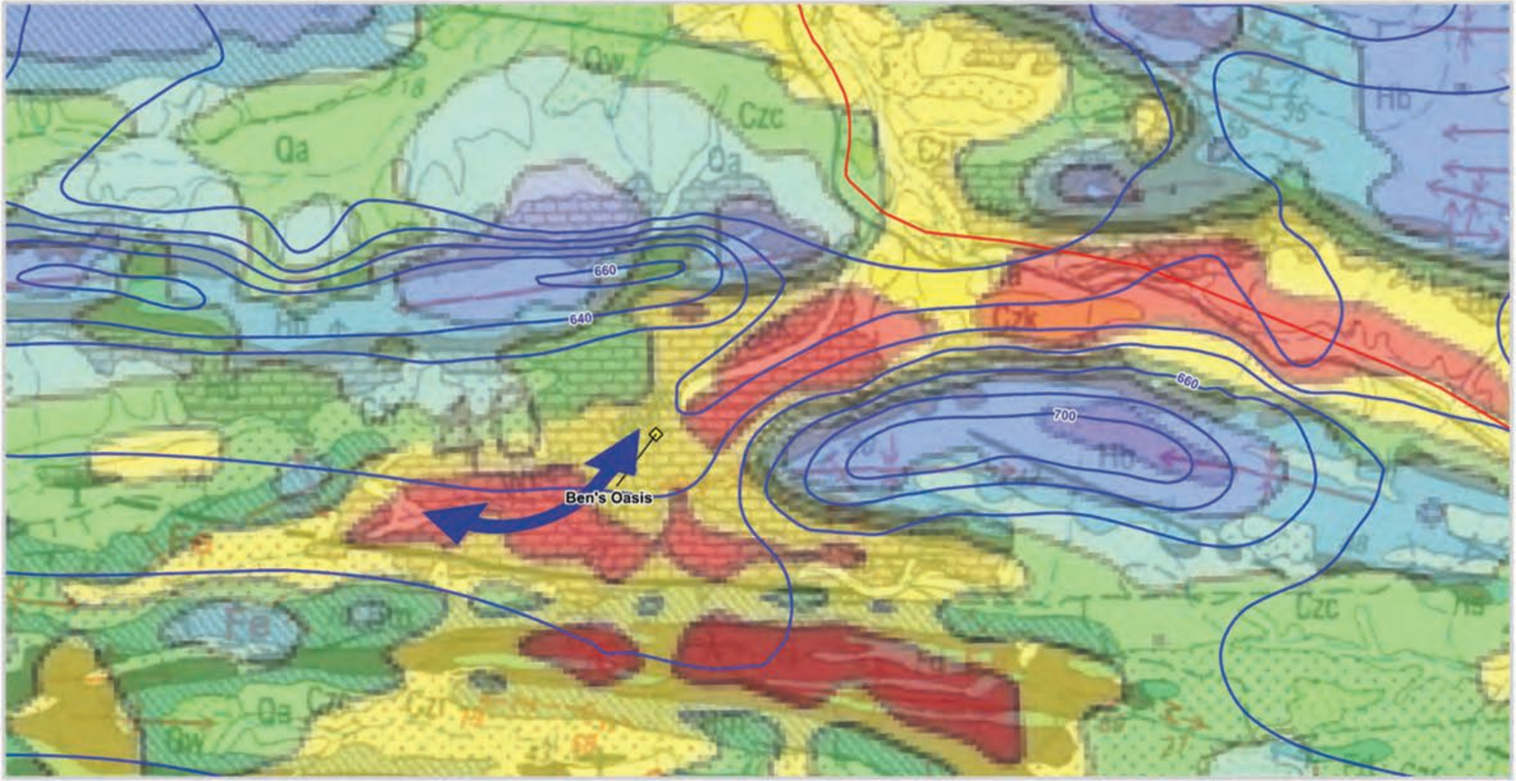
- Key Bore
- Receptor
- Cross Section Line
- Road
- Groundwater Contours (mRL)

DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 4.21

GROUNDWATER LEVEL CONTOURS (2005)
WEELI WOLLI SPRING



N

0 1 2

Kilometres

Scale: 1:75,000 @A4

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	C
DATE:	23/06/2014	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\Working\MapInfo\Workspaces\020a\Weeli Wolli\020a Figure 5.8

LEGEND

- Receptor
- Road
- Groundwater Contours (mRL)
- Extent of Surface Water

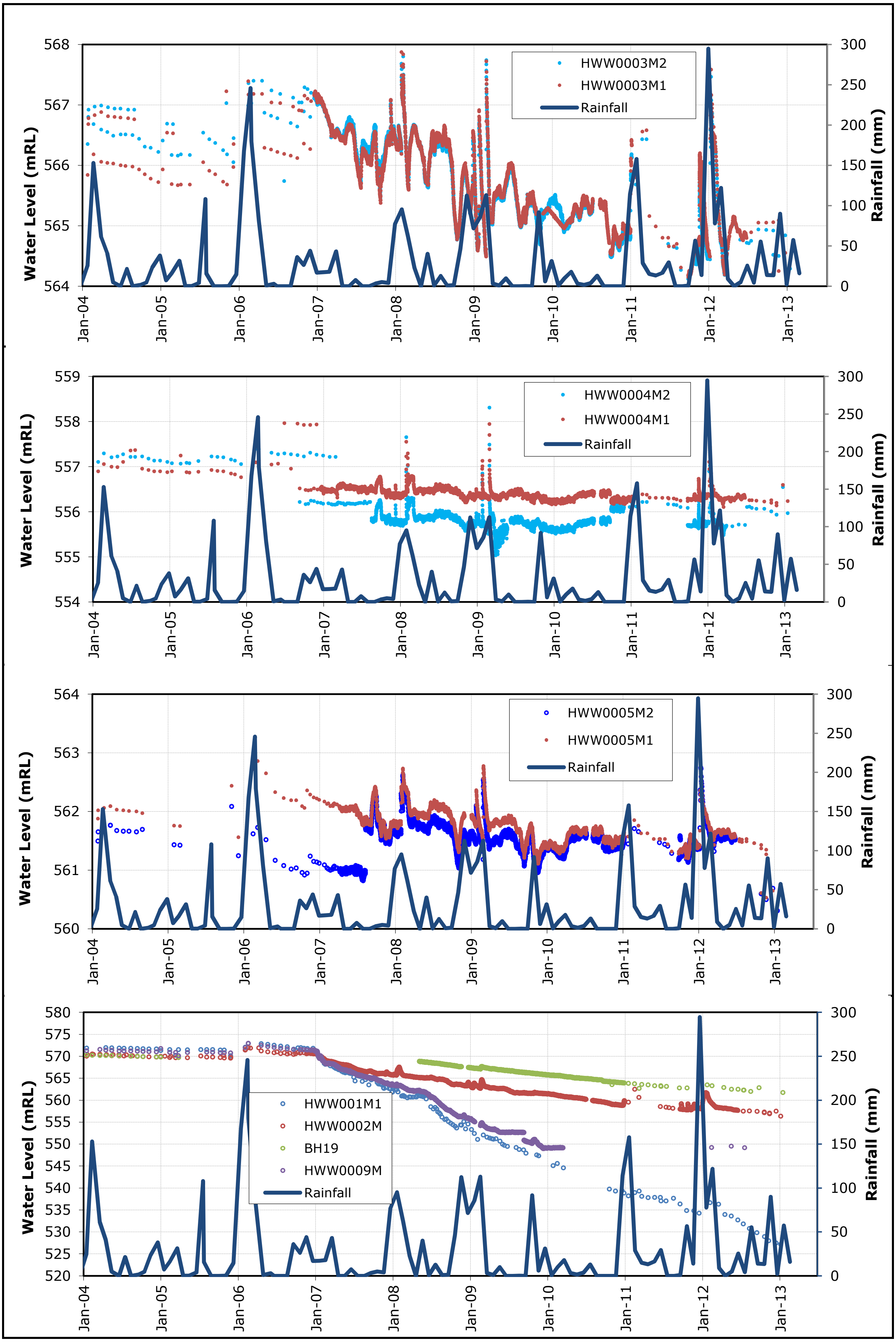
Depth to Water (m)

DATA SOURCES:
BHPB Iron Ore

RPS

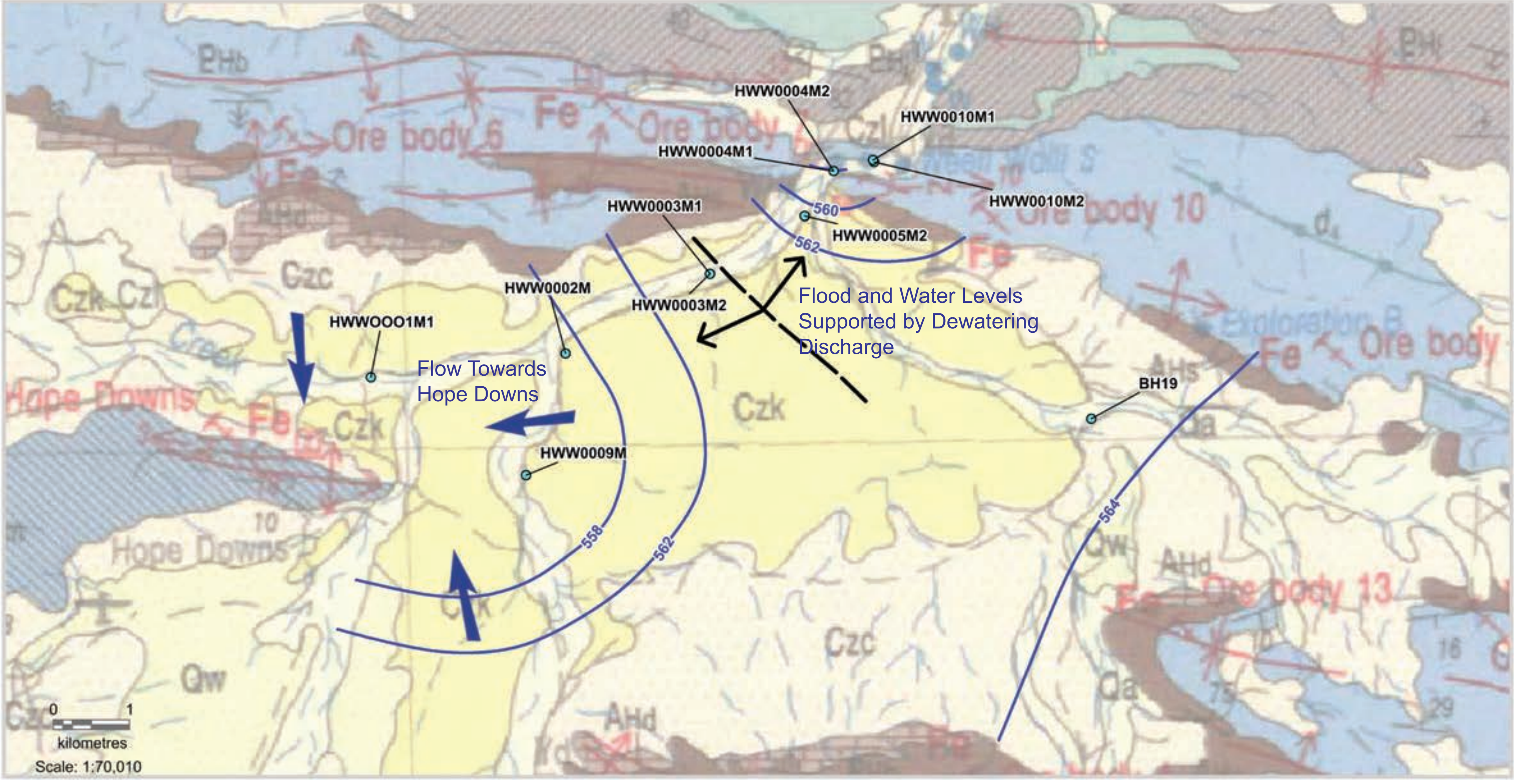
FIGURE 4.22

DEPTH TO WATER BEN'S OASIS



WEELI WOLLI SPRING HYDROGRAPHS FIGURE 4.23

F:\Jobs\1549B\300\Receptors\Weeli Wolli\[171a WW Hydrographs.xlsx]Figure 04-13



N

0 1 2

Kilometres

Scale: 1:70,000 @A4

GDA 1994 Zone 50

AUTHOR: JP	REPORT NO: 275
DRAWN: MR	REVISION: C
DATE: 23/06/2014	JOB NO: 1549B

Location: F:\Jobs\1549B\Spatial_Data\Working\MapInfo\Workspaces\020a\weeli Wolli\020a Figure 5.10_GWL Level 2012

LEGEND

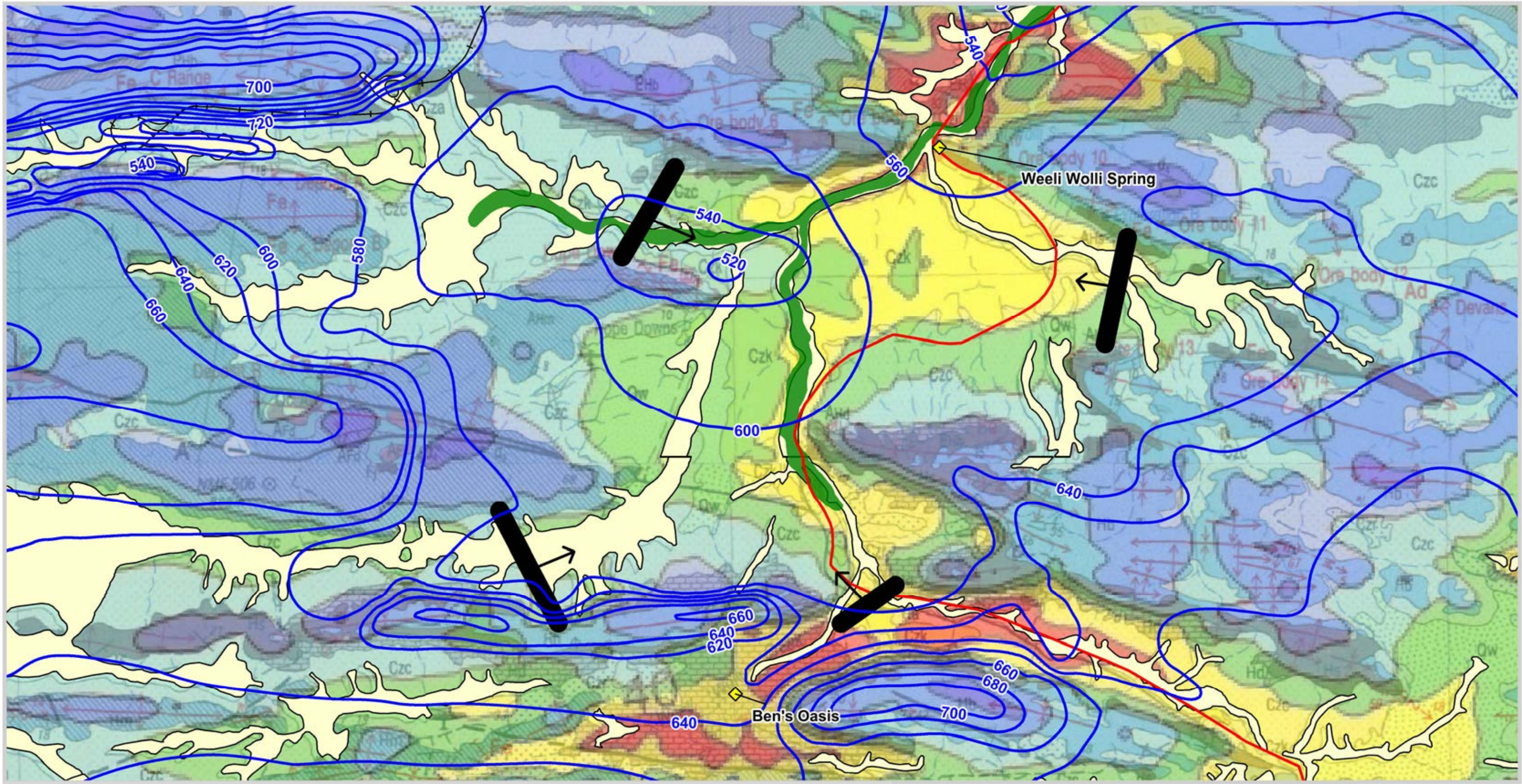
- Groundwater Level Contour (mAHD)
- Groundwater Divide
- Monitoring Bore

DATA SOURCES:
Input data source here

RPS

FIGURE 4.2

GROUNDWATER LEVEL CONTOURS (2012)
WEELI WOLLI SPRING



N

0 2 4

Kilometres

Scale: 1:150,000 @A4

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	c
DATE:	26/06/2014	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\Working\MapInfo\Workspaces\020a\Weeli Wolli\020a Figure 5.8

LEGEND

- Receptor
- Road
- Groundwater Contours (mRL)
- Alluvium Filled Channel
- Important Vegetation Community

Unsaturated

Saturated

Extent of Saturated Calcrete

DATA SOURCES:
BHPB Iron Ore

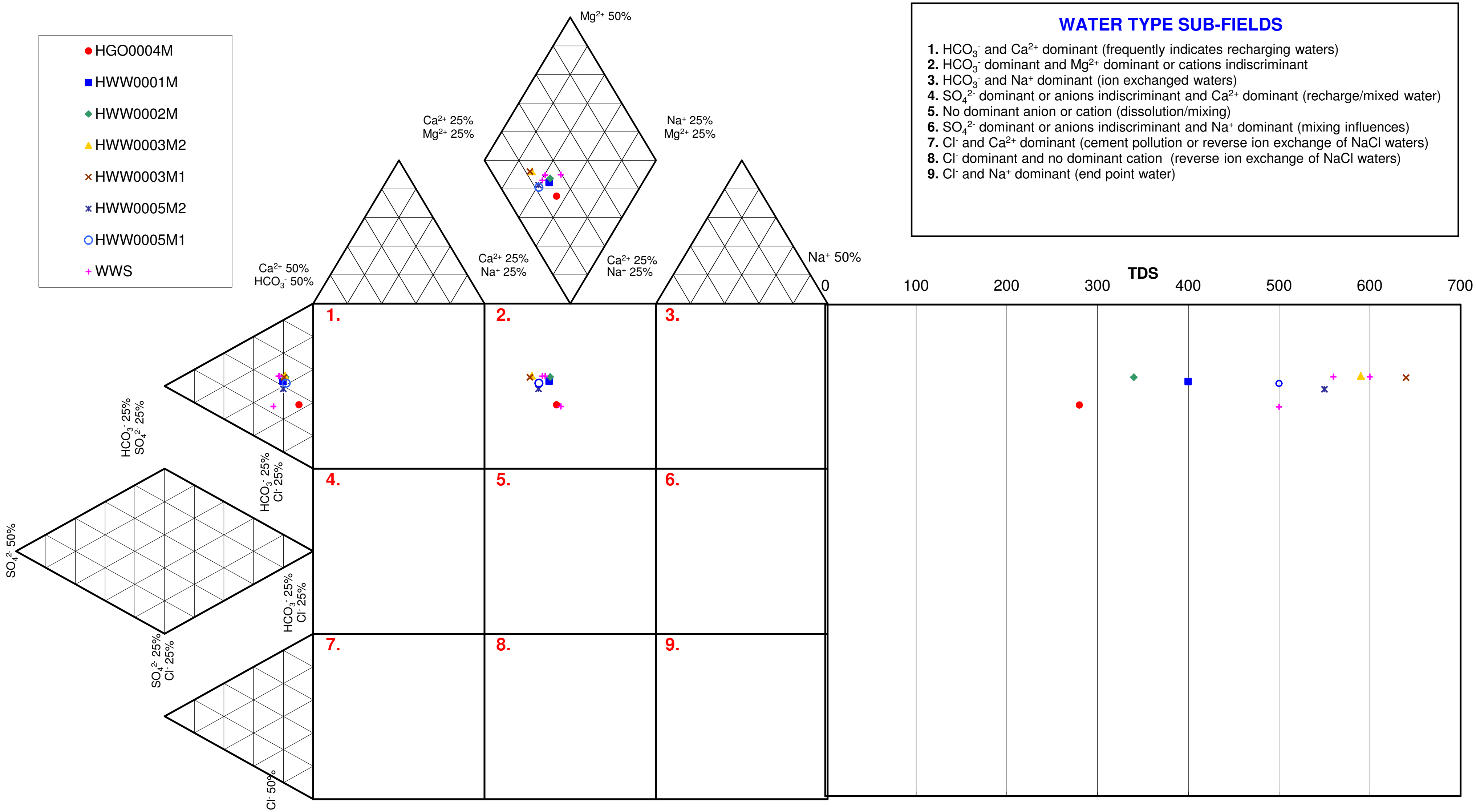
Depth to Water (m)

500
300
200
100
60
40
20
0

RPS

FIGURE 4.25

DEPTH TO WATER (2012)
WEELI WOLLI SPRING



WATER TYPE SUB-FIELDS

1. HCO_3^- and Ca^{2+} dominant (frequently indicates recharging waters)
2. HCO_3^- dominant and Mg^{2+} dominant or cations indiscriminant
3. HCO_3^- and Na^+ dominant (ion exchanged waters)
4. SO_4^{2-} dominant or anions indiscriminant and Ca^{2+} dominant (recharge/mixed water)
5. No dominant anion or cation (dissolution/mixing)
6. SO_4^{2-} dominant or anions indiscriminant and Na^+ dominant (mixing influences)
7. Cl^- and Ca^{2+} dominant (cement pollution or reverse ion exchange of NaCl waters)
8. Cl^- dominant and no dominant cation (reverse ion exchange of NaCl waters)
9. Cl^- and Na^+ dominant (end point water)

