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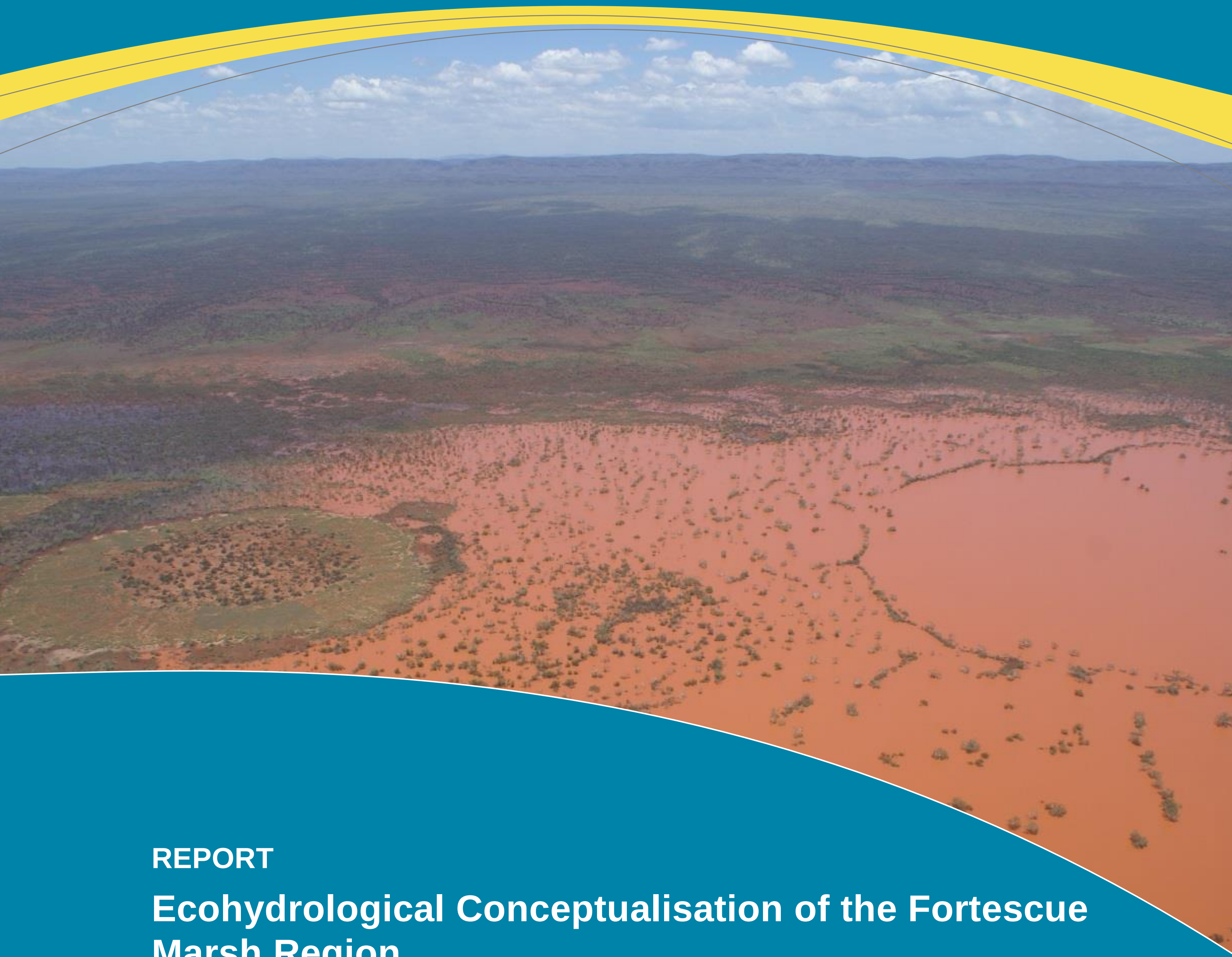

REPORT

Ecohydrological Conceptualisation of the Fortescue Marsh Region

Prepared for BHP Billiton Iron Ore

September 2015

This report 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 (Cth) 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 in this report 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 report.

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Executive Summary

Introduction

This report describes an ecohydrological conceptualisation of the Fortescue Marsh (the Marsh) Region and surrounding catchment areas. The project extent was defined based on catchment scale hydrology and the position of BHP Billiton Iron Ore's proposed mining projects within the vicinity of the Marsh.

It covers an area of 11,971 km^2 bound by the Chichester Range in the north; the Upper Fortescue River to the east; the Hamersley Range to the south; and a surface water and inferred groundwater divide in the west that separates the Goodiadarrie Swamp from the Lower Fortescue River. Despite BHP Billiton Iron Ore having no current mining operations near the Marsh, there are several proposed mining areas including Marillana, Mindy, Coondiner, and Roy Hill.

Study objectives

The objectives were to provide:

- an understanding of the natural water resource system (hydrology and hydrogeology), and key ecohydrological components, linkages and processes;
- a basis for assessing potential hydrological change associated with BHP Billiton Iron Ore operations (current and future) on the water resources, with particular focus on the interaction between key environmental receptors and the orebodies; and
- a knowledge foundation for future numerical modelling of ecohydrological processes associated with the Marsh and surrounding areas.

Ecohydrological conceptualisation

Nine landscape ecohydrological units (EHUs) were defined. Each EHU represents a landscape element with broadly consistent and distinctive ecohydrological attributes being summarised as.

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

Existing environment

The climate of the study area is semi-arid to arid, characterised by high temperatures and low, irregular rainfall. Most rainfall occurs between December and March in association with tropical cyclones and localised thunderstorms.

The east-west trending Fortescue River Valley separates the Hamersley Range (to the south) and Chichester Range (to the north). The Marsh is a brackish to saline, endorheic wetland formed in the drainage terminus of the Upper Fortescue River within the Fortescue Valley. The Goodiadarrie Hills form the catchment divide between the Upper and Lower Fortescue River catchments. Immediately west of the Goodiadarrie Hills, a series of freshwater claypans constitute the Freshwater Claypans of the Fortescue Valley Priority Ecological Community (PEC) occur in proximity to the Fortescue River channel.

The basement geology is dominated by the Hamersley Group which consists of various metasedimentary rocks including cherty banded iron formation, chert and carbonates interbedded with minor felsic volcanic rock and intruded by dolerite dykes. The Fortescue Valley is a flat-lying, complex sequence of Quaternary and Tertiary alluvial, colluvial and lacustrine sediments overlying the basement. The alluvial deposits increase in thickness away from the ranges towards the Marsh.

The vegetation of the Hamersley and Chichester Ranges is typically open and dominated by spinifex, acacia small trees and shrubs, and occasional eucalypts. On the flats of the Fortescue Valley surrounding the Marsh, the vegetation is a mosaic of spinifex grasslands and Acacia woodlands and shrublands. This includes areas of groved Mulga and Snakewood formations. The major drainages are fringed by eucalypt woodlands and tussock grassland communities.

The Marsh consists of sparsely vegetated, clay flats fringed by samphire vegetation communities. It is the largest ephemeral wetland in the Pilbara and has multiple conservation values. The Marsh is classified as a wetland of national importance within the Directory of Important Wetlands in Australia and contains a number of Priority Ecological Communities (PEC).

In July 2013, the EPA defined a Fortescue Marsh Management Area consisting of seven sub-zones partitioned into three conservation significance categories (EPA Report 1484; EPA 2013). The project area encompasses the management zones identified in the Fortescue Marsh Management Area. Portions of the Marsh have been identified for transition into conservation tenure and management, in relation to the expiry of pastoral leases in 2015.

Regional hydrology

Catchment areas contributing flows to the Marsh include downstream portions of the Fortescue River and Weeli Wolli Creek catchments, as well as Koodaideri, Chuckalong (between Weeli Wolli Creek and Mindy Mindy Creek), Coondiner and Mindy Mindy Creeks. There are minor surface water contributions from Goman, Sandy, Christmas, Kulbee, and Kulkinbah Creeks.

The Marsh itself consists of two basin areas (east and west) separated by a slightly elevated divide. The Upper Fortescue River provides the majority of surface water flow to the Marsh, with a catchment area of approximately 31,000 km2.The surface water hydrology is characterised by variable rainfall-runoff response with lower rainfall-runoff response associated with deeper soils and flatter areas, such as the Flat Rocks catchment; and higher rainfall-runoff response associated with steeper slopes and shallower soils, such as the Newman catchment.

Groundwater

The regional aquifer system is hosted in Tertiary detritals and underlying Wittenoom Formation (dominated by dolomite of the Paraburdoo Member). Tertiary calcrete or pisolitic limonite formed within valley-fill sequences is often highly permeable. The flanks of the valley rise into ranges comprising fractured-rock aquifers of low permeability and storage. In places, these basement rocks have more transmissive sections associated with orebodies and form localised aquifers. The extent of these orebody aquifers and their connectivity with larger groundwater flow systems may be enhanced by faulting or erosion or other structural features, and as such can vary widely and is site specific.

Depth to groundwater varies being shallowest beneath the Fortescue Marsh and deeper towards the flanks of the Fortescue Valley and adjacent ranges. Groundwater contribution to the Fortescue Marsh water balance is minor when compared to surface water contributions; however, the Marsh is underlain by a large storage of saline to hypersaline groundwater. Recharge is associated with major cyclonic events that are episodic and relatively short-lived resulting in some short-term mounding within the shallow groundwater system.

Key receptors

Environmental assets with a high level of connectivity to the hydrological system are considered to be ecohydrological receptors. In the project area, these include the Fortescue Marsh and the Freshwater Claypans of the Fortescue Valley PEC. The key ecohydrological features of these key receptors are:

Fortescue Marsh

- The Fortescue Marsh is an internally draining wetland feature. Much of its interior consists of sparsely vegetated clay flats within a series of low elevation flood basins. Fringing the lake bed are unique samphire vegetation communities including a number of rare flora taxa with species zonation being evident. The Marsh supports aquatic invertebrate assemblages of conservation interest and has not been sampled for stygofauna owing to a lack of sampling sites.
- A number of persistent pools, known as Yintas, are associated with associated with drainage scours along the Fortescue River channel and other major channel inflows. These are probably sustained by storage in the surrounding alluvium following flood events.
- The water balance of the Marsh is dominated by surface water flow from the Fortescue River and Weeli Wolli Creek, contributing around 52% and 19% of mean annual inflows respectively. The remainder (29%) of inflows are from the catchments reporting directly to the Marsh.
- Flooding is generally associated with cyclonic rainfall and runoff in the summer months, with large-scale inundation events estimated to occur once in every five to seven years. Inundation of the east and west basins may be different for smaller events.
- Ponding in the Marsh is facilitated by the presence of relatively low permeability clay and silcrete/calcrete hardpans in the surficial sediments of the Marsh. More permeable material in the ponding surface is assumed to occur in some areas of the Marsh facilitating the seepage of flood waters into the sub-surface.
- A shallow, unconfined section of the regional aquifer is situated in the upper surficial sediments. Groundwater levels range between 2 and 4 m bgl with the shallow watertable maintained by a combination of flooding events, groundwater inflow, leakage from deeper confined units and evapotranspiration.
- Soil moisture in the shallow, generally unsaturated alluvium of the Marsh is replenished by rainfall and surface water and groundwater inflows. During flooding events, the depth to watertable may reduce locally but only for relatively short time.

Freshwater claypans of the Fortescue Valley PEC

- The expansive bare clay flats are fringed with Western Coolibah and tussock grassland vegetation communities. The Western Coolibah trees may rely on stored soil moisture replenished by flooding to meet their water requirements. The claypans support diverse aquatic invertebrate assemblages during flood events, and vary inter-annually between seasons. They also provide foraging habitat for waterbirds, and breeding habitat for some species.
- Surface water runoff is considered the dominant hydrological process associated with the claypans. The estimated flooding frequency may be similar to the Fortescue Marsh; however, no information is available on flood levels/regimes required to support the claypan ecosystems.
- Soil moisture in the shallow sediments of the claypans is replenished by a combination of rainfall and surface inflows. Ephemeral waterbodies in the claypans are rapidly evaporate following flooding.

Groundwater levels may range between 2 and 4 m bgl. Little is known of the hydrostratigraphy beneath the claypan surfaces. The claypans are assumed to be underlain by low permeability sediments, which may result in localised perching above the regional watertable.

BHP Billiton Iron Ore

Ecohydrological Conceptualisation of the Fortescue Marsh Region

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KEY ACRONYMS

AHD	Australian Height Datum
bgl	below ground level
BIF	Banded Iron Formation
BoM	Bureau of Meteorology
CID	channel iron deposit
DAFWA	Department of Agriculture and Food, Western Australia
DEC	Department of Environment and Conservation
DEM	digital elevation model
DSITIA	Department of Science, Information Technology, Innovation and the Arts
DoW	Department of Water
EC	electrical conductivity
EIA	Environmental Impact Assessment
FMG	Fortescue Metals Group
HPPL	Hancock Prospecting Proprietary Limited
mg/L	milligrams per litre
mRL	metres above reference level
µS/cm	microSiemens per centimetre
PEC	Priority Ecological Community
PER	Public Environmental Review
RHIO	Roy Hill Iron Ore
TDS	total dissolved solids
TEM	transient electromagnetic

1 Introduction

1.1 Study description

BHP Billiton Iron Ore Pty Ltd (BHP Billiton Iron Ore) commissioned MWH to develop an ecohydrological conceptualisation of the Fortescue Marsh and surrounding catchment areas contributing to the Marsh. This study informs BHP Billiton Iron Ore's Strategic Environmental Assessment (SEA) process and has been undertaken in parallel with three other ecohydrological studies in adjacent landscapes: referred to as the Central Pilbara, Eastern Pilbara and Marillana Creek Regions.

The ecohydrological conceptualisation provides an integrated understanding og groundwater, surface water and ecological regimes in the vicinity of BHP Billiton Iron Ore's mining and infrastructure development activities. BHP Billiton Iron Ore has no current mining operations near the Fortescue Marsh; however, potential projects in the Marillana, Mindy, Coondiner and Roy Hill tenement areas are at various stages of assessment and development.

The ecohydrological conceptualisation is supported by maps of the region and study area which have been compiled into a map book (Fortescue Marsh Ecohydrological Conceptualisation Map Book). The map book should be referred to in conjunction with this document.

1.1.1 Location and extent

The Fortescue Marsh (the Marsh) is located in the Pilbara Region of Western Australia and is the largest ephemeral wetland in the region (Map 1-01). It is an extensive intermittent wetland within a broad valley, bound by the Chichester Range to the north and the Hamersley Range to the south.

The Marsh has formed at the terminus of the Upper Fortescue River catchment, which constitutes the upper portion of the Fortescue River Basin (Map 1-01). The Fortescue River Basin covers an area of 49,710 km^2. The Upper and Lower Fortescue River catchments occupy areas of 29,820 km^2 and 19,890 km^2, respectively. The Goodiadarrie Hills form the catchment divide between the Upper and Lower Fortescue Catchments. To the west of the Goodiadarrie Hills, the Lower Fortescue River catchment drains into the Indian Ocean.

The Upper Fortescue River catchment is an internally-draining catchment and is considered to have negligible or limited hydraulic connectivity, either via surface water or groundwater, to the Lower Fortescue River catchment. Flood flows are delivered to the Marsh by the Upper Fortescue River, Weeli Wolli Creek and numerous small creeks emanating from the surrounding ranges.

Study area delineation

MWH developed an appropriate spatial domain for the ecohydrological conceptualisation. A pragmatic approach was adopted, based on catchment scale hydrology and the location of BHP Billiton Iron Ore's proposed mining projects within the vicinity of the Marsh. The defined Fortescue Marsh study area (hereafter referred to as the study area) covers an area of 11,971 km^2 (Map 1-02).

The study area boundary depicted in Map 1-02 was selected with due consideration of:

- the purpose of the ecohydrological conceptualisation;
- areas encompassing prospective BHP Billiton Iron Ore's projects;
- ecophysiographic boundaries and broadly anticipated hydrological stresses on the Marsh and other ecosystems;
- sites of recognised ecological significance;
- hydrological requirements (reflected in catchment boundaries) for potential future construction of numerical models (including ecohydrological models); and
- potential stresses imposed by any existing or proposed mining/dewatering operations including those associated with parties other than BHP Billiton Iron Ore.

The project area encompasses the management zones described in the Environmental Protection Authority (EPA) *Guidance for environmental and water assessments relating to mining operations in the Fortescue Marsh area* (EPA, 2013). This is discussed in more detail in Section 2.6.6 of this report. It is generally bound to the north and south by surface water catchment divides along the Chichester and Hamersley Range, respectively. The eastern boundary is broadly defined by the Fortescue River course. The western boundary is defined by an inferred surface water and groundwater divide to the west of the Goodiadarrie Hills.

Key assumptions and limitations inherent in the delineation of the study area are as follows:

- The southern boundary extends sufficiently beyond the proposed BHP Billiton Iron Ore mine sites to enable assessment of flow contributions primarily from Weeli Wolli, Mindy Mindy and Coondiner Creeks into the study area.
- The study area boundary extends significantly beyond the inferred groundwater divide in the vicinity of the Coondiner mine site; delineation of the boundary in this area was designed to coincide with the surface water catchment boundary further south. Surface water contributions captured in the ecohydrological conceptualisation will be evaluated in some detail within this extended area, however, detailed characterisation of the hydrostratigraphy beyond the inferred groundwater divide will not be undertaken, and will be limited to a brief description of the stratigraphic sequence and groundwater flow interpretation primarily as a flux input into the Fortescue Marsh.
- The area to the west of the Goodiadarrie Hills, which includes the Goodiadarrie Swamp, constitutes an internally draining system disjunct from the Fortescue Marsh. Subsequent discussions regarding the Goodiadarrie Swamp throughout this document will reflect the functional difference between the Goodiadarrie Swamp and Fortescue Marsh.

There are currently three active mine sites within the study area, and one in the initial stages of operations (Table 1-1, Map 1-02). In addition, there are several proposed mining operations within the study area (Table 1-2). Public reports associated with project site characterisation and feasibility studies are available for the Christmas Creek, Cloudbreak, HPPL Roy Hill, Nyidinghu, Brockman, Marillana and Koodaideri projects. Data relevant to this study have been used where appropriate, and all reports are catalogued in Appendix A: Data Inventory and Catalogue.

Table 1-1: Active mine sites within study area

Operating Company	Mine Site	Location relative to Fortescue Marsh
Fortescue Metals Group (FMG)	Christmas Creek	North
Fortescue Metals Group (FMG)	Cloudbreak	North
Rio Tinto Iron Ore (RTIO)	Hope Downs 4	South
Roy Hill Iron Ore	Roy Hill	North East

Table 1-2: Proposed mining operations within study area*

Company	Proposed mine site	Location relative to Fortescue Marsh	Current status
BHP Billiton Iron Ore	Mindy	South	On-going resource definition
	Coondiner	South	On-going resource definition
	Roy Hill	Northwest	On-going resource definition
	Marillana	South	On-going resource definition
Brockman Resources	Brockman Marillana	South	Approved by the Environmental Protection Authority (EPA); Department of Mines and Petroleum (DMP) Approval pending
FMG	Mindy Mindy	South	On-going resource definition
	Nyidinghu	South	Referred to Office of the EPA
	Mt Lewin	East	On-going resource definition
Iron Ore Holdings	Iron Valley	South	EPA and DMP approvals pending
Rio Tinto	Koodaideri	Southwest	Referred to Office of the EPA

***Important note:** The content of the table above 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

1.1.2 Areas of ecological importance and significance

Fortescue Marsh

The Fortescue Marsh is the largest ephemeral wetland in the Pilbara and has multiple conservation values. It is recognised as a wetland of national importance and is classified as a Priority Ecological Community (Priority 1) by the Department of Parks and Wildlife (DPaW). Further details are provided in Section 2.6.6.

Mulga and Snakewood woodlands

Woodlands of Mulga (*Acacia aneura* and its close relatives) and Snakewood (*A. xiphophylla*) occur in the study area, most prominently on the alluvial plains surrounding the Fortescue Marsh. Both species sometimes occur in strongly banded (groved) formations. Mulga and Snakewood woodlands are generally considered to be susceptible to modified surface drainage regimes.

The alluvial plains on the northern side of the Fortescue Marsh include the northernmost occurrences of Mulga woodlands in Western Australia. In this area, the Mulga communities are floristically unique, in relatively good condition, mostly weed-free and have experienced reduced impacts from fire and pastoral grazing (EPA 2013). They are considered by DPaW to have high conservation priority.

In other areas the Mulga and Snakewood communities are degraded to varying degrees, but are still considered to have elevated conservation significance.

Groundwater dependent ecosystems

The Pilbara hosts a number of groundwater dependent ecosystems (GDEs), some of which occur in the study area. These include groundwater dependent vegetation and aquatic habitats associated with pools, springs, watercourses and subterranean habitats. GDEs have a restricted distribution in the Pilbara, and often have unique or unusual species assemblages and therefore have elevated conservation significance.

Rare flora, fauna and threatened ecological communities

The study area includes a number of State and Commonwealth listed rare flora and fauna species, which can occur in a wide range of habitats.

In addition to the Fortescue Marsh itself, the study area includes five priority ecological communities (PECs) recognised by DPaW (Table 1-3).

Table 1-3: Priority ecological communities (PECs) in the study area (DPaW 2013)

PEC name	Priority	Location
Fortescue Valley Sand Dunes	P3	At the junction of the Hamersley Range and Fortescue Valley, between Weeli Wolli Creek and the low hills to the west
Stony saline plains of the Mosquito Land System	P3	Near the north-eastern margin of the study area.
Freshwater claypans of the Fortescue Valley	P1	Downstream of the Fortescue Marsh - Goodiadarrie Hills on Mulga Downs Station.
Four plant assemblages of the Wona Land System	2 x P1 2 x P3	In the Chichester Range northwest of the Goodiadarrie Hills
Brockman Iron cracking clay communities of the Hamersley Range	P1	Near the western end of the Fortescue Marsh

1.2 Study objectives

The objectives of this study were to:

- provide a knowledge base for the natural water resource system (hydrology and hydrogeology);
- summarise the key ecological values and characteristics including major vegetation associations, landforms and soils, fauna habitats (including subterranean fauna), threatened species and communities, and waterbodies;
- present an understanding of the key ecohydrological components, linkages and processes;
- provide an understanding of the potential connectivity and interaction between ecological receptors and the orebodies;
- support the Strategic Environmental Assessment (SEA) being undertaken by BHP Billiton Iron Ore, by demonstrating an understanding of ecohydrological conditions and processes, and
- provide a platform for future numerical modelling of ecohydrological processes associated with the Marsh and surrounding areas.

1.3 Ecohydrology

1.3.1 What is ecohydrology?

Ecohydrology integrates a wide range of disciplines including meteorology, hydrology, hydrogeology, geomorphology, biogeochemistry, soil science, and the various branches of ecology.

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

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

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

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

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

1.3.2 Ecohydrology concepts

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

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 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 1-1). 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. Deep rooted vegetation has the capacity to redistribute water between depth layers, reducing exposure to drought stress and enabling greater access to nutrients (Sardans and Peñuelas, 2014).
- Surface flow along preferred pathways such as channels, rivers and floodplains as dictated by topography and geomorphology, but also influenced by vegetation (Figure 1-2).
- Groundwater flow driven by hydraulic gradients. In the study area, salinity gradients beneath the Fortescue Marsh may also be a driver of groundwater flow (i.e. density driven flow). 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.

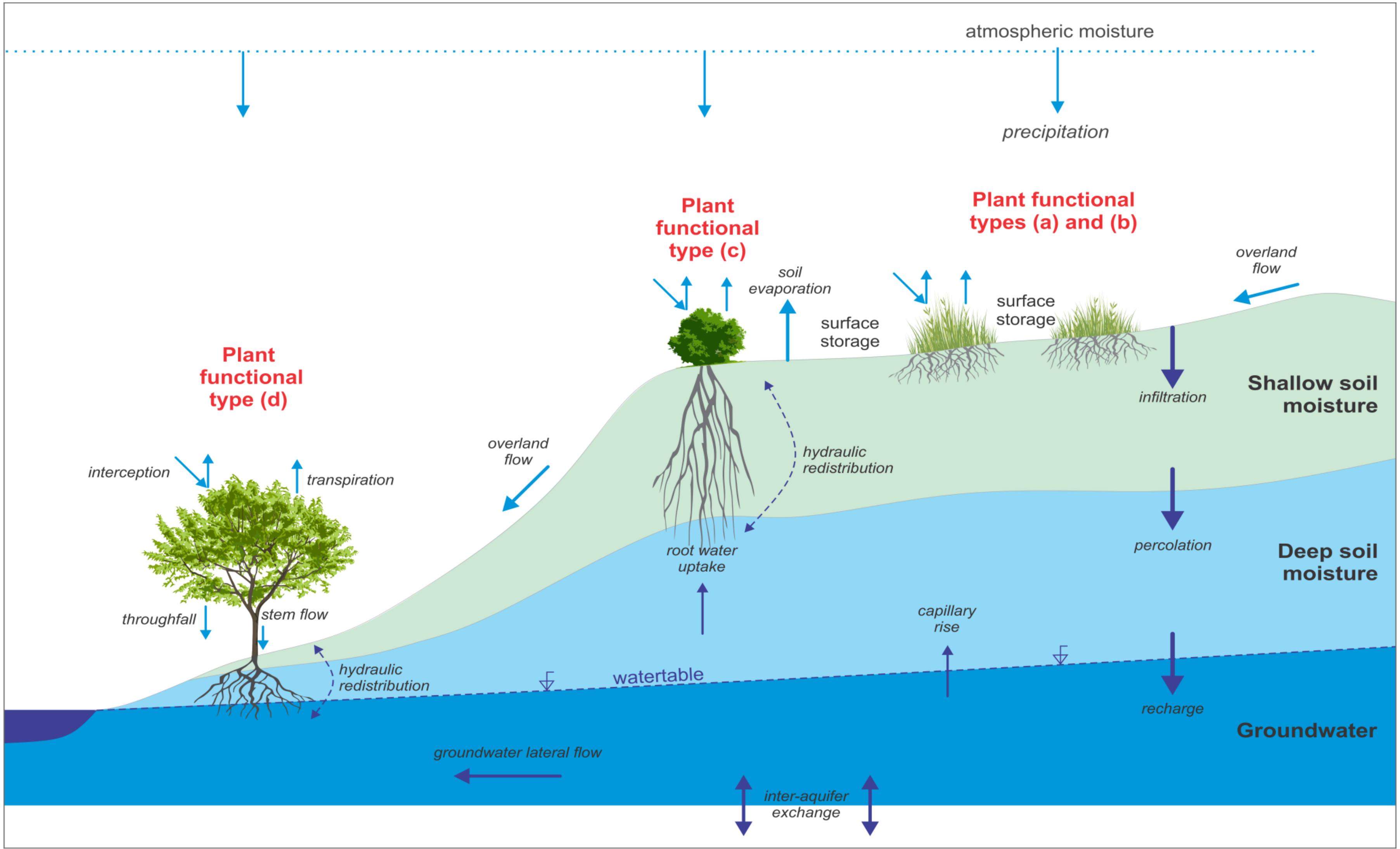


Figure 1-1: A conceptual diagram depicting lateral and vertical connectivity in an ecosystem with water as the primary medium (adapted from Miller et al. 2012).