RPS

Expanded Durov Diagram

Figure 4.26

Date: 13/10/14	Project:	CPR Conceptual Model	Description:	WQ Analysis
F:\Jobs\1549B\300\Receptors\Weeli Wolli\[174b HydroCHEM2.0.xls]Project Information	Project No:	1549B	Client:	BHP Billiton Iron Ore

HydroCHEM 2.0

Figure 4.27a Hydrological Regime Pre-Mining

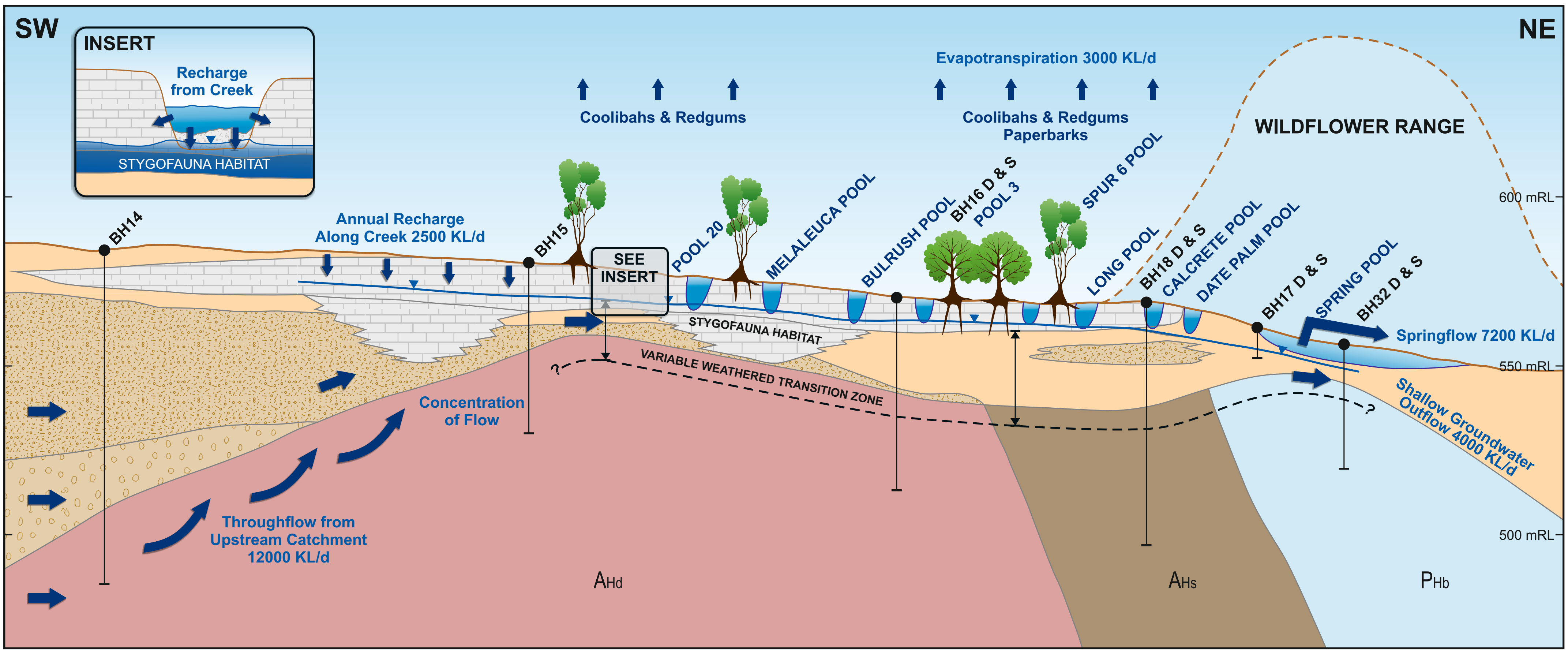
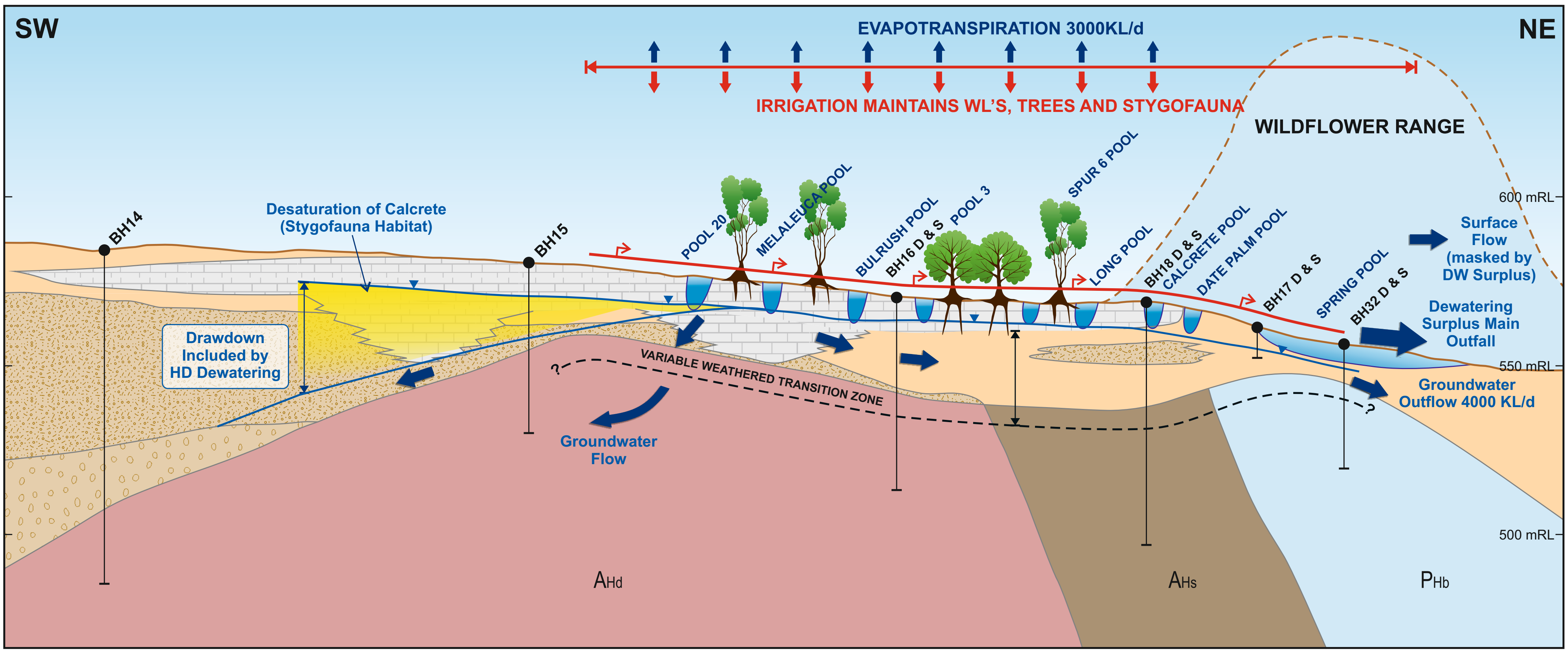


Figure 4.27b Hydrological Regime with Mining



Location: XXXX

0 0.5 1
Kilometres

AUTHOR:	JP	REPORT NO:	...
DRAWN:	RC	REVISION:	...
DATE:	...	JOB NO:	...

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
- 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 Mount Newman Member

Jeerinah Fm
- AFj

Granitoid Complex
- Ag
- Ore

- Surface Water Pool (elevation approximate)
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

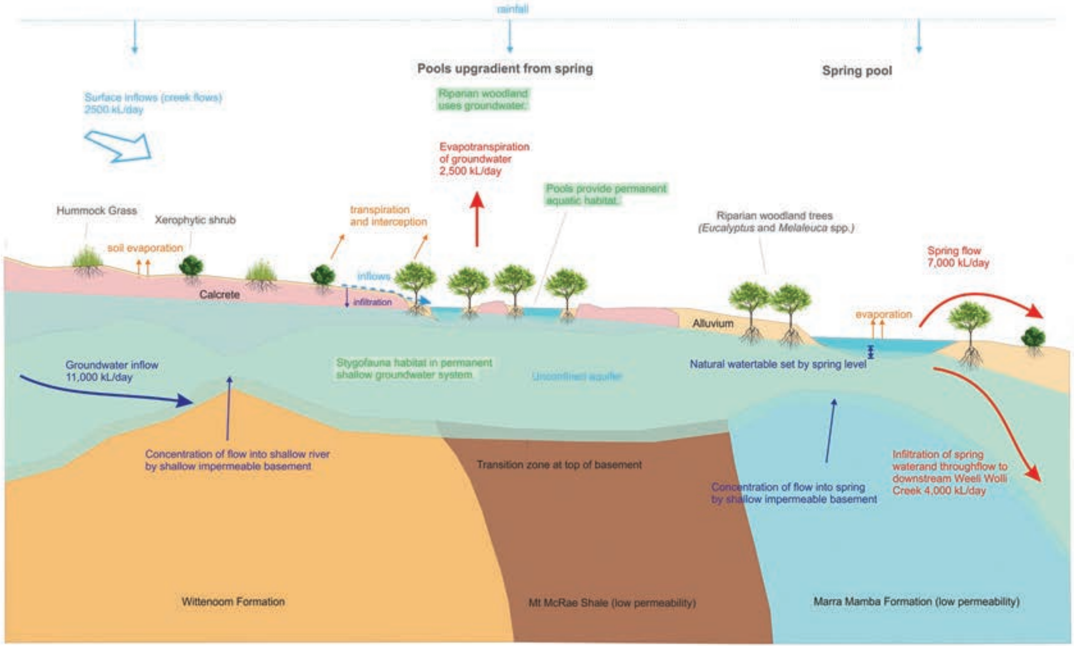
RPS

FIGURE 4.27

CONCEPTUAL HYDROLOGY POST-MINING WEELI WOLLI SPRING MINING AREA

DATA SOURCES:
Input data source here

Weeli Wolli Spring conceptual ecohydrological model



Not to Scale

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	C
DATE:	23/06/2014	JOB NO:	1549B

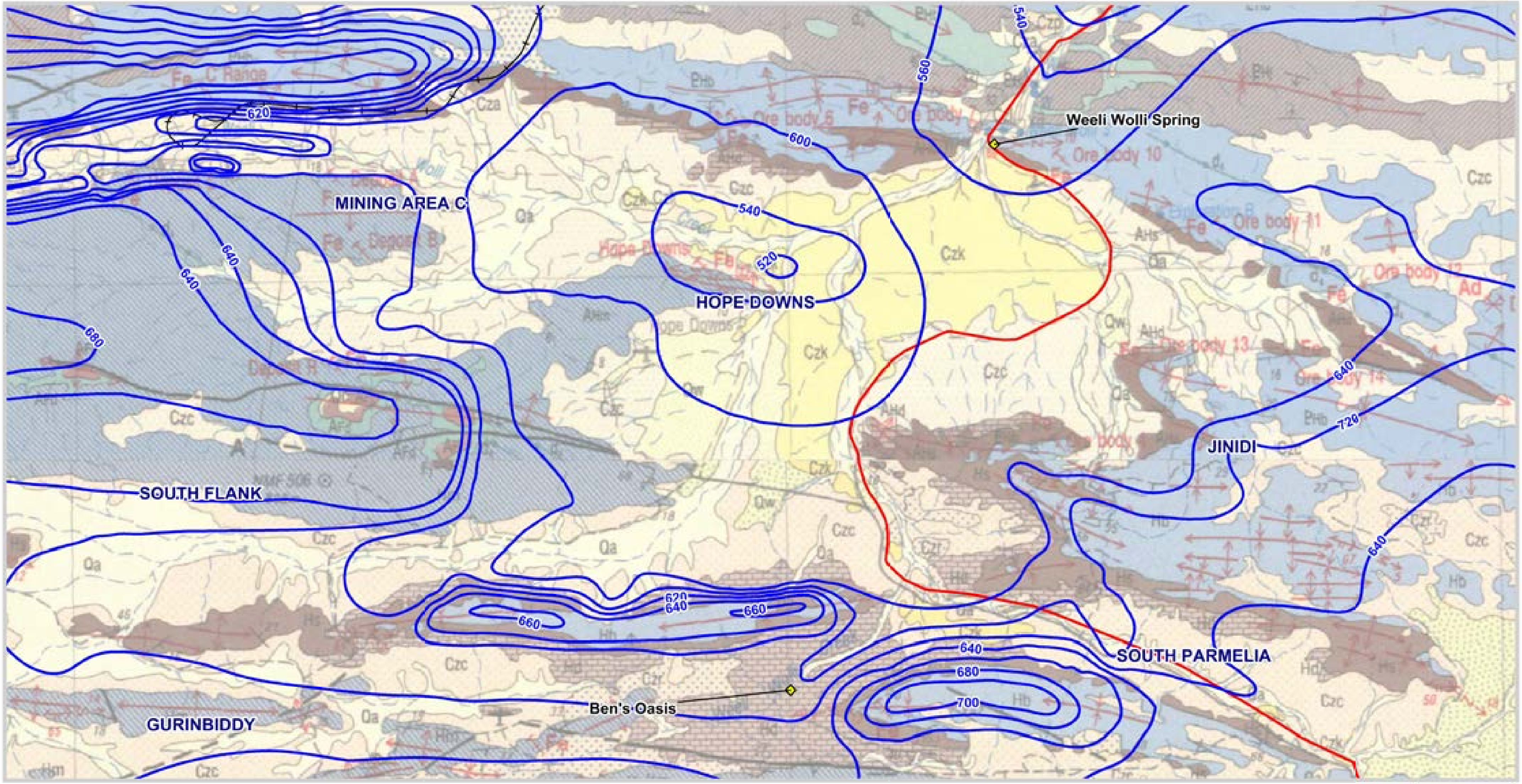
DATA SOURCES:
BHPB Iron Ore

RPS

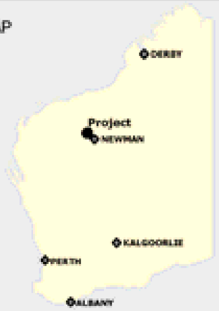
Figure 4.28

WEELI WOLLI SPRING ECO-CONCEPTUAL MODEL

F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\020a\Coondewanna\020a Figure 4.14 Eco Conceptual Model



LOCATION MAP



0 2 4
Kilometres

Scale: 1:150,000 @A4

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\Working\MapInfo\Workspaces\020a\Weeli Wolli\020a Figure 5.13

LEGEND

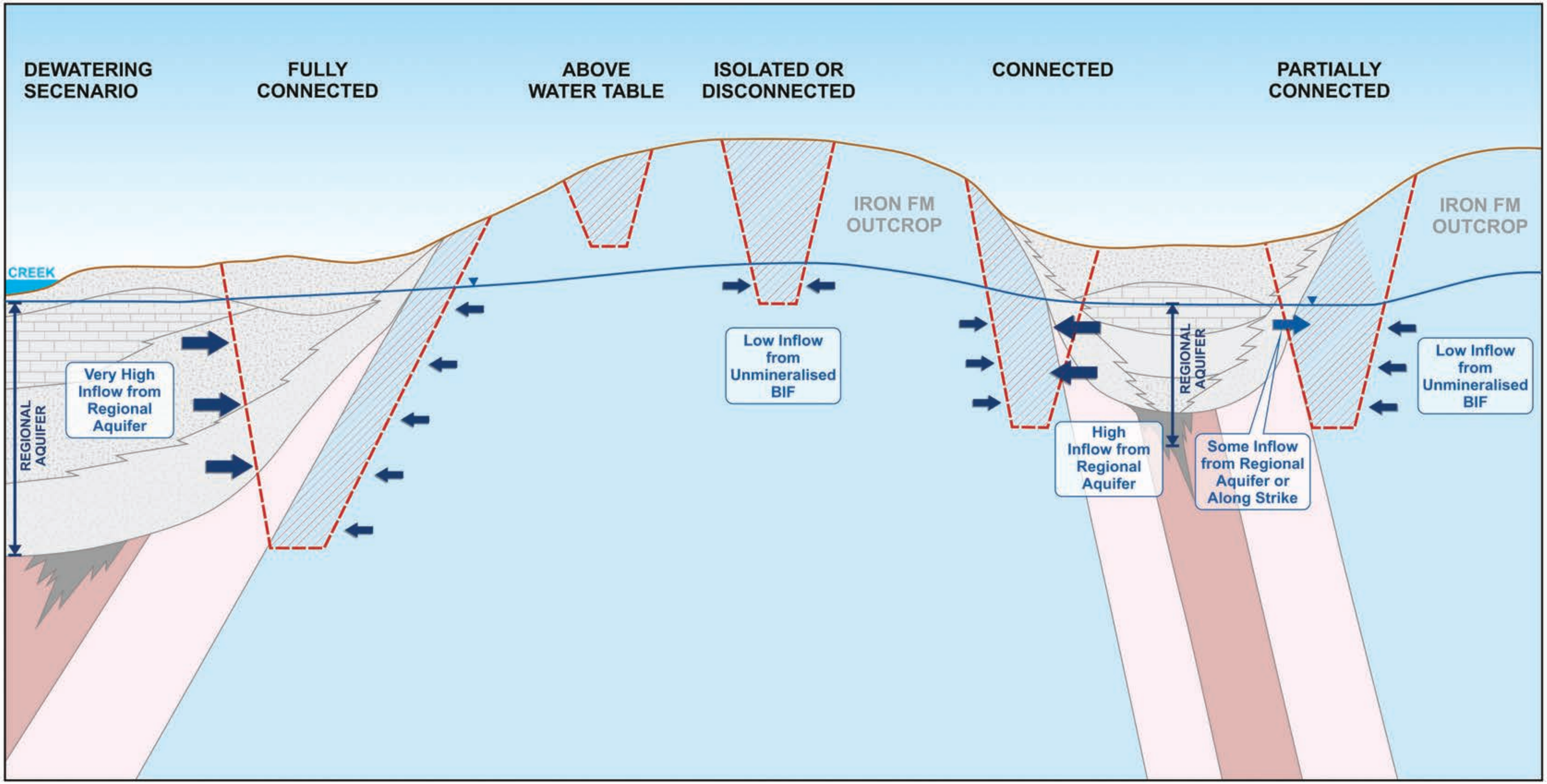
- Sub Water Table Deposit
- Groundwater Contours (mRL)
- Receptor
- Road

DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 4.29

BELOW WATER TABLE DEPOSITS IN THE VICINITY OF WEELI WOLLI SPRING



Location: XXXX

NOT TO SCALE

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	c
DATE:	29-3-2014	JOB NO:	1549B

LEGEND

Quaternary
- Undifferentiated
- Clay
- Alluvium
- Calcrete

Permability
- Low Permeability BIF
- Low Permeability Shale and BIF
- Variable Permeability Dolomite
- Moderate to High Permeability Ore

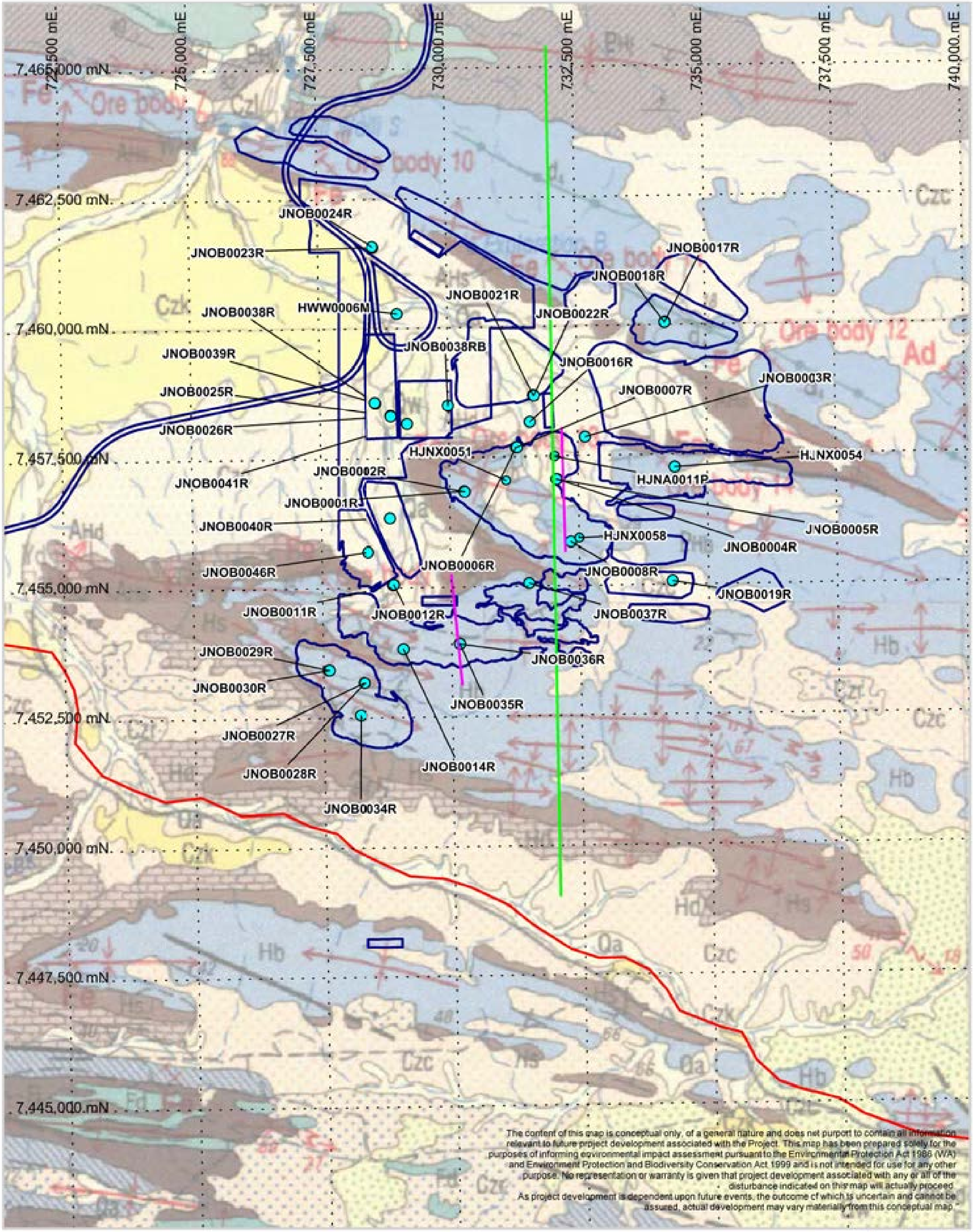
- Regional Water Table
- Potential Pit

Hydraulic Connection
- High
- Moderate
- Low

RPS

FIGURE 5.1

HYDROGEOLOGICAL SETTING AND DEWATERING SCENARIOS



LOCATION MAP

N

0 2.5

Kilometers

Scale: 1:100,000 @A4

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\275a\275a Figure 5.2 Jinidi Mining Area Location.wor