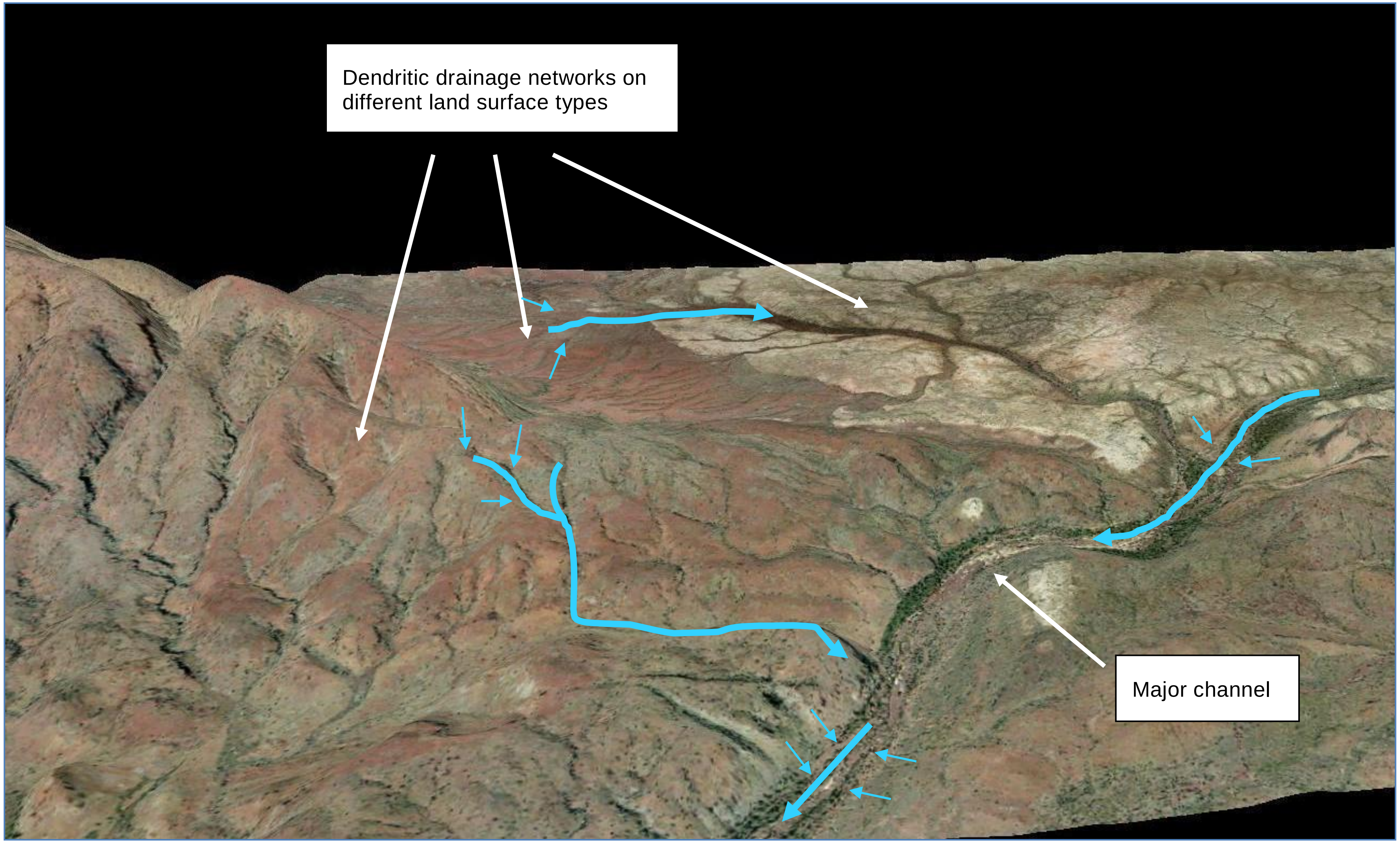


Figure 1-2 : Lateral and longitudinal connectivity in Pilbara uplands drainage systems. Note the concentration of denser vegetation along the major drainage lines.

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

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

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

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

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

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

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

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

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; and.
- 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 environmental 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.

Vegetation patterns

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

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

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

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

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 1-1) 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. drainage 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).

Landscape characteristics

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

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

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

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

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

Ecological water requirements of wetlands

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

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

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

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

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

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

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

1.3.3 Ecohydrological conceptualisation approach

Taking into account the ecohydrological principles discussed in Section 1.3.2, a landscape ecohydrological conceptualisation was developed through the definition of ecohydrological units (EHUs) for the study area. Each EHU represents a landscape element with broadly consistent and distinctive ecohydrological attributes (MWH, 2014).

In summary the spatial definition of the EHUs is based on interpretation of land system mapping units developed by the Department of Agriculture (Van Vreeswyk et al., 2004), surface drainage networks, groundwater systems, inferred vegetation water use behaviour based on vegetation mapping (structure and dominant species) and Landsat NDVI (Normalized Difference Vegetation Index).

Nine EHUs are recognised within the studystudy area as listed below:

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

The key attributes of each EHU are further described in Table 1-4. Factors considered in the definition of EHUs included:

- landscape position and land surface types, including soil characteristics;
- landscape water balance processes;
- surface drainage/redistribution processes;
- connectivity and interactions between surface water and groundwater systems; and
- major vegetation types and their water use strategies.

The EHUs transition from upland to lowland environments, in a spatial arrangement hierarchy depicted in Figure 1-3 and illustrated in a landscape context in Figure 1-4. 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.

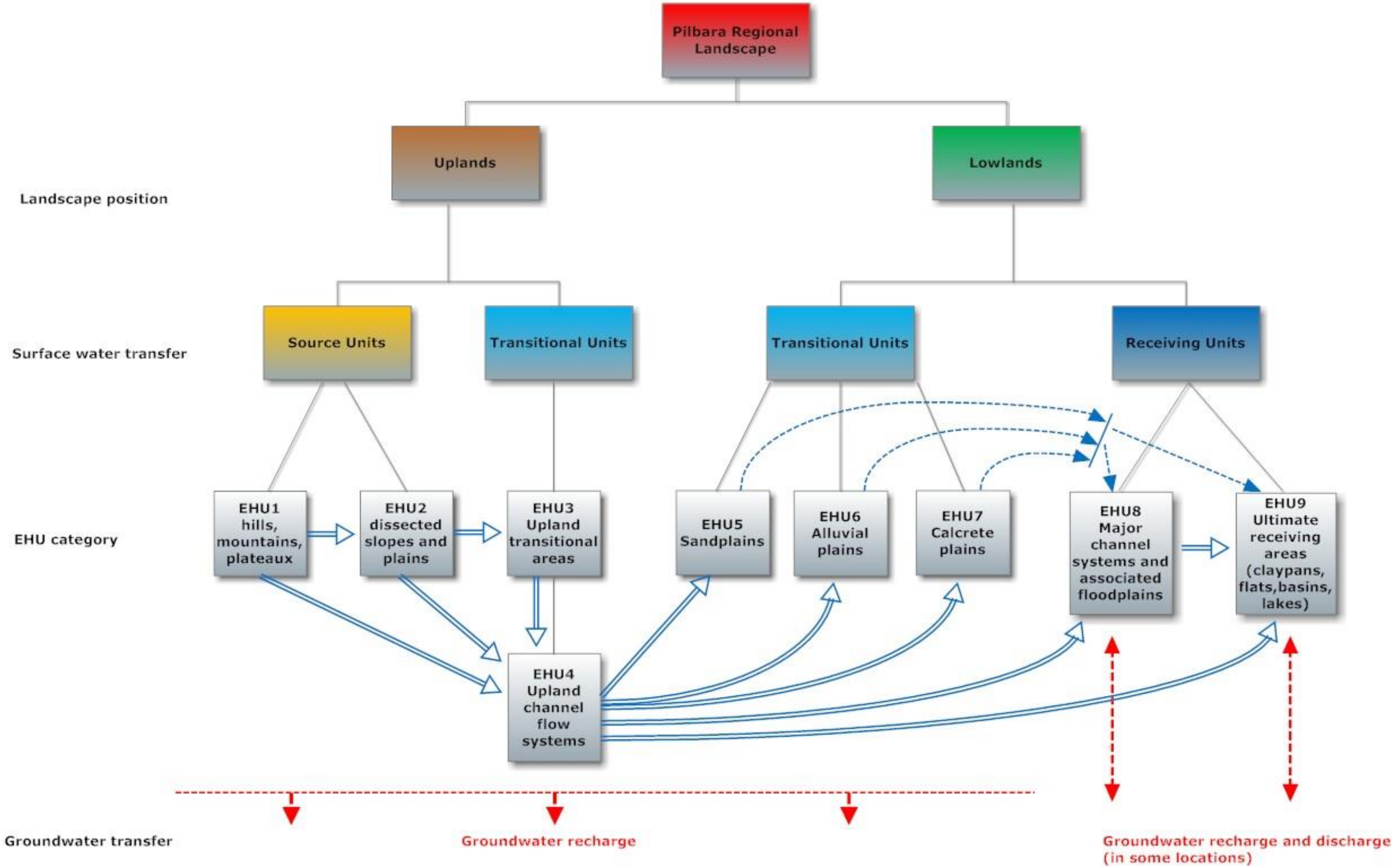


Figure 1-3: Landscape hierarchy of EHUs and major water flow connectivity

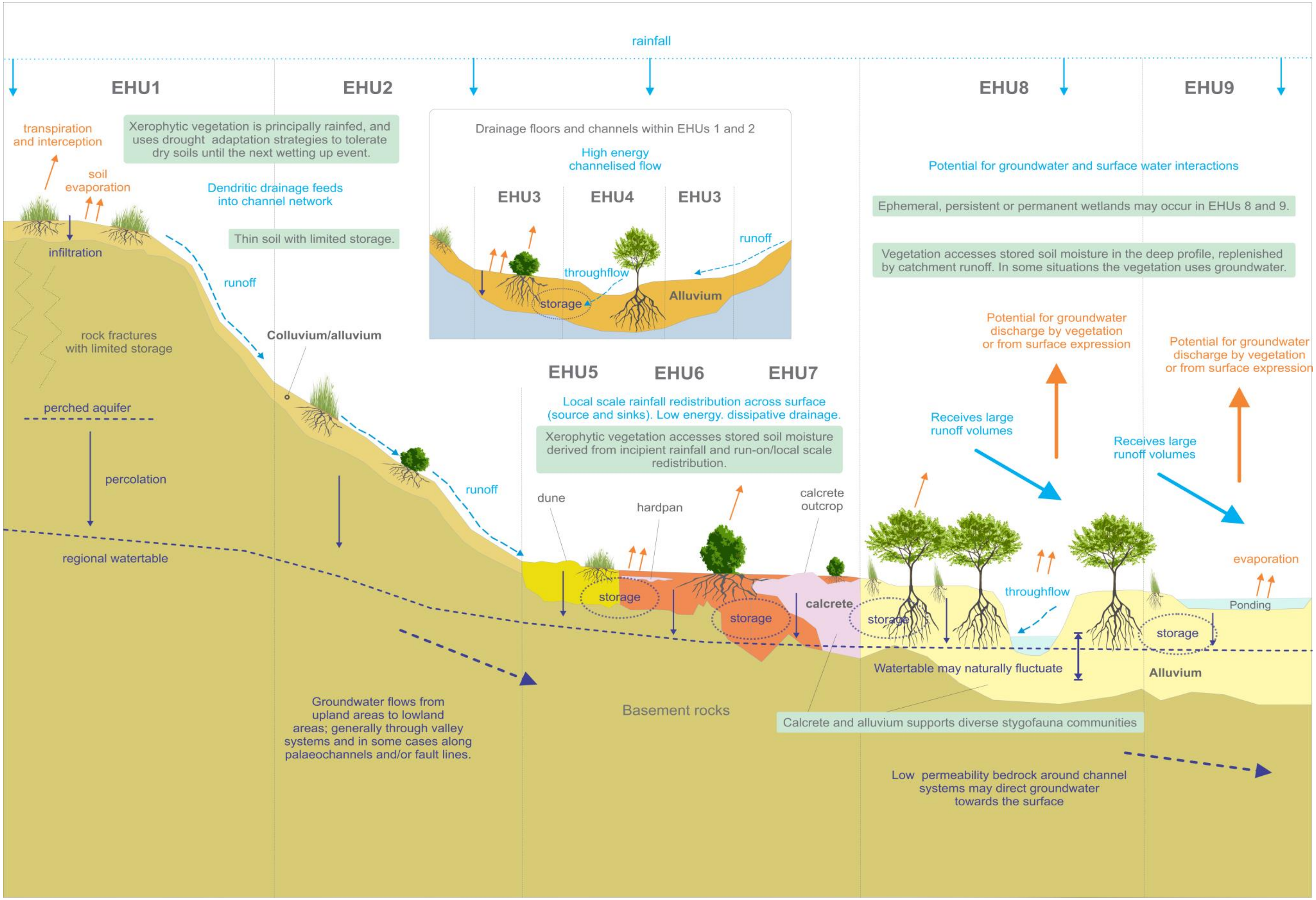


Figure 1-4: Landscape arrangement of EHUs

Table 1-4: General attributes of landscape ecohydrological units (EHUs) in the central Pilbara region

EHU	Landscape position, land surface and soils	Dominant landscape water balance processes	Dominant surface drainage/connectivity processes	Level of connectivity to groundwater systems	Major vegetation types
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 Run-off	Generally short distance overland flow into dendritic drainage networks (1st, 2nd and 3rd order streams).	Local and regional groundwater systems are deep and not accessible to vegetation. Preferential recharge can occur as dictated by local scale geology/regolith.	Hummock grasslands. Vegetation water demand met by direct rainfall and localised surface redistribution.
2	Upland source areas – dissected slopes and plains, down-gradient from EHU 1. Land surface is sloping with shallow to moderately deep colluvial soils.	Rainfall Infiltration Soil evaporation Run-off	Overland flow short distance into channel drainage systems (mainly 1st to 4th order streams).	Local and regional groundwater systems are deep and not accessible to vegetation Preferential recharge can occur as dictated by local scale geology/regolith.	Hummock grasslands. Vegetation water demand met by direct rainfall and localised surface redistribution.
3	Upland transitional areas – drainage floors within EHUs 1 and 2 which accumulate surface flows from up-gradient. Soils of variable depth derived from alluvium. Greater storage relative to soils in EHU 1 and 2.	Inflows Infiltration Storage Evapotranspiration	Surface accumulation and infiltration of flood flows (overland flows and channel breakouts). Excess volumes transferred to adjacent channels (EHU 4).	Local and regional groundwater systems are deep and not accessible to vegetation.	Smaller drainage floors support hummock grasslands; larger drainage floors support *Eucalyptus* and *Acacia* shrublands and woodlands. Vegetation water demand met by direct rainfall and stored soil water replenished by infrequent flood events.
4	Upland channel zones - channel systems of higher order streams (generally ≥5th order) which dissect EHU 1 and EHU 2. Channels are high energy flow environments, subject to bed load movement and reworking. Soils of variable depth derived from alluvium including zones of deep	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.	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.

EHU	Landscape position, land surface and soils	Dominant landscape water balance processes	Dominant surface drainage/connectivity processes	Level of connectivity to groundwater systems	Major vegetation types
	soils. Generally high infiltration rates.			In rare cases vegetation may access perched groundwater for periods of time.	
5	Lowland sandplains - landform characterised level or gently undulating plains up to 10 km in extent. Deep sandy soils of aeolian origin. Uncommonly features linear dunes up to about 15 m in height.	Infiltration Storage Evapotranspiration Groundwater recharge	Poorly organised drainage. High rainfall infiltration and recharge. Runoff is minimal and if it does occur is generally localised, with accumulation in swales or depressions. Sandplains may receive and infiltrate inflows from channels deriving from up-gradient areas.	Groundwater systems are generally deep and not accessed by vegetation. May include important zones of recharge, with associated groundwater mounding. Possibility of transient or more persistent perched groundwater at localised scales, depending on regolith characteristics.	Hummock grasslands, with *Acacia* sp. and other shrubs, occasional mallee Eucalypts. Distinctive grassland communities relative to other EHUs. Tracts receiving run-on include *Acacia* and *Eremophila* shrublands.
6	Lowland alluvial plains – broad depositional plains of low relief. Soils typically loams, earths and shallow duplex types. Subsurface calcareous hardpans are frequently encountered.	Localised surface redistribution Infiltration Storage Evapotranspiration	Complex surface water drainage/redistribution patterns. Land surfaces are generally dissected by low energy channels of variable form and size. Areas of sheetflow can occur, which may be associated with banded vegetation formations. Some areas may be subject to infrequent flooding. Infiltration may be significant at local scales in association with drainage foci, These areas are likely to be correlated with relatively higher leaf area index.	Groundwater systems are generally moderately deep (>10m) to deep (>20m) and not accessed by vegetation.	*Acacia* shrublands; less commonly Hummock grasslands, Tussock grasslands or low shrublands of Bluebush/Saltbush.
7	Lowland calcrete plains –plains of low relief generally bordering major drainage tracts and termini. Shallow soils underlain by calcrete of variable thickness, which occasionally outcrops.	Localised surface redistribution Infiltration Soil evaporation Groundwater recharge	Complex surface water drainage/redistribution patterns. Calcrete platforms may have varying permeability. Land surfaces are generally dissected by low energy channels of variable form and size.	Depth to groundwater may vary from shallow (<5 m) to deep (>20m). Preferred pathways may facilitate rapid recharge at local scale. Groundwater systems are generally not accessed by vegetation.	Hummock grasslands and *Acacia* scrublands with occasional Eucalypts. Distinctive vegetation communities relative to other EHUs.

EHU	Landscape position, land surface and soils	Dominant landscape water balance processes	Dominant surface drainage/connectivity processes	Level of connectivity to groundwater systems	Major vegetation types
			Generally characterised by numerous localised drainage termini.	Groundwater systems in calcrete can provide important stygofauna habitat.	
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 may vary from shallow (<5 m) to deep (>20m). Channels are significant recharge zones. Transient, persistent or permanent shallow groundwater systems may develop beneath channels in places, as dictated by local scale geology/regolith. These may be connected with pools in some situations. Groundwater is generally fresh. Groundwater systems can be accessible to vegetation in some situations. Evaporative discharge of shallow groundwater may occur.	Inflows from up-gradient sources sustain *Eucalyptus* and *Acacia* forest and woodland vegetation communities or Tussock grasslands. Supports most of the recognised groundwater dependant vegetation communities in the central Pilbara (with the key indicator species being *Eucalyptus camaldulensis*, *E. victrix* and *Melaleuca argentea*).
9	Lowland receiving areas - drainage termini in the form of ephemeral lakes, claypans and flats. Deep silty and clay textured soils. Variable surface salinity (resulting from evaporites). Soils may be underlain by calcrete/ silcrete hardpans of variable depth.	Inflows Ponding Infiltration Storage Soil evaporation Evapotranspiration Groundwater recharge Groundwater discharge (localised)	Drainage termini receive inflows from up-gradient drainage systems. Transient to persistent ponding may occur as dictated by flooding regimes, with spillovers possible in large flooding events. Sediment accumulation and evaporative concentration of salts.	Depth to groundwater may vary from shallow (<5 m) to deep (>20m). 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.

1.4 Data collection and collation

The status of data compilation and collation effort in support of development of the Fortescue Marsh ecohydrological conceptualisation is presented in Appendix A.

Data have been sourced from publicly available records from past and on-going projects in the vicinity. These broadly include data from the following:

1. Pre-feasibility and feasibility study reports
2. Baseline studies
3. Public environmental reports (PERs)
4. Research publications
5. Discrete data packages from BHP Billiton Iron Ore's projects (maps, bore logs, hydrochemical data, etc.)
6. Department of Water (WA) online database
7. Bureau of Meteorology online database
8. Science Delivery Division of the Department of Science, Information Technology, Innovation and the Arts (DSITIA).

All data collected is catalogued in the data catalogue: ***data catalogue*.**

2 Regional setting

2.1 Climate

The climate of the study area is semi-arid to arid, characterised by high temperatures and low, irregular rainfall. Daily temperatures in the summer months from November to February exceed 32°C and temperatures above 42°C are common. The winter season occurs from June to August with mean daily maximum and minimum temperatures of about 28°C and 13°C respectively.

Rainfall is highly variable with a large degree of intra-annual (within-year) and inter-annual variation. Mean annual rainfall may vary from 300 to 500 mm/yr (Map 2-01); however, in any given year the amount and timing of rainfall is unreliable. Average annual pan evaporation is between 2,800 and 3,200 mm/yr, which is an order of magnitude higher than the average annual rainfall (Figure 2-1).

Tropical lows and cyclones dominate the Pilbara's climate in the summer wet season. These may deliver widespread rain across the region; hence rainfall occurs mostly between December and March. During spring to autumn months a semi-permanent low pressure 'heat low' system influences the formation of convective thunderstorms of varying size and intensity, producing heavy localised falls over short periods (CSIRO, 2013). Relative contribution of thunderstorms to Pilbara rainfall totals is estimated at around 50% (pers. comm. I. Rea, BHP Billiton Iron Ore, 2014) and possibly higher in drier years.

During cyclones, daily rainfall events of between 70 and 400 mm/day have been recorded. This usually results in a distinct peak in rainfall distribution over any given month. Cyclonic and other large magnitude rainfall events are important for the generation of surface water flows and groundwater recharge.

The collection of climatic data for the study is further discussed in Appendix A: *Data Inventory and Catalogue*. The location of climate and rainfall stations used for this study is shown in Map 2-01.

2.2 Climate change

The future climate of the Pilbara has been recently considered in detail by CSIRO (Charles et al., 2013). Future climate scenarios were evaluated using Global Climate Models (GCMs).

The CSIRO report used projections from 13 GCMs for two different global greenhouse gas emissions scenarios (low and high emissions respectively) in addition to the base case (existing conditions). A scaling approach was then applied to modify historical daily rainfall and potential evaporation data to produce data sets of the historical data under future atmospheric conditions. The baseline period was 1961 to 2011.

The future climate was based on 2030 and 2050 atmospheric conditions for both low and high emission scenarios. Implications for key climate elements are considered below.

2.2.1 Annual rainfall

A wide range of future annual rainfall trends were predicted by the various climate models, with some predicting a decrease in rainfall and others an increase in rainfall. In general, the high emission scenario resulted in a dryer climate when compared to existing and lower emission scenarios. The median (between models) results suggest that future mean annual rainfall is unlikely to vary by more than 5% in comparison with current levels.

2.2.2 Extreme events

The global frequency of tropical cyclones in the Pilbara is likely to either decrease or remain unchanged as a result of global warming. Modelling of Australian tropical cyclones suggests an approximate 100 km southward shift in the genesis and decay regions of cyclones, together with an increase in the wind speed, rainfall intensity and integrated kinetic energy[1]. In broad terms, the intensity of cyclonic rainfall in the Pilbara is likely to increase. However, changes to thunderstorm intensity, which has important implications for runoff generation in smaller catchments, were not assessed in the CSIRO study. Potential changes to Intensity Frequency Duration curves under future climate scenarios are currently being studied by Bureau of Meteorology.

[1] a measure of Tropical Cyclone size and wind speed

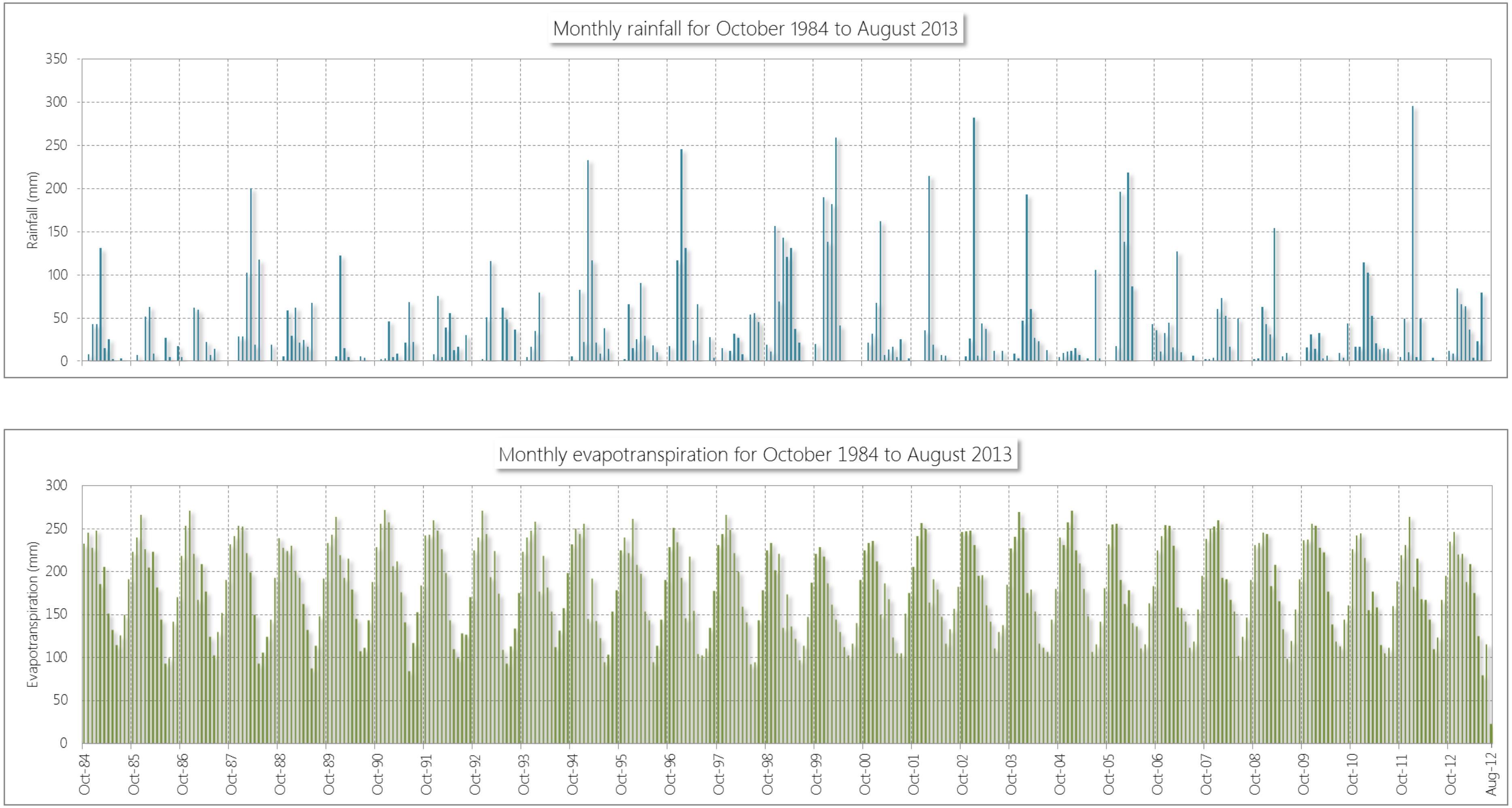


Figure 2-1: Rainfall and evapotranspiration for SILO 07[2] on the southern edge of Fortescue Marsh, from October 1984 to October 2013

[2] SILO data is synthetically generated daily rainfall data for Australia from 1889 to present and is available from the Science Delivery Division of DSITIA

2.2.3 Potential evaporation

The predicted changes in potential evaporation (PE) under future climate scenarios are more consistent than those obtained for rainfall; owing to the physical relationship between PE and temperature, solar radiation and relative humidity. The increase in potential evaporation is predicted to be higher under the higher emissions scenario. The median (between models) increase in PE is 3% and 4% for the two emissions scenarios at 2030 and 5% and 6% by 2050.

2.3 Topography

The major physiographic features of the study area are the Hamersley Range, the Fortescue Valley, and the Chichester Plateau and Range (Map 2-02). The east-west trending Fortescue Valley separates the Hamersley Range (to the south) and Chichester Range (to the north).

The Hamersley Range is an extensive mountainous area including peaks of over 1,250 metres above height datum (m AHD). The ridgelines and peaks are typified by steep slopes, with well-developed drainage incisions in the major valleys. At the base of the ranges, the topography transitions to gentle, undulating slope surfaces. The dominant drainage lines emanating from the Hamersley Range, including the Fortescue River, Weeli Wolli Creek, Coondiner Creek and Mindy Mindy Creek, exit the northern margin of the range into a series of deltaic areas which permeate into the Fortescue Valley.

The Chichester Range is a west-northwest/east-southeast trending plateau that is bound by the Fortescue Valley to the south. The Chichester Range rises to over 500 m AHD north of the Marsh and dips gently at less than 5° to the south. Runoff from the Chichester Range flows towards the Marsh via a series of floodplains, alluvial fans and multiple incised ephemeral creeks. These drainages are dispersed along the northern edge of the Marsh, between 5 and 10 km from the base of the Chichester Range and sloping at around 0.3%.

Separating the Hamersley and Chichester Range is the Fortescue Valley, an elongated alluvial plain which trends west-northwest. Its topography is described as gently undulating, with a maximum relief from the Fortescue Valley (400 to 450 m AHD) to the Chichester Range (500 to 600 m AHD) of approximately 50 to 200 m.

2.4 Regional drainage

The spatial distribution of upland and lowland EHUs in the study area align with regional drainage patterns (Map 2-03). Water within the landscape moves from the upland source areas (EHUs 1 and 2), via the upland transitional units or channel flow systems (EHUs 3 and 4), towards the lowland transitional areas (EHUs 5, 6, and 7) and major channel systems. All flows eventually aggregate in the receiving bodies, which are defined by the major channel systems and their associated floodplains, and drainage termini such as claypans, flats, basins, lakes and the Fortescue Marsh (EHUs 8 and 9).

The drainages of the study area are ephemeral, flowing for periods of up to weeks and months following significant cyclonic storm events. The discharge capacity of the channels reduces where defined drainages from the steeper slopes enter the lower slope areas, and in many instances they become less defined and braided or dispersed in flat areas. In major flow events, runoff tends to overspill the main channel flow zones in break-of-slope areas and spread over a wider front. Distinct vegetation communities areas (often dominated by *Acacia* trees and shrubs) are associated with these floodout zones, which are considered to be dependent on seepage water provided by the overland sheetflow process. The Fortescue River, Weeli Wolli Creek and other major channels crossing the Fortescue Valley typically support Eucalypt woodlands in their banks and floodplains.

The Marsh is the surface expression of sediment accumulation and evaporite formation in a broad, closed valley basin. Following significant rainfall events, runoff from the creeks in the catchments drain to the Marsh. Following smaller runoff events, isolated pools (Yintas[3]) form on the Marsh opposite the main drainage inlets, whereas larger events have the potential to flood the entire Marsh area.

Based on elevations from the 5 m digital elevation model (DEM) provided to MWH by BHP Billiton Iron Ore for this study, the lower bed levels in the Marsh lie between 404 m and 405 m AHD. It is estimated that the flood level in the Marsh would need to be around 412 m AHD to overspill westwards past the

[3] Waterholes

Goodiadarrie Hills. No published flood level data are available for the Marsh; however, anecdotal evidence suggests that over the last 50 years, flood levels of approximately 407 m AHD have occurred.

Flood levels have never overtopped BHP Billiton Iron Ore's railway crossing through the Marsh, although large floods in the early 1970s are reported to have caused inundation up to the existing railway track level. Based on elevations from the 5 m digital elevation model (DEM) provided to MWH by BHP Billiton Iron Ore for this study, the elevation of the railway track where it crosses the edge of the Marsh is around 410 m AHD.

The Goodiadarrie Hills form the divide between the Upper Fortescue River Catchment and the Lower Fortescue River Catchment. West of the Goodiadarrie Hills, runoff from the adjacent surrounding Hamersley and Chichester Ranges drains through outwash plains and into the Goodiadarrie Swamp. The Goodiadarrie Swamp is therefore disjunct from the Marsh, and sits within an internally draining sub-catchment in the upper reaches of the Lower Fortescue River catchment.

2.5 Geology

2.5.1 Structural setting

The study area is located within the Hamersley Basin, which is a depositional basin of Archaean to Lower Proterozoic sedimentary rocks overlying older Archaean granite and greenstone basement rocks (Trendall, 1990) (Table 2-1, Map 2.04, Map 2.05). The regional surface geology is depicted in the 1:250 000 geological mapping by the Geological Survey of Western Australia. The principal information for the study area is on the Roy Hill sheet (Sheet SF 50-12; Thorne, Tyler, 1996), however smaller parts of the study area are covered by adjacent sheets (i.e. Newman to the south and Balfour Downs to the east).

The granitoid rocks of the Pilbara Craton are approximately 2,800 to 3,500 million years old and are mostly concealed by Proterozoic sedimentary rocks, although some outcrops do occur to the north and east of the study area.

The Archaean Chichester Range Megasequence (Fortescue Group, Marra Mamba Iron Formation and Wittenoom Formation) were deposited during an episode of west-northwest to east-southeast directed crustal extension (Blake, 1993). An unconformity or condensed succession separates the top of the Archaean Chichester Range Megasequence from the early Proterozoic Hamersley Range Megasequence (Brockman and Woongarra Formations; Figure 2-2).

The Archaean Fortescue Group comprises an interlayered sequence of sedimentary and basaltic rocks that have been intruded by dolerite sills and dykes. The Fortescue Group is overlain conformably by the Archaean-Proterozoic Hamersley Group (Figure 2-2). The Jeerinah Formation is the youngest formation within the Fortescue Group, and marks the base of the orebodies within the overlying Hamersley Group.

The study area is cut by several regional scale faults (Map 2.04). The Poonda Fault at the base of the Hamersley Range is of particular importance as it may have an effect on groundwater flow originated in the Hamersley Range as it moves into the Fortescue Valley. The potential offsets between geological formations may affect lateral connectivity between fractured or fresh basement and detritals in the Fortescue Valley.

Another set of faults cut in a SW-NE direction and are apparent in the ranges on both sides of the Fortescue Valley. It is assumed that they extend across the valley beneath the Tertiary/Quaternary cover. A series of dolerite dykes which also trend SW-NE have been identified in the study area (Map 2-04). Dolerite dykes commonly constitute low-permeability barriers to groundwater flow, however the thermal contact during their formation can often increase the permeability of host rocks in the contact zone.

Table 2-1: Summary of stratigraphic units in the study area

Age	Group	Formation	Member	Dominant lithology	Hydrogeology
Cainozoic	Quaternary	Eolian deposits (Qs)		Sand in sheets and longitudinal dunes	Generally unsaturated
		Alluvium (Qa, Ql, Qw)		Unconsolidated silt, sand, and gravel, in drainage channels and on adjacent floodplains	Often unsaturated, occasional aquifer, can be heterogeneous depending on texture
		Colluvium (Qc)		Unconsolidated quartz and rock fragments in soil	While unsaturated, may form localised, temporary, perched aquifers
	Tertiary Detritals (TD)	TD3		Valley-fill sandy silt (top) to clay (towards the base), calcretised in places	Generally aquitard
		Calcrete, silcrete, ferricrete		Lacustrine sediments including sheet carbonate (calcrete), Oakover Formation	Aquifer
		TD2		Channel iron deposits (CID), generally occurring at depth in palaeodrainages	Aquifer
	Hamersley Group	Boolgeeda Iron Formation		Iron formation, pelite and chert	Low permeability material
		Woongara Rhyolite		Metamorphosed volcanicsand BIF	Low permeability material
		Weeli Wolli Formation		BIF, pelite, chert, doleritessills	Mostly unsaturated
		Brockman Iron Formation	Yandicoogina Shale Member	Interbedded chert and shale	Low permeability material
			Joffre Member	BIF with minor shale bands	Limited aquifer(s) in mineralised zones
			Whaleback Shale Member	Interbedded shale, chert and BIF	Low permeability
			Dales Gorge Member	Interbedded BIF and shale	Limited aquifer(s) in mineralised zones
Early Proterozoic - Archaean		Mount McRae Shale		Shale and dolomitic shale with minor thinly bedded chert	Low permeability (in general), pockets of shale may form minor aquifers
		Mount Sylvia Formation		Shale, dolomitic shale, and BIF	Low permeability (in general), pockets of shale may form minor aquifers
		Wittenoom Formation	Bee Gorge Member	Graphitic shale with minor sequences of carbonate, chert, volcaniclastic rock, and BIF	Low permeability
			Paraburdoo Member	Dolomite with minor amounts of chert and shale - karstic in areas	Aquifer at regional scale, especially where karstified
			West Angela Member	Dolomite, dolomitic shale, and chert	Minor, localised aquifers
		Marra Mamba Iron Formation	Mount Newman Member	Chert, banded iron-formation, and shale	Aquifer in mineralised zones
			MacLeod Member	Well podded to laminar chert and chert BIF with shale macrobands	Low permeability
			Nammuldi Member	BIF with chert and shale	Aquifer in mineralised zones
Archaean	Fortescue Group	Jeerinah Formation	Roy Hill Shale Member	Dark-gray to black graphitic shale and chert; locally pyritic	Low permeability
			Warrie Mamber	Dolomite with inter-bedded chert (locally ferruginous), shale and mudstone	Low permeability

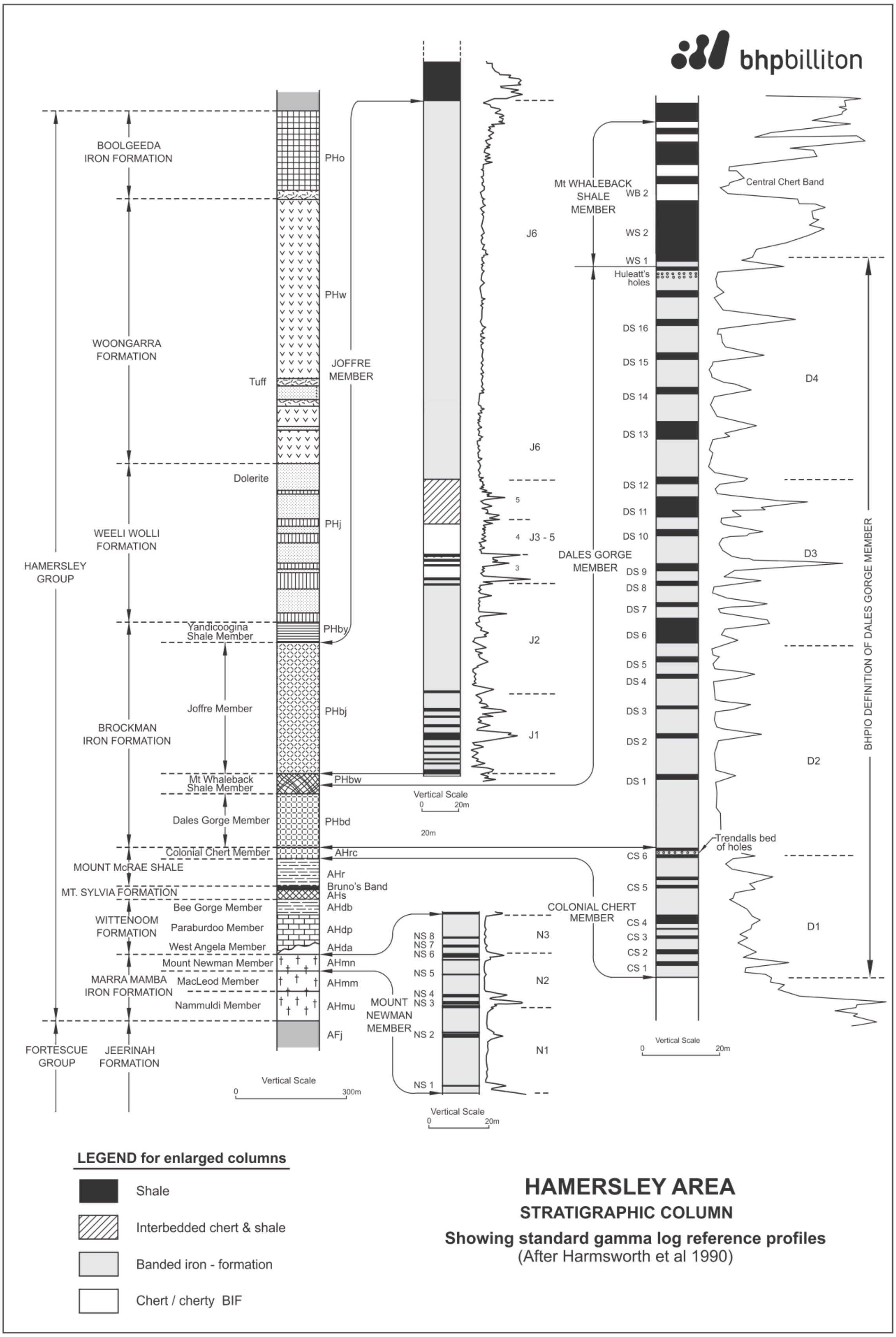


Figure 2-2: Stratigraphic sequence of basement geology (after Harmsworth *et al*, 1990)

2.5.2 Lithology

The basement geology is dominated by the Hamersley Group which consists of various metasedimentary rocks including cherty banded iron formation (BIF), chert and carbonates interbedded with minor felsic volcanic rock and intruded by dolerite dykes. The upper formations of the Hamersley Group are remarkably uniform in distribution and stratigraphy.

The axis of the Hamersley Basin that runs south of the study area is parallel to the direction of the Fortescue Valley. It is an east-northeast to west-southwest trending feature that includes the Fortescue Marsh and Fortescue River systems, and is bound by the Hamersley Range to the south and the Chichester Range to the north.

In the Pilbara, these ranges typically develop as strike-ridges of iron-rich, erosion-resistant material. The Hamersley Range correlates with the outcrop of Brockman Iron Formation, while the Chichester Range is defined by the outcrop of Marra Mamba Iron Formation (Figure 2-3). The significant width of the Fortescue Valley in this area is likely a function of the low dip (almost horizontal) of the basement stratigraphy, and the preferential erosion of the Wittenoom Formation in the valley floor.

A concise geological description of geology for the three major physiographic components within the Hamersley Basin is presented below.

Chichester Range

The general stratigraphy of the Chichester Range consists of Tertiary Detritals (alluvium/colluvium, pisolites), Oakover Formation (calcrete), Marra Mamba Formation (banded-iron formation (BIF) and Jeerinah Formation (shale, chert) (see Table 2-1).The alluvial and colluvial deposits occur on the lower slopes, generally increasing in thickness in a south-westerly direction towards the Fortescue Valley. Tertiary calcrete outcrops to the south of the Chichester Range, where it is deposited widely along major drainage lines and on the fringes of the Marsh.

The dolomitic Wittenoom Formation is not typically encountered in the Chichester Range. The Wittenoom Formation is inferred to exist beneath the Marsh and outcrop at places along the Hamersley Range escarpment. Dolomite was intercepted in one bore to the south of Cloudbreak Mine (FMG, 2005) and regional bores within the Fortescue Valley.

The basal unit of the Marra Mamba Iron Formation is the Nammuldi Member. Results of drilling programs covering much of the Chichester Range indicate the lower part of the Nammuldi Member remains over most of the Range and outcrops occur along the southern flanks of the Chichester Range. The Nammuldi Member is typically 60 m in thickness (FMG, 2005). The remaining members, Macleod and Mount Newman, are inferred to be either in sub-crop below the Quaternary and Tertiary sedimentary sequence that occupies the palaeochannel of the Fortescue River, or have been removed by erosion. It is reported that approximately 15 m of the Mt Newman Member, the complete McLeod Member and the upper part of the Nammuldi Member were encountered in small north-south synclines preserved near Mulga Downs homestead (Lascelles, 2000).

Within much of the Chichester Range, the Marra Mamba Formation overlies the shale, chert, basalt and dolomite of the Jeerinah Formation. The Roy Hill Shale is the uppermost unit of the Jeerinah Formation, and is locally pyritic and dolomitic.

Fortescue Valley

The Fortescue Valley is a flat-lying, complex sequence of Quaternary and Tertiary alluvial, colluvial and lacustrine sediments that have been deposited in a valley incised in the Hamersley Group. The alluvial deposits increase in thickness away from the ranges towards the Marsh, where a thickness of up to 70 m has been recorded (WML, 1982; CRA, 1992; Norman Mining, 1978). The deposits make up a palaeochannel with its deepest section generally towards the northern edge of the current valley, which may reflect the progress of erosional migration of the palaeo Fortescue River from south to north.

Along the ephemeral creeks and riverbeds of the valley, the alluvial sequence typically comprises unconsolidated silt, sand and gravel, whereas finer-grained sediments including clays predominate across the adjacent floodplains (FMG, 2010). Detritals are usually directly connected with the underlying Marra Mamba Formations.

Tertiary detritals comprising silty and clayey playa deposits overlie calcrete of the Oakover Formation, with weathered and crystalline dolomite of the Wittenoom Formation at depth. At the flanks of the Chichester Range the Oakover Formation also developed directly on the cherty unmineralised BIF Marra

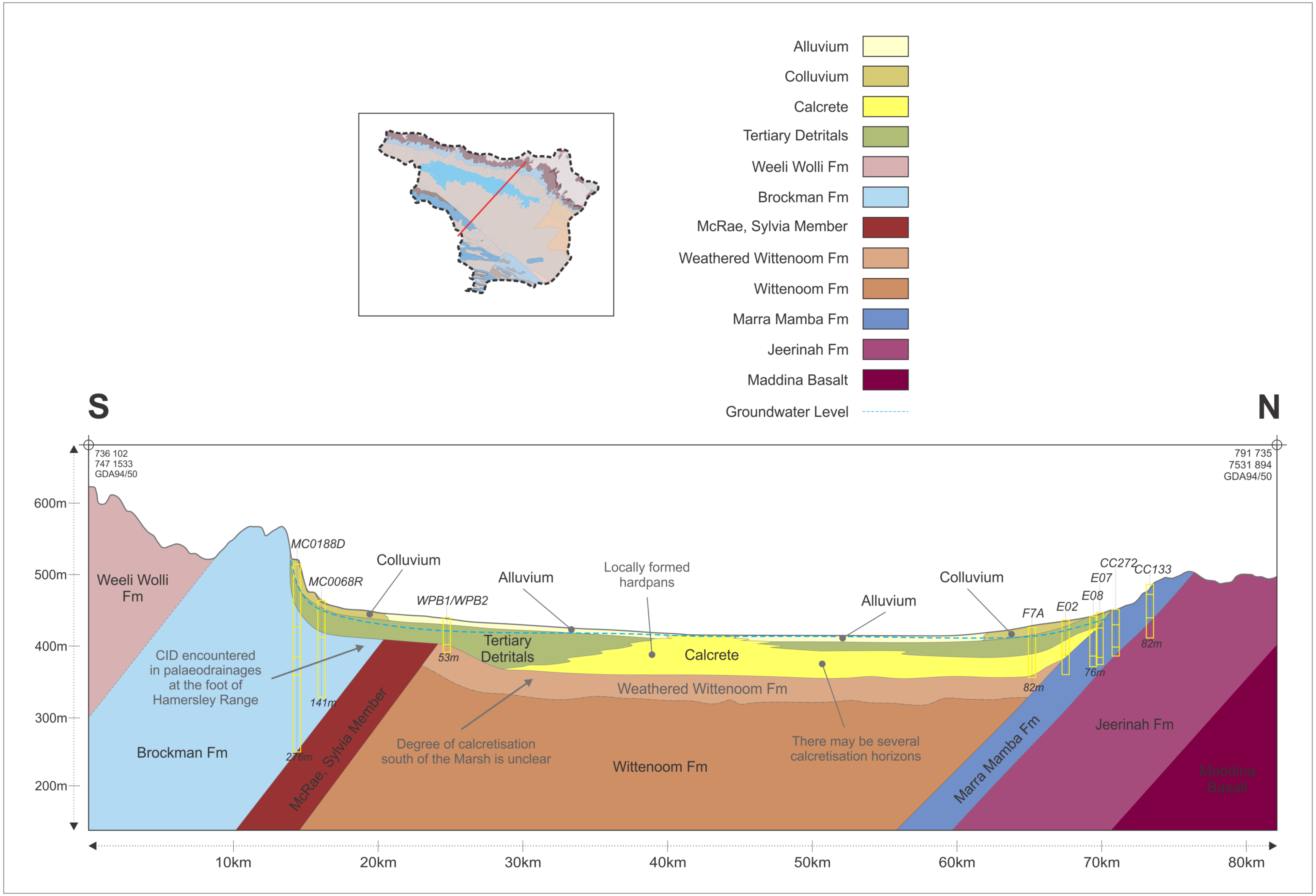


Figure 2-3: Typical geological section across the study area (south-north)

Mamba Formation and ferruginous chert of the lower Marra Mamba Formation. FMG (2010) states that the Oakover Formation does not directly overlie highly permeable mineralised parts of the Marra Mamba Formation.

A unit shown as calcrete in geological maps may occur within the upper two metres of the Fortescue Marsh sediments. It forms 'hardpan' or 'claypan' features on the surface facilitating accumulation of water. Supporting the presence of such a unit is observations of calcrete/silcrete hardcap in the upper metre of several shallow monitoring bores on the margin of the Marsh established by the University of Western Australia (UWA, 2013).

The Wittenoom Formation dolomite consists of a lower sequence of thinly-bedded to massive dolomite with rare beds of black chert, overlain by interbedded dolomite with chert, shale and minor iron formation (Trendall & Blockley, 1970). The dolomite contains appreciable manganese, and where it has been extensively weathered, black manganiferous clay may occur. The upper weathered dolomite may be locally karstic. The thickness of this unit appears to be poorly understood; an interpreted thickness of 531 m (161 to 692 m bgl) was documented in exploration bore FVG-1 (CRA, 1984), drilled in the Fortescue Valley.

Hamersley Range

The general stratigraphy of the Hamersley Range within the study area consists of unconsolidated to consolidated sediments of Tertiary to Quaternary age overlying Proterozoic Brockman Iron Formation. The Weeli Wolli Formation, which overlies the Brockman Formation, outcrops at the southern edge of the study area.

The thickness of Cainozoic sediments is believed to be in excess of up to 200 m within the Weeli Wolli alluvial fan, overlying Proterozoic bedrock (Aquaterra, 2008). Coarse creek-bed sediments within the modern-day Weeli Wolli Creek drainage system grade to finer grained sediments outside the main channels and within floodplain areas. Finer, silty and clayey sediments occur below this sequence and above coarser detritals and partially-consolidated iron-rich goethitic Channel Iron Deposits (CID) deposited within well incised, Tertiary-aged palaeochannels.

The Proterozoic bedrock consists of the Brockman Iron Formation. The Brockman Iron Formation outcrops extensively in the Hamersley Range, and is comprised of four members (Table 2-1) as follows:

- Yandicoogina Shale Member: alternating thin bands of shale and chert;
- Joffre Member: mostly banded-iron formation (BIF), with shale interbeds, typically 335 m thickness (Trendall and Blockley, 1970), where the entire sequence is encountered;
- Whaleback Shale Member: interbedded chert and shale with two BIF horizons near the formation base, with a typical thickness between 45 and 65 m; and
- Dales Gorge Member: alternating BIF and shale macro-bands, with thickness ranging from 85 to 185 m.

The Brockman Iron Formation is underlain by the Mt McRae Shale and Mt Sylvia Formation. These formations typically comprise interlayered shale, dolomitic shale and chert with minor BIF. The Mt McRae and Mt Sylvia Formations range from 45 to 75 m and 35 m in thickness, respectively.

The underlying Wittenoom Formation is a deep-water sedimentary facies. It occurs largely north of the Poonda Fault and is inferred to underlie the Fortescue Marsh to the north. The Wittenoom Formation consists of a lower sequence of thinly-bedded to massive dolomite with rare beds of black chert, overlain by interbedded dolomite with chert, shale and minor iron formation (Trendall and Blockley, 1970).

The north-northwest to south-southeast trending Poonda Fault system runs along the Hamersley Range on the southern margin of the Fortescue Valley. The fault system offsets the Wittenoom Formation found occurring to the north of the fault to the Brockman Iron Formation (e.g. Dales Gorge Member and others) found to the south of this fault system.

Orebodies

Along the Hamersley Range, locally-enhanced mineralisation of the Brockman Iron Formation (BIF) has resulted from groundwater leaching of gangue minerals, together with deposition of iron minerals. This has enhanced porosity and iron content, principally hematite-goethite, and is referred to as Bedded Iron Deposit (BID). In addition, partially consolidated, iron-rich goethitic channel iron deposits (CID) occur in economic quantities within well-incised Tertiary palaeochannels.

Geochemical alteration associated with post-depositional processes resulted in formation of a hematite to goethite range of orebodies in the Nammuldi Member in the Chichester Range. The typical vertical zonation that resulted from the geochemical overprinting of the original depositional sequence includes the hardcap (porous goethite), hydrated and dehydrated zones (secondary goethite and hematite), primary ore zone (dominated by micro-platey hematite), ochreous goethite zone and unmineralised BIF and chert.

2.6 Landscape and environment

2.6.1 Bioregion

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

Four geographically distinct biogeographic subregions are recognised in the Pilbara taking into account information on geology, landform, climate, vegetation and animal communities (Pepper et al., 2013). Of these, three subregions are represented in the study area:

- 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).

The majority of the study area intersects the Fortescue subregion (approximately 70% of study area) (Map 2.06). The study area also intersects the Hamersley subregion along the northern flanks of the Hamersley Range (15% of study area), and the southern fringe of the Chichester subregion south of the Chichester Range catchment divide (13% of study area).

2.6.2 Land systems

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

The study area encompasses 40 land systems (Map 2-07), with the characteristics outlined in Table 2-2.

Van Vreeswyk et al. (2004) grouped the land systems into 20 land surface types according to a combination of more generic landforms, soils, vegetation and drainage patterns (Table 2-2). This grouping provides information more suitable for regional scale assessments and has contributed to the delineation of landscape EHUs (refer to Section 1.4 and “Development of Pilbara Landscape Ecohydrological Units, MWH, 2014).

Table 2-2: Description of land systems in the Fortescue Marsh study area

Land system	Type	Percent of study area	Description	Geomorphology and soils
Adrian	6	0.6%	Stony plains and low silcrete hills supporting hard spinifex grasslands.	Erosional surfaces typified by rounded hills and rises. Short drainage lines with radial patterns away from rises. Soils are stony and shallow.
Billygoat	5	0.4%	Dissected plains and slopes supporting hard spinifex grasslands.	Erosional surfaces including extensive dissected gravelly/stony plains, minor plateaux and residual upper plains and occasional low breakaways. Narrow interfluves and slopes with dendritic drainage networks. Slopes marginal to drainage lines are often calcreted. Soils are shallow and stony/gravelly.
Bonney	6	0.5%	Low rounded hills and undulating stony plains supporting soft spinifex grasslands.	Erosional surfaces including low hills, undulating rises and gently undulating stony plains. Widely spaced drainage patterns of narrow drainage floors with minor channels. Upland soils are shallow and stony, with a mix of non-cracking clays, calcareous loamy earths and red loamy earths on rises and plains.
Boolgeeda	8	3.2%	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.
Brockman	14	0.6%	Alluvial plains with cracking clay soils supporting tussock grasslands.	Depositional surfaces derived from Quaternary alluvium. Non-saline alluvial plains with clay soils and gilgai micro-relief, flanked by slightly more elevated hardpan washplains. Sluggish internal drainage with occasional channels. Soils are mainly self-mulching cracking clays and red/brown non-cracking clays, with some red loamy earths on elevated washplains.
Calcrete	18	4.0%	Low calcrete platforms and plains supporting shrubby hard spinifex grasslands.	Tertiary calcrete formed in detrital 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.
Capricorn	1	0.2%	Hills and ridges of sandstone and dolomite supporting shrubby hard and soft spinifex grasslands.	Erosional surfaces including ranges and hills with steep, rocky upper slopes, more gently sloping stony footslopes, and restricted stony lower plains and valleys. Moderately spaced tributary drainage patterns. Soils are shallow and stony.
Christmas	15	1.9%	Stony alluvial plains supporting Snakewood and Mulga shrublands with sparse tussock grasses.	Depositional surfaces; level to gently inclined stony plains subject to sheetflow with numerous small, diffuse drainage foci and groves. Soil types mainly include deep red/brown non-cracking clays, with some deep red loamy duplex soils. Restricted to the Fortescue Valley and considered to have elevated conservation significance (EPA 2013).
Coolibah	17	2.4%	Floodplains with weakly gilgaied clay soils supporting Coolibah woodlands with Tussock grass understorey.	Depositional surfaces; active floodplains and alluvial plains associated with the Fortescue river (i.e. non-Fortescue Marsh sections). Soil types mainly include deep red/brown non-cracking clays, with some deep red loamy duplex soils.

Land system	Type	Percent of study area	Description	Geomorphology and soils
Cowra	15	1.4%	Plains fringing the Marsh land system and supporting Snakewood and Mulga shrublands with some halophytic undershrubs.	Depositional surfaces; almost level plains of non-saline and weakly saline alluvium with gravelly surfaces. Drainage foci and tracts support denser vegetation, included banded formations in some places. Soils mainly include red loamy earths and duplex types; with abundant cobbles and stony mantles. Restricted to the Fortescue Valley and considered to have elevated conservation significance (EPA 2013).
Divide	11	9.3%	Sandplains and occasional dunes supporting shrubby hard spinifex grasslands.	Depositional surfaces reworked by Aeolian processes. Drainage is generally indistinct. Soils are mainly red deep sands and red sandy earths, with occasional shallower soils overlying gravel or rock.
Egerton	5	0.2%	Dissected hardpan plains supporting Mulga shrublands and hard spinifex hummock grasslands.	Erosional surfaces, formed on Tertiary colluvium. Minor residual hardpan plains with extensive marginal dissection zones. Numerous dendritic drainage lines. Dissected slopes adjacent to major drainage lines are often calcreted. Soils are mainly red shallow loams and sands.
Elimunna	10	2.1%	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).
Fan	12	12.2%	Washplains and gilgai plains supporting groved Acacia shrublands (Mulga and Snakewood) and minor tussock grasslands.	Flat depositional surfaces subject to overland flow and banded vegetation formations. Soils are generally deep red loamy earths.
Fortescue	17	1.1%	Alluvial plains and floodplains supporting patchy grassy woodlands and shrublands and tussock grasslands.	Depositional surfaces associated with river channels and commonly subject to fairly regular flooding. Soils are mainly deep red/brown non-cracking clays and self-mulching cracking clays.
Granitic	1	0.03%	Rugged granitic hills supporting shrubby hard and soft spinifex grasslands.	Erosional surfaces including hill tracts and domes on granitic rocks with rough crests, rocky hill slopes and restricted lower stony plains. Narrow, widely spaced tributary drainage floors and channels.
Jamindie	12	6.4%	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.
Jurrawarrina	12	0.3%	Hardpan plains and alluvial tracts supporting Mulga shrublands and tussock and spinifex grasslands.	Depositional surfaces derived from Quaternary alluvium and colluvium. Plains receiving overland sheetflow characterised by banded Mulga vegetation; and broad drainage tracts with or without defined channels. Soils are a mixture of red/brown clays, loams, earths and duplex types.
Kumina	3	0.02%	Duricrust plains and plateaux remnants supporting hard spinifex grasslands	Erosional surfaces including undulating plateaus remnants and stony uplands. Widely spaced tributary drainage tracts which may be channelled or unchannelled. Soils are generally red loamy earths.