LEGEND

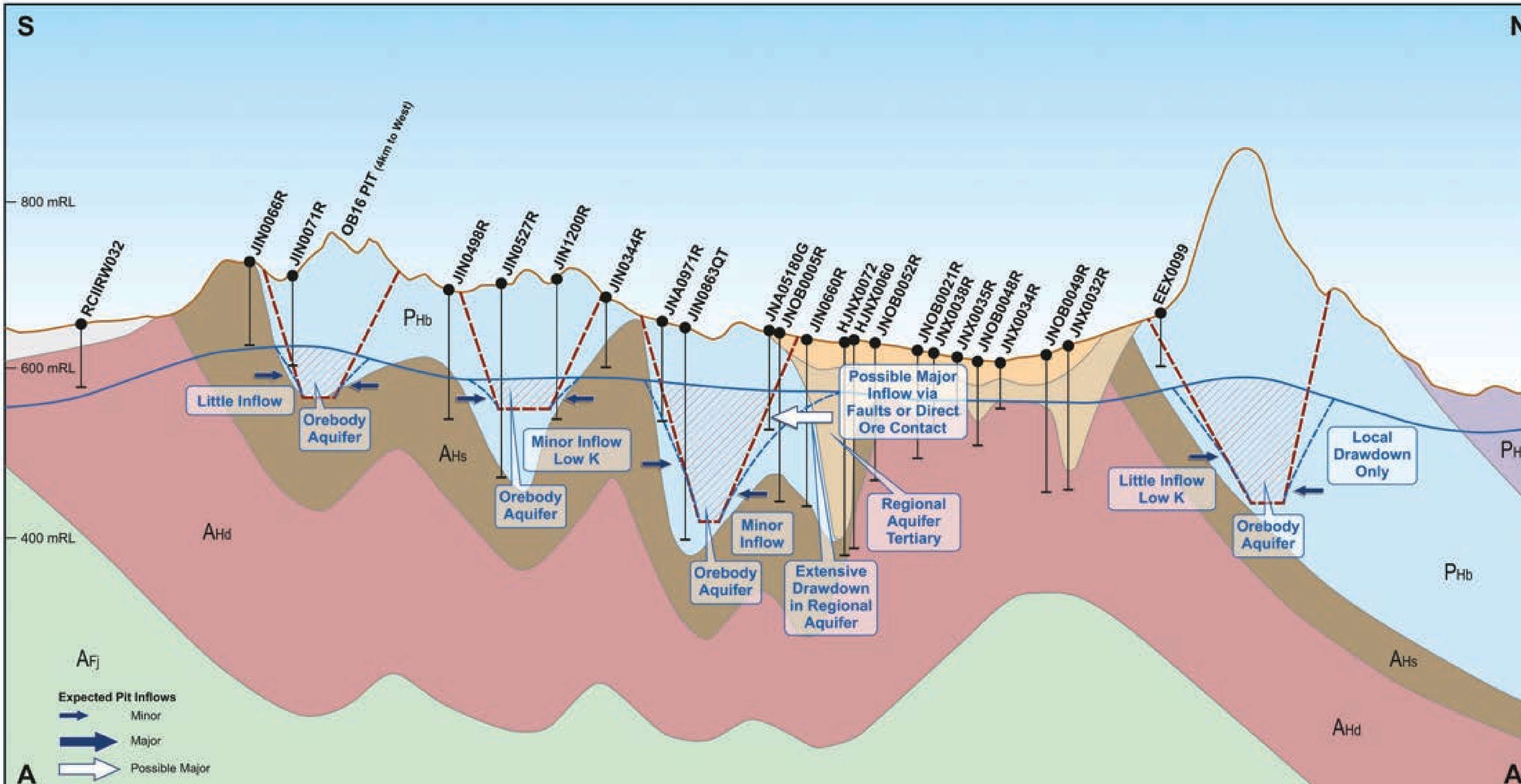
- Key Bore
- Road
- Rail
- Section Line
- Indicative BHP Billiton Iron Ore Disturbance
- URS Section Line (2012)

DATA SOURCES:
Input data source here

RPS

FIGURE 5.2

LOCATION PLAN
JINIDI MINING AREA



Location: XXXX

0 1 2
Kilometres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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

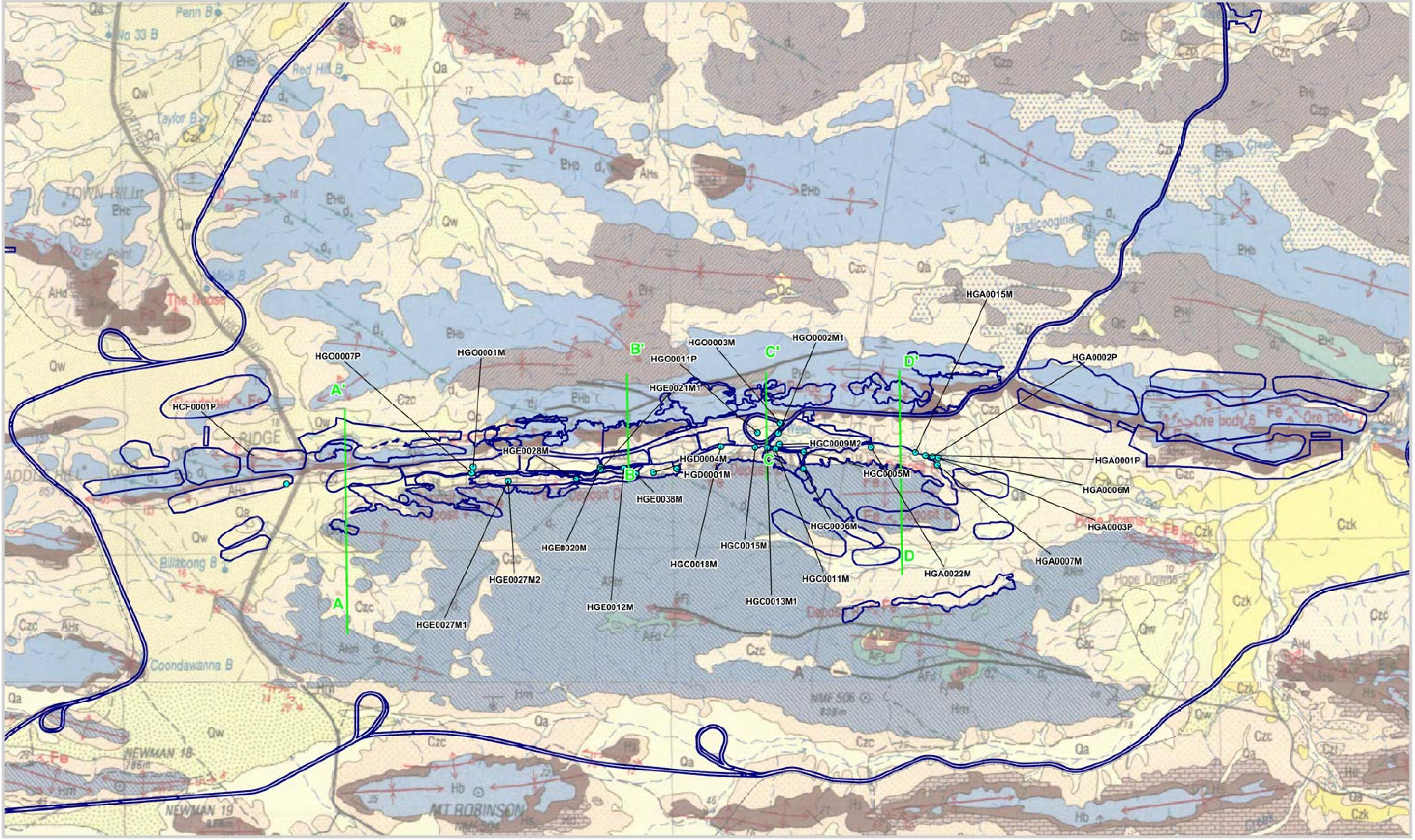
- Ore
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 5.3

SECTION A INFLUENCE OF DEWATERING JINIDI MINING AREA

DATA SOURCES:
Input data source here



LOCATION MAP

N

0 1 2

Kilometres

Scale: 1:125,000 @A3

GDA 1994 Zone 50

AUTHOR:	RS	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	05/05/2015	JOB NO:	1549B

Location: F:\Jobs\1549F\Spatial_Data\MapInfo\Workspaces\275a\NorthFlank\275a Fig 5.4 location map

LEGEND

- Key Bore
- Section line
- Indicative BHP Billiton Iron Ore Disturbance
- Rail

DATA SOURCES:
BHPBIO

RPS

FIGURE 5.4

LOCATION PLAN
MAC 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."

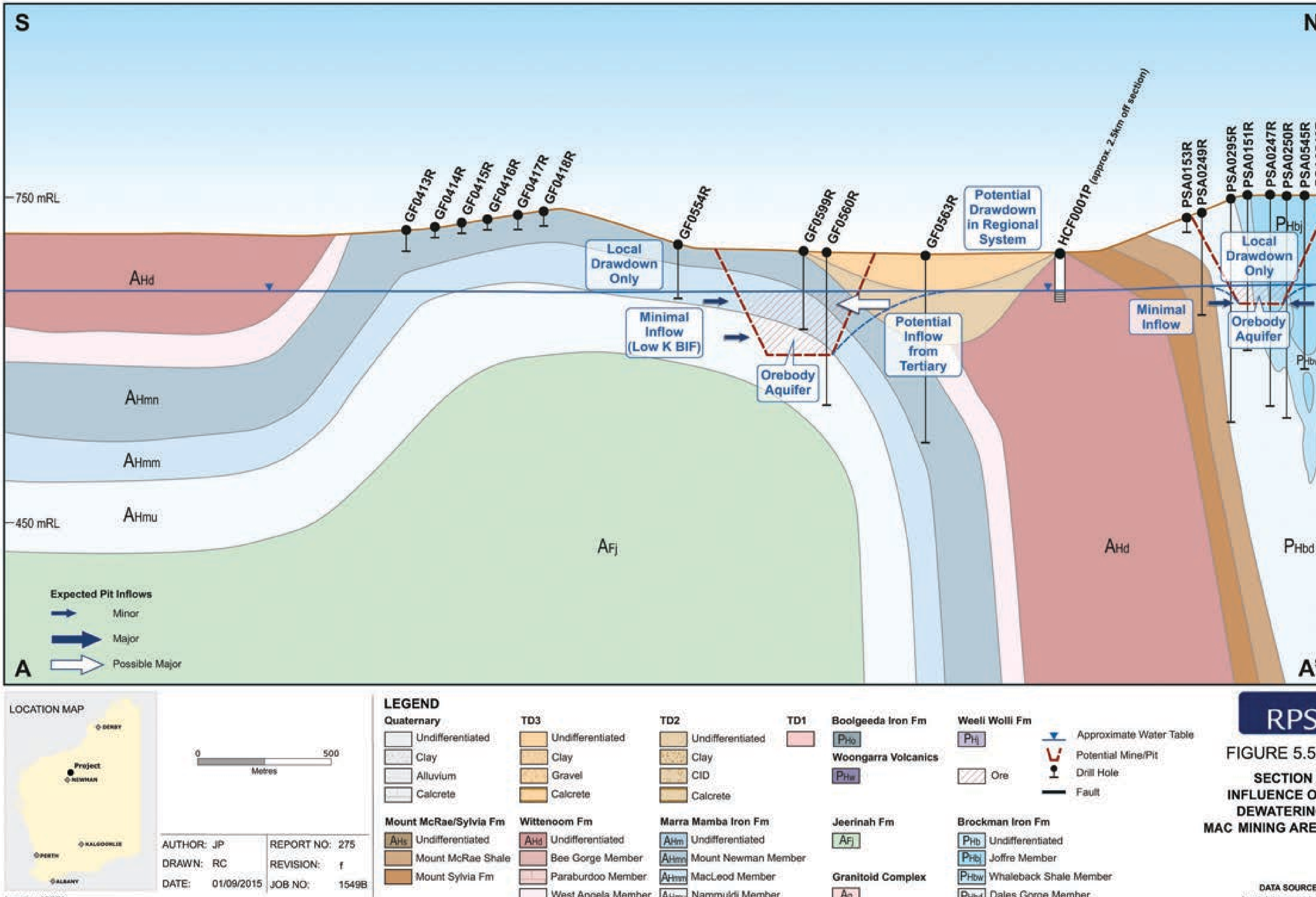
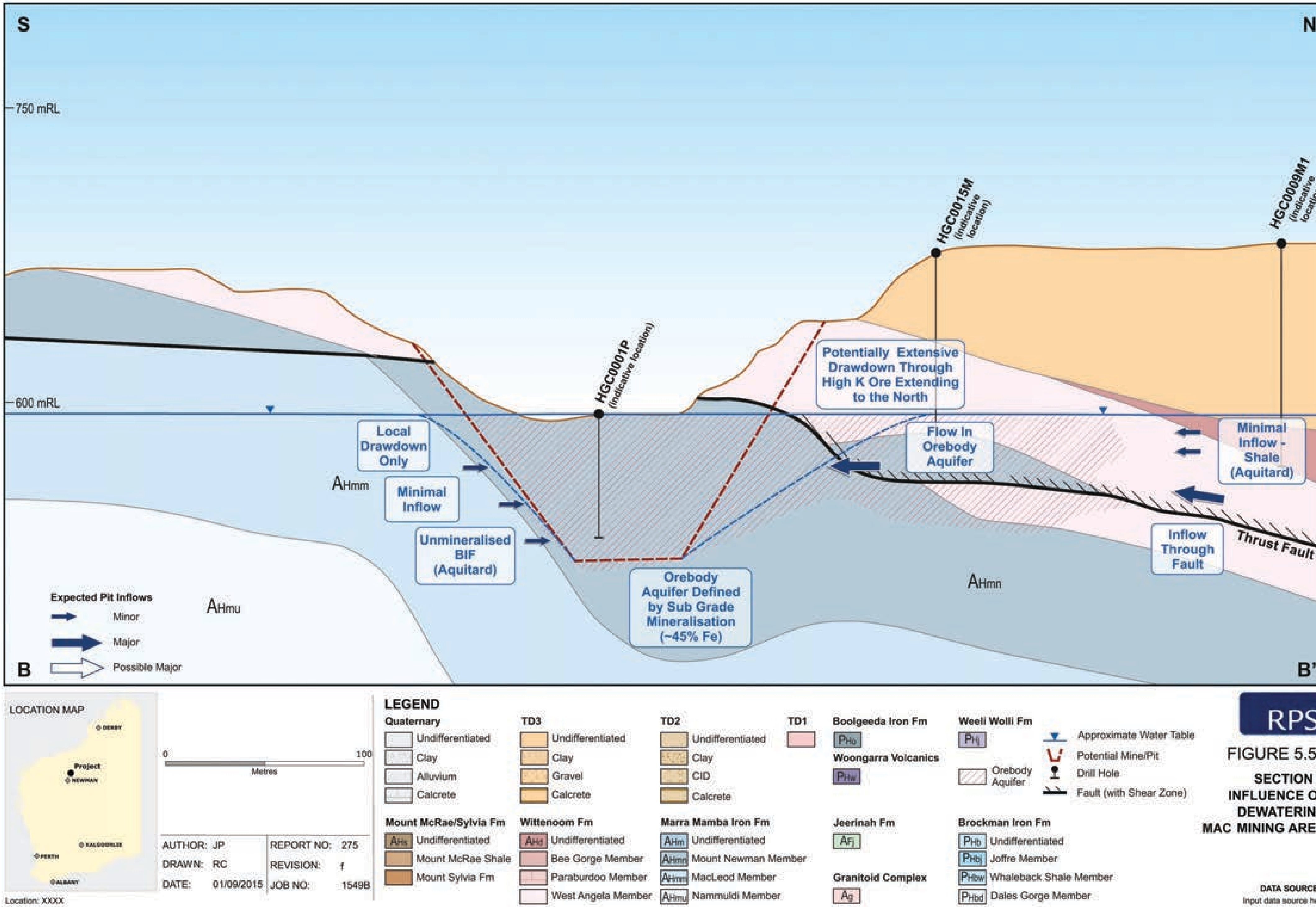
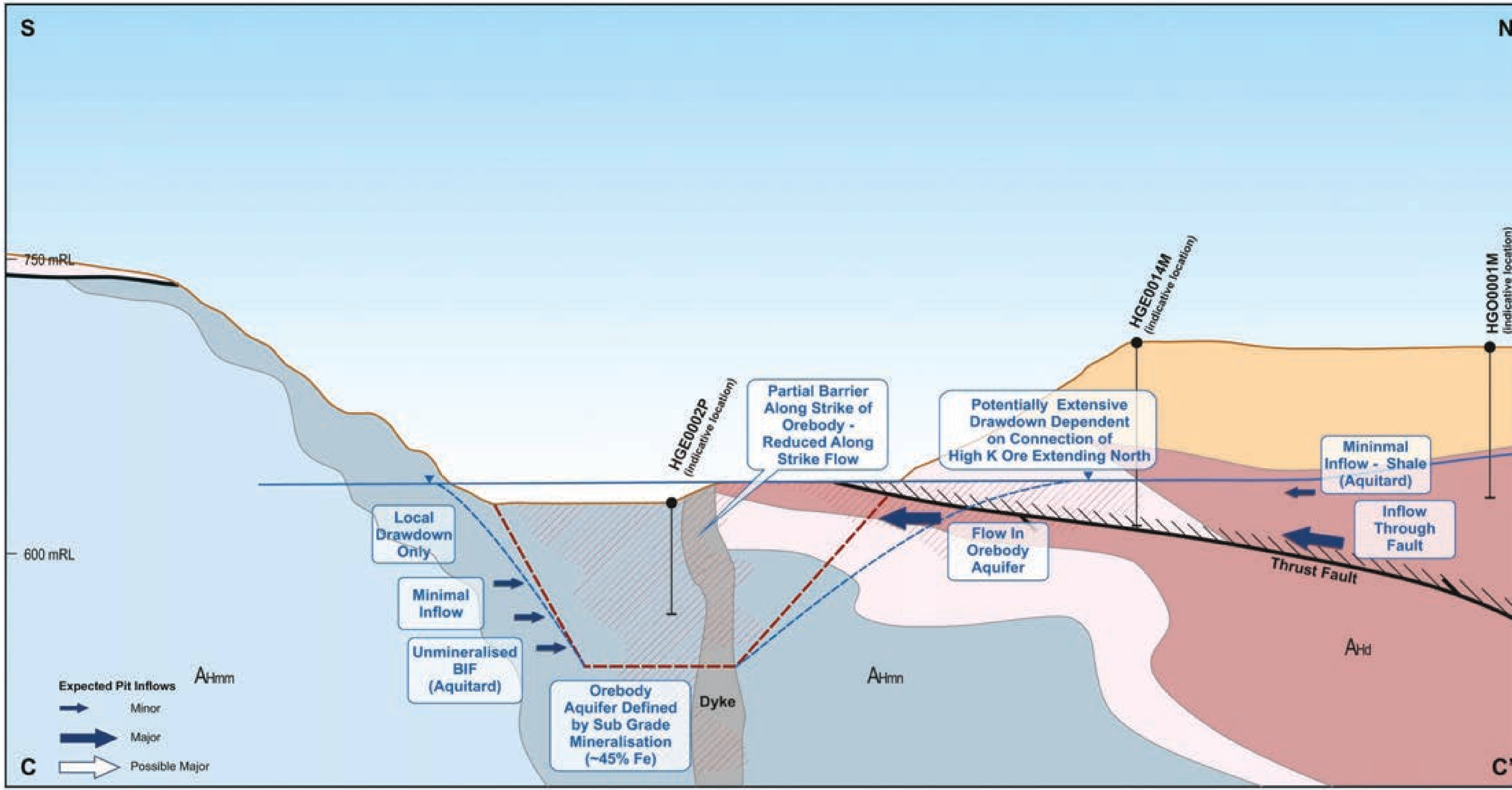