Land system	Type	Percent of study area	Description	Geomorphology and soils
Lake Bed	20	0.01%	Bare lake beds inundated for short periods after rain.	Flat depression basins. Generally heavy soil types.
Laterite	4	0.7%	Laterite mesas and gravelly rises supporting Mulga shrublands.	Erosional surfaces formed by dissected parts of the old Tertiary plateaux. Mesas and breakaways, gravelly footslopes and lower plains. Drainage tracts and floors with sluggish drainage or sub-parallel braided creeks (frequently saline). Soils are generally shallow sands and gravels; with red/brown cracking and non cracking clays in low lying areas.
Marillana	15	3.5%	Gravelly plains with large drainage foci and unchannelled drainage tracts supporting Snakewood shrublands and grassy Mulga shrublands.	Depositional surfaces derived from Quaternary alluvium. Sheetflow areas occur and are associated with stony surface mantles. Broad, unchannelled drainage tracts can receive more concentrated through flow. Soils are generally deep red loamy earths, duplex soils or clays. Restricted to the Fortescue Valley and considered to have elevated conservation significance (EPA 2013).
Marsh	20	8.2%	Lakebeds and floodplains subject to regular inundation, supporting samphire and halophytic shrublands	Depositional surfaces derived from Quaternary alluvium and lacustrine deposits. Soils include red/brown clays, often with high alkalinity and gypsum content. Soils can be underlain by siliceous or calcareous hardpans.
McKay	1	8.2%	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.
Mosquito	6	0.4%	Stony plains and prominent ridges of schist and other metamorphic rocks supporting hard spinifex grasslands.	Erosional surfaces including stony plains and pediments with prominent ridges and hills with steep upper slopes and more gently inclined footslopes. Moderately spaced tributary flow lines and channels. Shallow loamy soils, with some saline clay soils in low lying plains and interfluves.
Narbung	15	1.3%	Alluvial washplains with prominent internal drainage foci supporting Snakewood and Mulga shrublands with halophytic low shrubs.	Almost level alluvial plains receiving overland sheetflow. Localised internal drainage, with no defined channel features. Soil types generally include red deep sandy duplex and shallow sandy duplex soils.
Newman	1	17.2%	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.
Pindering	12	0.8%	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	0.5%	Dissected slopes and raised plains supporting hard spinifex grasslands.	Erosional surfaces formed by partial dissection of the old Tertiary surface. Stony upper plains are separated by closely spaced dendritic or sub-parallel drainage lines, incised up to 30 m below the surrounding land surface. Soils are mainly red shallow loams and stony types, with red loamy earths in dissection zones.

Land system	Type	Percent of study area	Description	Geomorphology and soils
River	17	0.6%	Active floodplains 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	0.1%	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	2.8%	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	1.8%	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, mesa and lower plains supporting Mulga and Senna shrublands and minor spinifex grasslands.	Erosional surfaces formed by dissection of the old Tertiary surface (low dissected plateaux with breakaways). Moderately to widely spaced tributary and non-tributary drainage floors and channels. Soils are predominantly calcareous and red shallow loams.
Turee	14	4.7%	Stony alluvial plains with gilgaied and non-gilgaied surfaces supporting tussock grasslands and grassy shrublands.	Mosaic depositional surfaces of low relief (hardpan, stony and gilgai plains) inter-dispersed with few drainage channels. Localised sheetflow can occur. Soils include various earths, loams and clays often with abundant surface cobbles.
Urandy	13	1.2%	Stony plains, alluvial plains and drainage lines supporting shrubby soft spinifex grasslands.	Depositional surfaces of low relief. Plains and fans of sandy alluvium with widely spaced through going or sub-parallel distributor creek lines and channels. Soil types mainly include red loamy earths, with some red shallow sandy duplex soils.
Wannamunna	12	0.3%	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.
Warri	18	0.2%	Low calcrete platforms and plains supporting Mulga and Senna shrublands	Depositional surfaces of low relief. Calcrete layers, with narrow inter-bedded areas. Soil types mainly include calcareous shallow loams and loamy earths. Surface mantles commonly include calcrete pebbles and fragments.
Washplain	12	0.3%	Hardpan plains supporting groved mulga shrublands.	Depositional surfaces including alluvial level hardpan plains. Discrete drainage foci associated with groved vegetation, with some drainage tracts receiving more concentrated flow. Soils are generally deep duplex types, and red loamy earths; commonly with hardpans at depth.
Wona	9	0.4%	Basalt upland gilgai plains supporting tussock grasslands and minor hard spinifex grasslands.	Mainly erosional surfaces including uplands and subdued plateaux with gently sloping stony gilgai plains, minor hills and benched slopes. Sparse patterns of incised drainage with narrow drainage and steep, stony slopes. Soils are predominantly cracking and non-cracking clays.

2.6.3 Vegetation and flora

The 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 (Table 2-3, Map 2.08). Major plant families represented include Fabaceae (*Acacia* spp.), Myrtaceae (*Eucalyptus* spp.), Scrophulariaceae (*Eremophila* spp.), Chenopodiaceae (Samphires, Bluebushes, and Saltbushes), Asteraceae (Daisies) and Poaceae (Grasses).

Table 2-3: Description of vegetation association in the Fortescue Marsh study area mapped by Beard (1975)

Vegetation Association Reference	Percent of study area	Description
18	3.3%	Low woodland; mulga (*Acacia aneura* and its close relatives)
29	42.7%	Sparse low woodland; mulga, discontinuous in scattered groups
82	14.0%	Hummock grasslands, low tree steppe; snappy gum over *Triodia wiseana*
93	0.02%	Hummock grasslands, shrub steppe; kanji over soft spinifex
111	10.7%	Hummock grasslands, shrub steppe; *Eucalyptus gamophylla* over hard spinifex
157	0.3%	Hummock grasslands, grass steppe; hard spinifex *Triodia wiseana*
166	0.9%	Low woodland; mulga and *Acacia victoriae*
173	12.2%	Hummock grasslands, shrub steppe; kanji over soft spinifex and *Triodia wiseana* on basalt
175	0.4%	Short bunch grassland - savannah/grass plain (Pilbara)
197	2.1%	Sedgeland; sedges with scattered medium trees; *Eucalyptus victrix* over various sedges and forbes
216	0.03%	Low woodland; mulga (with spinifex) on rises
562	6.6%	Mosaic: Low woodland; mulga in valleys/Hummock grasslands, open low tree-steppe; snappy gum over *Triodia wiseana*
676	6.8%	Succulent steppe; samphire

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 are summarised below:

Fortescue Valley

- Protrusions of the Chichester Range into the Fortescue Valley support *Acacia* low shrubland (*A. trachycarpa, A. arrecta*) over hummock grasses.
- Lowland sandplains (occasionally with small dunes) support open Mulga (*Acacia aneura* and its close relatives), Pilbara box (*Eucalyptus xerothermica*), northwest box (*E. tephrodes*) or desert bloodwood (*Corymbia deserticola*) woodlands with some blue-leafed mallee (*E. gamophylla*) over soft hummock grasses (*Triodia pungens, T. melvillei*). Low scrub and heath comprising conspicuous sandy desert floral elements (*Grevillea juncifolia*, *G. eriostachya*, *Kennedia prorepens*, *Leptosema chambersii*, *Diplopeltis stuartii)* persist in dune areas.
- Bajadas[4] and hardpan plains in the north of the subregion (below the Chichester Range) include open mulga woodland and snakewood (*A. xiphophylla*) shrubland over tussock grasses (*Themeda triandra*, *Chrysopogon fallax*, *Eragrostis* spp.) or open hummock grasses (*Triodia pungens*, *T. wiseana*).
- Bajadas and hardpan plains in the east of the subregion are typically covered by low mulga woodlands over open shrubs (*Eremophila forrestii, E. cuneifolia, E. lanceolata*) and scattered hummock grasses. Herbs (e.g. *Ptilotus exaltatus*, *P. auriculifolius*, *P. helipteroides*) are abundant in season.
- Bajadas and hardpan plains in the south of the subregion include open mulga woodlands, Western Gidgee (*Acacia pruinocarpa*) and snakewood shrublands over tussock grasses (*Eragrostis* spp.) or open hummock grasslands (*Triodia wiseana, T. melvillei*).
- Floodout zones associated with the Fortescue River and its major tributaries upstream of the Fortescue Marsh support woodlands of Western Coolibah (*Eucalyptus victrix*), Western Ghost Gum (*Corymbia candida*), Whitewood (*Atalaya hemiglauca*), Mulga, Weeping Wire Wood (*Acacia coriacea* subsp. *pendens*) and *A. distans* over tussock grasses (**Cenchrus ciliaris*, *Eragrostis benthamii*, *Eulalia aurea*) and herbs (*Calotis multicaulis*, *Ptilotus helipteroides*, *P. gomphrenoide*s).
- The alluvial and lacustrine deposits of the Fortescue Marsh and surrounds are dominated by low mulga woodlands over bunch grass (*Aristida* spp., *Enneapogon* spp.) on the non-saline alluvial plains, fringing wattle (*Acacia ampliceps*, *A. sclerosperma* var. *sclerosperma*) shrublands on saline clay banks and calcareous rises, scattered samphire (*Tecticornia* spp.), saltbush (*Atriplex* spp.) and *Eremophila spongiocarpa* shrubs on saline cracking and non-cracking clay flats, and a shrubby grassland of salt water couch (*Sporobolus virginicus*) with false lignum (*Muellerolimon salicorniaceum*) and lignum (*Muehlenbeckia florulenta*) on floodplains.

Hamersley

- On mountain summits, the vegetation is characteristically shrub mallee (*E. kingsmillii, E. ewartiana, E. lucasii*) with emergent Snappy Gum (*Eucalyptus leucophloia*) or Iron Bloodwood (*Corymbia ferriticola*) over shrubs (*Acacia arida, Gastrolobium grandiflorum, Hibbertia glaberrima, Daviesia eremaea*) and hard spinifex (*Triodia brizoides*).
- The rolling hills and stony plains support an open woodland of snappy gum (*Eucalyptus leucophloia*) over low shrubs (*Acacia bivenosa, A. ancistrocarpa, A. maitlandii, Keraudrenia spp*.) and hard spinifex (*T. wiseana, T. basedowii, T. lanigera*), with upland drainage features supporting slightly denser vegetation mostly comprising wattle shrubs with some Pilbara bloodwood (*Corymbia hamersleyana*). Shrub mallee (*Eucalyptus gamophylla, E. trivalva, E. socialis* subsp. *eucentrica, E. striaticalyx*) over tea tree (*Melaleuca eleuterostachya*) and hard hummock grasses (*T. basedowii, T. longiceps, T. angusta*) are also a common community on stony plains and rolling hills, particularly on calcareous pediments.
- The ironstone and basalt ridges, ranges and hills of the subregion 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.*

[4] a series of coalescing alluvial fans along a mountain front.

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 above detrital banded ironstone deposits and valley-fills support a cover of Acacia woodland and shrubland dominated by mulga (*A. aneura* s.l., *A. ayersiana, A. minyura*) over an understorey of open shrubs (*Ptilotus obovatus, Rhagodia eremaea, Senna glutinosa*) and tussock grasses (*Chrysopogon fallax, Eragrostis* spp., *Eriachne* spp.).
- The small drainages are dominated by emergent Pilbara Bloodwoods, Pilbara Box (*Eucalyptus xerothermica*), Western Coolibah with Acacia (*A. maitlandii, A. monticola, A. tumida* var. *pilbarensis, A. ancistrocarpa*) shrubland over hard and soft hummock grasses (*T. wiseana, T. pungens*) and occasional tussock grasses (*Themeda* spp.) depending on landscape position.
- The large channels contain extensive alluvium and fine depositional deposits and support a fringing riparian open tall woodland of River Red Gums (*Eucalyptus camaldulensis*) and Western Coolibahs over woodlands or tall shrublands of Pilbara jam (*Acacia citrinoviridis*), slender petalostylis (*Petalostylis labicheoides*) and weeping wire wood over soft hummock grasses (*T. pungens, T. epactia*) and tussock grasses such as buffel grass, kangaroo grass and silky browntop (*Eulalia aurea*).
- In sites where the drainage is interrupted and the watertable rises, extensive Silver Cadjeput (*Melaleuca argentea*) forests with River Red Gums and Western Coolibah woodlands over native cotton (*Gossypium* spp.) and sedgelands of stiffleaf sedge (*Cyperus vaginatus*) may exist.
- Internal drainage basins 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 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.

Chichester

- Along the escarpment of the Chichester Range in the south of the Chichester subregion, short, parallel drainages empty onto the alluvial plains of the Fortescue Valley. Open mulga woodlands, snakewood shrublands and hard hummock grasslands with emergent Hamersley bloodwoods (*Corymbia hamersleyana, C. semiclara*) or Snappy Gums occupy these slopes.
- Tablelands of decomposing basalt are a distinguishing feature of the Chichester Plateau along the southern margin of the Chichester subregion. These tablelands, described as the Wona Land System (*Van Vreeswyk* et al., *2004*), comprise gilgai plains or self-mulching cracking clays supporting tussock grasslands dominated by Mitchell grass (*Astrebla* spp.), sorghum (*Sorghum* spp.*)* and Roebourne Plain grass (*Eragrostis xerophila*) and/or herbfields of ephemeral Papilionaceae (*Desmodium* spp., *Glycine spp., Rhynchosia* spp.), and Amaranthaceae (*Ptilotus* spp.).

Over the past decade, BHP Billiton Iron Ore has undertaken more detailed vegetation surveys in parts of the study area, mostly in areas proximal to the Hamersley Range and associated with the rail corridor passing the western fringe of the Fortescue Marsh (Map 2-09). Significant additional portions of the Hamersley Range, Chichester Range, major drainages and sections of the Fortescue valley have been surveyed by other mining companies (Map 2-09).

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, this mapping has spatially delineated vegetation units including the potentially groundwater dependent species *Eucalyptus camaldulensis* and *E. victrix*. These species are invariably associated with EHU 8 and in some cases larger drainage 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. Several priority listed flora, as recognised by the 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.

2.6.4 Terrestrial and aquatic fauna

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

- mountainous rugged terrain associated with the Hamersley Range comprising ridges, plateaus, steep hills with free faces and stream channels;
- rolling hills and foothills associated with the Hamersley Range;
- rolling hills and foothills associated with the Chichester Range;
- gently sloping to level alluvial plains within the broader Fortescue Valley;
- calcrete platforms and plains, generally adjacent to the Fortescue Marsh;
- the major drainage systems and floodplains, featuring riparian Eucalypt woodlands. These are principally associated with Weeli Wolli Creek, Mindy Mindy Creek, Coondiner Creek south of the Fortescue Marsh; and Christmas Creek north of the Marsh; and
- Fortescue Marsh including clay flats and fringing samphire communities.

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).

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

- Pilbara Olive Python (*Liasis olivaceus barroni)* - occurs in rocky areas, showing a preference for habitats near water in particular rock pools.
- Pilbara Leaf-nosed Bat (*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 waterbodies associated with major drainage systems and lakes, including the Fortescue Marsh. The Fortescue Marsh is known to support a variety of migratory waterbird species, including Clamorous Reed-warbler (*Acrocephalus stentoreus*), Great Egret (*Ardea alba*), Swamp harrier (*Circus approximans*) and Whiskered Tern (*Chlidonias hybridus*), as well as Sacred Kingfisher (*Todiramphus sanctus*). It is a major breeding area for the Australian Pelican (*Pelecanus conspicillatus*) and Black Swan (*Cygnus atratus*) (DEC, 2009).

The Fortescue Marsh and claypans west of the Goodiadarrie Hills support diverse aquatic invertebrate communities, which contribute to the conservation significance of these wetland environments. Endemic macoinverebrates reported to occur in the Marsh include a *Coxiella* snail, several undescribed ostracods (*Mytilocypris* n. sp., *Heterocypris* n. sp. - these are also known from Weelarrana Lake south of Newman), an enchytraeid oligochaete, a cladoceran (*Alona* n. sp.) and a *Tanytarsus* chironomid (EPA 2013). In addition, two species of macroinvertebrates sampled from the Marsh (caldocerans *Dadaya macrocops* and *Celsinotum parooensis*) are the only known records for these species in Western Australia (EPA, 2013).

2.6.5 Subterranean fauna

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

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

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

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

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

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

Nine areas of high stygofauna richness have been identified in the Pilbara region, where some protection of stygofauna values may be warranted if not already in place (Halse et al., 2014). However, none of these occur within the study area.

2.6.6 Ecological assets

The study area does not include any areas with conservation management tenure. Karijini National Park is the nearest conservation area, located about 10 km from the south western edge of the study area at its closest point.

Parts of the study area under pastoral tenure have been proposed for transfer into the conservation estate post-2015 by DPaW (Map 2-10); including large portions of the Fortescue Marsh. It is important to note that current pastoral leases were granted under the now repealed *Land Act 1933* (WA), and will expire on 30 June 2015 (EDO, 2010).

The Fortescue Marsh is recognised as being a unique and extensive inland floodplain system within the Pilbara region (McKenzie *et al.* 2009). It is classified as a wetland of national importance within the Directory of Important Wetlands in Australia (DIWA) based on the following criteria (DEC, 2009):

- It is an example of a large-scale wetland type occurring within a biogeographic region in Australia. It is the only feature of this type in the Pilbara bioregion.
- It has important ecological and hydrological roles in the natural functioning of a major wetland system/complex.
- It is important as the habitat for animal taxa at a vulnerable stage in their life cycles, or provides a refuge when adverse conditions such as drought prevail. It is a significant drought refuge area for native vertebrate fauna in the Pilbara bioregion. It is also known to support migratory

waterbird species, including Clamorous Reed-warbler (*Acrocephalus stentoreus*), Great Egret (*Ardea alba*), Swamp Harrier (*Circus approximans*) and Whiskered Tern (*Chlidonias hybridus*), as well as Sacred Kingfisher (*Todiramphus sanctus*). It is a major breeding area for the Australian Pelican (*Pelecanus conspicillatus*) and Black Swan (*Cygnus atratus*).

- It has considerable historical or cultural significance. The Marsh Yintas, such as Moorimoordinina Pool, are of cultural significance to the local Aboriginal people.

The Fortescue Marsh is recognised as providing habitat for several bird species listed under the Japan Australia Migratory Bird Agreement (JAMBA), China Australia Migratory Bird Agreement (CAMBA) and Republic of Korea Australia Migratory Bird Agreement (ROKAMBA) which are treaties for the protection of certain migratory bird species. The treaties require each country to take appropriate measures to preserve and enhance the environment of bird species subject to the treaty provisions.

The Fortescue Marsh (Marsh Land System) is classified as a Priority Ecological Community (PEC) by DPaW, described as follows (DPaW, 2013):

"Fortescue Marsh is an extensive, episodically inundated samphire marsh at the upper terminus of the Fortescue River and the western end of Goodiadarrie Hills. It is regarded as the largest ephemeral wetland in the Pilbara. It is a highly diverse ecosystem with fringing mulga woodlands (on the northern side), samphire shrublands and groundwater dependant riparian ecosystems. It is an arid wetland utilized by waterbirds and supports a rich diversity of restricted aquatic and terrestrial invertebrates. Recorded locality for Night Parrot and Bilby and several other threatened vertebrate fauna. Endemic Eremophila species, populations of priority flora and several near endemic and new to science samphires. Recognised threats include: mining, altered hydrology (watering with fresh water), grazing and weed invasion."

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 occur including:

- Fortescue Marsh (Marsh Land System) (Priority 1): previously described.
- Fortescue Valley Sand Dunes (Priority 3) - These red linear sand dune communities lie on the Divide Land system at the junction of the Hamersley Range and Fortescue Valley, between Weeli Wolli Creek and the low hills to the west (five discrete occurrences within the study area). A small number are vegetated with Acacia dictyophleba scattered tall shrubs over *Crotalaria cunninghamii*, *Trichodesma zeylanicum var. grandiflorum* open shrubland. They are regionally rare, small and fragile and highly susceptible to threatening processes. Threats include weed invasion especially buffel grass and erosion.
- Stony saline plains of the Mosquito Land System (Priority 3) - Described as saltbush community of the duplex plains - Mosquito Creek series (Nullagine). Known to contain two endemic Acacia species. One occurrence known on stony plains, and one on rocky ground (both in the far eastern portion of the study area). Threats include preferential grazing, prospecting, mining and increasing erosion.
- Freshwater Claypans of the Fortescue Valley (Priority 1) - Freshwater claypans downstream of the Fortescue Marsh - Goodiadarrie Hills on Mulga Downs Station. There are three occurrences in the study area. Important for waterbirds, invertebrates and some poorly collected plants. Eriachne spp., Eragrostis spp. grasslands. A unique community notable for having few Western Coolibah trees. Threats include weed invasion, infrastructure corridors, altered hydrological flows, and inappropriate fire regimes.
- Four plant assemblages of the Wona Land System - A system of basaltic upland gilgai plains with tussock grasslands occurs throughout the Chichester Range in the Chichester-Millstream National Park, Mungaroona Range Nature Reserve and on adjacent pastoral leases. This includes the north western fringe of the study area. There are a series of community types identified within the Wona Land System gilgai plains that are considered susceptible to known threats such as grazing or have constituent rare/restricted species, as follows:
    - Cracking clays of the Chichester and Mungaroona Range (Priority 1). This grassless plain of stony gibber community occurs on the tablelands with very little vegetative cover during the dry season, however during the wet a suite of ephemerals/annuals

and short-lived perennials emerge, many of which are poorly known and range-end taxa.

  - Annual Sorghum grasslands on self-mulching clays (Priority 1). This community appears very rare and restricted to the Pannawonica-Robe valley end of Chichester Range.
  - Mitchell grass plains (*Astrebela spp.*) on gilgai (Priority 3).
  - Mitchell grass and Roebourne Plain grass (*Eragrostis xerophila*) plain on gilgai (typical type, heavily grazed) (Priority 3).

- Brockman Iron cracking clay communities of the Hamersley Range (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. Known from near West Angeles, Newman, Tom Price and boundary of Hamersley and Brockman Stations. One occurrence near the western end of the Fortescue Marsh within the study area.

2.6.7 Fortescue Marsh environmental management framework

In July 2013, the EPA defined a Fortescue Marsh Management Area consisting of seven sub-zones partitioned into three conservation significance categories (EPA 2013; Map 2-10). This aimed to provide clarity and consistency in relation to environmental assessment and approvals processes relevant for mining and mining-related activities in the vicinity of the Marsh. The process of developing and describing the management areas (Table 2-4) involved wide ranging stakeholder consultation. The Fortescue Marsh management areas reflect the distribution of environmental values and their relative priority in and around the Marsh.

Table 2-4: Description of the Fortescue Marsh Management Zones (EPA 2013)

Management zone	Relative priority	Environmental values	Management objectives
1a – Northern Flank	High	Fresh/brackish springs and seepages (along the southern edge of this zone) Groundwater dependent ecosystems Floristically unique mulga woodlands and shrublands Flora and fauna of conservation significance[5]. Stygofauna and troglofauna present, with potential for restricted species but limited data. Cultural and spiritual heritage Christmas and Cowra land systems (restricted to the Fortescue Valley).	Protect natural pools and springs. Minimise disruption to groundwater in aquifers supporting groundwater dependant ecosystems. Protect the hydrological and ecological integrity of major tributaries entering the Marsh. Maintain the natural flow regime at the boundary between Northern Flank and Marsh zones. Protect Mulga and mixed Acacia woodland and shrublands. Minimise disruption to groundwater dependent ecosystems. Maintain groundwater levels to protect mulga vegetation communities. Protect species of conservation significance (in particular Night Parrot and Northern Quoll) and their habitat. Enhance knowledge of local subterranean fauna. Minimise impacts to the Christmas and Cowra land systems.
1b - Marsh	High	Pools present for prolonged periods following flow events Fresh/brackish springs Unique, ephemeral wetland Hydrogeology Samphire vegetation communities Aquatic invertebrates Waterbirds Flora of conservation significance[6]	Protect natural pools and springs. Minimise disruption to aquifers supporting the Marsh. Maintain the natural flow regime of the Marsh (including at the Marsh boundary). Minimise disturbance to native vegetation. Maintain water quality in the Marsh. Protect species of conservation significance and their habitat. Protect samphire and halophytic vegetation. Enhance understanding of samphire (*Tecticornia* spp.).

[5] Australian Bustard; Bilby; Bush Stone-curlew; Night Parrot; Northern Quoll; Peregrine Falcon; *Eremophila youngii* subsp. *lepidota; Goodenia nuda*

[6] (*Atriplex flabelliformis; Eleocharis papillosa; Eremophila spongiocarpa; E. youngii* subsp. *lepidota*; *Nicotiana heterantha*; *Peplidium* sp. Fortescue Marsh (S. van Leeuwen 4865); *Tecticornia* sp. Christmas Creek (K.A. Shepherd *et al.* KS 1063); *T.* sp. Fortescue Marsh (K.A. Shepherd *et al.* KS 1055); *T.* sp. Roy Hill (H. Pringle 62))

Management zone	Relative priority	Environmental values	Management objectives
		Fauna of conservation significance[7] Cultural and spiritual heritage Recreation	Enhance knowledge of local invertebrates. Protect waterbird habitat and foraging habitat.
Calcrete Flats (2a)	Medium - important to protect and rehabilitate where possible	Natural water regimes Subterranean fauna Aquatic invertebrates Vegetation communities Flora of conservation significance[8] Cultural and spiritual heritage	Maintain the natural flow regimes, especially at the Marsh boundary. Maintain natural cycles of wetting for clay pan habitats. Minimise disruption to aquifers from activities in neighbouring zones. Enhance understanding of local subterranean fauna Enhance understanding of aquatic invertebrates Minimise impact to native vegetation communities Rehabilitate native vegetation where possible. Protect species of conservation significance and their habitat
2b - Poonda Plain	Medium	Natural water regimes Fortescue Valley sand dune communities (PEC Priority 3). Flora of conservation significance[9] Fauna of conservation significance[10] Subterranean fauna Aquatic invertebrates Cultural and spiritual heritage	Maintain the natural flow regime at the boundary between Northern Flank and Marsh zones. Maintain the natural flow regime of tributaries entering the Marsh. Protect the hydrological and ecological integrity of major tributaries entering the Marsh. Protect the Fortescue Valley sand dune PECs. Protect species of conservation significance and their habitat. Enhance understanding of local subterranean species. Enhance understanding of aquatic invertebrates.
2c – Fortescue River Coolibah	Medium	Natural water regimes Riparian vegetation (stands of *Eucalyptus victrix*)	Maintain natural water balances and function of the aquifer. Maintain the natural flow regime at the Marsh boundary. Minimise impacts to riparian native vegetation.

[7] Bilby; Common Greenshank; Eastern Great Egret; Night Parrot; Wood sandpiper
[8] *Eremophila spongiocarpa; Goodenia nuda; Myriocephalus scalpellus*
[9] *Themeda* sp. Hamersley Station (M.E. Trudgen 11431)
[10] Australian Bustard; Bilby; Bush Stone-curlew; Ghost Bat; Northern Quoll; Western Pebble-mound Mouse; Mulgara

Management zone	Relative priority	Environmental values	Management objectives
		Fauna of conservation significance[11] Subterranean fauna Cultural and spiritual heritage	Maintain the natural surface water flows and flooding regime of the alluvial and gilgai plains. Minimise disruption to aquifers supporting groundwater dependent ecosystems and riparian vegetation. Protect species of conservation significance and their habitat. Enhance understanding of local subterranean fauna.
3a - Kulbee Alluvial Flank	Low	Natural water regimes Natural springs and pools Mulga woodlands Flora of conservation significance[12] Fauna of conservation significance[13] Subterranean fauna Cultural and spiritual heritage	Maintain the natural flow regime at the Marsh boundary. Protect the hydrological and ecological integrity of major tributaries entering the Marsh. Protect the natural pools and springs. Manage impacts to Mulga vegetation. Manage overland surface water flows. Protect species of conservation significance and their habitat. Enhance understanding of local subterranean fauna.
3b - Marillana Plains	Low	Natural water regimes Land systems Mulga woodlands Flora of conservation significance[14] Fauna of conservation significance[15] Subterranean fauna Aquatic invertebrates Cultural and spiritual heritage	Maintain the natural flow regime at the Marsh boundary. Manage impacts to the Marillana land system (which is restricted to the Fortescue Valley). Manage impacts to mulga vegetation. Maintain the natural overland surface water flow regime. Minimise native vegetation clearing. Undertake surveys to identify and map distributions of conservation significant species. Enhance understanding of local subterranean fauna and aquatic invertebrates.

[11] Bilby
[12] *Eremophila youngii* subsp. *lepidota; Goodenia nuda; Rhagodia sp. Hamersley (M. Trudgen 17794*)
[13] Australian Bustard; Bush Stone-curlew; Ghost Bat
[14] *Atriplex flabelliformis; Calocephalus beardii; Goodenia nuda*
[15] Australian Bustard

2.7 Water use

Water use across the study area is dominated by mining operations with mine dewatering and discharge of surplus water.

In general, water use falls into one of three categories:

- Pastoral - pastoral stations require water for livestock. Water is obtained from bores and permanent pools within ephemeral watercourses. The volume of water used for stock watering is negligible, when compared with abstraction for mining and town water supplies.
- Environmental water use – water which maintains the area's environmental needs.
- Mining - the main water requirements are mineral processing and dust suppression. An additional water supply is often required for the construction of road and rail infrastructure. Dewatering of orebodies for mining can generate substantial volumes to be discharged.

The pastoral industry has traditionally been a minor water user; however, access to water resources is crucial to its function. Shallow bores and hand-dug wells were initially constructed to meet the pastoral requirements for stock watering. Most pastoral bores and wells tend to be concentrated in the low-lying areas in alluvial aquifers. Most are less than 30 m deep and are typically equipped with a windmill, with yields of up to 10 m^3/day.

It is difficult to determine the number of functioning bores and wells for pastoral use with most abandoned or poorly maintained. Water licensing for stock and domestic use is not required under the *Rights in Water and Irrigation Act 1914* unless the water is from an artesian source (DoW, Pilbara Regional Water Plan 2010-2030, 2008).

The mining industry is the major groundwater user in the study area. Mining operations generally abstract several GL/yr (common rates are more than 10 GL/yr), from mine dewatering and borefields. Abstracted water is used for dust suppression, mineral processing and ore beneficiation, but a significant part is also returned to the aquifer system (e.g. FMG's Cloudbreak operation).

Mine dewatering borefields are designed to lower the watertable in advance of mining to facilitate safe mining conditions. In order to achieve dewatering, pumping rates must exceed the groundwater throughflow, resulting in localised storage depletion. In cases where dewatering exceeds the mine water demand, the discharge has to be responsibly managed in accordance with permit requirements. On completion of mining and cessation of dewatering, groundwater levels are expected to recover to near pre-pumping levels.

The largest users in the study area are:

- FMG – Cloudbreak and Christmas Creek iron ore projects;
- Roy Hill – Roy Hill iron ore project;
- BC Iron – Bonnie Downs project;
- BHP Billiton Iron Ore – Newman Railroad; and
- Numerous mineral exploration companies.

3 Regional hydrology

This section presents a conceptual understanding of regional hydrology, both surface and subsurface (hydrogeology), within the study area. Functional relationships and interactions between hydrological processes and ecosystems are evaluated where possible; particularly where applicable to the Fortescue Marsh. This forms the conceptual basis for assessing how potential changes (natural or anthropogenic) to the hydrological system may affect ecosystems, and which factors may be important for the formulation of mitigation strategies.

3.1 Surface water

3.1.1 Setting and key features

The Fortescue River Basin (49,750 km^2) is defined by the Chichester Range to the north and the Hamersley Range to the south (Map 3-01). It is divided into the Upper Fortescue River Catchment (30,279 km^2) and the Lower Fortescue River Catchment (19,890 km^2).

A small portion of the study area (in proximity to BHP Billiton Iron Ore's proposed Roy Hill operations) lies within the Lower Fortescue River Catchment, in a sub-catchment which drains into Goodiadarrie Swamp (Map 3-01). The remainder of the study area lies within the Upper Fortescue River Catchment, for which the Marsh is the drainage terminus.

Goodiadarrie Hills, which separate the Marsh from the Goodiadarrie Swamp, constitutes a surface water and potential groundwater divide. A second groundwater and surface water divide exists to the west of the Goodiadarrie Swamp, separating the Goodiadarrie Swamp from the Lower Fortescue River. Shallow groundwater in the internally draining Goodiadarrie Swamp is brackish to saline; whereas groundwater in the lower portion of the Fortescue River is fresh, implying the presence of a groundwater and surface water divide between the two hydrogeological systems. Fresh water may collect on the surface of playa lakes or clay pans within the Goodiadarrie Swamp during prolonged 'wet' periods.

Two major drainage systems, the Fortescue River and Weeli Wolli Creek, contribute point source surface water inflows (Map 3-01). All other sub-catchments receive no inflows from external catchments. Significant drainages include the Weeli Wolli Alluvial Fan and Mindy Mindy / Coondiner Creek catchments in the Hamersley Range, and Kulbee Creek / Christmas Creek / Kulkinbah Creek catchments in the Chichester Range (Map 3-01).

The Upper Fortescue River, with a total catchment area of 16,281 km^2, contributes significant surface water flow volumes into the eastern end of the Marsh. These flows are largely derived from upland areas, and delivered through numerous tributaries such as Homestead Creek, Whaleback Creek and Jimblebar Creek. Since the completion of Ophthalmia Dam in December 1981, natural flows emanating from the upper catchment have been partially attenuated. Downstream of Ophthalmia Dam, at the entrance of the Fortescue River to Fortescue River Valley (Ethel Gorge), there is a major deltaic feature.

Weeli Wolli Creek has a catchment area of 4,982 km^2 and drains into the central-southern part of the Fortescue Marsh, forming an extensive and broadly-shaped alluvial fan at the foot of the Hamersley Range. Weeli Wolli Creek receives contribution from Weeli Wolli Spring located higher in the catchment (outside the study area), as well as Yandicoogina and Marillana Creeks which discharge into Weeli Wolli Creek at approximately 25 km upstream of the point where the creek exits the Hamersley Range (Map 3-01). Where the creek enters the study area, it drains into a braided channel system within a more extensive delta (referred to as Weeli Wolli Alluvial Fan Catchment for the purpose of this study). Since the 1990s, natural surface water flow in the Weeli Wolli Creek has been supplemented by surface discharge from mining operations located upstream of the study area.

The drainage systems are ephemeral and flow in direct response to rainfall. Streamflow mainly occurs during the summer months of December to March and is generally associated with the major rainfall events such as the passage of tropical cyclones. Runoff can persist for periods of weeks to months.

3.1.2 Rainfall

Rainfall is the key driver of the hydrological processes within the study area. Consideration of temporal and spatial variation in rainfall is necessary for an accurate hydrological conceptualisation. Rainfall data have been used to develop rainfall runoff relationships for catchments within the study area and catchments contributing point inflows to the study area – i.e. Weeli Wolli Creek Catchment and Fortescue River Catchment.

To develop an understanding of rainfall distribution, data was collected from the rainfall stations shown in Map 2-01. The data was compiled and evaluated as described in Appendix A. Based on this evaluation, SILO rainfall data was deemed appropriate in combination with records from individual rainfall stations.

Data from a single rainfall station or SILO data point does not adequately represent the spatial and temporal variation of rainfall across a major surface water catchment. Combinations of rainfall stations were therefore used to develop catchment rainfall for each of the surface water catchments (Table 3-1).

There are four gauged catchments relevant to the study area for which annual catchment rainfall can be calculated: based on gauge station records at Waterloo Bore, Flat Rocks, Tarina and Newman (Map 3-01; refer to Section 3.1.3 for further description of these catchments). Waterloo Bore is located within the study area in the lower reaches of Weeli Wolli Creek, while the remaining gauging stations are located in upstream catchments outside the study area. While rainfall record periods were generally significantly longer than the available streamflow records, the rainfall runoff analysis was limited to the streamflow record periods (as discussed in Section 3.1.3).

Recorded rainfall data was primarily used in developing rainfall runoff relationships for the gauged catchments. Given the wide contour intervals of the annual rainfall isohyets as shown in Map 2-01, a Thiesson-polygon approach was used to determine contributions of individual rainfall stations to catchment rainfall.

While rainfall over the Marillana Creek catchment is generally higher than that of the surrounding catchments, there are no significant spatial variations on an annual basis (Figure 3-1). There are some temporal variations, with a generally drier period between 1985 and 1993, followed by a wetter period 1994 to 2005, and indications of a drying period 2006 to present.

As discussed in Section 2.1, annual rainfall is unreliable and dependent on cyclones passing over the area. This is further confirmed by annual rainfall varying between 200 and 1,000 mm, compared to the long-term average annual rainfall of between 300 to 500 mm/yr (Figure 3-1; Map 2-01).

Table 3-1: Rainfall stations used to develop catchment rainfall estimates

River	Catchment	Rainfall Station	Mean Annual Rainfall (mm)	Catchment Rainfall	
				Period	mm
Marillana Creek	Flat Rocks	Packsaddle Camp	411	12/1984 – 04/2013	412
		Munjina	439		
		Flat Rocks	385		
Weeli Wolli Creek	Tarina	Wonmunna	379	12/1984 – 04/2013	380
		Rhodes Ridge	414		
		Tarina	368		
Weeli Wolli Creek	Waterloo Bore	Packsaddle Camp	411	12/1984 – 04/2013	390
		Munjina	439		
		Flat Rocks	385		
		Rhodes Ridge	414		
		Wonmunna	379		
		Tarina	368		
		Waterloo Bore	401		
Fortescue River	Newman	SILO_05	347	01/1980 – 04/2013	330
		SILO_08	319		
		East Giles	376		
		Mideroo	294		
		Newman	315		
		Southern Fortescue	356		

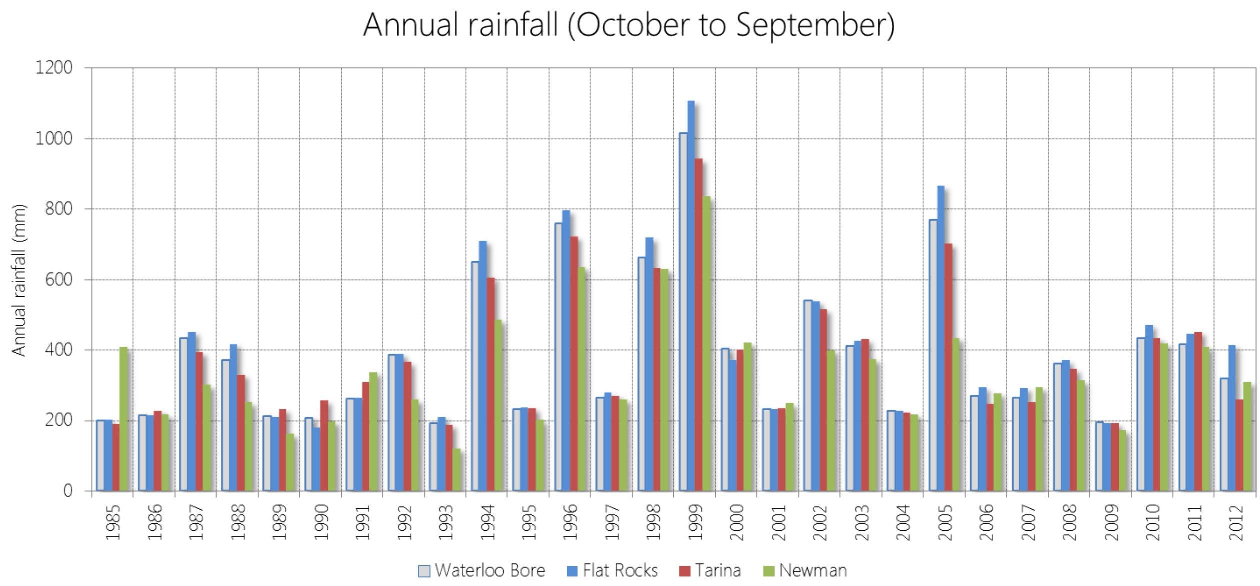


Figure 3-1: Annual catchment rainfall calculated from combinations of rainfall station data

3.1.3 Streamflow

Records from gauging stations at Waterloo Bore, Flat Rocks, Tarina and Newman (Table 3-2) have been considered as the basis for estimating inflows, and for developing an understanding of catchment responses to rainfall. It should be noted that runoff calculations and comparisons for these catchments were based on the standard hydrological year October to September.

Table 3-2: Streamflow gauges in proximity to the study area

Creek/River	Station Name	Station Number	Location	Catchment Area (km²)	Record Period
Gauges within study area					
Weeli Wolli Creek	Waterloo Bore	708013	Lat: -22.72S Long: 119.34E	3,991	30/11/1984 to date
Gauges outside study area					
Marillana Creek	Flat Rocks	708001	Lat: -22.72S Long: 119.97E	1,369	15/08/1967 to date
Weeli Wolli Creek	Tarina	708014	Lat: -22.88S Long: 119.23E	1,512	10/05/1985 to date
Fortescue River	Newman	708011	Lat: -23.40S Long: 119.79E	2,822	01/07/1980 to date

Weeli Wolli Creek Catchment

The Weeli Wolli Creek catchment has four operating streamflow gauging stations (Map 3-01), three of which have been used for this study:

- Waterloo Bore (3,991 km²), the most downstream station, records flow prior to entering the Weeli Wolli alluvial fan area.
- Flat Rocks (1,369 km²) records flow from the upper Marillana Creek catchment upstream of the confluence with the Weeli Wolli Creek.
- Tarina (1,512 km²) records flow from the upper reaches of the Weeli Wolli and Pebble Mouse Creeks being located 13 to 15 km downstream of the operating Hope Downs 1 minesite.

Streamflow analysis for the Weeli Wolli Creek sub-catchments (Figure 3-2) was based on the Waterloo Bore record period of 1984 to 2013. This allowed for a consistent period for comparison and analysis across the Waterloo Bore, Flat Rocks and Tarina gauging stations respectively. Note that while the Flat Rocks record starts in 1967, the record period 1967 to 1984 contains a number of data gaps.

The impact of cyclones and typical variable nature of streamflow in the Pilbara is illustrated in Figure 3-2. The high annual flow for 1999 resulted from tropical cyclone John in December 1999, followed by cyclones Kirrily (January/February 2000) and Norman (February/March 2000).

Comparison of annual streamflow at the three streamflow gauges shows that the average annual runoff at Tarina (12.8 mm) is higher than at Waterloo Bore (8.4 mm) (Table 3-3). However for the period 1985 to 2006, average annual runoff at Waterloo Bore (9.7 mm) is higher than at Tarina (9.0 mm). Annual flows at Waterloo Bore are generally higher than the Tarina flows for most of the record period (Figure 3-2), with a change noticeable in 2007. A change in runoff (increase in Tarina flows) coincides with the commencement of dewatering releases from Hope Downs 1 upstream of the Tarina gauge since early 2007 (Figure 3-3). The additional volumes of water are not reflected in the Waterloo Bore record, suggesting significant losses are experienced along the Weeli Wolli Creek between the Tarina and Waterloo Bore streamflow gauges.

Table 3-3: Annual runoff comparison – Weeli Wolli Creek Catchments (1984 to 2013)

River/Creek	Gauging Station	Average annual runoff		Median annual runoff	
		GL	mm	GL	mm
Marillana Creek	Flat Rocks	7.33	5.4	3.10	2.3
Weeli Wolli Creek	Tarina	19.4	12.8	8.0	5.3
Weeli Wolli Creek	Waterloo Bore	33.54	8.4	1.92	0.5

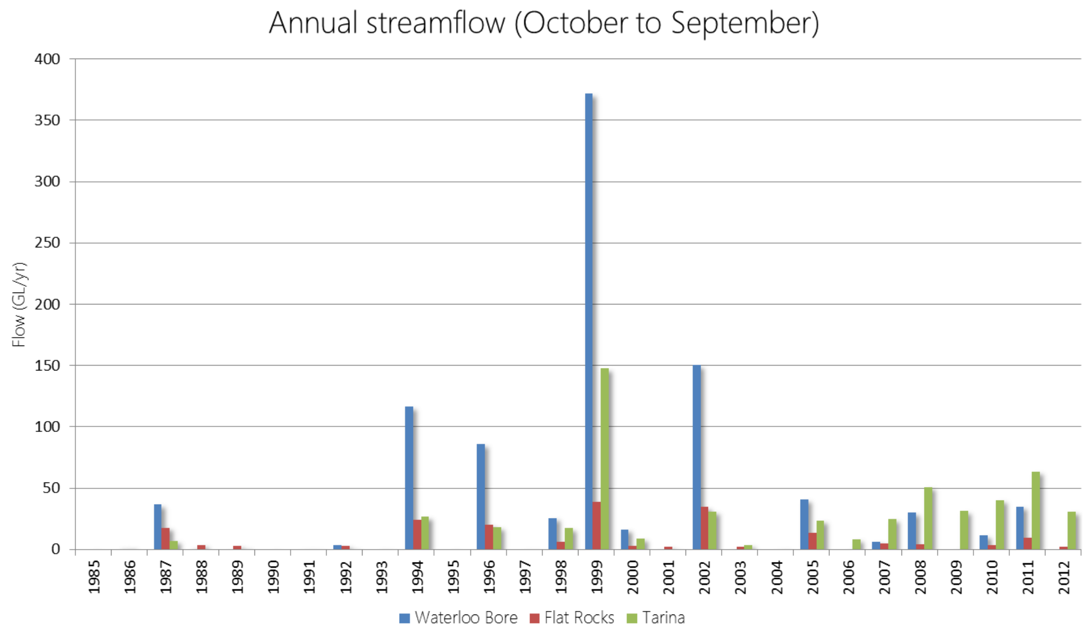


Figure 3-2: Annual recorded streamflow for Weeli Wolli Creek catchments

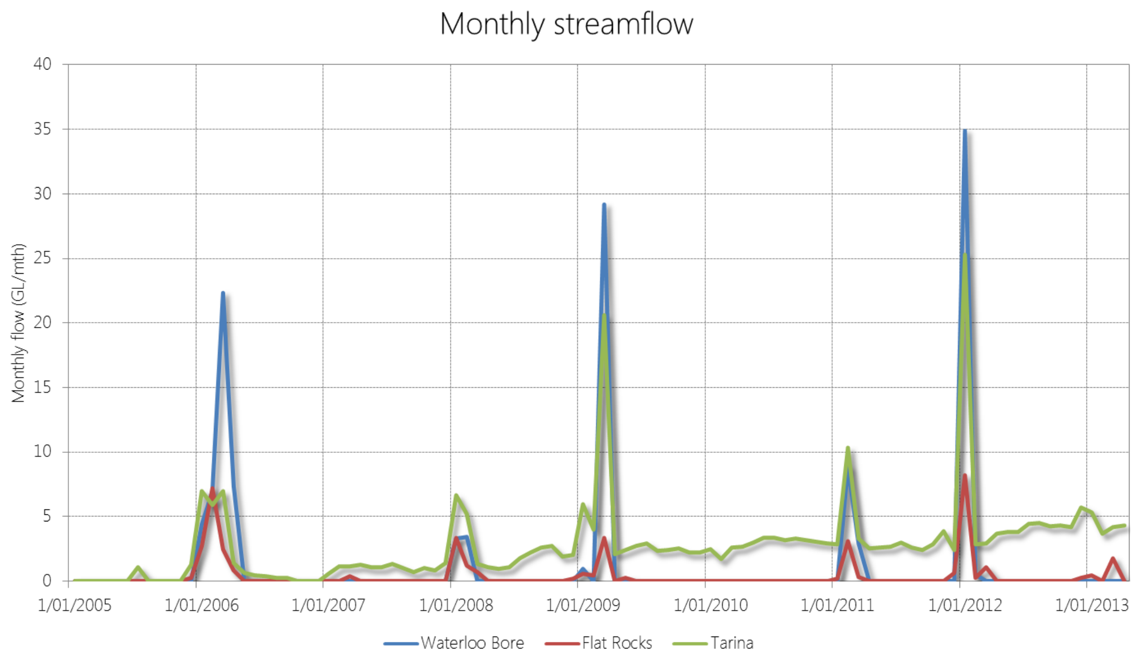


Figure 3-3: Weeli Wolli Creek flow gauges - monthly flow comparison

With dewatering releases included in the streamflow measured at the Tarina gauge, the record does not accurately reflect the catchment response to rainfall. Using the Tarina streamflow record in a rainfall runoff analysis would result in an inflated catchment response to rainfall. The Tarina streamflow record was therefore adjusted to remove the volumes of dewatering water reflected in the Tarina flow record. The use of this adjusted flow record is discussed further in Section 3.1.4.

The mean annual runoff for Marillana Creek at Flat Rocks is 8.4 mm when considering the full record period from 1967 to 2013. This increase in runoff from 5.4 mm to 8.4 mm is largely due to high runoff following cyclone Joan. It also illustrates the event-driven nature of the hydrology with the 46 year streamflow record skewed by a single event.

Fortescue River (Newman) Catchment

The only operating streamflow gauge on the Fortescue River is located at the Fortescue River road bridge near the Newman Airport. The Newman gauge is located approximately 10 km upstream of the Ophthalmia Dam, and the catchment area reporting to the gauge is 2,822 km². This catchment is referred to as the Fortescue River (Newman) catchment for the purposes of this study.

In the period 1980 to 2012 the average annual runoff at the Newman gauging station was 49.1 GL (Table 3-4). However annual runoff varied markedly over this period (Figure 3-4), with the median annual flow at only 18.9 GL. Note that Ophthalmia Dam is located downstream of the Newman gauge and as such any storage impacts will not affect flows recorded at the Newman gauge, but may influence flows reporting to the Fortescue Marsh.

The impact of cyclones on streamflow is evident in Figure 3-4. The high annual streamflow for the 1996 hydrological year is largely associated with a combination of cyclone Pancho/Helinda (20 January to 5 February 1997) and a tropical low over the area between 25 January and the end of February 1997, resulting in the single highest recorded monthly flow of 164 GL (February 1997).The period December 1999 to March 2000 had three cyclones, John (December 1999), Kirrily (January/February) and Norman (February/March 1999) bring heavy rainfall to the area. These three cyclones resulted in the second highest recorded monthly flow of 137 GL, and the highest three-month total of 314 GL.

Table 3-4: Annual runoff – Fortescue River (Newman) catchment (1980 to 2012)

River/Creek	Gauging Station	Average annual runoff		Median annual runoff	
		GL	mm	GL	mm
Fortescue River	Newman	49.1	17.4	18.9	6.7

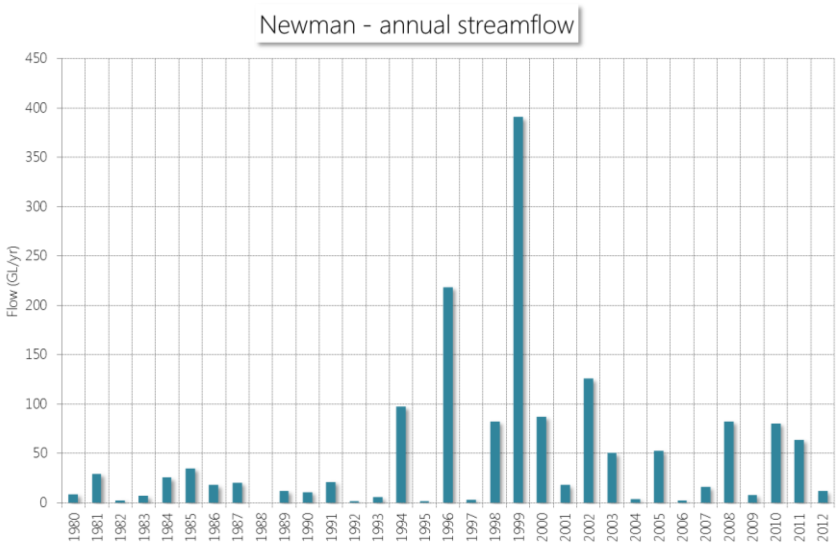


Figure 3-4: Annual recorded streamflow – Fortescue River (Newman) catchment

3.1.4 Catchment response to rainfall

Catchment response to rainfall is attributable to catchment physical characteristics. Surface water runoff is the result of excess rainfall, i.e. rainfall available for surface runoff after infiltration and evaporation/evapotranspiration losses. Factors impacting the amount of runoff include antecedent soil moisture conditions, duration and intensity of rainfall, in addition to landscape characteristics (as per landscape EHUs). Major flooding events are generally the result of large, intense cyclonic rainfall events, with runoff coefficients varying significantly between rainfall events. Streamflow mainly occurs during the summer months of December to March (Figure 3-5).

Streamflow data is not available for the sub-catchments of the study area. However runoff volumes can be estimated using sub-catchment areas and rainfall-runoff relationships developed using flow records from Waterloo Bore, Flat Rocks, Tarina and Newman gauged catchments.

The study area also receives point source inflows from the Upper Fortescue River and Weeli Wolli Creek. In order to construct a water balance for the Fortescue Marsh, estimates of surface water inflows are required for the study area sub-catchments and these external catchment inflows.

Weeli Wolli Creek is gauged at Waterloo Bore near the edge of the study area boundary. The recorded flows from Waterloo Bore can therefore be used as direct inflows to the study area. The Fortescue River is ungauged within or near the study area boundary; hence no gauge records are available for the single largest contributing source of inflow to the study area and Fortescue Marsh.

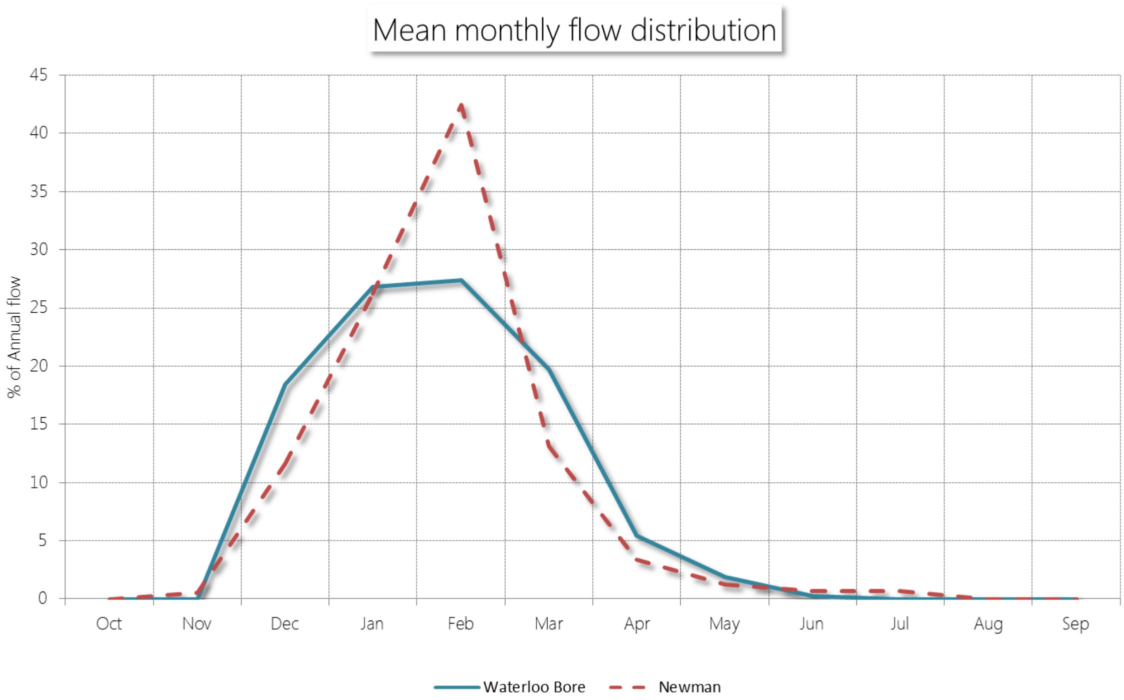


Figure 3-5: Monthly flow distribution at the Waterloo Bore (Weeli Wolli Creek) and Newman (Fortescue River) gauging stations

Rainfall-runoff relationships were developed for each of the four catchments (Figure 3-6) and provided a basis for estimating rainfall runoff response for the study area sub-catchments. Note that the dewatering volumes were removed from the Tarina record for this comparison. The process used is discussed in detail in Section 4.2.4.