FIGURE 5.5a
SECTION A
INFLUENCE OF
DEWATERING
MAC MINING AREA



S
N
750 mRL
600 mRL
HGC0001P (indicative location)
HGC0015M (indicative location)
HGC0009M1 (indicative location)
Potentially Extensive Drawdown Through High K Ore Extending to the North
Local Drawdown Only
Flow In Orebody Aquifer
Minimal Inflow - Shale (Aquitard)
AHmm
Minimal Inflow
Unmineralised BIF (Aquitard)
Orebody Aquifer Defined by Sub Grade Mineralisation (~45% Fe)
Inflow Through Fault
Thrust Fault
AHmn
AHmu
Expected Pit Inflows
Minor
Major
Possible Major
B
B'
LOCATION MAP
Project
Location: XXXX
0
100
Metres
AUTHOR: JP
DRAWN: RC
DATE: 01/09/2015
REPORT NO: 275
REVISION: f
JOB NO: 1549B
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
Orebody Aquifer
Approximate Water Table
Potential Mine/Pit
Drill Hole
Fault (with Shear Zone)
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 5.5b
SECTION B
INFLUENCE OF DEWATERING
MAC MINING AREA
DATA SOURCES:
Input data source here



Location: XXXX

0 100
Metres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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

- Orebody Aquifer
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault (with Shear Zone)

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 5.5c

SECTION C
INFLUENCE OF
DEWATERING
MAC MINING AREA

DATA SOURCES:
Input data source here

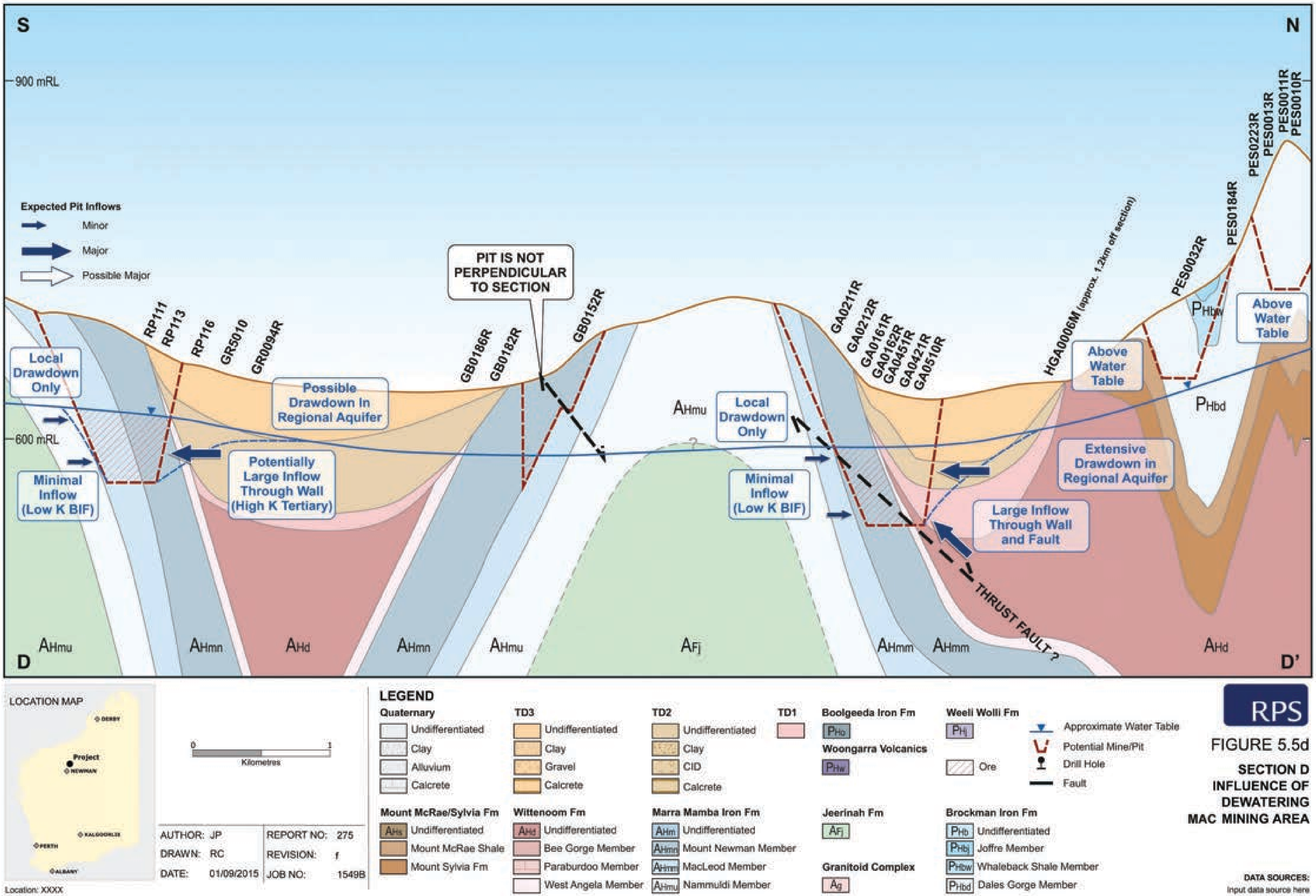
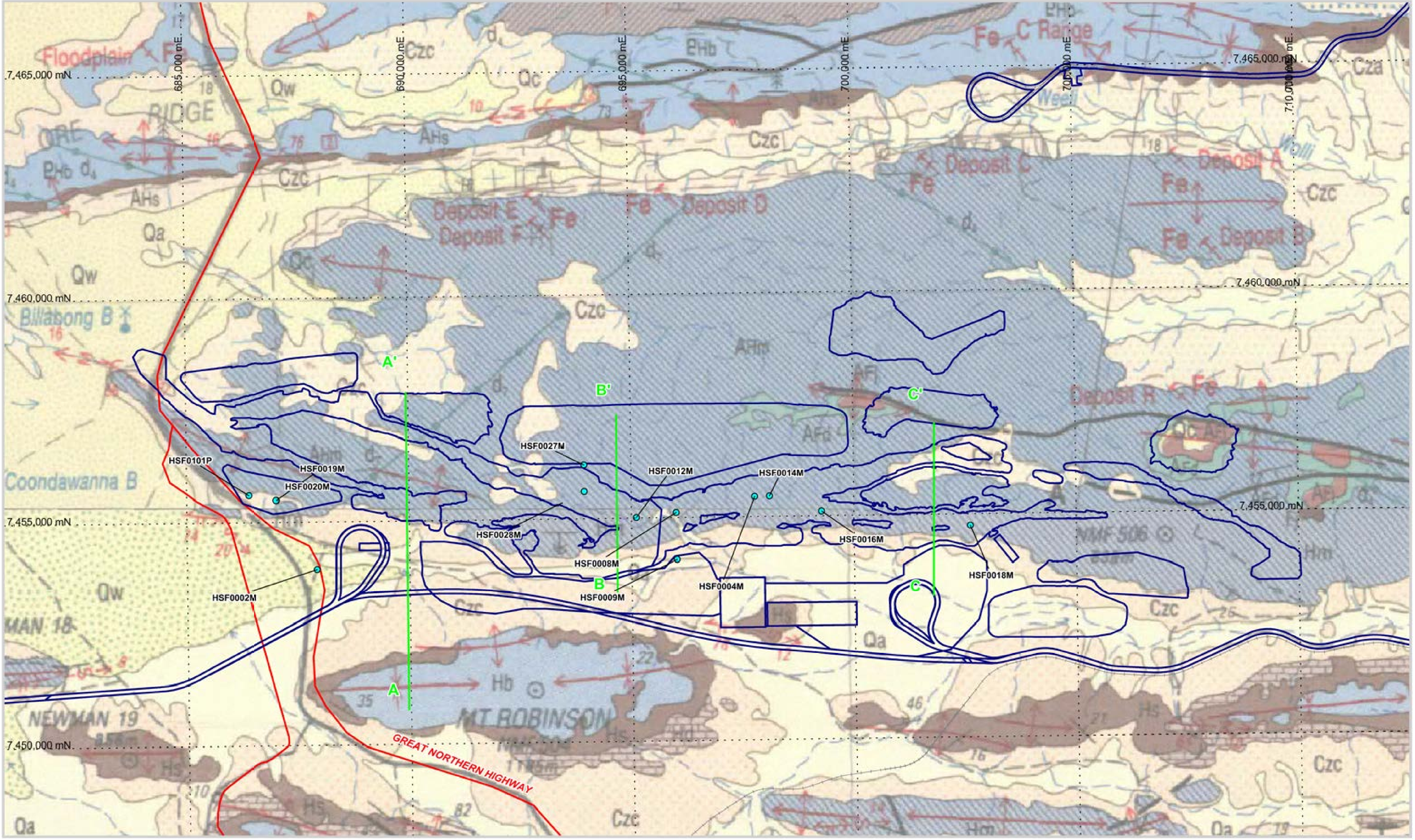


FIGURE 5.5d

SECTION D INFLUENCE OF DEWATERING MAC MINING AREA



LOCATION MAP

N

0 2.5

Kilometres

Scale: 1:80,000 @A3

GDA 1994 Zone 50

AUTHOR:	RS	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

Location: F:\Jobs\1549F\Spatial_Data\MapInfo\Workspaces\275a\275a Fig 5.6 location.map

LEGEND

- Key Bore
- Section line
- Major Road
- Indicative BHP Billiton Iron Ore Disturbance
- Rail

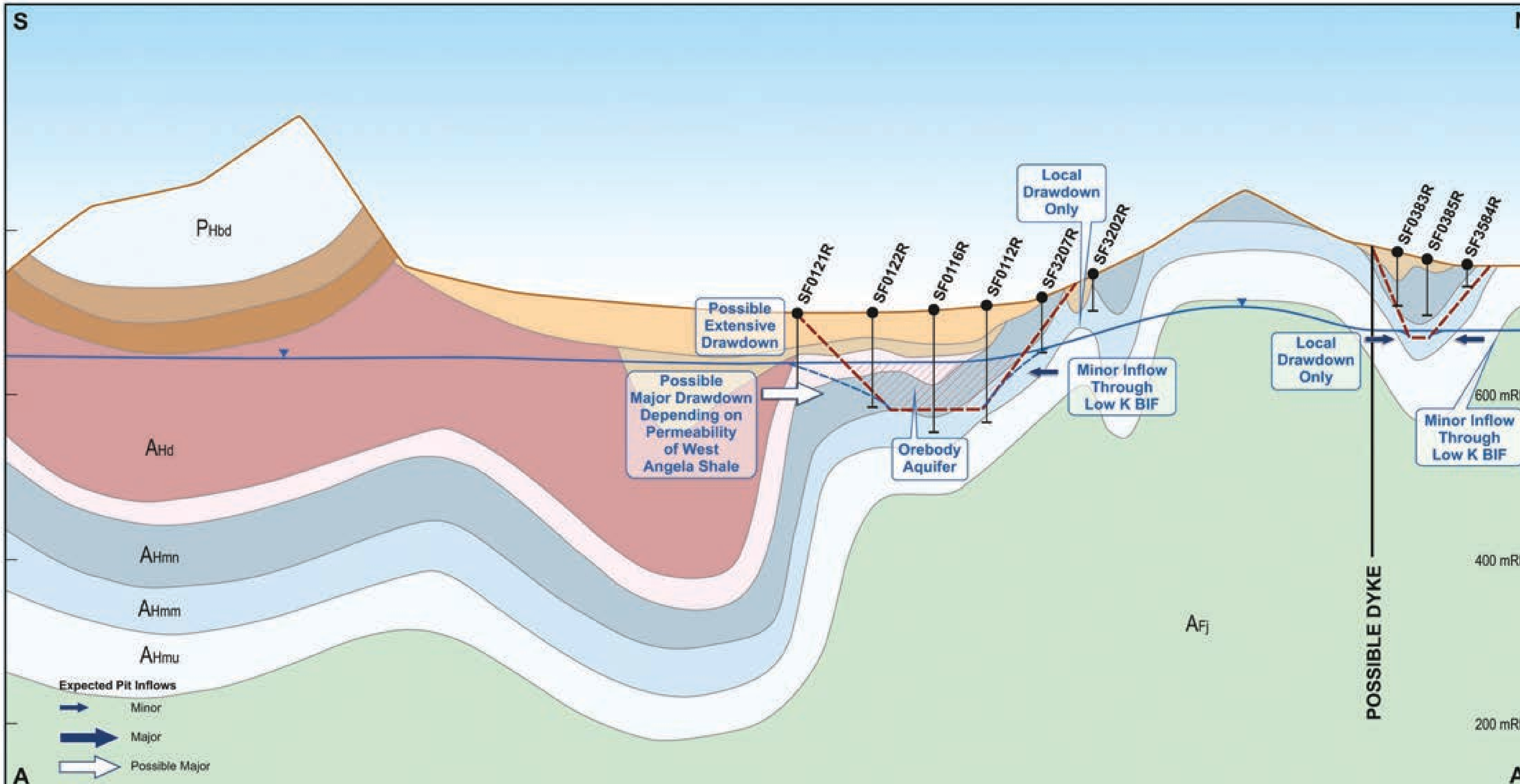
DATA SOURCES:
BHPBIO

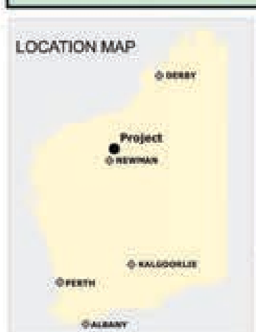
RPS

FIGURE 5.6

LOCATION PLAN
SOUTH FLANK 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 — 1
Kilometres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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

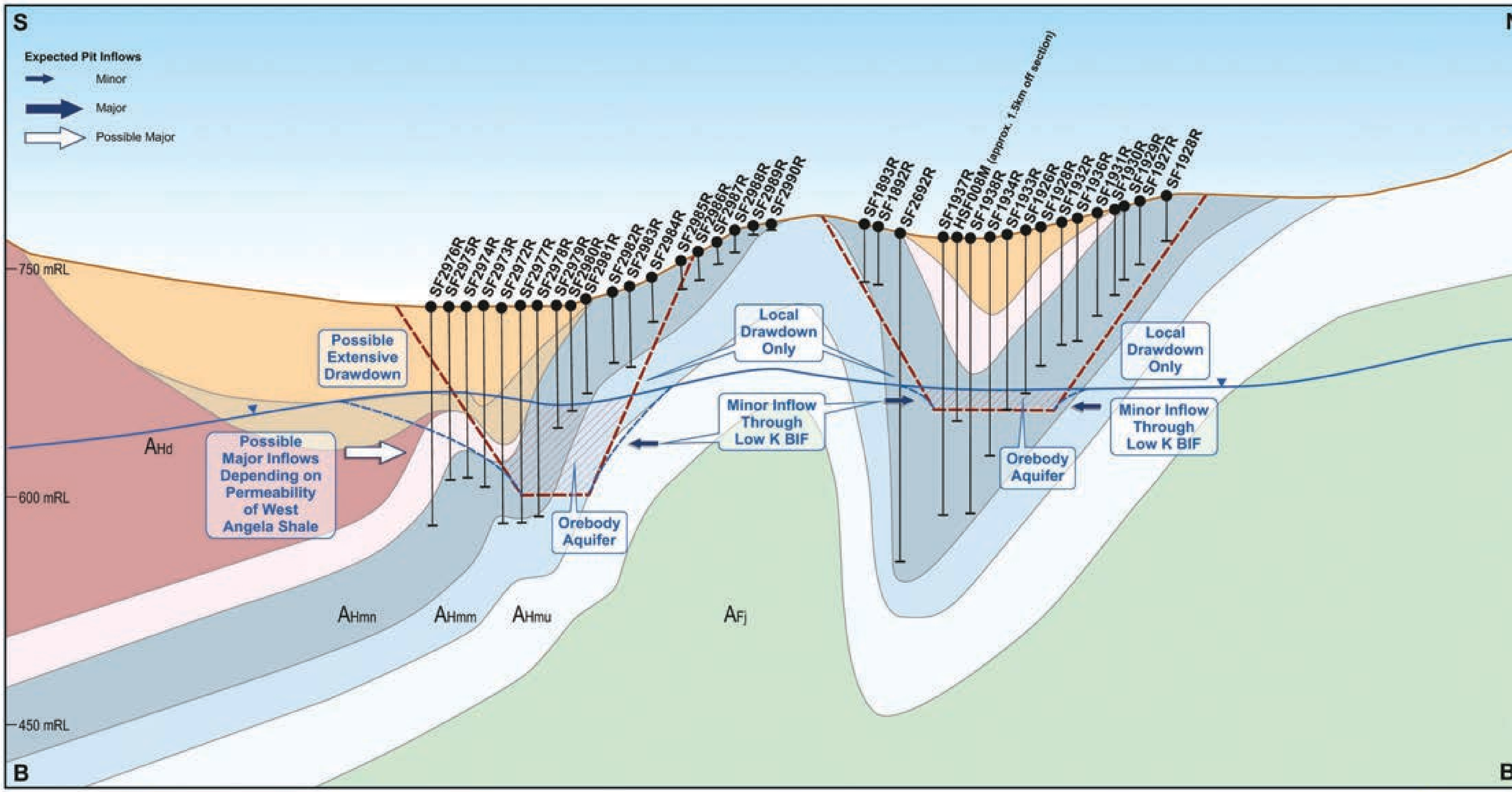
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

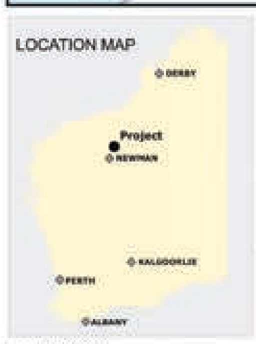
RPS

FIGURE 5.7a

SECTION A INFLUENCE OF DEWATERING SOUTH FLANK MINING AREA

DATA SOURCES:
Input data source here





0 500
Metres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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 5.7b