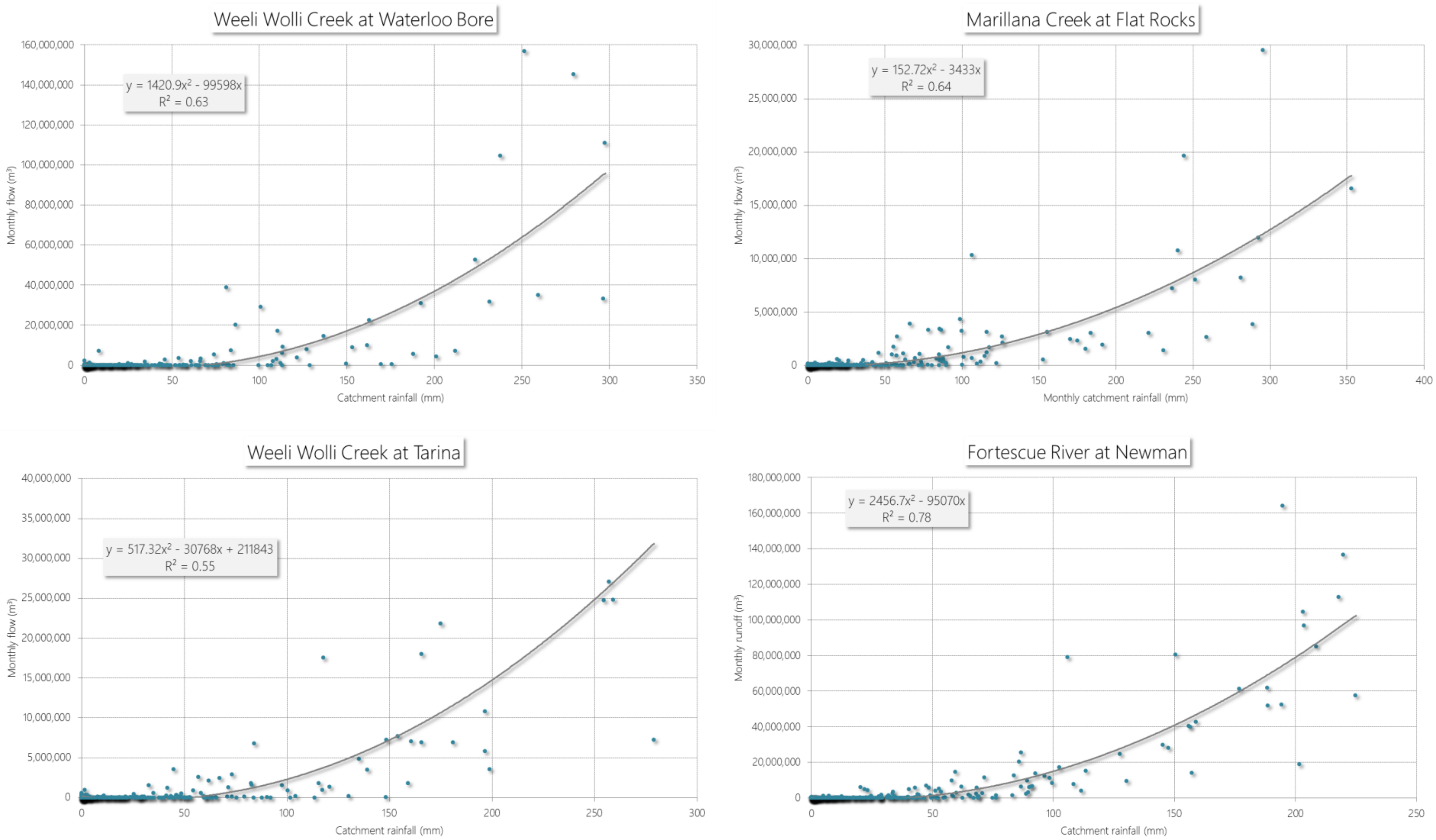


Figure 3-6: Rainfall versus runoff relationshipes for the Waterloo Bore, Flat Rocks, Tarina and Newman catchments

The Flat Rocks catchment contains large areas of low relief including the Munjina Claypan, which provide significant storage within the catchment upstream of the Flat Rocks gauge and hence attenuation of flows. In contrast, the Fortescue River catchment upstream of the Newman gauge includes significant areas of granite outcrop/subcrop, steeper slopes and shallower depth to groundwater. These factors reduce the volume of water required to satisfy soil moisture deficit, resulting in higher runoff.

Comparisons of rainfall-runoff relationships for the gauged catchments (Table 3-5, Figure 3-7) demonstrate these differences, with Flat Rocks runoff (1.3%) significantly lower than at Newman (5.3%).

Table 3-5: Annual rainfall runoff relationships for gauged catchments in proximity to the study area

River/Creek	Gauging Station	Record period	Average Annual		
			Runoff (mm)	Rainfall (mm)	Runoff as % rainfall
Marillana Creek	Flat Rocks	1/11/1984 – 1/4/2013	5.4	412	1.3%
Weeli Wolli Creek	Tarina	1/11/1984 – 1/4/2013	12.8	380	3.3%
Weeli Wolli Creek	Waterloo Bore	1/11/1984 – 1/4/2013	8.4	390	2.1%
Fortescue River	Newman	1/1/1980 – 1/3/2013	17.4	330	5.3%

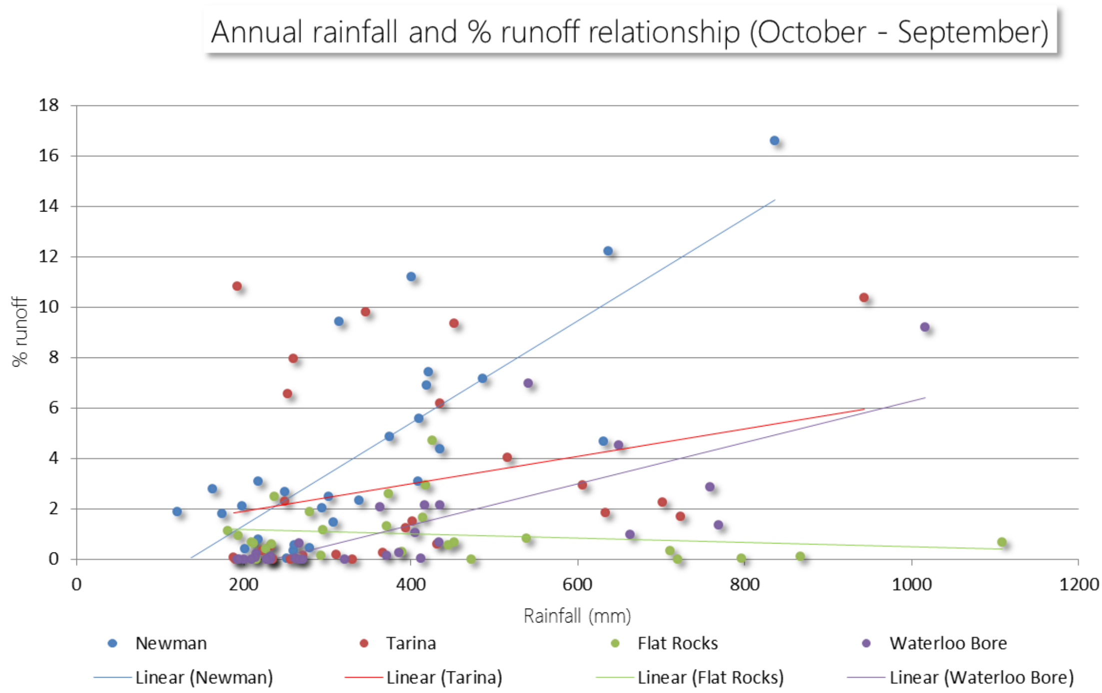


Figure 3-7: Annual rainfall and % runoff for four gauged catchments in the Pilbara region

The runoff response to rainfall in the Newman catchment is high in comparison to the Weeli Wolli and Marillana Creek catchment responses (Table 3-5; Figure 3-7). The Newman average annual runoff is 17.4 mm, compared with 5.4, 12.8 and 8.4 mm for the Flat Rocks, Tarina and Waterloo Bore gauges respectively. The Tarina gauge annual average runoff decreases to 9 mm when adjusting the flow record for dewatering volumes from Hope Downs 1 upstream of the gauge. Tarina monthly flows were adjusted by subtracting an indicative dewatering volume of 3 GL per month.

A simple water balance of the four catchments further summarises the different rainfall run off response for each of the four gauged catchments (Figure 3-8). In terms of runoff volumes, the Newman catchment generates the largest volume (49 GL/yr), seven times that of the lowest volumes from the Flat Rocks catchment.

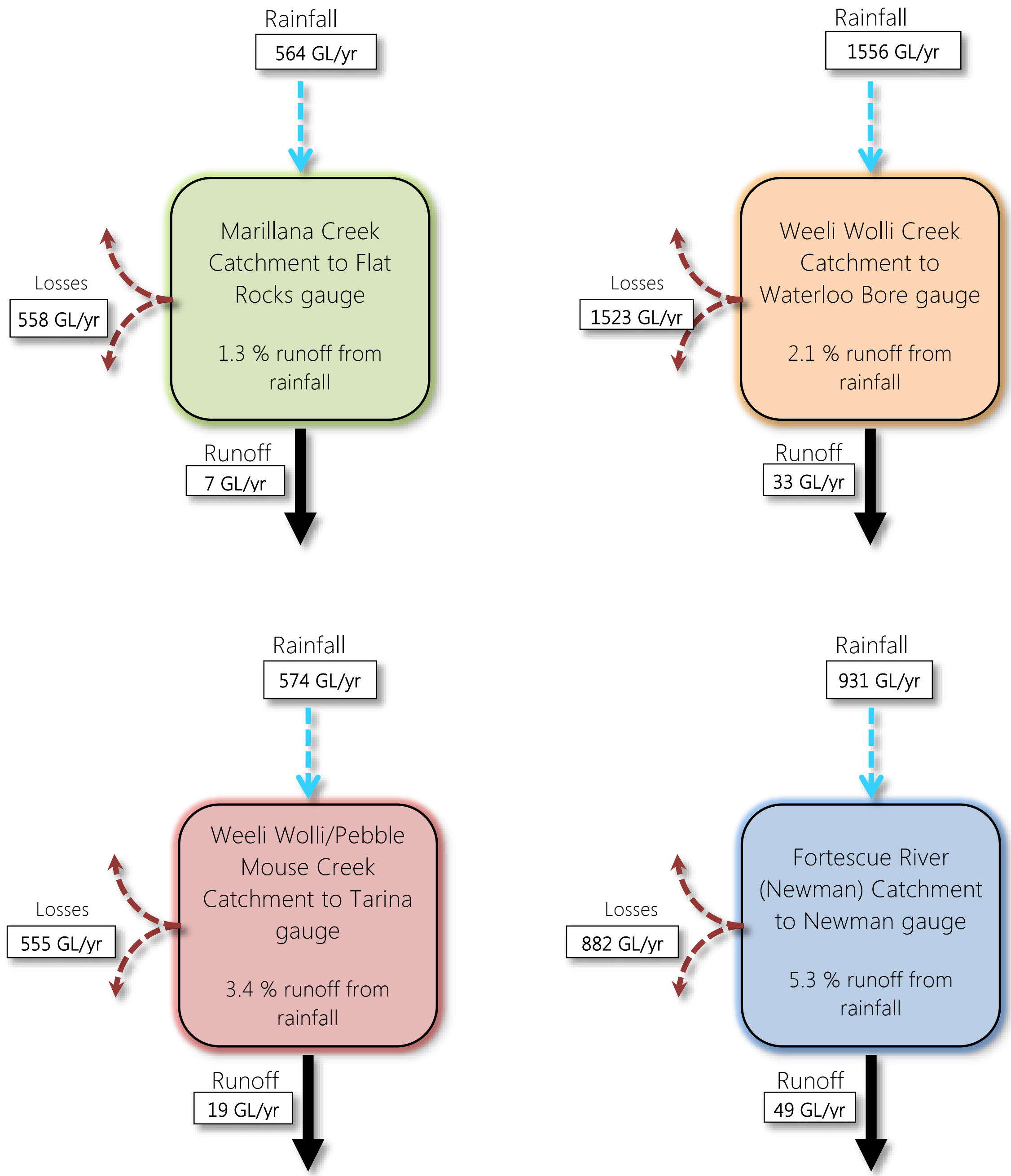


Figure 3-8: Summary of annual rainfall-runoff relationships for gauged catchments

Table 3-6: Water balance for four gauged catchments in proximity to the study area

River/Creek	Gauging Station	Average Annual			Runoff as % rainfall
		Rainfall (GL)	Losses (GL)	Runoff (GL)	
Marillana Creek	Flat Rocks	564	558	7	1.3
Weeli Wolli Creek	Tarina	574	555	19	3.4
Weeli Wolli Creek	Waterloo Bore	1556	1523	33	2.1
Fortescue River	Newman	931	882	49	5.3

3.1.5 Surface water summary

In developing an ecohydrological conceptualisation for the Fortescue Marsh, the following are considered to best reflect the surface water conditions:

- runoff is highly dependent on the intensity and duration of rainfall events;
- average runoff volumes are presented (Table 3-6) to provide an indication of flow volumes. However, volumes vary widely between years;
- rainfall-runoff response varies, depending on catchment physical characteristics;
- lower rainfall-runoff response is associated with deeper soils and flatter areas, such as the Flat Rocks catchment (Table 3-6);
- higher rainfall-runoff response is associated with steeper slopes and shallower soils, such as the Newman catchment (Table 3-6); and
- volumetric runoff coefficients range from 1.3% (Flat Rocks) to 5.3% (Newman) (Table 3-6); and
- based on a simulation period of 27 years, on average, around 203 GL/yr of surface water flows into Fortescue Marsh. Inflow volumes however vary widely, with the median inflow as low as 61 GL/yr and maximum annual inflow of more than 1,400 GL/yr.

3.2 Groundwater

3.2.1 Major aquifer systems

The regional groundwater system in the study area comprises Fortescue Valley aquifers hosted in Tertiary and Quaternary sediments and the underlying Wittenoom Formation (dolomite of the Paraburdoo Member). Tertiary calcrete and silcrete or pisolitic limonite formed within previous valley fill sequences constitute chemically-deposited aquifers developed in portions of the valley. Tertiary calcrete outcrops toward the Marsh, and is generally highly permeable.

The dolomite of the Wittenoom Formation, which is inferred to occur beneath the Marsh and much of Fortescue Valley, exhibits low permeability where fresh and relatively unfractured. In the upper layers of the Wittenoom Formation, there is fracturing, dissolution and karstification that has enhanced permeability. It is anticipated that this upper horizon may have considerable but varied permeability.

The flanks of the valley rise into ranges, which comprise fractured basement of generally low permeability and storage. Basement includes Proterozoic and Archaean sedimentary and volcanic rocks (dolomite, sandstone, shale, chert, banded-iron formation and basalt) which host sections of more transmissive material associated with orebodies. They form localised aquifers. The extent of these orebody aquifers and their connectivity with larger groundwater flow systems may be enhanced by faulting or erosion or other structural features, and as such can vary widely and are site specific.

The alluvial/colluvial sediments within upland areas, which may also include outcropping or subcropping calcrete, can form local aquifers typically with limited lateral extent.

Alluvial/colluvial deposits situated on the lower slopes of the Chichester and Hamersley Ranges progressively increase in thickness towards the Marsh/Goodiadarrie Swamp, where they may be partly saturated.

3.2.2 Hydrostratigraphical units and their hydraulic properties

The hydraulic characterisation for uplands (Table 3-7) and lowlands (Table 3-8) hydrostratigraphical units is based on site-specific data from previous hydrogeological investigations performed in support of the environmental approvals for mining developments in the study area.

MWH developed a set of regional estimates for hydraulic parameters applicable to the project (Table 3-9), based on a literature review of hydrogeological data and projects across the Pilbara region. Appropriate values suitable for regional-scale evaluations of parameters are usually median or mean values that characterise broad aquifer properties. However, with regard to site specific issues, it is necessary to include ranges of parameters to properly characterise the behaviour of each hydrogeological unit. There is a considerable range in estimates of hydraulic conductivity and storativity (or specific yield), which reflects natural variation within the tested formations (Table 3-10). Both detrital and Paraburdoo Member (Wittenoom Formation) aquifers in particular exhibit considerable variation in parameters.

The review of hydraulic parameters, also taking into account their ecohydrological relevance, suggests that the major hydrostratigraphical units in the study area can be characterised as follows:

- The most ecohydrologically important hydrostratigraphical units are the widespread Quaternary and Tertiary sediments. Quaternary deposits are heterogeneous and moderately to highly permeable, but are often unsaturated and typically sustain only localised, potentially perched and temporary groundwater systems. The top Tertiary Detrital unit, TD3, that is of ecohydrological relevance, has generally low permeability due to its varied but significant clay content (permeability is less than 0.1 m/day).
- Moderate to highly permeable aquifers include calcrete of the Oakover Formation, silcrete, ferricrete and CID channels (TD2), karstified top sections of the Witenoom Formation, and mineralised sections of Brockman Iron and Marra Mamba Formations, with hydraulic conductivity of up to several tens of m/day. Unlike the basement formations, the Oakover Formation outcrops to the surface and is of direct ecohydrological relevance.
- Basement, in the flanks of the Hamersley and Chichester Ranges, has generally low permeability (less than 0.1 m/day), hosting pockets of more permeable mineralised sections (up tens of metres per day).

Groundwater storage is considered to be significant within the Tertiary sediments. Higher porosity and dissolution channels increase otherwise low storage properties of basement, in particular in the Wittenoom Formation and mineralised BIF.

Table 3-7: Summary of hydrogeological units in uplands of the Chichester and Hamersley Ranges

Hydrogeological unit	Description and spatial occurrence	Hydrogeological characteristics
Chichester Range		
Marra Mamba Formation	Cherty BIF shale and ferruginous chert; Intrusive hypogene hematite deposits and post-depositional supergene geochemical alteration and iron enrichment zones; upper portion is typically mineralised; lower unmineralised portion (chert and banded-iron formation) is geochemically unaltered. Integral part of the groundwater flow system; variably connected hydraulically along a 90 km strike length of the Chichester Range; unconfined to partially confined.	Upper mineralised portion range of K is 10 to 300 m/day; mean K is 226 m/day; average storativity is 0.005; Unmineralised portion range of K is 1 to 32 m/day; mean K is 13 m/day; average storativity $1.7x10^{-3}$; permeability of lower unmineralised portion may be enhanced along faults, fractures and at the contact with the Roy Hill Shale. MMF overall range of K is 10 to 390 m/day; mean K is 100 m/day; average storativity 0.002.
Jeerinah Formation	Dark-gray to black graphitic shale and chert; stratigraphically underlies the MMF; locally pyritic and dolomitic; Roy Hill Shale is the uppermost member and overlies the Warrie Member.	Generally thought to have low transmissivity; zones of relatively enhanced permeability associated with structures (fault zones) and weathering, or associated with layers of chert.
Hamersley Range		
Dolerite	Dyke feature intruding Weeli Wolli and Brockman Iron Formations	Sub-vertical dolerite to metadolerite dyke; 20 to 30 m thick; mean K is 0.004 m/day; S_y is 0.001; S_s is $2x10^{-7}$; minor dykes and/or sills also identified.
Brockman Iron Formation (mineralised or fractured)	Extending along the base of the Hamersley Range to at least the western end of BHP Billiton Iron Ore's Marillana deposit Conceptually simplified to extend from the top of bedrock downwards.	Up to over 100 m thick in some areas; enhanced mineralisation locally as a result of groundwater leaching of gangue minerals, resulting in enhanced porosity; locally mean K of 3 m/day.
Brockman Iron Formation unmineralised, unfractured	Unmineralised, clayey BIF, shale and BIF; throughout the Hamersley Range, south of the Poonda Fault; beneath upper alluvium, CID and Tertiary Detritals	Mean K is 0.002 m/day; S_y is 0.001; S_s is $1x10^{-6}$.
Mt McRae Shale and Mt Sylvia Formations	Described as interlayered shale, dolomitic shale and chert with minor BIF; potential aquitard; deposits to the north may include chert, clays and goethite.	Low permeability based on textural descriptions; S_y is 0.002 to 0.01; S_s is $1x10^{-6}$.
Weathered silicified dolomite (Wittenoom Formation)	Less weathered and leached but overall fractured; north of and coincident with the Poonda Fault. Exposed in outcrop; directly overlies fresh dolomite	Average thickness is 40 m; peak recorded thickness is 227 m; mean K is 10.7 m/day; S_y is 0.01 to 0.03; S_s is $5x10^{-7}$.
Fresh dolomite (Wittenoom Formation)	Lower sequence of thinly-bedded to massive dolomite with rare beds of black chert, overlain by interbedded dolomite with chert, and shale; throughout Fortescue Valley. Considered the basal unit, overlain by all others.	Mean K is 0.03 m/day; Sy is 0.002

Table 3-8: Summary of hydrogeological units in lowlands of the Fortescue Valley

Hydrogeological unit	Description and spatial occurrence	Hydrogeological characteristics
Coarse alluvium (with creekbed gravels), south of the Marsh	Throughout much of the valley floor apart from bedrock outcrop zones. Creekbed gravels limited to the main creek channels. Uppermost unit in all areas of occurrence.	Varies from fine alluvial sands with variable silt content on the valley floor, to coarse, colluvial sub-angular gravel and cobbles in a silty sand matrix on the valley slopes; thickness up to 55 m; mean K of 0.1 m/day; K_v 5 -20% of K_h; S_y 0.03 to 0.13.
Fine alluvium (south of the Marsh)	Predominantly Weeli Wolli Creek outwash zone. Beneath coarse alluvium in all areas of occurrence.	Varies texturally from sandy silt, trace clay, with variable gravel content, to a silty clay, generally texturally finer towards Fortescue Marsh; significant thickness in the Fortescue Valley; thinner on the lower slopes of the Hamersley Range; mean K of 0.004 m/day; K_v 5 -20% of K_h; S_y 0.01 to 0.05.
Tertiary Detritals (Alluvium, colluvium and pisolites), north of the Marsh (TD3)	Generally unconsolidated clays, silts and minor sandy gravel layers predominantly derived from ranges; broadly categorised as proximal to source (Upper TD3); clayey (variable) maghemite pisolitic gravels (Lower TD3). Variable unit thickness but thickness generally increases toward the Fortescue Valley and within incised channels.	Areas of low yield and storage include chert and BIF gravels deposited proximal to source (Upper TD3) and clayey (variable) maghemite pisolitic gravels (Lower TD3); More distal Lower TD3 deposits tend to be rich in clay and less permeable. Mean K less than 0.5 m/day; average storativity = 9 x 10^{-4}.
Calcrete/silcrete (Oakover Formation)	Includes calcrete, silcrete and calcareous sediments; fluvial and lacustrine sediments dominated by bleached and mottled clays and micritic limestones; occurs throughout the Fortescue Valley; 10 to 20 m thick at northern extent where it overlies the Marra Mamba Formation beneath the southern flanks of the Chichester Range; can be up to 46 m thick within the Fortescue valley.	Likely zone of chemical precipitation of carbonates and silica associated with fluctuating watertable; locally karstic; carbonate and silica deposition may occur directly overlying bedrock. High permeability; range of K is 115 to 170 m/day (north of the Marsh; mean K is 140 m/day (north of the Marsh), 20 m/day (south of the Marsh); average storativity = 8 x 10^{-3} (north of the Marsh), S_y = 0.01 to 0.05 (south of the Marsh)
Channel Iron Deposits (CID) (TD2)	Limited to creek palaeochannels and associated outwash Oldest Tertiary unit, incised within bedrock of the Weeli Wolli and Brockman Iron Formation. May also be incised into Wittenoom Formation.	Generally consists of ooids, pisoids, and peloids, with a sandy to clayey matrix; varying amounts of goethite cementation; presence of mineralised wood fragments; enhanced permeability in lower, highly altered portion; mean K of 5 m/day; S_y 0.03; S_s 10^{-5}.
Pinjan Chert	Pinjan Chert – uncertain age, often overlying the Wittenoom Formation.	Moderately to highly weathered fine-grained porous siliceous sediment with alternating laminated chert, which is often vuggy. Observed north of the Poonda Fault. K = 10 $mday^{-1}$, S_y 0.02 to 0.05
Wittenoom Formation	Dolomite, chert and shale; forms the bedrock below the Tertiary sequence in the Fortescue Valley; weathering has resulted in a low permeability clay-dominated zone in places within the upper profile, however leaching created highly permeable weathered horizon.	Crystalline and massive where fresh with poor intergranular permeability; locally permeable zones associated with faulting may have developed.

Table 3-9: Summary of regionally estimated hydraulic parameters

Hydrogeological unit	Number of solutions	Number of testing locations	No. of bores	Avg K_h (m/day)	10th percentile K_h (m/day)	90th percentile K (m/day)	Ss	Sy	Confidence level	Comments
Coarse alluvium	4	4	3	0.07	0.006	3	$1x10^{-5}$	3-10%	Low to moderate	Some grain-size interpretation
Fine alluvium	3	3	2	0.002	0.0007	0.02	$5x10^{-5}$	1-5%	Low to moderate	All grain-size interpretation, no field testing
Calcrete	7	3	3	37	18	97	$1x10^{-6}$	1-5%	Moderate	
Slope deposits	4	4	4	13	8	22	$1x10^{-5}$	1-5%	Moderate to high	Includes some “Tertiary Detritals”
Channel Iron Deposits	30	24	22	10	2	35	$1x10^{-5}$	3%	Moderate to high	
Mineralised Brockman Bedded Iron Deposit	160	14	12	14	5	48	$5x10^{-7}$	1-2%	Moderate to high	Definition of “mineralised” BID difficult to determine
Unmineralised Brockman Banded Iron Formation/ shale	0	0	0	-	-	-	$1x10^{-6}$	0.1–0.5%	Low	
Weathered/ karstic Wittenoom Formation	30	4	4	17	9	34	$5x10^{-6}$	2-5%	Moderate	
Mt. Sylvia/ Wittenoom Formation	3	2	2	0.018	0.006	0.09	$1x10^{-6}$	0.2 – 1%	Low to moderate	

Table 3-10: Summary of hydraulic properties of study area lithologies from various sources

Unit	Source	Location	Average T (m^2/d)	Average K_h (m/day)	K_v (m/day)	Sy	Ss
Creek bed gravel (coarse alluvium – Weeli Wolli Ck.)	(Rio Tinto, 2011)	Yandicoogina	-	10	1	10%	$1x10^{-5}$
	(Woodward-Clyde, 1997)	Marillana Creek	-	10	-	20%	-
Alluvium/ weathered bedrock (upper and fine alluvium)	(Rio Tinto, 2011)	Yandicoogina	-	5 - 10	0.5 - 1	10%	$1x10^{-5}$
Alluvium (upper and fine alluvium)	(Aquaterra, 2010)	Marillana	-	0.2	0.02	1%	$1x10^{-5}$
	(Aquaterra, 2004)	Mindy Mindy	-	10	10	-	-
Tertiary Detritals	(Aquaterra, 2010)	Marillana	-	2 – 4.5	0.2 – 0.45	5%	$1x10^{-5}$
Oakover Fm Calcrete/ Pinjan Chert	(Aquaterra, 2010)	Marillana	-	6	0.6	5%	$1x10^{-5}$
Calcrete	(Woodward-Clyde, 1997)	Marillana Creek	-	5	-	20%	$1x10^{-4}$
Channel Iron Deposits	(Rio Tinto, 2011)	Yandicoogina	-	10	1	5%	$1x10^{-5}$
	(Aquaterra, 2000)	-	200 - 2000	-	-	3%	-
	(Aquaterra, 2004)	Mindy Mindy	-	30	30	3%	$3x10^{-3}$
	(Aquaterra, 2010)	Marillana	-	6 - 15	0.6–1.5	3%	$1x10^{-5}$
	(Woodward-Clyde, 1997)	Marillana Creek	-	10 - 50	-	3%	$1x10^{-4}$
Brockman Iron Formation (Mineralised BID?)	(Woodward-Clyde, 1997)	Marillana Creek	30	1	-	1%	$1x10^{-5}$
Mineralised BIF (Dales Gorge, Whaleback Shale and Joffre)	(Aquaterra, 2012)	BHP Billiton Iron Ore Marillana	-	0.5 - 12	-	5%	$1x10^{-5}$
Unweathered Bedrock (Weeli Wolli Fm/ Brockman) (Unmineralised BID)	(Rio Tinto, 2011)	Yandicoogina	-	0.1	0.01	5%	$1x10^{-5}$
Weeli Wolli Formation	(Woodward-Clyde, 1997)	Marillana Creek	30	0.1	-	1%	$1x10^{-5}$
Unmineralised Brockman Banded Iron Formation/ Shale	(Aquaterra, 2004)	Marillana	-	0.1	0.01	0.1%	$1x10^{-5}$
Mt. Sylvia/ Wittenoom (Carrawine) Dolomite (Unweathered Dolomite)	(Aquaterra, 2010)	Marillana	-	0.1	0.01	0.1%	$1x10^{-5}$
Mt McRae Shale/Mt Sylvia Formation	(Aquaterra, 2012)	BHP Billiton Iron Ore Marillana	-	0.01	-	0.1%	$1x10^{-6}$
Wittenoom Formation (Dolomite)	(Aquaterra, 2012)	BHP Billiton Iron Ore Marillana	-	0.01	-	0.1%	$1x10^{-6}$

3.2.3 Hydrostratigraphic connectivity

Hydraulic connectivity between the major hydrostratigraphic units in the study area is of particular importance with respect to surface water/groundwater interactions, groundwater recharge and flow and the impact of mine dewatering on EHUs. The degree of hydraulic connection between adjacent hydrogeological units, and between non-adjacent units connected by fault or other structures, is a key factor in developing reasonable estimates of mine pit inflows, designing and implementing dewatering strategies and assessing connectivity with receptor.

The following general features of hydrostratigraphic and hydraulic connection are of relevance:

- Connectivity between the mineralised zones (potential orebodies) in the ranges and the Tertiary Detrital and Witenoom Formation regional aquifer. Mineralised BIF locations in the Hamersley Range situated to the south of the Mt Sylvia Formation, which acts as aquitard, are considered to have limited connectivity with the Tertiary sediments in the Fortescue Valley. At locations where the Mt Sylvia Formation has been eroded or cut through by drainage, groundwater originated in the Hamersley Range can move into the Tertiary Detritals of the Fortescue Valley. There are numerous drainages on the northern slopes of the Hamersley Range, which may enhance connectivity between Hamersley basement units and the Fortescue Valley.
- Mineralised Tertiary Detritals, such as CID, are assumed to be in direct connection with the aquifer system in the Fortescue Valley.
- The hydraulic functioning of the Poonda Fault, which runs from SSE to the NNW along the Hamersley Range, is unresolved. This fault line could conceivably act as preferential flowpath or obstruct groundwater flow.
- Connectivity between the mineralised Marra Mamba Formation in the Chichester Range and the highly permeable TD2 unit (calcrete) was reported to be not significant (FMG, 2010). However the Marra Mamba Formation and the TD3 unit are considered to be connected, even though the TD3 sediments have relatively low hydraulic conductivity which places a limit on the exchange of water between the units.
- The TD3 deposits generally act as a significant, laterally extensive aquitard across the Fortescue Valley. These deposits limit interactions between surface water sources and the aquifer system developed in the deeper Tertiary sediments and potentially in the weathered section of the Wittenoom Formation at the base of the Tertiary sediments. However, TD3 may contain minor, more permeable subareas, in which interaction between surface water and groundwater may be more substantial (this needs to be supported by drilling investigation).
- Alluvial deposits along the main drainage lines act as zones of preferential recharge, which are active during and after the significant rainfall events that generate surface water flow.
- Alluvium of the Weeli Wolli Creek, flowing to the northwest after emerging from the Hamersley Range, is of particular relevance due to the large flow volumes that infiltrate into this system following major rainfall events. Previous modelling work by Aquaterra (2012) assigned it comparatively higher recharge rates indicating that the creek actively recharges the underlying aquifer system.
- The connectivity between the surface water in the Marsh during flooding and the aquifer underneath the Marsh is assumed to be poor, with deep percolation restricted by heavy clay and/or hardpan layers. It is considered that the hydraulic link between the surface water and groundwater in the Marsh is constrained to discrete, spatially restricted areas of the Marsh footprint where the claypan/hardpans are less well developed. An indication where such areas may occur can be drawn from the work of Barron (2013) who used remote sensing data to derive groundwater dependent areas in the Marsh. Based on that work it is then assumed that groundwater areas, as depicted in Figure 3-9, provide an indication of where such areas may occur and where connectivity between occasionally ponded water and the aquifer underneath's is enhanced. This hypothesis, too, needs to be supported by further field investigation.

In the regional context the connectivity issues are described as follows:

Chichester Range

Where Tertiary detritals directly overlie the Marra Mamba Formation, a significant degree of hydraulic connectivity has been observed in the Christmas Creek area (FMG, 2010). The TD3 units, whilst generally having lower permeability, still has groundwater storage. Vertical leakage between the TD3 units and the Marra Mamba Formation is observed to occur, which illustrates that directly drawing groundwater from the Marra Mamba Formation induces drawdown in the overlying TD3 unit. Consequently, high leakage from the TD3 units which would supplement the storage in the Marra Mamba Formation would be expected to increase the sustainability of the fresh water resource by limiting the extent of drawdown associated with drawing water from the Marra Mamba Formation and therefore reducing saline water intrusion (FMG, 2010). High leakage also suggests that abstracting water from the Marra Mamba Formation would also drain the overburden.

In general, it is expected that the hydraulic connection between groundwater present in the TD3 unit and the Marra Mamba Formation decreases towards the Marsh due to textural changes in the TD3. Areas of low to moderate yield and storage include chert and BIF gravels deposited close to source (Upper TD3) and clayey (variable) maghemite pisolitic gravels (Lower TD3). More distal lower TD3 deposits tend to be rich in clay and are less permeable.

The level of hydraulic connection between the Roy Hill Shale (Jeerinah Formation) and the Marra Mamba Formation is important to understand with regards to the potential for upwelling of saline water as well as geotechnical issues during mining operations. Investigations in this regard in the Christmas Creek area (FMG, 2010) have shown that while abstraction from the Marra Mamba Formation does induce depressurisation of the Roy Hill Shale unit, this does not lead to an increase in the salinity of the abstracted water.

While this relationship indicates reasonable connection between the units, it suggests that the Roy Hill Shale contributes a small volume of groundwater through upward leakage. However, this scenario is likely to vary spatially and temporally, as influenced by factors such as total volume of water abstracted and proximity to the Fortescue Marsh. Throughflow is likely to be variable, depending on fracture development and extent of weathering.

Hamersley Range

Aquifers within the alluvial and CID-filled palaeovalley extending south beneath the present day Weeli Wolli drainage are hydraulically connected to the underlying fractured and mineralised bedrock aquifers of the Brockman Iron Formation.

The CID is also understood to be in direct hydraulic connection with the underlying Brockman Iron Formation, with only local separation from remnant unmineralised shale bands. Impermeable bedrock units underlying the mineralised bedrock aquifers are not considered to have significant storage or throughflow potential.

To the north of the Weeli Wolli Creek entering the Fortescue Valley, the aquifers described above are variably connected to the sedimentary, chemical and bedrock aquifers of the Fortescue Valley (FMG, 2012). Weathered and underlying fresh dolomite of the Wittenoom Formation is inferred to potentially abut the Brockman Iron Formation, with a potentially significant hydraulic connection between the Brockman Iron Formation and the permeable weathered dolomite.

Though the hydraulic connection of weathered dolomite basement with high-permeability mineralised and/or fractured Brockman Iron Formation is not well established, hydraulic connection of weathered dolomite with an interpreted CID channel has been inferred north of the Weeli Wolli Creek. Considering the CID also appears to be in good hydraulic connection with mineralised BIF, it is considered that there is a significant hydraulic connection between the weathered dolomite and the mineralised or fractured Brockman Iron Formation.

Connectivity of the upland areas allowing drainage from the range to enter the Fortescue Valley takes place mainly through drainage channels facilitating the connection between water stored in fractured basement and the detritals in the Fortescue Valley. Due to presence of less permeable units (such Mt Sylvia Formation) situated along the strike; the groundwater throughflow originated in the Range towards the Fortescue Valley is reduced as part of the groundwater flow is presumed to report to areas south of the study area.

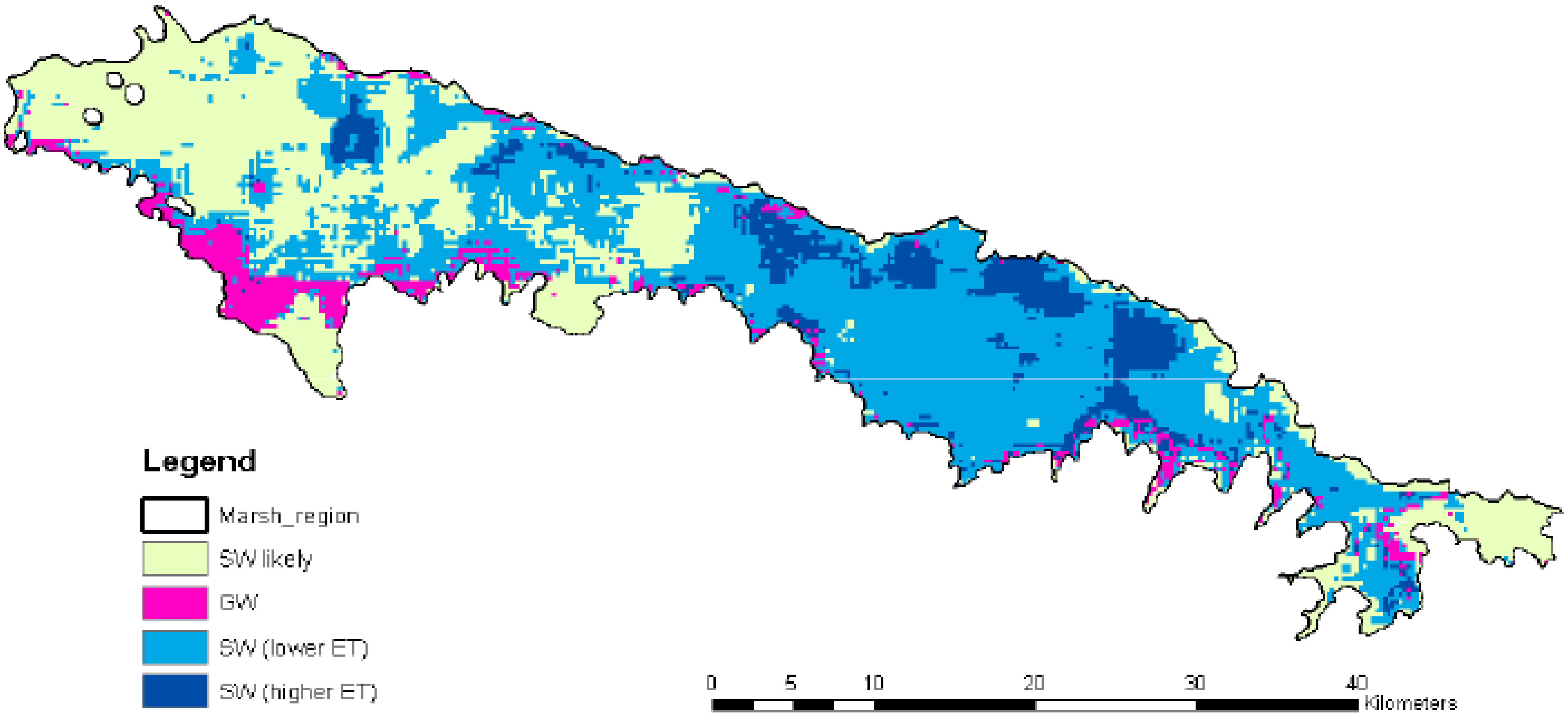


Figure 3-9: Areas of groundwater use by vegetation (purple) could represent connectivity between ponded surface water and underlying aquifer in the Fortescue Marsh footprint (image after Barron, 2013)

Legend refers to zones where vegetation water use is inferred to be principally sustained by surface water (SW) or groundwater (GW) inputs.

Transitional and terminal units

The Fortescue Valley comprises alluvium and Tertiary Detritals overlying localised basement aquifers in the Wittenoom Formation and Marra Mamba Iron Formation. It is inferred that a good hydraulic connection exists between the calcrete/silcrete and the underlying dolomite, however it has not be proven whether calcrete is present along the southern edge of the Fortescue Valley. Hydraulic connectivity may be limited where low-permeability clay-dominated zones resulting from weathering of the upper profile of the Wittenoom Formation (FMG, 2010) are present.

Clay lenses in Tertiary Detritals are likely to locally impede connectivity between the shallow and deep aquifers.

3.2.4 Groundwater recharge

Groundwater recharge in the study area takes place principally through surface drainage systems and within parts of the footprint of the Fortescue Marsh when it floods.

Cyclonic-related stream flows are concentrated into drainages, which infiltrate into the streambeds and underlying deposits in creeks and tributaries. The key surface water features that contribute to groundwater recharge within the study area are the Upper Fortescue River, Fortescue Marsh, and major creek systems (e.g. Weeli Wolli Creek).

Other components of groundwater recharge include runoff concentration and infiltration at the base of the ranges, and sheetflow concentration on Fortescue Valley alluvial fans. The vertical contribution from precipitation may be locally important in some parts of the study area such as weathered outcrops.

Chichester Range

Recharge mechanisms include:

- Marra Mamba Formation outcrops (EHU 1) receive direct recharge from higher magnitude rainfall events. Intense rainfall may not result in substantial infiltration in the hills due to the sloped land surface, but is likely to cause significant surface runoff that may infiltrate into the ground when it reaches break-of-slope areas or within the drainage lines. Recharge is expected to be enhanced in outcrop and subcrop zones near (and south of) the Chichester Range's break of slope, where the Chichester Range's hilly zones transition to alluvial fan systems extending to the Fortescue Marsh. These break-of-slope regions include outcrop/subcrop with drainage-incisions resulting in direct connection between surface water and aquifers.
- The alluvium/colluvium of upland drainage floors and channels (i.e. EHUs 3 and 4) and detritals are recharged via rainfall infiltration and surface runoff redistribution. These may also provide enhanced recharge in to the underlying Marra Mamba Formation via leakage.
- Aquifers are also recharged via throughflow from the Roy Hill Shale (the upper part of the Roy Hill Shale has moderate permeability) to the Tertiary Detritals and Marra Mamba Formation along the southern flank of the Chichester Range, though data from Christmas Creek suggest that this recharge mechanism is relatively minor (FMG, 2010).

Hamersley Range

The mechanism and processes of recharge are generally similar to the Chichester Range. Notable differences include:

- The Weeli Wolli Formation forms most of the outcrop areas; however its low permeability suggests it would not facilitate significant infiltration.
- The Hamersley Range is characterised by the presence of aquitard units, notably those situated on the northern side of the Range. In situations where recharge volumes are captured within the Range, the aquitard units may limit groundwater redistribution towards the down-gradient aquifer systems in the Fortescue Valley.
- Due to the structural placement of the low permeability McRae Shale and Mt Sylvia Formations in the northern slopes of the Hamersley Range, at a regional scale a part of groundwater flow is likely to be directed to the south, in contrast with drainage and the surface water flow in the northern slopes of the Range which is generally directed northwards towards the Marsh. This means that not all groundwater flows deriving from recharge in the Hamersley Range will report to the study area.

- The aquitard or barrier effect of the Mt McRae Shale and Mt Sylvia Formations is reduced by the deep cut drainage that is present in the northern slopes. These drainages provide connectivity with the Fortescue Valley detritals, more significantly so, during sizeable rainfall events.
- The most important drainage system is the Weeli Wolli Creek, which currently transmits water from upstream mining discharges in addition to natural flows. These mining discharges provide a constant combination of surface water flow and groundwater throughflow in the Weeli Wolli Creek gravels and underlying CID units, estimated at about 7 GL/yr. The groundwater-attributed proportion of this throughflow has been estimated at 1.5 to 2.4 GL/yr.
- Break-of-slope areas at the foot of the ranges, which are usually covered by deep detritals, may be important zones of recharge deriving from streamflow and sheetflow. The watertable is typically deep in these locations. As observed in groundwater hydrographs of BHP Billiton Iron Ore Marillana, a clear groundwater level response to the high rainfall or runoff at the beginning of 2012 (Figure 3-10) is evident; a pattern that is generally consistent with other monitoring bores in the Pilbara.

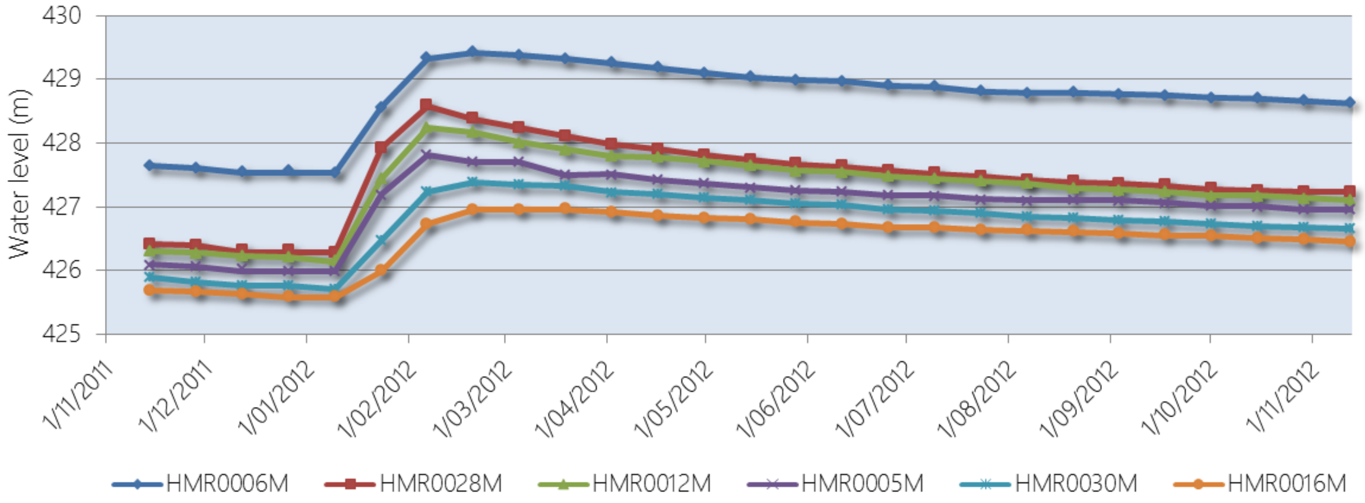
Fortescue Valley and Fortescue Marsh

The recharge mechanism in the Fortescue Valley is a combination of several processes:

- Topographically driven throughflow in the valley sediments (lateral recharge) is supplemented with periodic and sparse recharge events in the present day drainages (EHU 8) (drainage focused) with relatively small and locally occurring contribution from vertical recharge (direct rainfall infiltration).
- Flooding of the Marsh (EHU 9) represents an infrequent but notable recharge input to the groundwater system proximal to the Marsh. It occurs via partial infiltration of floodwaters from the large upstream catchment drainage. The infiltration properties of the Marsh floor are considered to be poor, which limits the percolation of floodwaters into the subsurface. However this interpretation is largely inferred from a limited set of observations and anecdotal evidence of the surficial environment of the Marsh. It is proposed that spatially restricted windows of enhanced permeability in the generally less permeable Marsh surface are likely to enhance connectivity with groundwater and represent areas of focused recharge. Work done by CSIRO on time series evaluation of modified NDVI (Barron, 2013) indicates that there are several potential areas in the Fortescue Marsh floor where vegetation is considered to be groundwater dependent (Figure 3-9) as opposed to generally larger areas of the Marsh where vegetation is dependent on surface water only. The presence of groundwater-dependent vegetation would require better surface connectivity with the aquifer and thus providing potentially more suitable infiltration conditions for ponded surface water to recharge the underlying aquifer.
- Floodwaters bring fresh quality water quality into the Marsh floodplain, which recharges areas underneath and around the Marsh while forming an ephemeral zone of shallow groundwater mounding. Evapotranspiration processes rapidly dissipate the mounded groundwater, concentrating dissolved solids and re-establishing saline conditions on the Marsh surface.

Cycles of flooding and evaporation have contributed to the development of a hypersaline groundwater beneath the Fortescue Marsh, which is an important feature in the groundwater flow system. Dense, hypersaline groundwater has been slowly sinking below the inundation area, controlled by the complicated structure of discontiguous clay layers at depth within the Tertiary Detritals. The hypersaline mound mixes with groundwater flowing toward the Marsh in a transition zone where the less dense groundwater is forced up and over the hypersaline waterbody via low permeability alluvial sediments.

Groundwater discharge takes via soil evaporation (where depth to the watertable is shallow, generally less than 5 m bgl), evaporation from open water depressions (where present) and evapotranspiration at the fringes of the Marsh (FMG, 2010); although the overall magnitude of discharge is small in the context of the overall Marsh water balance (further detail is provided in Section 4.2). The high evaporation and transpiration rate from the Marsh area and its fringes ensures that the Marsh functions as a net groundwater sink, resulting in radial flow towards the Marsh being sustained at almost all times by inflows from originated from the ranges around the Fortescue Valley.



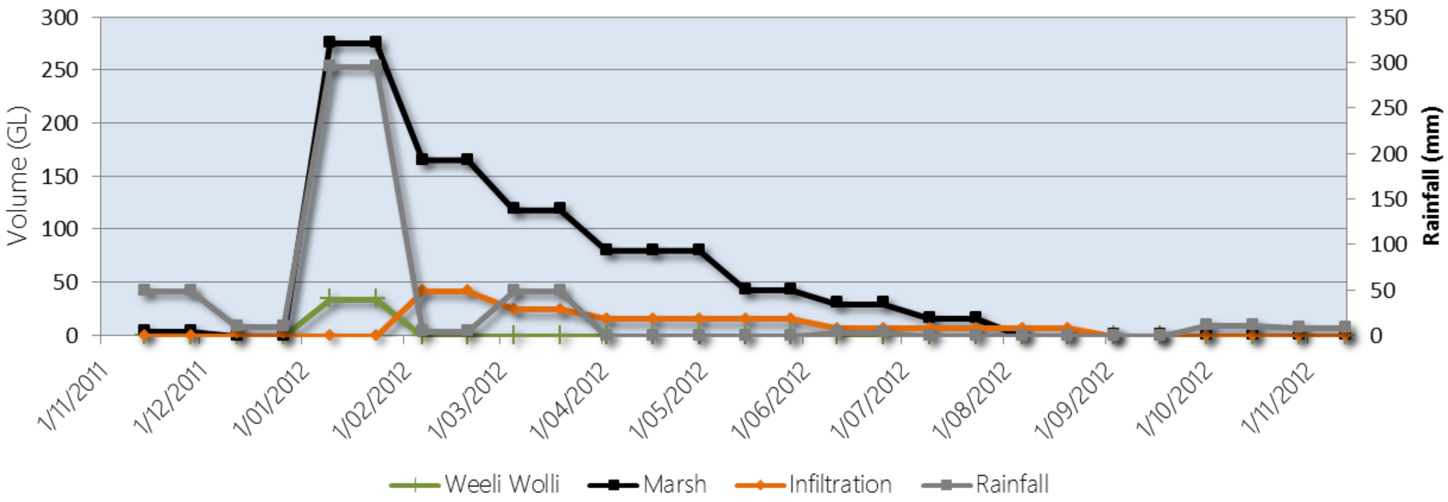


Figure 3-10: Typical groundwater level rise in response to a recharge event as observed in selected bores in BHP Billiton Iron Ore's Marillana tenement. Also shown, on the bottom plot, are the modelled Weelli Wolli Creek and Marsh flow volumes

Isotope studies of Fortescue Marsh

Skrzypek et al. (2013) and Dogramaci et al. (2012) undertook stable isotope studies at Fortescue Marsh. Their studies were focused on understanding the mechanisms of the Marsh hydrology and groundwater flow. While these studies did not provide quantitative estimates of recharge, they discussed issues related to groundwater recharge, in particular Skrzypek et al. (2013) concluded that:

- Chloride concentrations in shallow groundwater under the Marsh are lower than at depth consistent with the existence of a periodic recharge regime.
- Stable isotope data indicate that the prevalent component of groundwater flow at the Marsh is vertical rather than horizontal. This is consistent with low hydraulic gradients in the Fortescue Valley and confirms that replenishing of groundwater from floodwaters occasionally takes place.
- Groundwater under the upper Fortescue River, smaller tributaries and the alluvial fans adjacent to the Marsh is always fresh and has isotope signatures similar to that of the large volume rainfall events. The groundwater under the alluvial fans of Coondiner, Weeli Wolli and Sandy Creeks is also fresh with negative stable oxygen isotope values characteristic of high rainfall events (more than 20 mm events).
- The shallow saline groundwater under the Marsh extends more than 80 km along the Fortescue River from 14 Mile Pool to near the Goodiadarrie Hills.
- Groundwater in the detritals and alluvium at some distance away away from the Marsh's perimeter shows no seasonal changes in stable isotope concentrations, suggesting that there is no significant evaporation even after prolonged drought conditions. This is also an indication that vegetation interaction in these areas would be insignificant. Conversely, only samples from the bores in shallow groundwater around and within the Marsh show marked seasonal variations consistent with infiltration of floodwaters and subsequent veaporation. They also indicate that Marsh inundation raises chloride concentrations in shallow groundwater due to dissolution and mobilisation of precipitated salts.

Dogramaci et al. (2012) also showed that:

- Most surface water pools associated with the Marsh appear to be separated from groundwater and their contribution to groundwater recharge is limited, but groundwater can be an occasional source of water. This conclusion however requires more on-site confirmation work.
- The more frequent, but smaller, rainfall events are insignificant for groundwater recharge.
- Creeklines are zones of focused recharge providing preferential pathways through which groundwater recharge can occur.

3.2.5 Recharge estimation

Recharge estimation using chloride method

Estimates of regional groundwater recharge in the Pilbara are often quoted at 1 to 3% of annual rainfall. By applying these blanket values (which essentially lump recharge volumes from different recharge mechanisms) to the study area this would represent the average annual recharge of 31 to 93 GL/yr.

The chloride mass balance (CMB) method is a widely used approach for estimating recharge (Somaratne and Smettem, 2014). CMB estimates suggest that the recharge rate is closer to 1%, based on the study by Fellman et al. (2011) of major ion and isotope chemistry in pools and bores along the Coondiner Creek.

Chloride concentrations from six locations along a 10 km profile in April 2009 in the Fellman (2011) study were consistent with an average value of 44 mg/L. Application of the CMB method yields the recharge rate of 3.5 mm/yr when using a rainfall chloride concentration of 0.5 mg/L (Dogramaci et al, 2012) and hence close to the total study area value of 30 GL/yr.

A modification of CMB method, in water balance sense, has also been used for the estimation of groundwater throughflow in the Weeli Wolli Creek. RPS (2014) estimated the groundwater throughflow at Weeli Wolli Spring to be approximately 4,000 m^3/d (1.5 GL/yr), similar to the baseflow estimate at the Weeli Wolli Spring by Parsons Brinckerhoff (2013) which was 5,095 m^3/d (1.9 GL/yr). These values are close to numerical modelling estimates (2 to 2.3 GL/yr) presented in Aquaterra (2000).

Parsons Brinckerhoff (2013) also estimated that the combined groundwater/surface water outflow from the Weeli Wolli catchment was 7.3 GL/yr, or 20,000 m^3/d.

Recharge mound during a high rainfall event at the Marsh

A flood event at the Marsh is considered to influence groundwater levels underneath and in the vicinity of the Marsh and create a mound that extends beyond the perimeter of the Marsh.

The footprint of the maximum mound development is approximated as an area around the Marsh with groundwater levels less than six metres deep and is approximately 1,500 km^2 (Map 3-03). The average mounding effect is assumed to raise the water level by approximately one to two metres. By using an alluvium storativity range of 0.05 to 0.1 this would theoretically represent an added volume of 75 to 150 GL into the aquifer.

While this is close to the upper end of the regional CMB estimate of 93 GL/yr, it is assumed to be additional recharge occurring only once in three to four years. The Marsh flood component of groundwater recharge is considered to be short-lived and rapidly lost to evapotranspiration.

Recharge estimates from modelling studies

Three numerical groundwater flow studies which include the Fortescue Marsh area have been completed to date as follows:

- Aquaterra (2010) completed a groundwater modelling study for the Brockman Resources Marillana project. The study covered the Marillana deposit and included part of the Fortescue Marsh. Several recharge zones were distinguished:
    - basement/alluvium contact at the foot of the Hamersley Range
    - Weeli Wolli Creek alluvium
    - Fortescue Marsh

  The combined recharge from these zones related to the whole model domain equated to 7 mm/yr, which is consistent with regional recharge estimates.
- FMG (2010) covered the large part of the Fortescue Marsh with a numerical modelling study as part of the hydrogeological assessment for the Cloudbreak water management scheme. The recharge rates presented in the study were spatially distributed as follows:
    - Alluvial zone to the south of the Marsh (1% of rainfall, 3 mm/yr)
    - Weeli Wolli alluvium (5%, 16 mm/yr)
    - Fortescue Marsh (no recharge in the steady state model)
    - Exposed bedrock (0.2%, 0.6 mm/yr)
    - Alluvium to the north of the Marsh (1%, 3 mm/yr)
    - Marra Mamba Formation outcrop (3%, 3 mm/yr)
    - Transient calibration of the numerical groundwater flow model established that 8 GL/yr of groundwater recharge occurs in the Chichester Range and flanking areas. The area that this recharge covers is not clearly delineated so it is not possible to reliably calculate area recharge rates. Marsh flooding events, according to the FMG model, are responsible for approximately 300 GL (specific yield of the alluvium underneath the Marsh was set at 0.1).
- MWH (2009) groundwater numerical model for dewatering of the Roy Hill Mine covered the entire area of the Fortescue Marsh and made use of the following recharge rates:
    - Ranges and outcrops (3 mm/yr)
    - Fortescue River alluvium, Coondiner, Mindy Mindy and Weeli Wolli Creek alluvial fans (18 mm/yr)
    - Transitional areas at the foot of the ranges (8 mm/yr)

Summary of recharge estimates

Estimates of recharge using the various aforementioned methods suggest that an appropriate regional scale recharge rate for the study area should not exceed 1.5% of annual rainfall (Table 3-11). This is based on CMB method assuming fresh groundwater chloride concentrations influenced by recent recharge at minimum of 40 mg/L. This rate is considered conservative.

These estimates could be improved by using the recharge mound approach once there is data available documenting the extent and the dynamics of the mound formation and dissipation.

A summary of reviewed recharge rates is presented in Table 3-11.

Table 3-11: Comparison of recharge rate estimates in the study area

Method	Rate	Area	Comments
Chloride balance	7 to 18 mm/yr	Upland/freshwater units	Assuming groundwater concentrations in 40 to 70 mg/L range and rainfall chloride 0.5 to 2 mg/L
Regional/"diffuse"	3 to 9 mm/yr	Study area	Based on 1 to 3% of mean annual rainfall. Marsh flooding not specifically included. It can represent 100 to 300 GL, however at low frequency (once in 3 to 4 years)
Modelling studies	7 mm/yr	Marillana and downstream (Aquaterra, 2010)	Covers Weeli Wolli Creek alluvium, the Marsh and Hamersley/alluvium contact
	8 GL/yr	North of Fortescue Marsh (Cloudbreak, FMG)	
	300 GL/yr	Marsh, following flooding (Cloudbreak, FMG)	
	3 to 18 mm/yr	Roy Hill (MWH)	Covers individual rates for the ranges, transitional units and alluvial fans

3.2.6 Groundwater levels and flow

Groundwater flow and occurrence within the study area is complex and influenced by the following factors:

- topography (Hamersley and Chichester Range, Fortescue Valley);
- geological structure;
- the major drainages and their flow regimes (Upper Fortescue River, Weeli Wolli Creek);
- evapotranspiration losses; and
- density-driven convection.