SECTION B INFLUENCE OF DEWATERING SOUTH FLANK MINING AREA

DATA SOURCES:
Input data source here

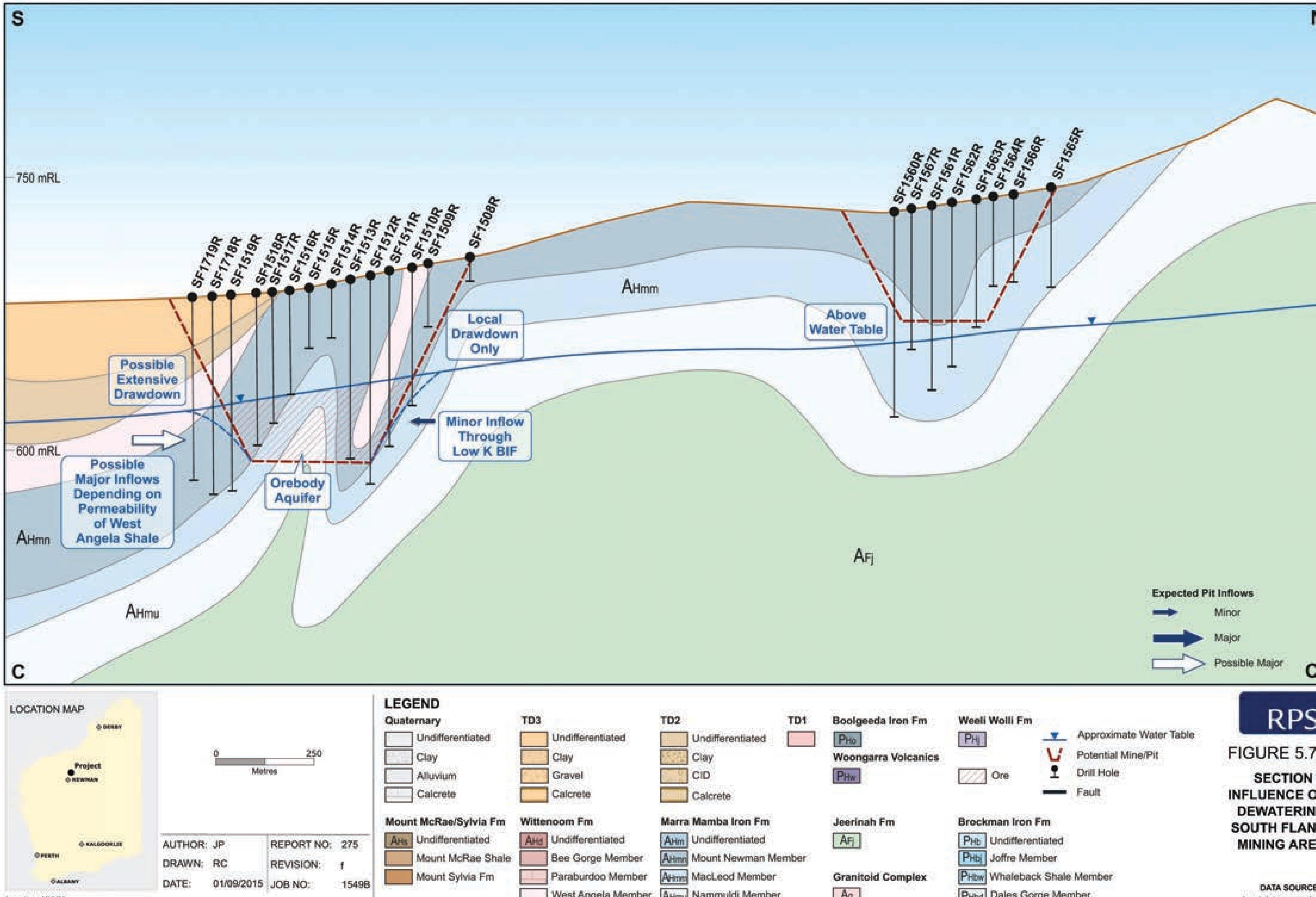
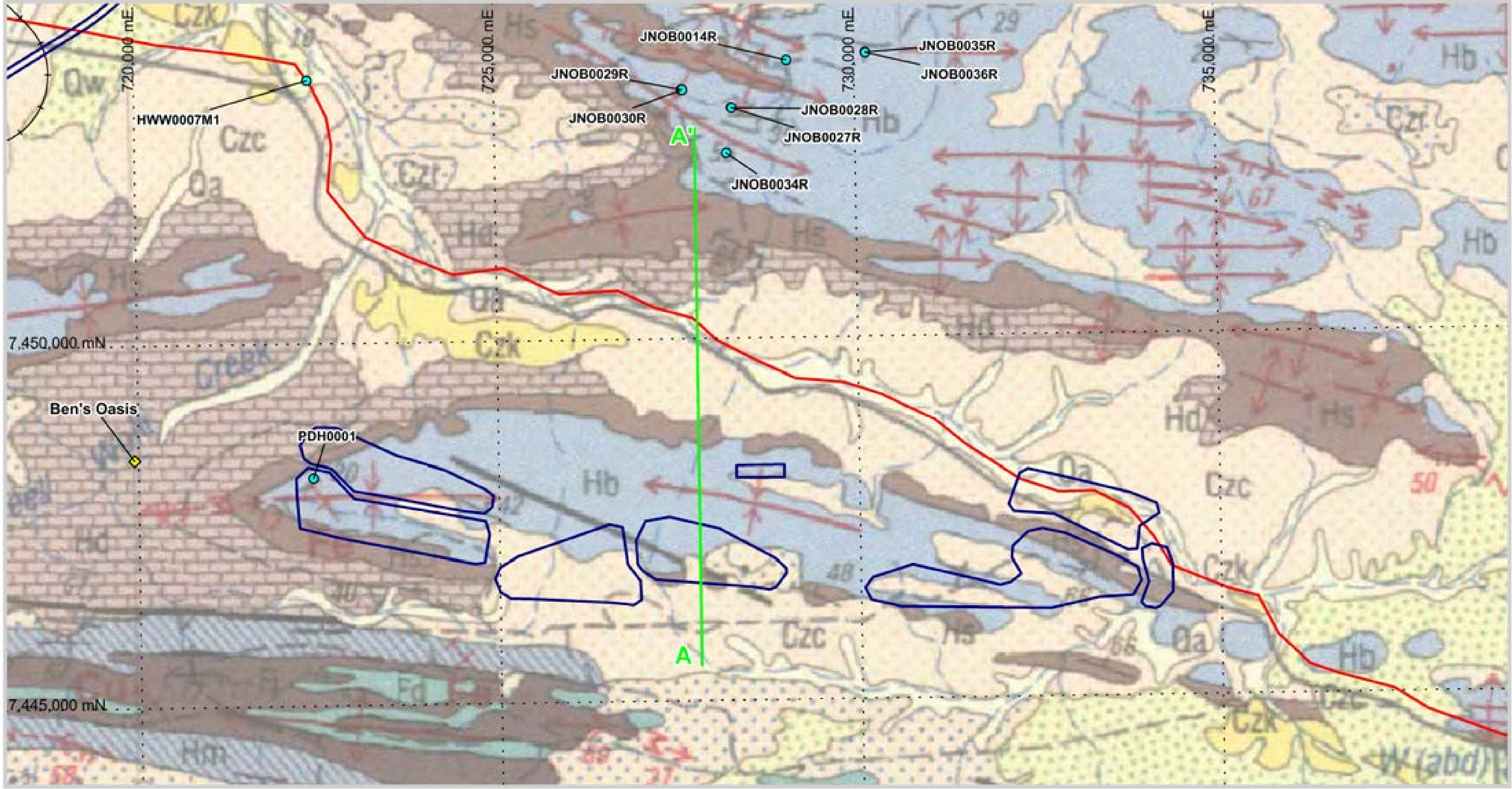
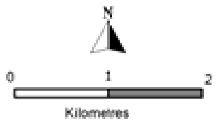


FIGURE 5.7c

SECTION C INFLUENCE OF DEWATERING SOUTH FLANK MINING AREA



LOCATION MAP



Scale: 1:75,000 @A4

GDA 1994 Zone 50

AUTHOR:	AW	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\275a\275a Figure 5.8 South Parmelia Mining Area Loc

LEGEND

- Key Bore
- Receptor
- Cross Section Line
- Indicative BHP Billiton Iron Ore Disturbance
- Road

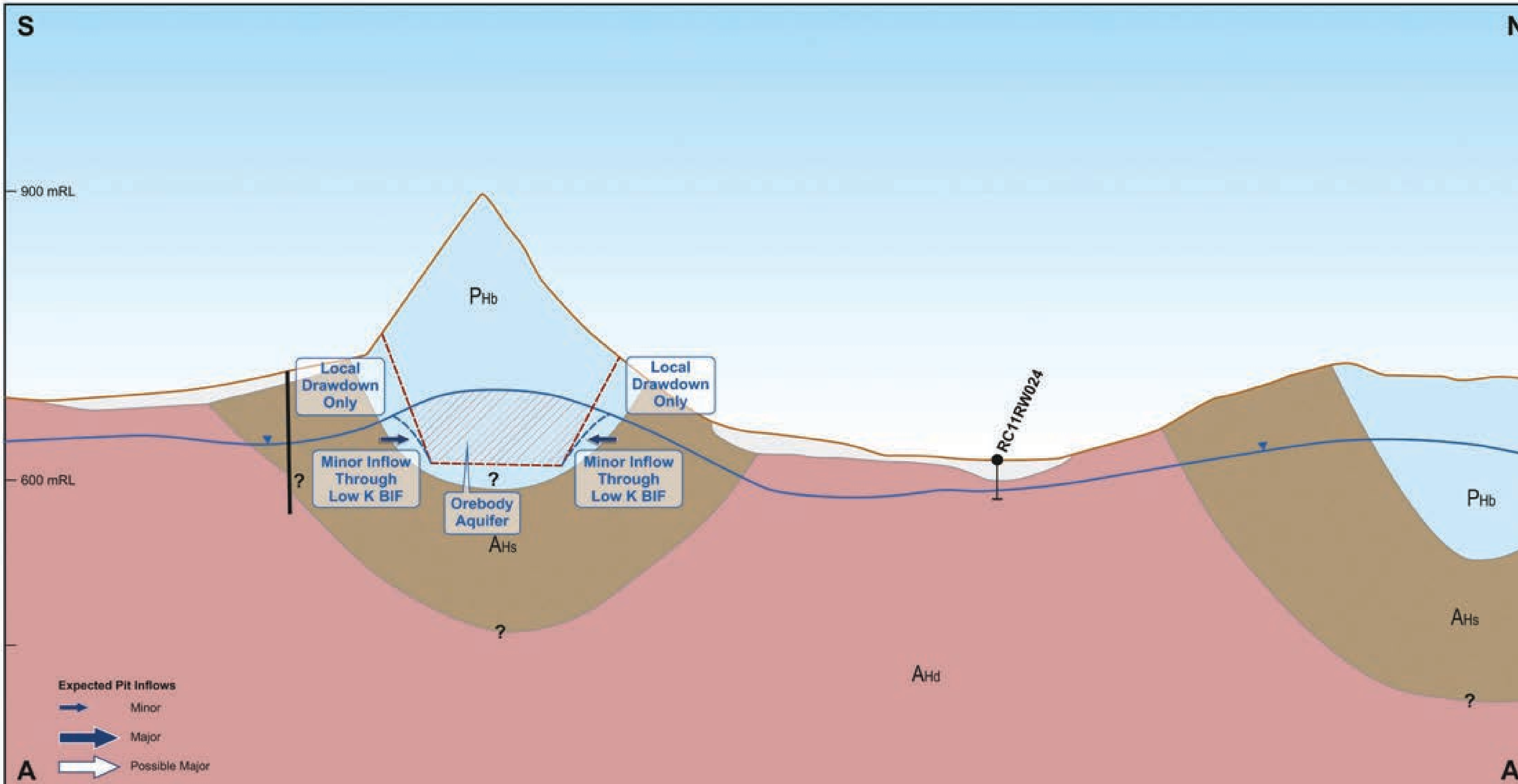
DATA SOURCES:
BHPB Iron Ore

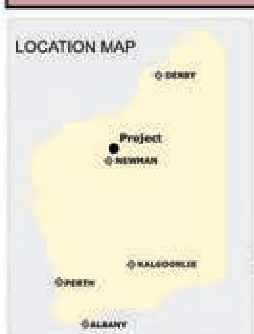
RPS

Figure 5.8

LOCATION PLAN
SOUTH PARMELIA 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 1
Kilometres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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

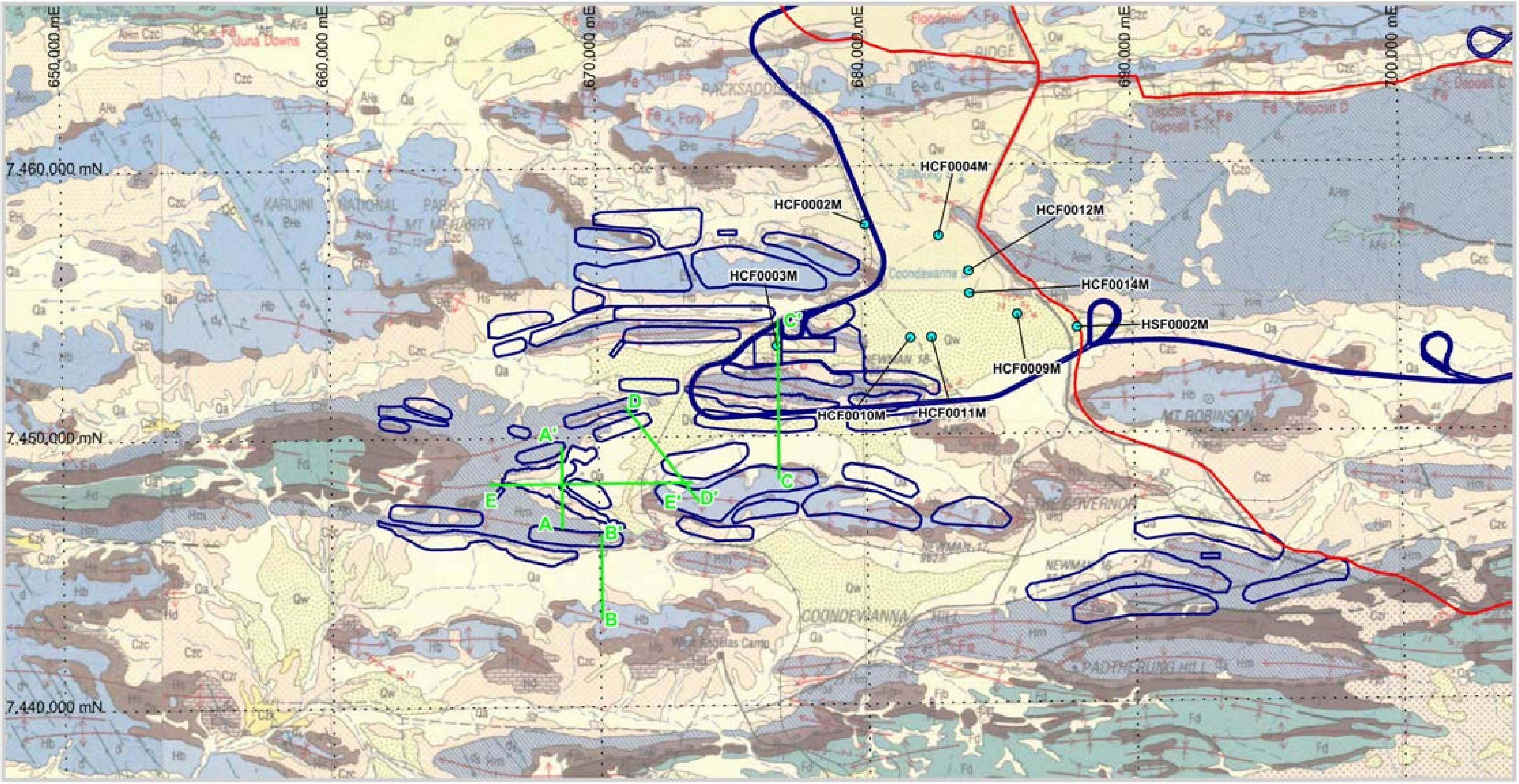
- Ore
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

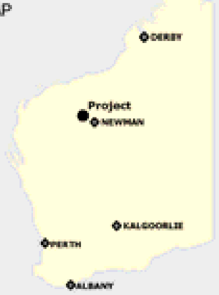
FIGURE 5.9

SECTION A DEWATERING SOUTH PARMELIA MINING AREA

DATA SOURCES:
Input data source here



LOCATION MAP



N

0 2.5 5

Kilometres

Scale: 1:200,000 @A4

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

F:\Jobs\1549F\Spatial_Data\MapInfo\Workspaces\275a\275a Figure 5.10 Mudlark Mining Area.Loc

LEGEND

- Key Bore
- Cross Section Line
- Road
- Indicative BHP Billiton Iron Ore Disturbance
- Rail

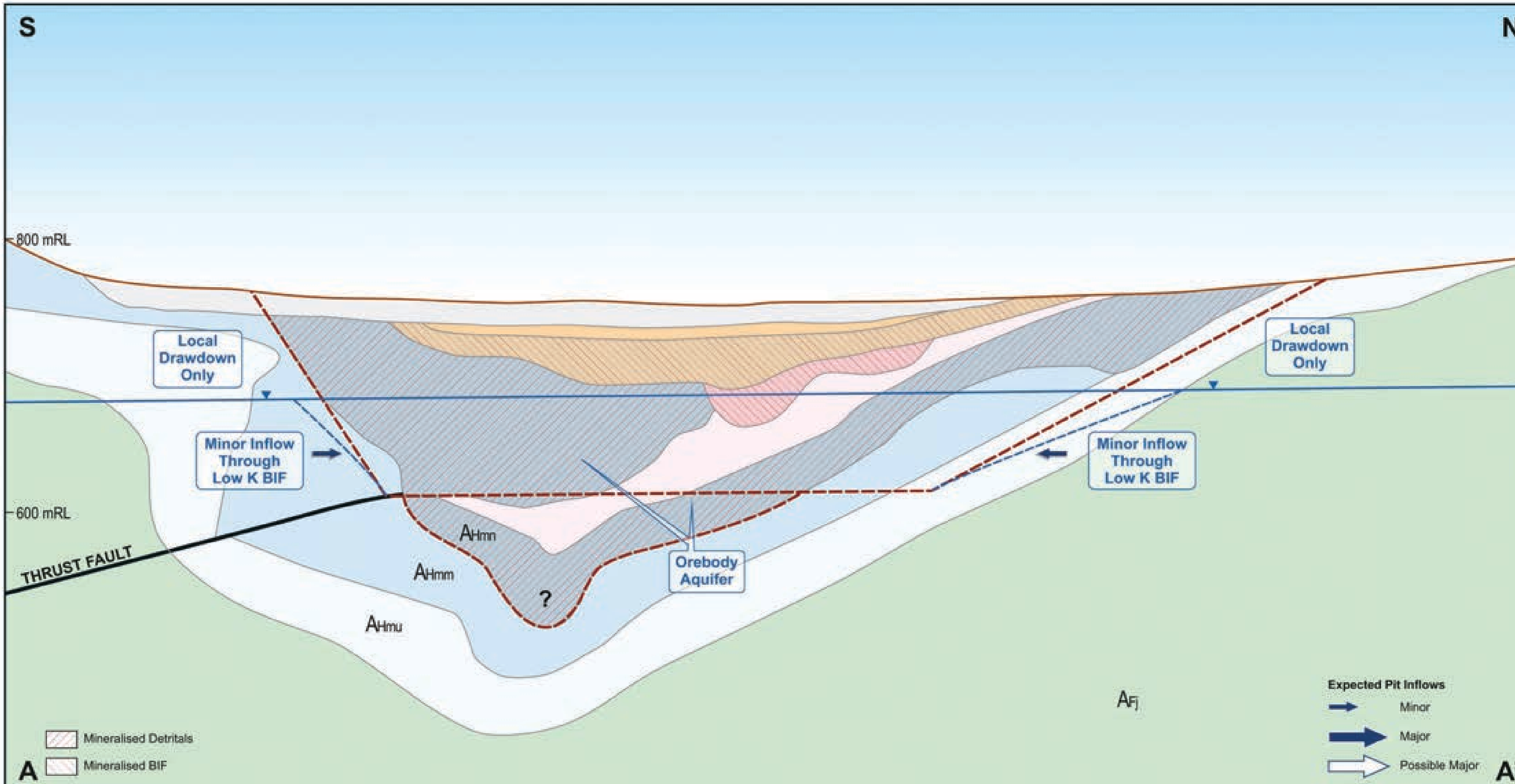
DATA SOURCES:
BHPB Iron Ore

RPS

Figure 5.10

LOCATION PLAN
MUDLARK 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

0 100 200
Metres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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

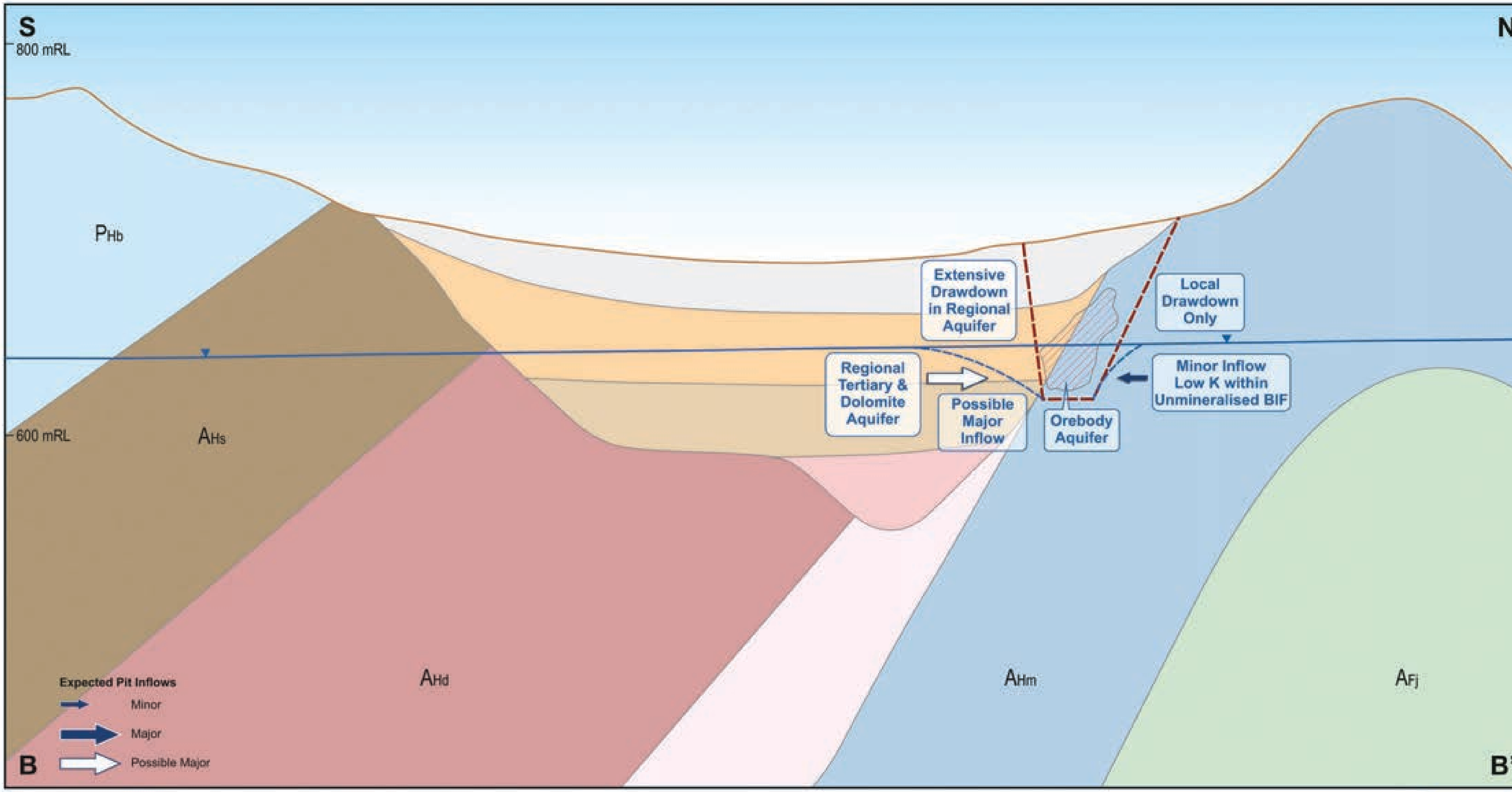
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.11a

SECTION A INFLUENCE OF DEWATERING MUDLARK MINING AREA

DATA SOURCES:
Input data source here



Location: XXXX

0 250 500
Metres

AUTHOR: JP
DRAWN: RC
DATE: 01/09/2015
REPORT NO: 275
REVISION: f
JOB NO: 1549B

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

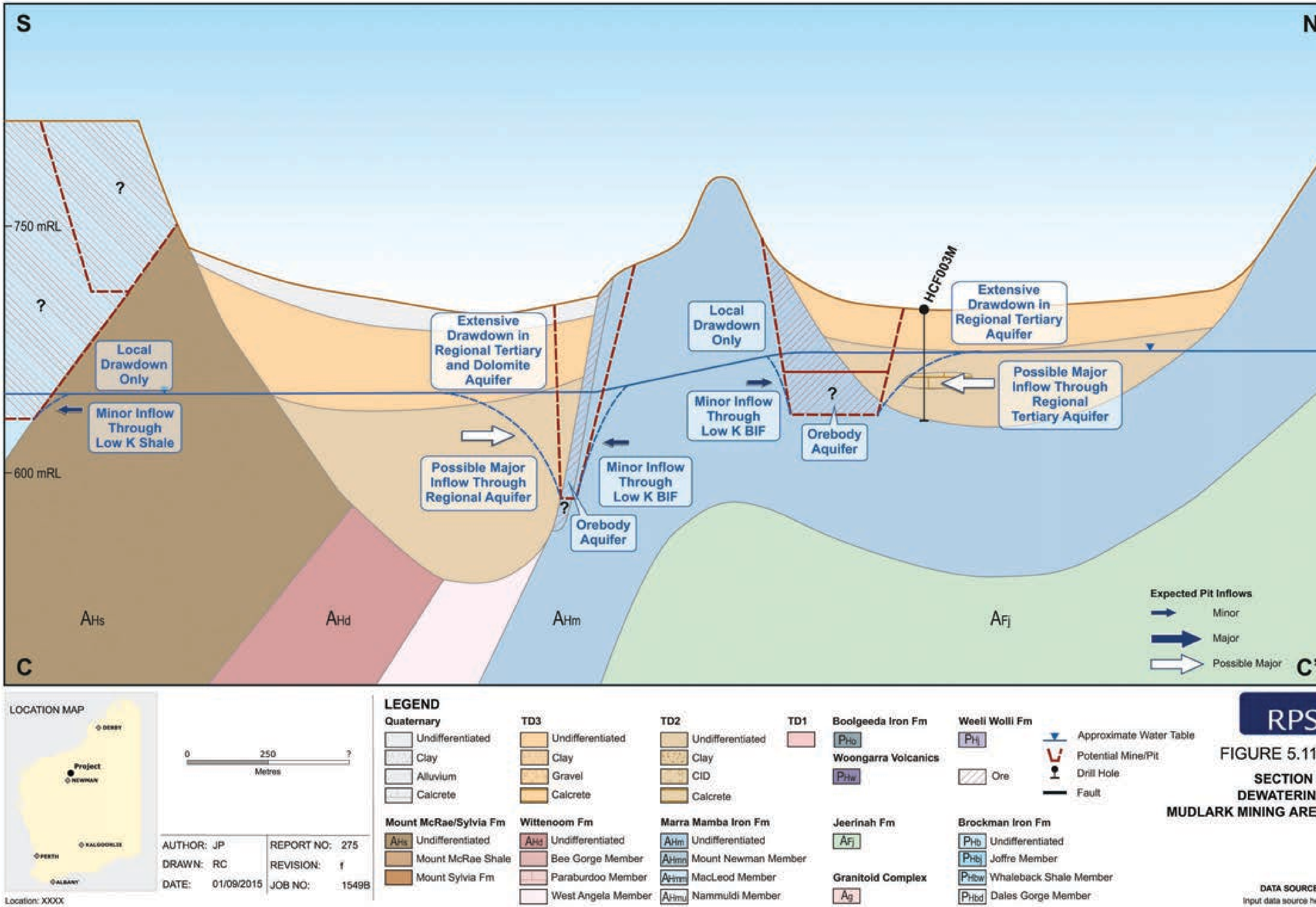
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

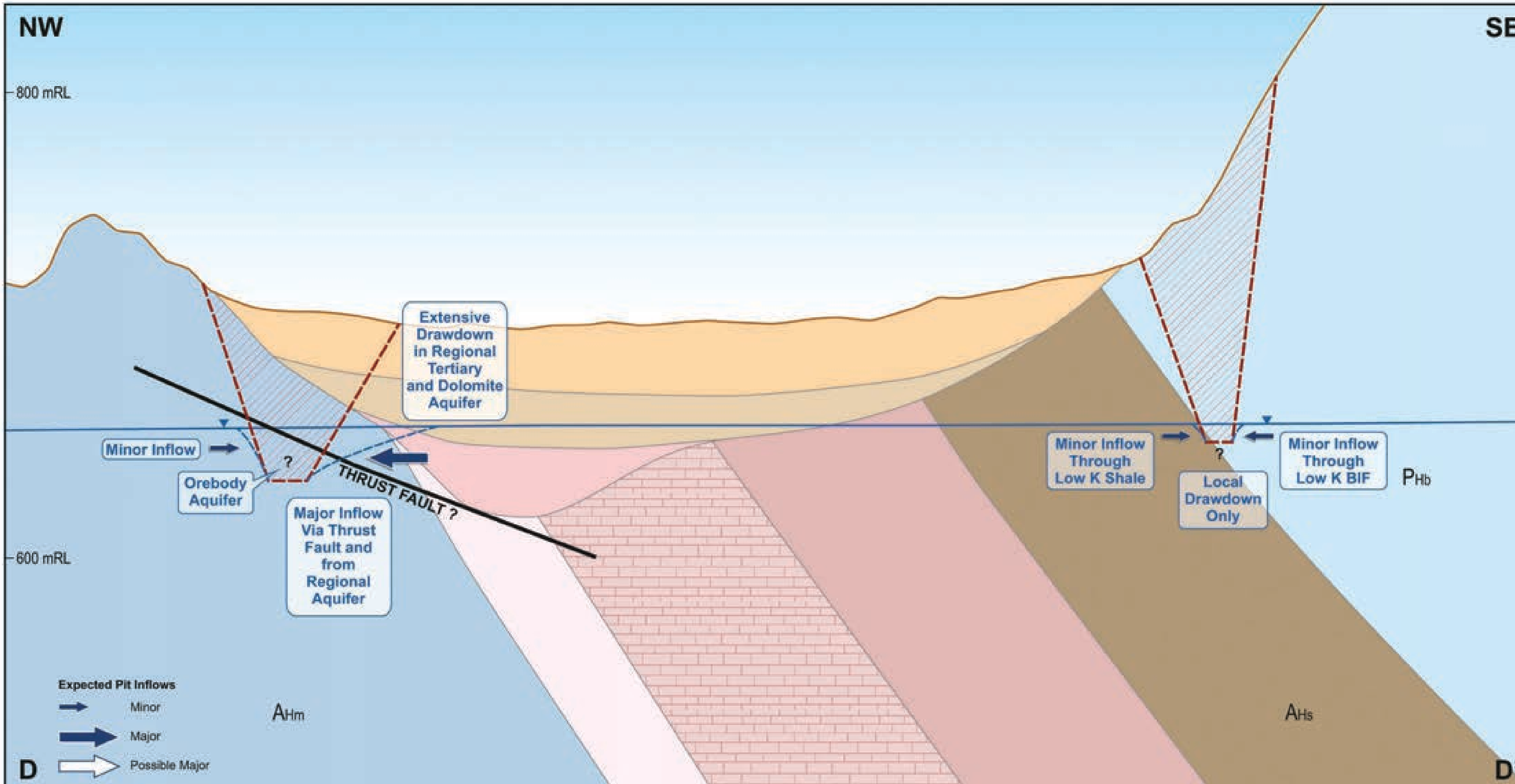
RPS

FIGURE 5.11b

SECTION B INFLUENCE OF DEWATERING MUDLARK MINING AREA

DATA SOURCES:
Input data source here


S
N
750 mRL
600 mRL
?
?
Local Drawdown Only
Minor Inflow Through Low K Shale
Extensive Drawdown in Regional Tertiary and Dolomite Aquifer
Possible Major Inflow Through Regional Aquifer
?
Orebody Aquifer
Minor Inflow Through Low K BIF
Local Drawdown Only
Minor Inflow Through Low K BIF
?
Orebody Aquifer
HCF003M
Extensive Drawdown in Regional Tertiary Aquifer
Possible Major Inflow Through Regional Tertiary Aquifer
AHs
AHd
AHm
AFj
Expected Pit Inflows
Minor
Major
Possible Major
C
C'
LOCATION MAP
DERBY
Project
NEWMAN
KALGOORLIE
PERTH
ALBANY
Location: XXXX
0
250
?
Metres
AUTHOR: JP
DRAWN: RC
DATE: 01/09/2015
REPORT NO: 275
REVISION: f
JOB NO: 1549B
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
DEWATERING
MUDLARK MINING AREA
DATA SOURCES:
Input data source here



Location: XXXX

0 250 500
Metres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	1
DATE:	01/09/2015	JOB NO:	1549B

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
- Thrust 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

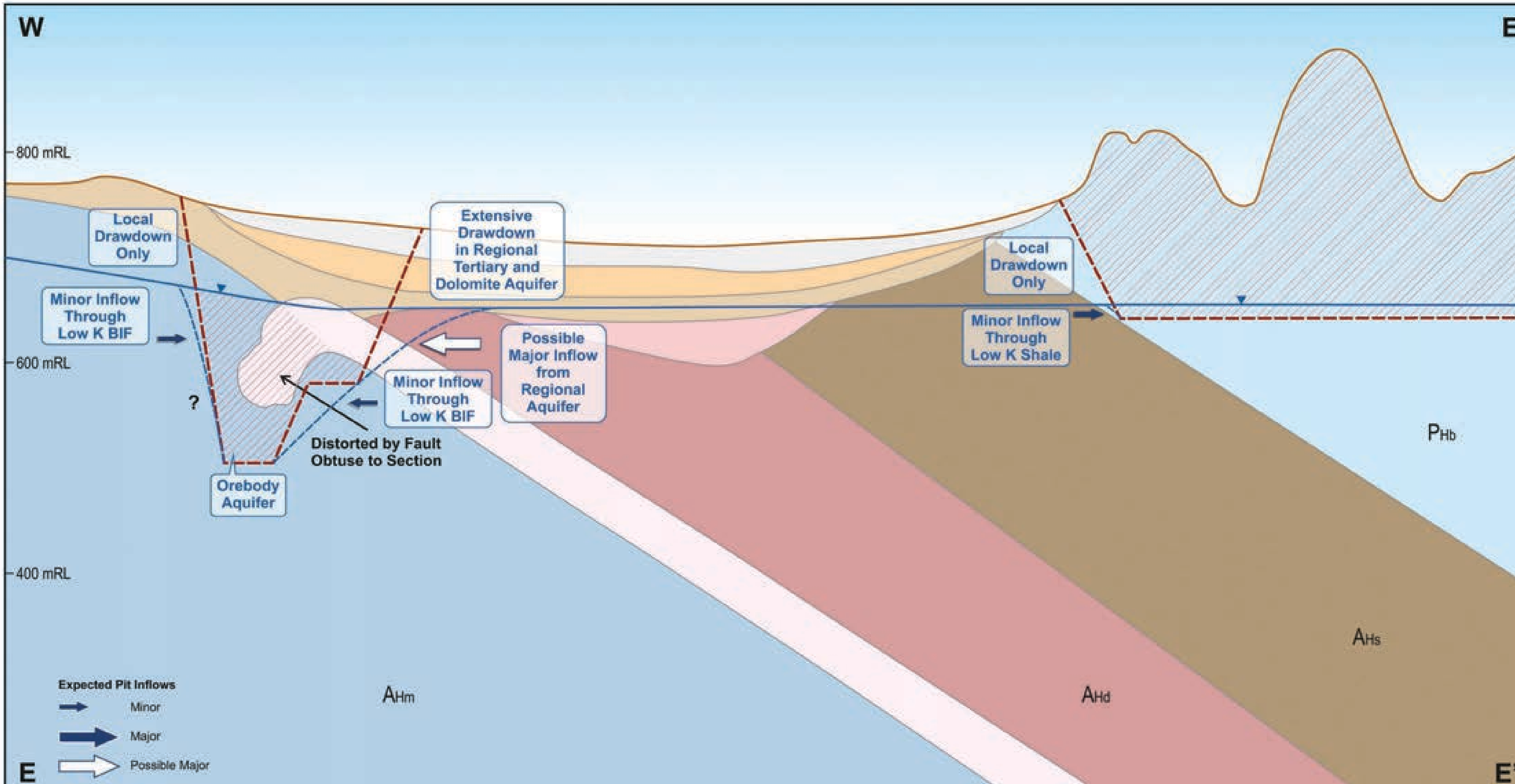
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

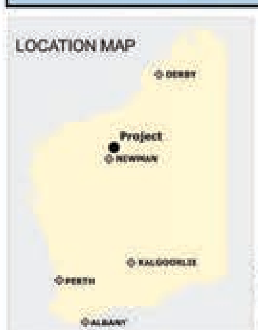
RPS

FIGURE 5.11d

SECTION D DEWATERING MUDLARK MINING AREA

DATA SOURCES:
Input data source here





Location: XXXX

0 — 1
Kilometre

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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

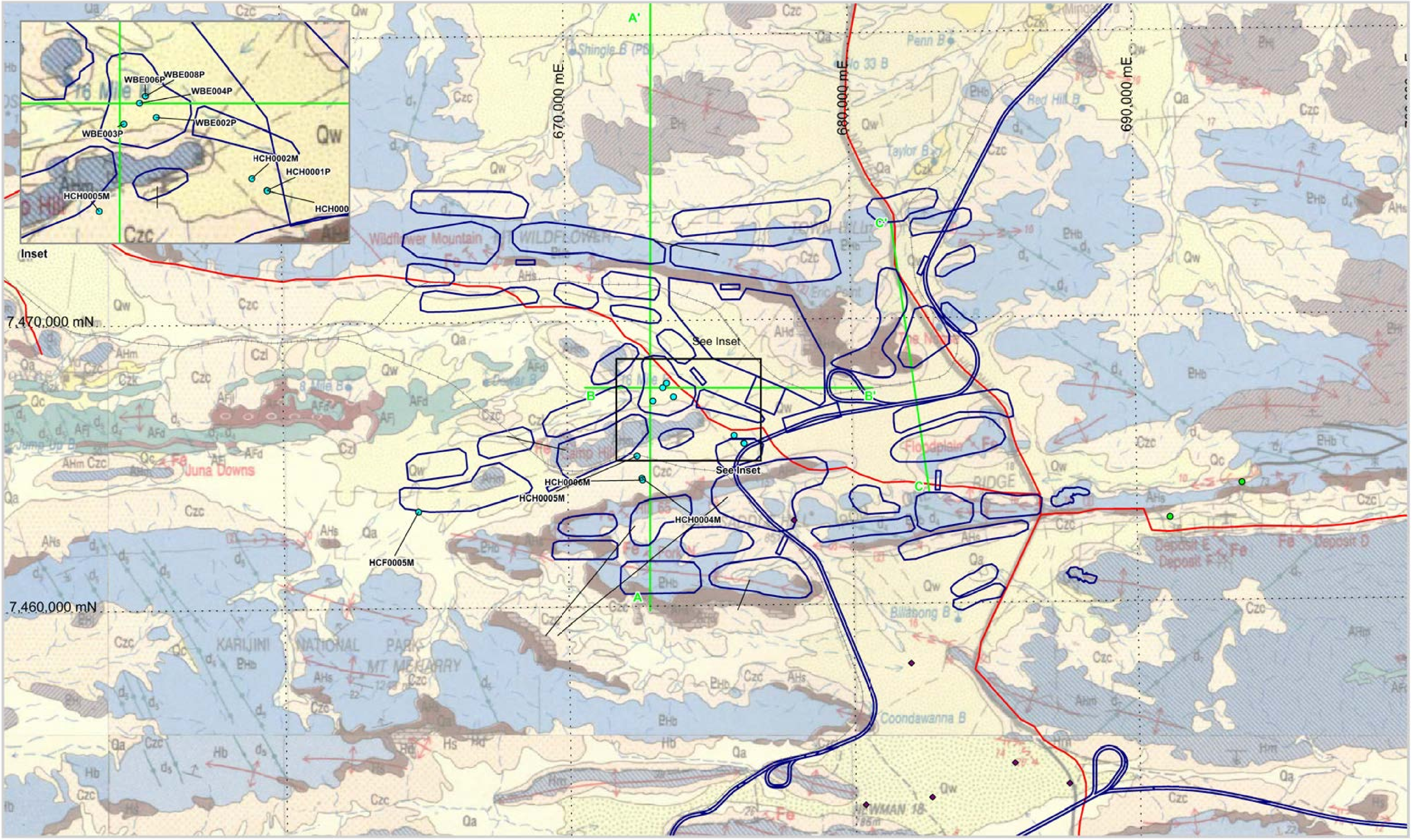
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.11e

SECTION E INFLUENCE OF DEWATERING MUDLARK MINING AREA

DATA SOURCES:
Input data source here



N

0 2 4 6

Kilometres

Scale: 1:125,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	f
DATE:	05/05/2015	JOB NO:	1549B

Location: F:\Jobs\1549F\Spatial_Data\Working\MapInfo\Workspaces\275a Figure 5.12 Tandanya Mining - Recom

LEGEND

- Key Bore
- BHPBIO Surface Water Position (Water Level)
- BHPBIO Surface Water Quality Sampling Location
- Cross Section Line
- Road
- Indicative BHP Billiton Iron Ore Disturbance
- Rail

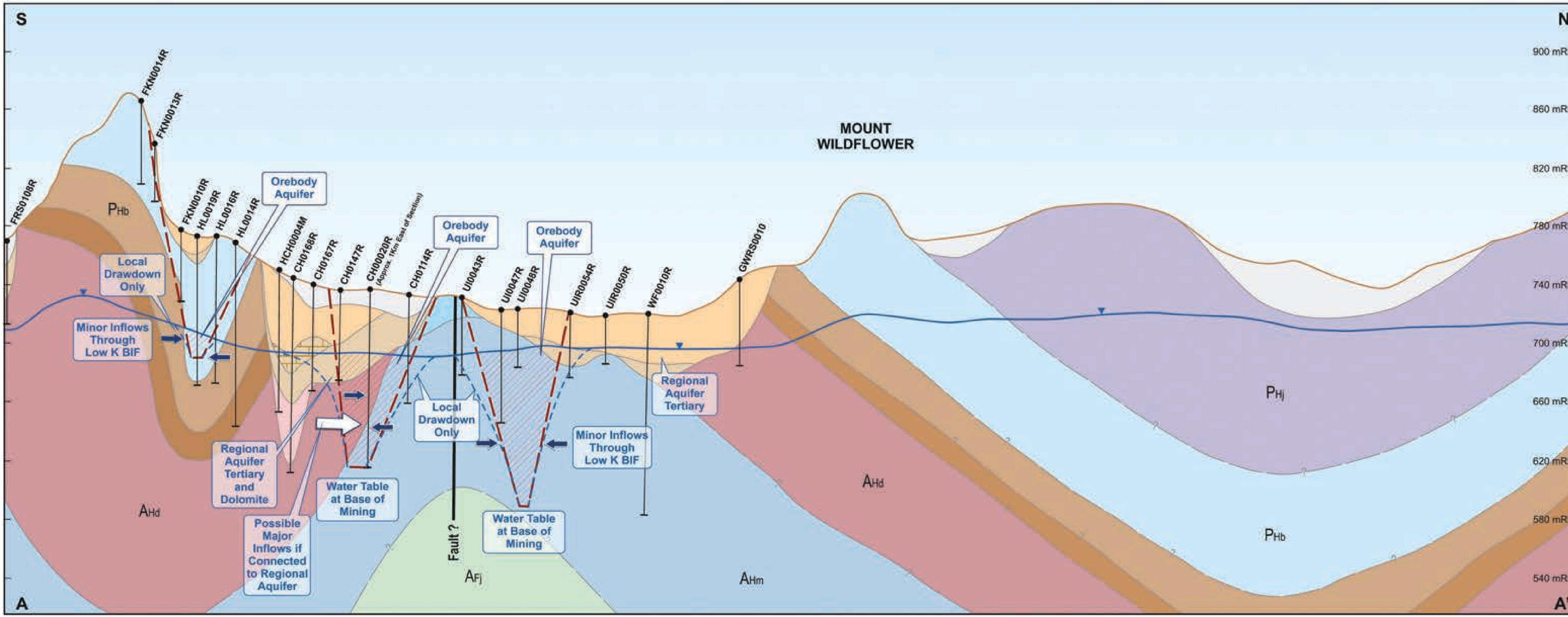
DATA SOURCES:
BHPB Iron Ore

RPS

FIGURE 5.12

LOCATION PLAN
TANDANYA 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 1 2
Kilometres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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

Expected Pit Inflows
- Minor
- Major
- Possible Major

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 5.13a

SECTION A INFLUENCE OF DEWATERING TANDANYA MINING AREA

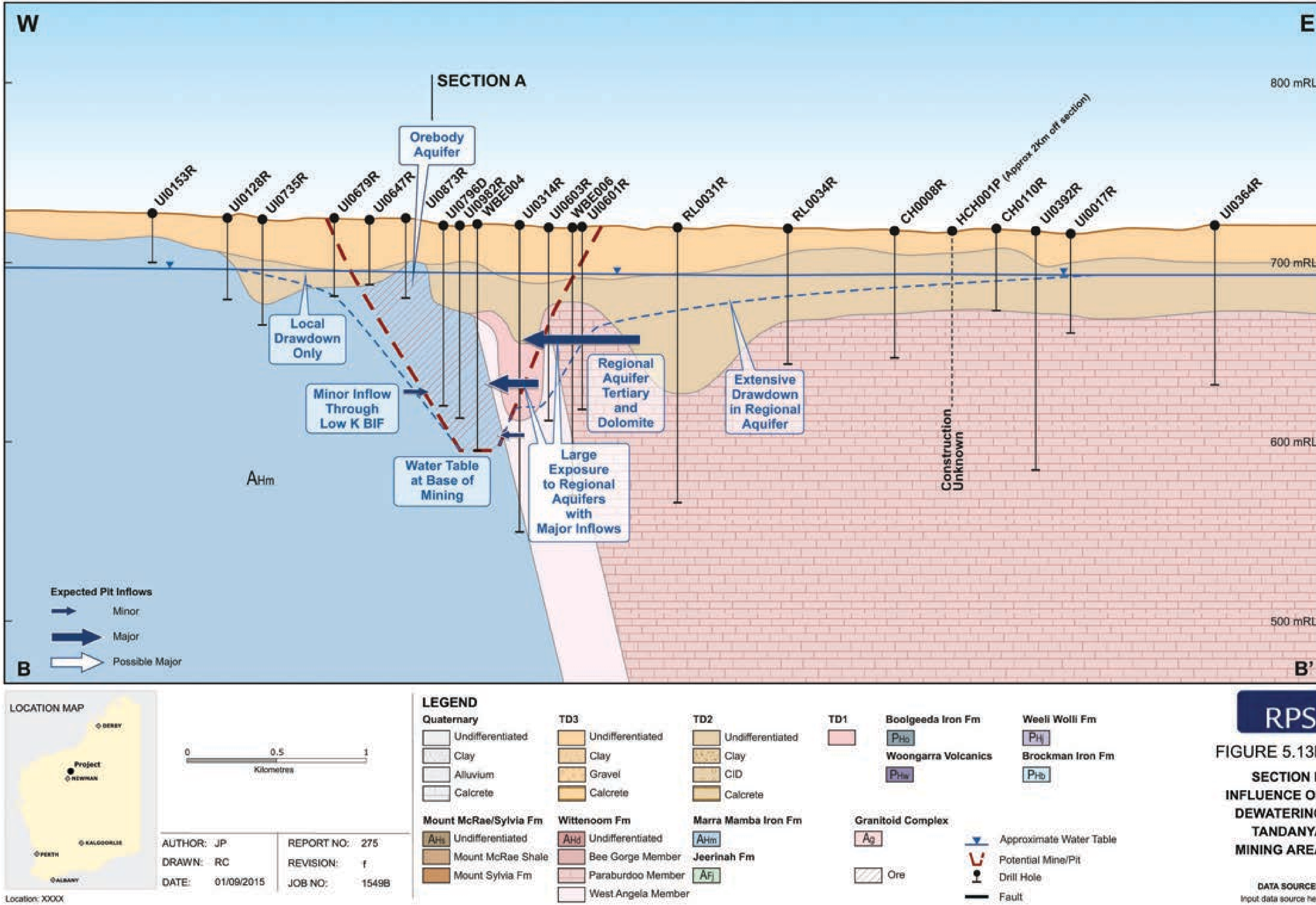
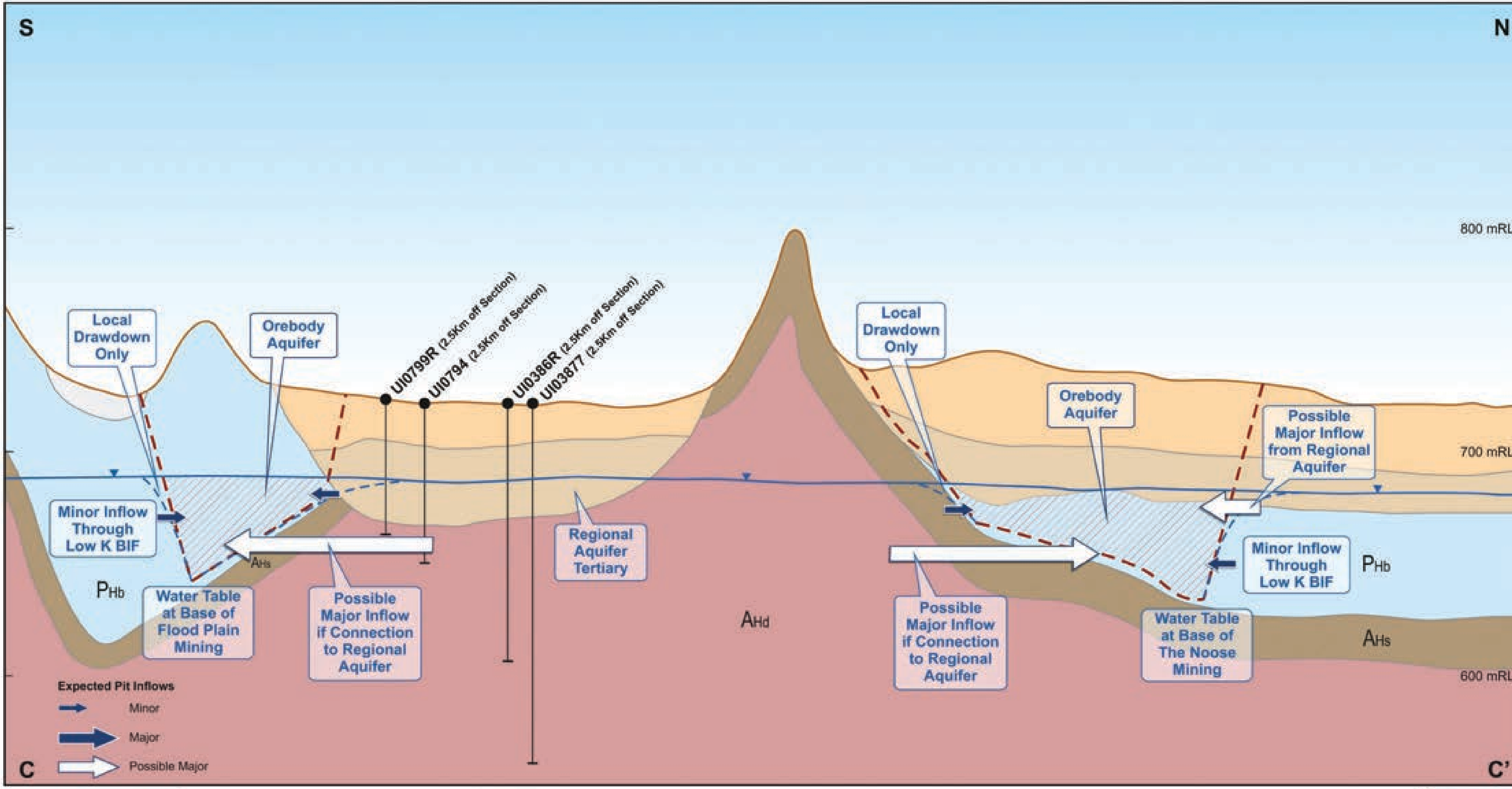


FIGURE 5.13b

SECTION B
INFLUENCE OF
DEWATERING
TANDANYA
MINING AREA



Location: XXXX

0 0.5 1
Kilometres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	f
DATE:	01/09/2015	JOB NO:	1549B

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

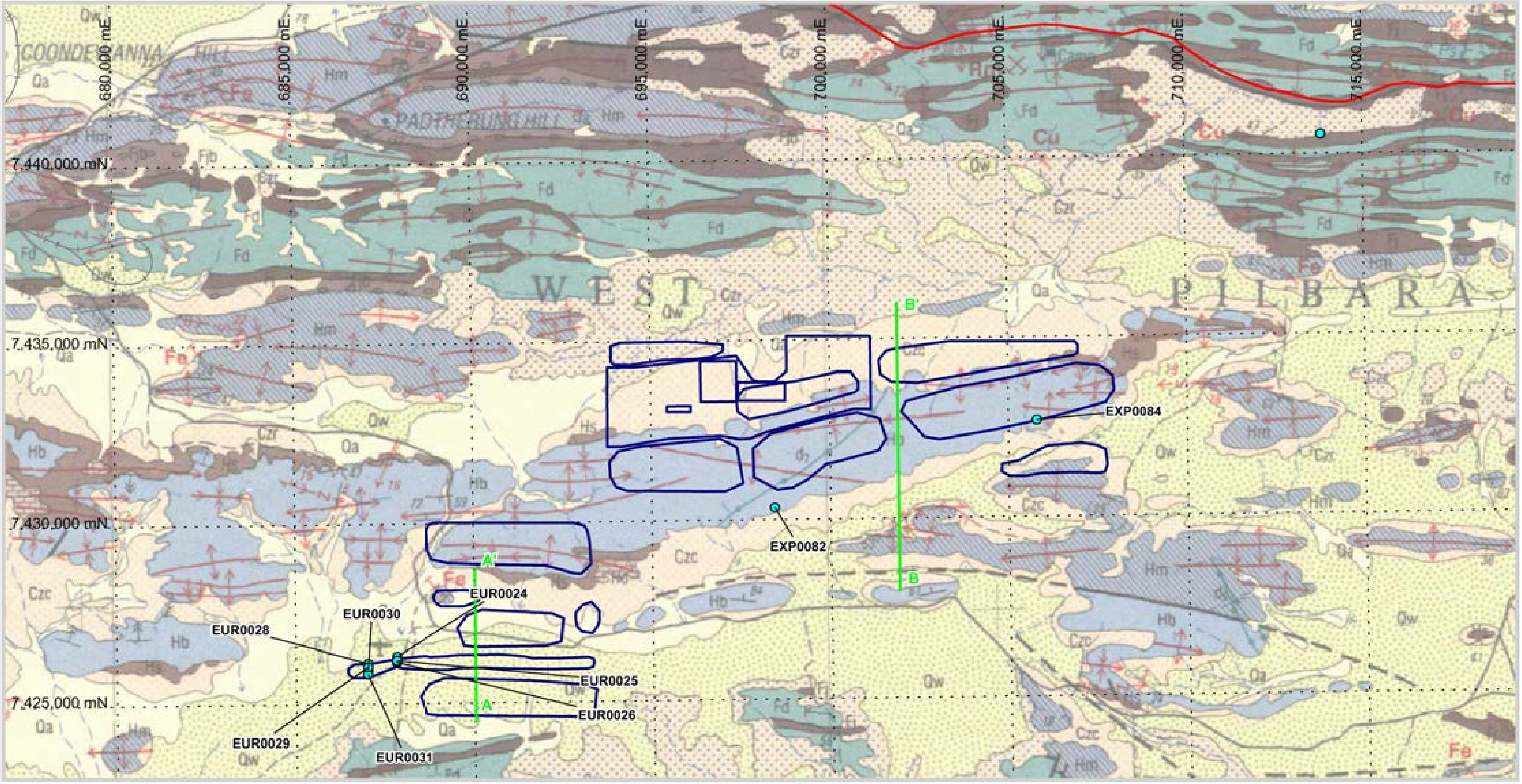
- Approximate Water Table
- Potential Mine/Pit
- Drill Hole
- Fault

RPS

FIGURE 5.13c

SECTION C INFLUENCE OF DEWATERING TANDANYA MINING AREA

DATA SOURCES:
Input data source here



N

0 5

Kilometres

Scale: 1:150,000 @A4

GDA 1994 Zone 50

AUTHOR: AW	REPORT NO: 275
DRAWN: MR	REVISION: f
DATE: 01/09/2015	JOB NO: 1549B

F:\Jobs\1549F\Spatial_Data\MapInfo\Workspaces\275a\275a Figure 5.14 Gurinbiddy Mining Area.Loc

LEGEND

- Key Bore
- Cross Section Line
- Indicative BHP Billiton Iron Ore Disturbance
- Road
- Rail

DATA SOURCES:
BHPB Iron Ore

RPS

Figure 5.14

LOCATION PLAN
GURINBIDDY MINING AREA

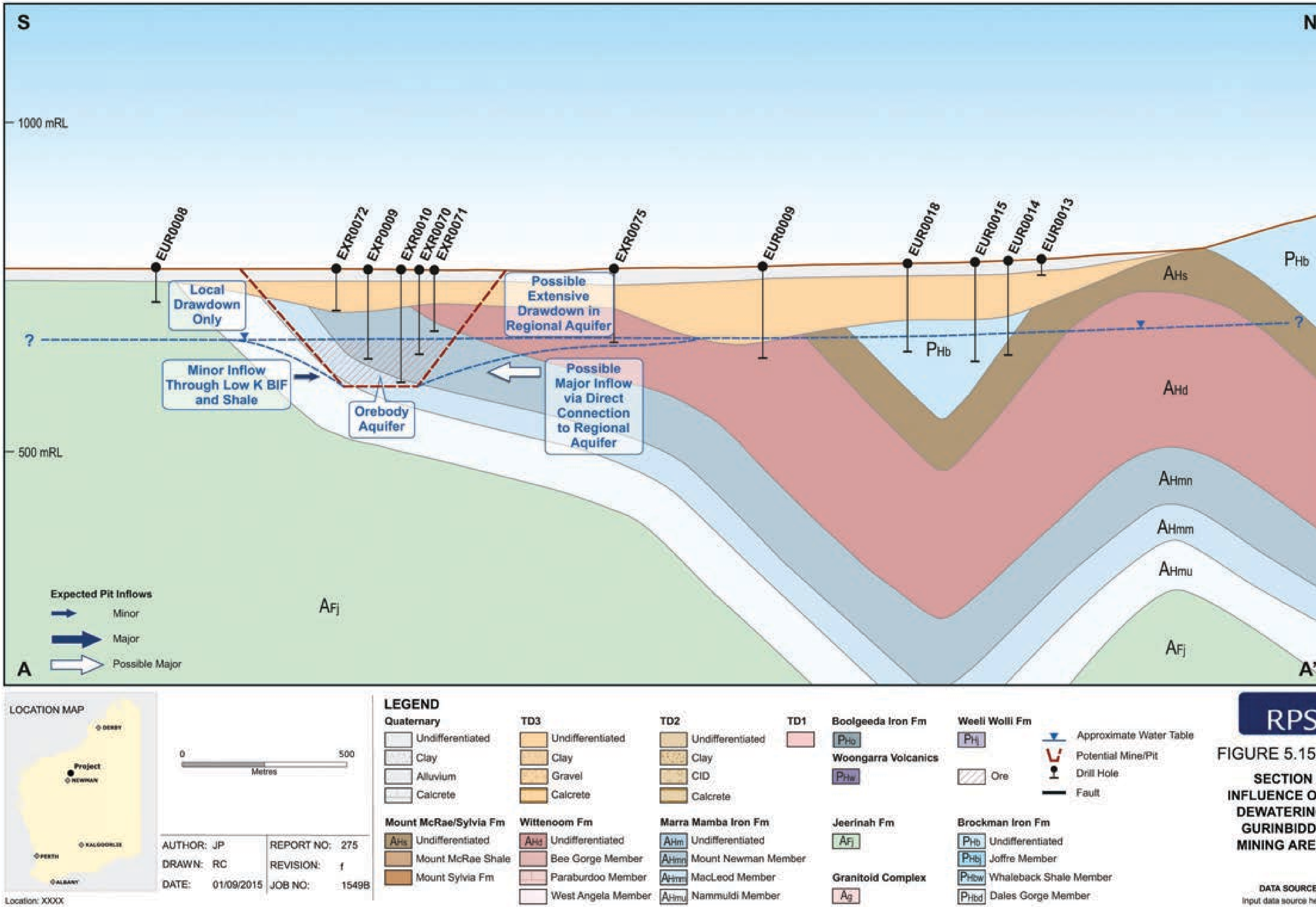
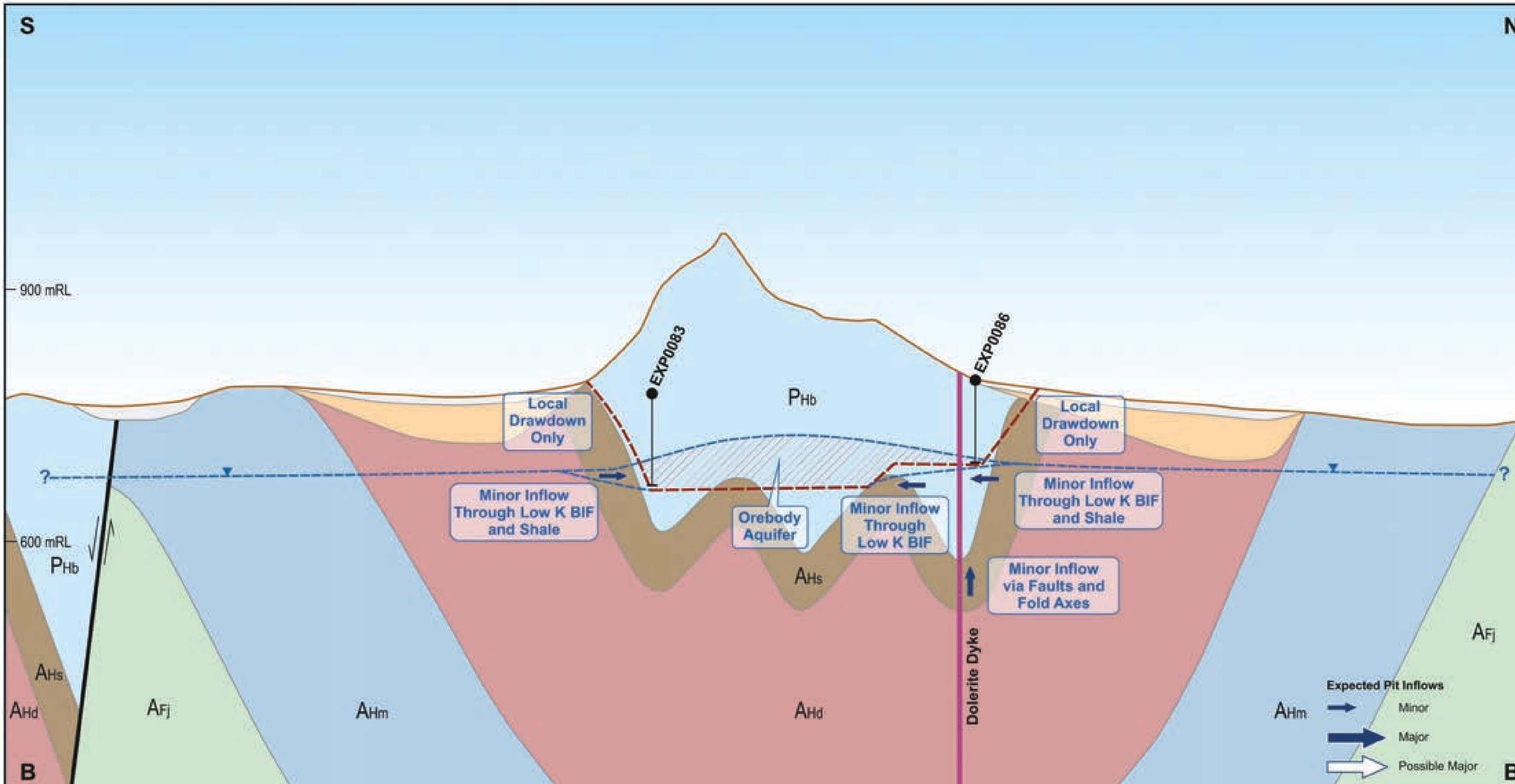


FIGURE 5.15a

SECTION A
INFLUENCE OF DEWATERING
GURINBIDDY MINING AREA



Location: XXXX

0 250
Metres

AUTHOR:	JP	REPORT NO:	275
DRAWN:	RC	REVISION:	1
DATE:	01/09/2015	JOB NO:	1549B

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

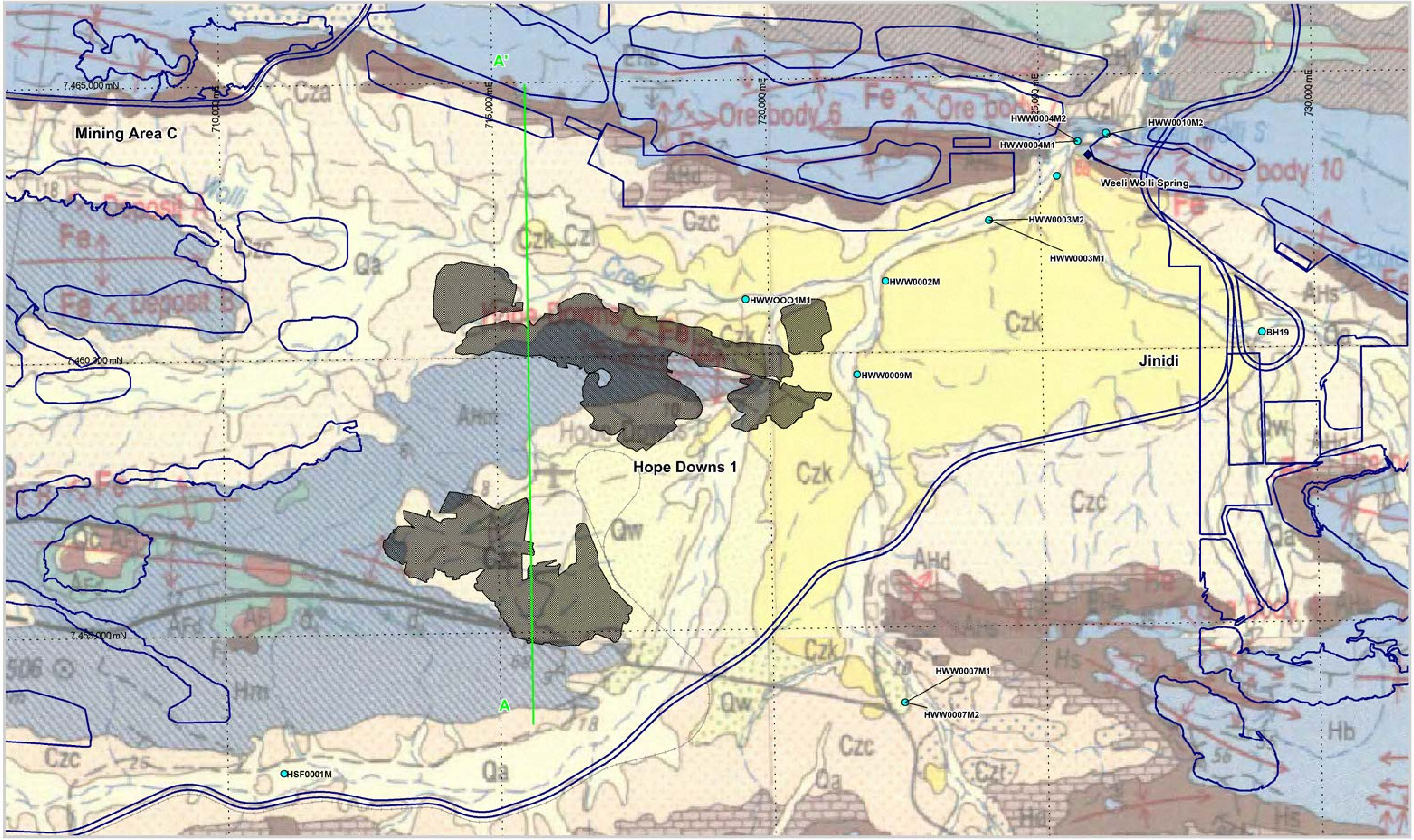
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.15b

SECTION B INFLUENCE OF DEWATERING GURINBIDDY MINING AREA

DATA SOURCES:
Input data source here



N

0 1 2.5

Kilometres

Scale: 1:65,000 @A3

GDA 1994 Zone 50

AUTHOR: RS	REPORT NO: 275
DRAWN: MR	REVISION: f
DATE: 05/05/2015	JOB NO: 1549B

Location: F:\Jobs\1549F\Spatial_Data\MapInfo\Workspaces\275a\Hope Downs\275a Fig 5.16 location map

LEGEND

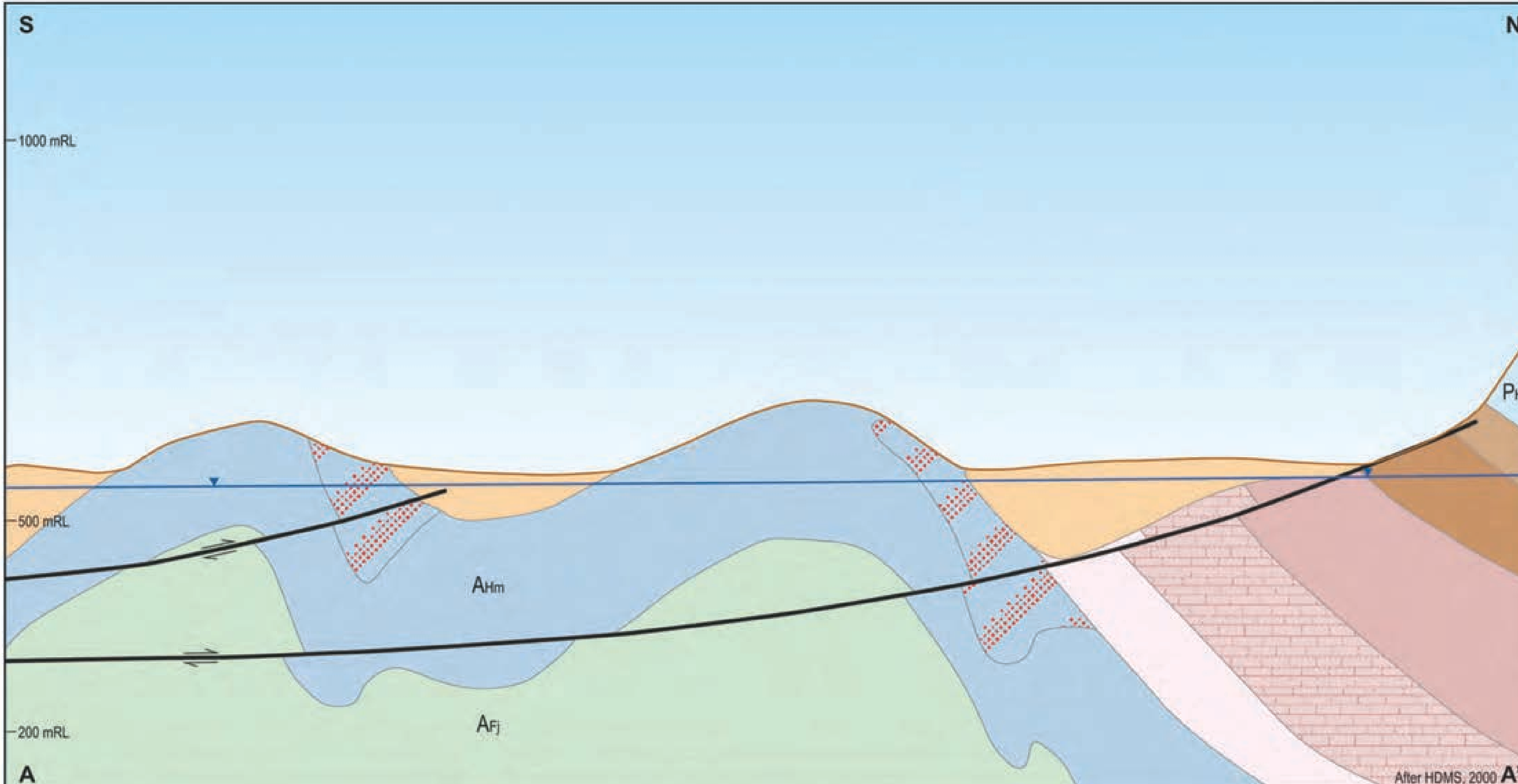
- Key Bore
- Environmental Asset
- Section Line
- Indicative BHP Billiton Iron Ore Disturbance
- Existing Third Party Disturbance
- Rail

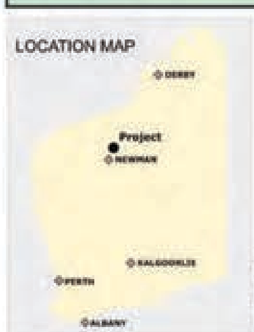
DATA SOURCES:
BHPBIO

RPS

FIGURE 5.16

LOCATION PLAN
HOPE DOWNS





Location: XXXX

NOT TO SCALE

AUTHOR: JP
DRAWN: RC
DATE: 01/09/2015
REPORT NO: 275
REVISION: f
JOB NO: 1549B

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

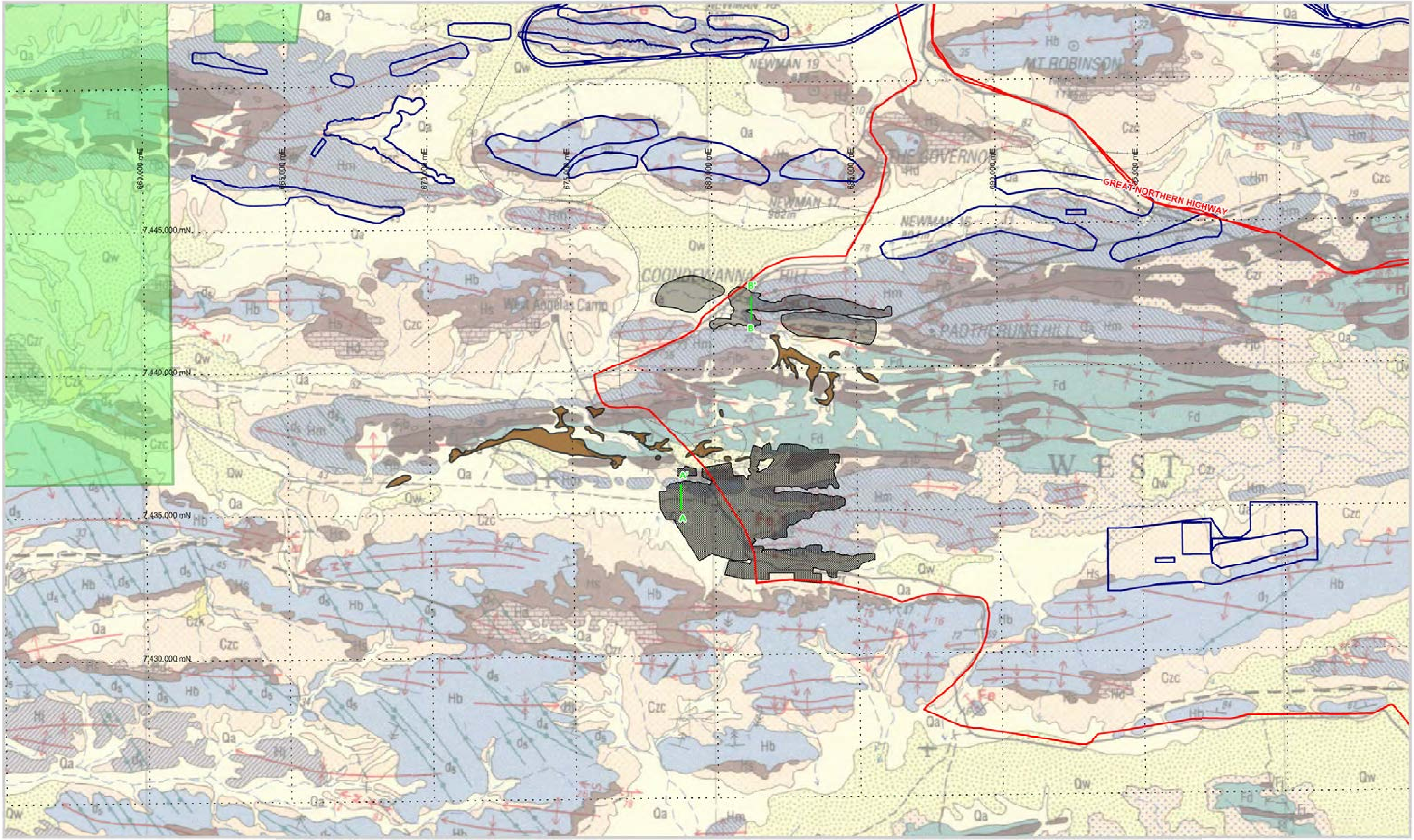
Brockman Iron Fm
- PHb Undifferentiated
- PHbj Joffre Member
- PHbw Whaleback Shale Member
- PHbd Dales Gorge Member

RPS

FIGURE 5.17

SCHEMATIC SECTION A HOPE DOWNS MINING AREA

DATA SOURCES:
Hope Downs Management Services (2000) PER



N

0 5

Kilometres

Scale: 1:125,000 @A3

GDA 1994 Zone 50

AUTHOR:	JP	REPORT NO:	275
DRAWN:	MR	REVISION:	I
DATE:	01/09/2015	JOB NO:	1549B

Location: F:\Jobs\1549B\Spatial_Data\Mapinfo\Workspaces\275c Figure 5.54

LEGEND

- Geological Cross Section
- Road
- Indicative BHP Billiton Iron Ore Disturbance
- Existing Third Party Disturbance
- Third Party Reasonable Forseeable Disturbance
- West Angelas Cracking Clay
- National Park Boundary
- Rail

DATA SOURCES:
BHPB Iron Ore

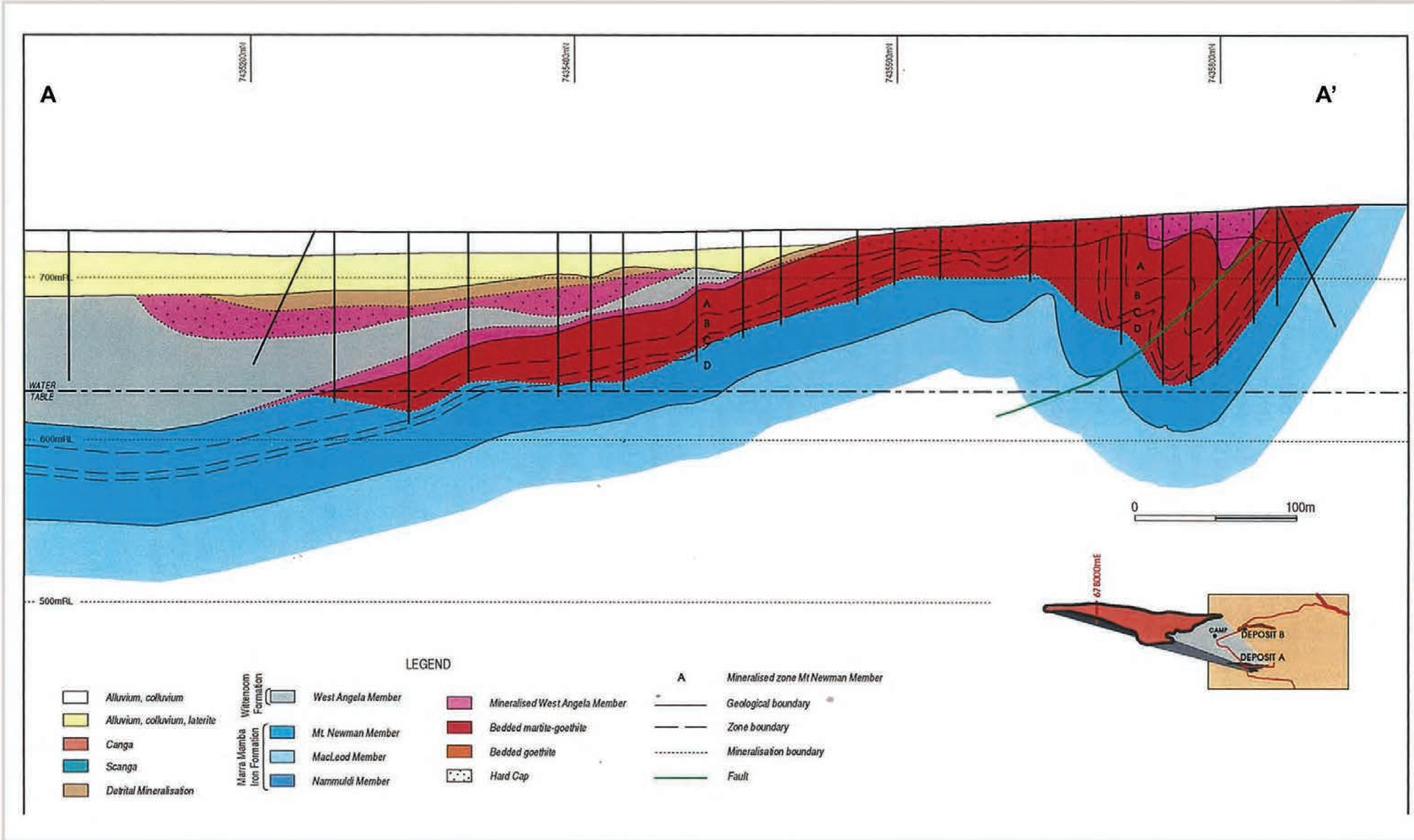
RPS

FIGURE 5.18

LOCATION PLAN
WEST ANGELAS 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



N

LEGEND

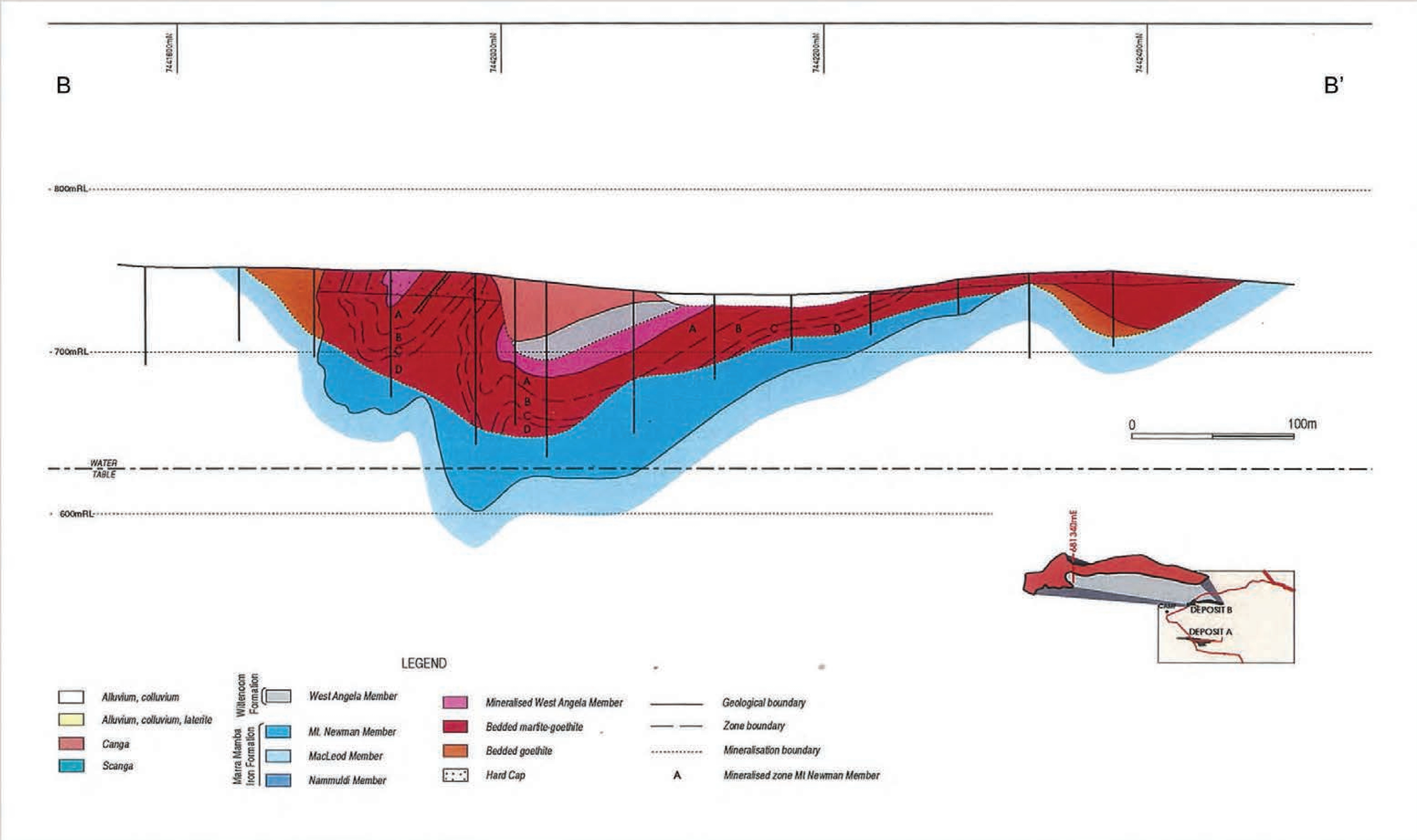
AUTHOR: JP	REPORT NO: 275
DRAWN: MR	REVISION: c
DATE: 15/10/2014	JOB NO: 1549B

Location: F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\275c\275c Fig 5.55

DATA SOURCES:
Ecologia

RPS

FIGURE 5.19
WEST ANGELAS DEPOSIT A GEOLOGICAL CROSS SECTION



LOCATION MAP

N

AUTHOR: JP
DRAWN: MR
DATE: 15/10/2014
REPORT NO: 275
REVISION: c
JOB NO: 1549B

LEGEND

DATA SOURCES:
Ecologia

Location: F:\Jobs\1549B\Spatial_Data\MapInfo\Workspaces\275c\275c Fig 5.56

RPS

FIGURE 5.20

WEST ANGELAS DEPOSIT B
GEOLOGICAL CROSS SECTION

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