These factors influence the depth to watertable, groundwater flow processes and gradients. At a regional scale the depth to groundwater is a subdued reflection of the surface topography. Groundwater is generally deepest and freshest within the flanks of the Ranges, and becomes progressively shallower and more saline toward the Fortescue Marsh and Goodiadarrie Swamp. Typical regional groundwater level contours compiled from various sources are presented in Map 3-03; depth to watertable is displayed in Map 3-02.

Depth to groundwater of up to 170 m bgl has been measured in the Hamersley Range (RPS, 2012) and is known to be up to 40 m bgl in the southern flanks of the Chichester Range (FMG, 2010). Depth to groundwater beneath the Marsh and Goodiadarrie Swamp ranges between 3 and 5 m bgl depending on the intensity, duration and frequency of precipitation events.

Based on similarities in groundwater system conceptualisation, it is anticipated that hydrogeological processes discussed with regards to the Fortescue Marsh are also functionally applicable to the Goodiadarrie Swamp, except where otherwise noted.

In general, groundwater flows from higher elevations in the flanks of the Hamersley and Chichester Ranges towards the Fortescue Marsh (Map 3-02 and 3-03). Local deviations in the groundwater flow direction may occur in areas where relatively high permeability (e.g., palaeochannels) influence flow direction (e.g., the inferred Weeli Wolli Creek palaeochannel at the BHP Billiton Iron Ore Marillana site). On the eastern side of the Marsh, groundwater flow is generally from the east to east-southeast (from Upper Fortescue River catchment areas) to the west-northwest towards the Marsh.

Hamersley Range

Within the Hamersley Range, groundwater flow direction is generally expected to align with topography (i.e. flow from upland areas to drainage floors and channels). Seasonal runoff infiltrates and accumulates beneath the major creek beds, resulting in temporary groundwater mounding and associated lateral (and some vertical) groundwater flow away from the distributary creek channels. The CID fill in palaeochannels provides preferred pathways for groundwater flow, and may be variably connected with groundwater systems in surrounding unconsolidated sediments (for example as observed in the mid and lower reaches of Marillana Creek).

Depth to watertable decreases northward from approximately 40 m at the base of the Hamersley Range (and has been measured as deep as 170 m bgl higher up the flanks in BHP Billiton Iron Ore's Marillana's project area) to an estimated 3 to 5 m at the Fortescue Marsh (10 to 20 km north of the Hamersley Range), with seasonal flow away from creek channels along sections in which the streams lose water.

In addition to topography, groundwater levels and flows are also locally controlled by the presence of structural features, for example by the northeast-southwest trending dolerite dyke at the base of the Hamersley Range. At the Brockman Resources Marillana project site, static water levels in July 2010 and September 2012 were measured at depths ranging from 6 to 18 m bgl (in the range of 474 to 477 m AHD) in the monitoring bores located south and upstream of the dyke and at depths ranging from 30 to 35 m bgl (428 to 430 m AHD) in monitoring bores located north (downstream) of the dyke. These water level data support interpretations that the major dolerite dyke may form a hydraulic barrier to local groundwater flow, with steep hydraulic gradients across the dyke. It is also possible that fractured margins of the dolerite dyke provide preferred groundwater flow paths.

Chichester Range

Within the Chichester Range, groundwater flow direction is topographically driven, (i.e. similarly to the Hamersley Range). Groundwater flow is driven by gravity in the southern flanks of the Chichester Range and transitions to density-driven flow towards the Marsh. Note that hydraulic gradients are higher (0.2%) in the elevated southern flanks and relatively flat (0.1%) toward the Marsh (Map 3-03). The groundwater flow direction is towards the Marsh, from the north/north-east to the south/south-west.

Depth to groundwater varies from 30 to 40 m bgl in the elevated southern flanks of the Chichester Range, to between 3 and 5 m bgl near the Fortescue Marsh (Map 3-02). Seasonal fluctuations have been observed, with groundwater levels rising up to 2 m at some locations.

Water level data from Christmas Creek and Cloudbreak mines (FMG, 2010) indicate groundwater levels declined by 1 to 1.5 m between 2007 and 2010 in response to the prolonged drought period since the prior flood in 2006. The data indicate the groundwater recession between 2006 and 2007 was about 1 m, and between 2007 and early 2009 approximately 0.5 m/a.

The groundwater recession trend was punctuated by a rainfall event in 2009. In addition, data from shallow groundwater monitoring piezometers in the RHIO Roy Hill project area indicate an overall 'drying' trend through 2010, punctuated by a significant precipitation event in early 2011 and a second significant event in early 2012 similar to data recorded in Marillana hydrographs shown in Figure 3-10.

Fortescue Valley/Fortescue Marsh

Groundwater flow within the Fortescue Valley and beneath the Fortescue Marsh is influenced by inflows from the fringes of the valley and partly by density-driven flow. Shallow groundwater flow is generally directed toward the centre of the Fortescue Valley, with a component of down-valley flow.

The transition from relatively deep levels at the fringes of the valley (20 m bgl or more) to a few metres below ground level within the Marsh occurs over a low hydraulic gradient (a vertical drop of approximately 1 m per 1 km).

The groundwater flow gradient towards the Marsh generally increases in the western part of the study area and is the largest north of Koodaideri.

Data from the Brockman Resources Marillana project (Brockman Resources, 2010) identified the existence of a palaeochannel that extends west from the modern day drainage of the Weeli Wolli Creek at the base of the Hamersley Range, and perhaps shifting to a northerly alignment towards the Marsh west of the BHP Marillana project area. Water level data suggest that within the palaeochannel groundwater flow is in a north-westerly direction. On the northern side of the Marsh the flowlines between the upland units and the Marsh are relatively short and groundwater flow gradients are approximately twice larger than those on the southern side.

Surface water which drains to the Marsh after cyclonic rainfall events accumulates to a depth of up to several metres above the Marsh bed. Historical records (hydrographs and Landsat imagery of flood waters) show that groundwater levels beneath and near the Fortescue Marsh respond only when prolonged inundation (ponding) occurs, and that ponding is caused by rainfall events above approximately 100 mm/month (FMG, 2010). Surface water in the Marsh is considered to be directly controlled by rainfall and surface water flows, rather than groundwater discharge.

The presence of clay sediments in the Marsh, which may also include hardpans, restricts recharge into the deeper groundwater system beneath the Marsh. Without significant surface water and groundwater outlets, ponded water gradually evaporates causing increased salinity and eventually leading to salt precipitation on the surface.

Salts have accumulated in the groundwater beneath the Marsh (Skrzypek et al. (2013) over long periods of time, which is thought to have established a density driven groundwater flow regime within the Fortescue Valley proximal to the Marsh (FMG, 2010).

The groundwater flow of the saline body underneath the Marsh is complex and not well understood. Most of the Fortescue valley is considered to be underlain by a low permeability clay unit (TD3), which restricts vertical flow. However the clay layer is not considered to be contiguous or hydraulically homogenous.

3.2.7 Groundwater discharge and other losses

Within the study area, groundwater discharge and other system losses could occur by various mechanisms as follows:

- Groundwater abstraction (e.g. water supply bores); mine dewatering
- Springs;
- Evapotranspiration; and
- Outflows from the upper Fortescue Valley.

Mine dewatering and mine water supply

Significant dewatering is currently occurring in the northern portion of the study area associated with FMG's Christmas Creek and Cloudbreak mining operations. The impacts of the dewatering activities on the Marra Mamba Formation aquifer are partially mitigated by reinjection of some of the excess dewatering discharge at locations between the mining operations and the Fortescue Marsh, and by the very large groundwater storage within the Fortescue Valley groundwater system.

Based on data for the period from August 2011 through July 2012, the total volume of water abstracted from the Christmas Creek mining operations was 10.2 GL with additional 1.7 GL sourced from Cloudbreak. Of this volume, 3.3 GL was reinjected into the aquifer (FMG, 2012). The combined groundwater abstraction from both, Cloudbreak and Christmas Creek operations in 2012 was reported to be 45 GL/yr, of which 22 GL/yr was reinjected (FMG, 2013). The Cloudbreak Life of Mine Project approval report (EPA, 2012) makes provision for dewatering and reinjection at Cloudbreak of up to 100 GL/yr and 85 GL/yr, respectively.

To the south of the Marsh, there are no active mine dewatering operations within the study area. The impacts of dewatering operations further south of the study area (Rio Tinto's Yandi Junction South East mining operations in the CID aquifer) are expected to be mitigated by the mine discharge into the Marillana Creek. These effects may extend slightly into the study area as an enhanced groundwater outflow.

If any of the potential future mine projects (BHP Billiton Iron Ore's Coondiner, Mindy and Marillana; FMG's Nyidinghu and Marillana; Brockman Iron's Marillana) at the southern extent of the study area become operational in the future, definition of net groundwater removed from the ground/surface water system and associated impacts on the Fortescue Marsh will be required. It is likely that the effects of groundwater abstraction associated with these projects would be cumulative if they were developed concurrently.

Other groundwater abstraction

In addition to mining operations, other groundwater abstraction is associated with pastoral use (stock water supply), resource definition drilling programs and other infrastructure developments. In all cases the abstraction volumes involved are modest. The effect of these activities on groundwater levels within the study area is considered to be insignificant.

Springs

The Koodaideri Spring, located in an incised foothill valley on the eastern Koodaideri deposit, is the only known spring within the study area. The Koodaideri Spring is believed to be fed by a local groundwater system in the foothills of the Hamersley Range (Rio Tinto, 2013). Available data indicate the surveyed water level of the spring at its source (504 m AHD) is consistent with the groundwater level in the surrounding bores (504.6 to 507 m AHD).

Evapotranspiration

The study area has a high annual moisture deficit, a result of an average annual rainfall between 300 and 400 mm and average potential evapotranspiration rates in the order of 1,500 to 1,600 mm (BoM, 2014).

In general, where groundwater is less than approximately five metres below surface it is considered likely that some soil evaporation and vegetation transpiration discharge will occur from the watertable. However, the magnitude of groundwater discharge may vary considerably at local scales as influenced by surface conditions, substrate characteristics and vegetation. Potential areas of groundwater discharge are expected to occur largely within drainages and within the Fortescue Marsh, especially during late wet season/ early dry season when groundwater levels are highest.

Based on consideration of the study area water balance, areas within the Marsh are thought to be responsible for the largest regional loss of groundwater (under natural conditions). The proportion between the rate of groundwater inflow in areas of active evapotranspiration is commonly smaller than the applicable evapotranspiration rate, which together with the low groundwater gradient keeps the depth to groundwater relatively steady and stable around the Marsh area.

The potential for evapotranspiration in the Marsh area is considered to significantly exceed the available recharge. For an area of approximately 1,500 km^2, and an actual evapotranspiration rate of 300 mm/yr, the net effect of water loss due to evapotranspiration could theoretically be up to 450 GL/yr, although in reality this number is smaller as there is simply not enough water to match that evapotranspiration rate.

In contrast, the recharge volume to the entire study area and for average climatic conditions is not likely to exceed 31 to 93 GL/yr. Therefore, the recharge component represents only about 20% of the evapotranspiration that could theoretically occur at the fringes of the Marsh.

A flooding event in the Marsh is estimated to add up to approximately 150 to 250 GL of recharge within and around the footprint of the Marsh. This is still below the evapotranspiration 'capacity' of the Marsh environs, and hence much of this recharge component would be rapidly lost to evapotranspiration.

Values of actual evapotranspiration (BoM, 2013) vary across seasons, for example monthly values for February and August are 70 and 10 mm/month, respectively, representing possible losses of 10.9 to 1.3 GL/month, respectively. Since recharge events are usually co-incident with high evapotranspiration, recharge is gradually but relatively quickly (within weeks or months) countered by evapotranspiration.

Outflow from Fortescue Basin

Since the Upper Fortescue River catchment is considered to be an endorheic system, surface water outflow from the catchment rarely occurs, due to the presence of Goodiadarrie Hills, which effectively dam the lower valley. However, the potential for groundwater flow beneath the Goodiadarrie Hills is poorly understood.

While groundwater outflow is considered to be minimal on the basis of a low hydraulic gradient and the radial effect the Marsh has on groundwater levels in the Fortescue Valley, it is possible that some flow could occur via structural conduits such as faults. The silcrete deposits associated with the Goodiadarrie Hills may form permeable zones and, if similar to units encountered elsewhere within the Fortescue Valley, may allow for groundwater outflow at depth. This could be investigated by comparing water level on both sides of the Goodiadarrie boundary, however there is currently no monitoring instrumentation in place to allow for such a comparison. An upper estimate of losses through a potentially developed palaeochannel between the Goodiadarrie Hills and the Hamersley Range is up to 2 GL/yr (based on an upper estimate of hydraulic conductivity value of 50 m/d, and the width of the channel of up to 2 km). A smaller outflow, possibly by an order of magnitude, is however more likely to occur.

The Marra Mamba Formation in the southern flanks of the Chichester Range system has limited connection with relatively high-permeability silcretes and calcretes of the Oakover Formation (open fluvial facies). Surface discharge from topographically-driven groundwater flow in the MMF aquifer is considered to be relatively low due to the poor hydraulic connection that it has with the discharge area (the surface of the Fortescue Marsh).

Groundwater discharge to surface drainages

Within the study area, groundwater discharge to surface drainage is considered to be negligible under natural conditions. Virtually all of the creek systems in the study area are ephemeral, except for a few drainage line pools that are known to occur in the area.

At the southern extent of the study area, drainage from groundwater to surface water is largely influenced by the following factors:

- Mine discharge from projects upstream Weeli Wolli Creek
- Creek morphology
- Heavy precipitation events

Prior to upstream Weeli Wolli Creek mine discharge, the Weeli Wolli Creek could be considered a gaining creek system. With the advent of upstream mine water discharge, permanently elevated groundwater levels for a substantial distance (estimated minimum of 25 km) downstream of the discharge point has the potential to contribute to bank storage and groundwater baseflow to the creek following flood events. The elevated groundwater levels could potentially contribute to more extensive and prolonged flood events in the lower Weeli Wolli Creek system extending into the Fortescue Valley, and increased flow loss through the base of the creek.

Note that the artificially shallow watertable created by mine water discharge is sensitive to changes in the upstream anthropogenic inputs to the Weeli Wolli Creek. Seasonal expressions of groundwater have been observed in incised parts of the Weeli Wolli Creek bed, and have been reported to migrate upstream and downstream. The locations of these temporary pools are affected by creek bed morphology.

Throughflow

The majority of groundwater throughflow from the Chichester Range area toward the Fortescue Valley is within the permeable upper Marra Mamba Formation where mineralised, and Tertiary Detritals. Hydraulic properties within the Marra Mamba Formation vary both laterally and vertically, with permeability enhanced in the upper mineralised zones. Permeability within the lower unmineralised portion of the Marra Mamba Formation (chert and banded iron formation) may be enhanced along faults. Most of the recharge to these aquifers is from direct precipitation particularly in upland regions along the Chichester Range, and vertical leakage from the overlying alluvium (FMG, 2010).

Shallow groundwater throughflow from the southern flanks of the Chichester Range to the Fortescue Marsh is considered to be minimal relative to the Marsh's recharge, storage and evapotranspirative fluxes.

Groundwater throughflow via deeper units such as Oakover Formation and Wittenoom Formation to the north of the Marsh is more substantial (estimated to be more than 20 GL/yr). Throughflow is constrained by the presence of dense water beneath the Fortescue Marsh, which forces fresher water upwards through relatively low permeability sediments towards the surface of the Marsh.

The contribution from the south of the study area is considered to be smaller (7 GL/yr) due to the presumed pinching out of the Oakover Formation to the south of the Marsh. This unit has not been observed in the area south of the Marsh to the same extent as in the north of the Marsh and has not been consistently encountered in the bores on the southern margin of the Fortescue Valley.

Groundwater throughflow to the Fortescue Valley and the Marsh occurs within the sediments and creek gravels beneath the Upper Fortescue River and its major tributaries. Mine discharge currently provides a relatively stable groundwater throughflow in the modern Weeli Wolli Creek gravels and underlying CID units, estimated at about 1.5 to 2.4 GL after evapotranspirative losses, which flows directly to the sediments in the Fortescue Valley.

Groundwater throughflow towards the Marsh also occurs beneath the major tributaries within the eastern and north-eastern catchments of the Fortescue River (e.g. Jigalong Creek). Groundwater flow in this region is generally from east to west towards the Marsh and is estimated at 8 to 10 GL/yr.

3.2.8 Hydrochemistry

Salinity

The Fortescue Valley is a large subsurface store of brackish to hypersaline water resulting from internal drainage and high evaporation rates. Water sampling undertaken by (Aquaterra, 2004) have shown that the Marsh waterbodies contain brackish water with Total Dissolved Solids (TDS) in the order of 7,500 mg/L in spring, which becomes progressively more saline towards summer (10,000 mg/L TDS in October) as water levels in the Marsh decline.

Based on studies completed at the Marillana project (Brockman Resources, 2010) and data compiled from the DoW’s AQWABASE system (Aquaterra, 2010), salinity of groundwater within the shallow (Tertiary) aquifer proximal to the base of the Hamersley Range is fresh (TDS less than 1000 mg/L). Salinity increases gradually within this aquifer towards the Fortescue Marsh, reaching 6,000 mg/L approximately 15 km to the north of Brockman’s Marillana project.

Point measurements of TDS across the study area are shown in Map 3-05. Based on the water quality analysis from various groundwater studies performed in the area, a correlation factor of TDS = 0.7xEC was used to convert the data from µS/cm to mg/L. Limited data is available in the vicinity of the Fortescue Marsh, however Skrzypek et al. (2013) provide some recent data on concentrations and mechanisms of salinity development.

Based on the reported information above, maps and figures in various publications and also on MWH’s assessment of the spatial distribution of groundwater salinity, an estimate of basin-wide salinity distribution was produced using Leapfrog Hydro TM model. Figure 3-11 schematically shows interpreted salinity contours, developed in Leapfrog Hydro, on a cross section for 5,000, 10,000, 20,000, 50,000 and 100,000 mg/L TDS based on a composite of available bore data, maps and figures presented various publications and reports and developed in Leapfrog 3D application (for example, Brockman Resources, 2010; FMG, 2010; FMG, 2012).

Saline zones are often aligned with structural lineaments (such as the Poonda Fault) and preferential flow paths. It is notable that freshwater recharge provided by the Weeli Wolli Creek results in somewhat fresher water quality within the Weeli Wolli alluvial fan, and groundwater becomes progressively more saline towards the Marsh (Map 3-06).

Overall, salinity data suggests a mound of saline to hypersaline water originating from the Marsh, dipping towards the south, as shown in Map 3-06, under density-driven flow gradients. Wedges of fresh water reside on top of this mound on the edges of the Marsh. It is uncertain what average “source” TDS is appropriate for the mound of saline water beneath the Fortescue Marsh, however a source concentration of 100,000 mg/L (hypersaline) has been assumed in this study.

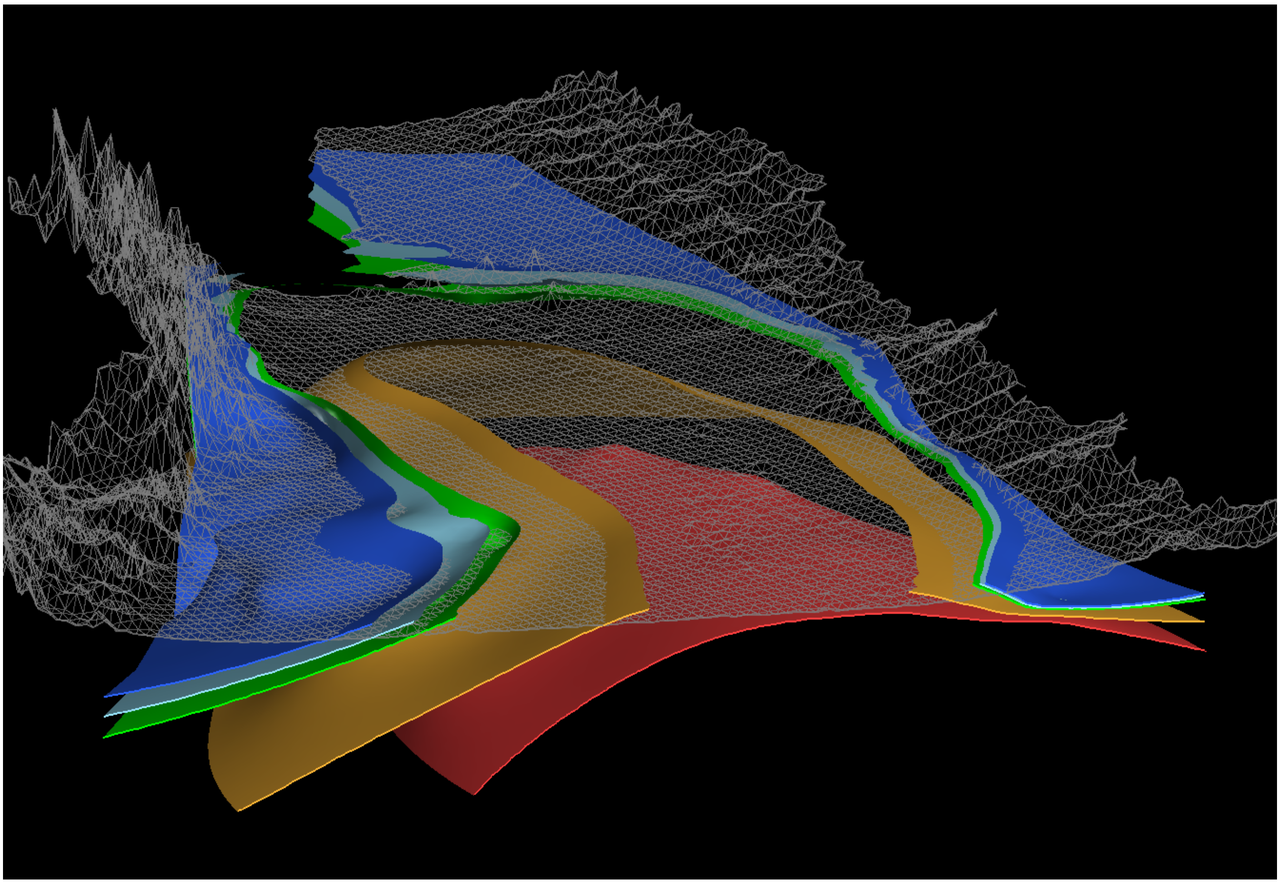


Figure 3-11: Conceptual isosurfaces of brine situated underneath the Fortescue Valley (looking west, groundwater salinity is represented as follows: red 100,000 mg/L, orange 50,000 mg/L, green 10,000 mg/l, pale blue 5,000 mg/L, blue 1,000 mg/L TDS)

Hydrochemical types

The spatial distribution of hydrochemical types based on major ion hydrochemistry is shown on Map 3-04. It shows that the majority of samples are of Na-Cl type being consistent with the original rainfall signature that evolved through widespread evaporative processes in the study area, in particular in transitional units of the study area in the Fortescue Valley, and, presumably within the Marsh.

Groundwater samples characterising the upland units are available from the Chichester Range and from the Coondiner sub-catchment in the Hamersley Range. The Ca-Mg-HCO_3 type is dominant, consistent with water entering the groundwater system from rainfall with low residence times in these areas, constituting recharge to groundwater.

Some of the samples in the Chichester upland units show increased sulphate concentration that is not present in samples from the Hamersley Range. This indicates the potential influence of Jeerinah Shale Formation which has sulphidic mineral enrichment.

On entering the Fortescue Valley the groundwater rapidly becomes chloride-dominated, sometimes with notable contents of sulphate. These anions are both indicative of strong evaporative processes and potential role of sulphide oxidation.

Hydrochemical evolution of groundwater from upland recharge producing areas to discharge areas is also evident from the Piper diagram of different hydrogeological units in the study area (Figure 3-12). For example, samples from 'Alluvium' show evolution from Ca-Mg-HCO_3 type on the left side of the Piper diamond to Na-Cl on the right side of the diamond. Samples from all upland units plot within the left side of the Piper diagram consistent with their position at the beginning of the groundwater cycle. These include the Brockman Iron Formation, CID and alluvium in upland areas of the Hamersley Range as well as basalt in the Chichester Range.

The samples from the Paraburdoo Member dolomite are affected by the brine underneath the Fortescue Valley which is overriding the original dolomite water signature.

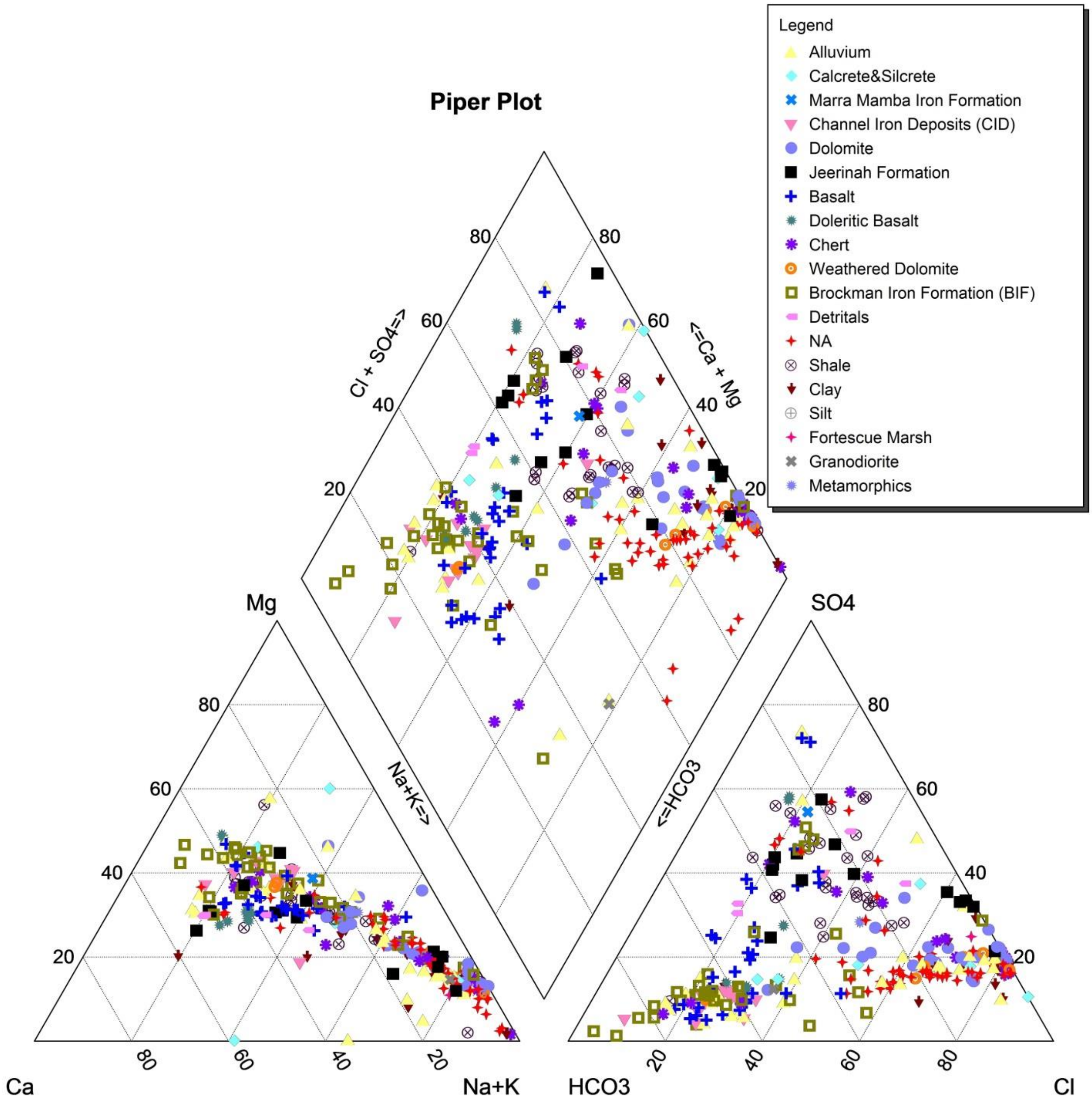


Figure 3-12: Piper diagram of water samples from different hydrogeological units in the study area

3.2.9 Key water balance components based on hydrogeological conceptualisation

The overall water balance for the aquifer system of the study area is focused on the Marsh being the terminal discharge point of the relatively large catchment area that extends beyond the study area. The key components of the water balance are related to the hydrological processes observed or assumed to be working at the Marsh and include surface water groundwater interaction, groundwater recharge and discharge and changes in groundwater storage.

The presented water balance is considered high-level as there is limited information available on surface water flows and water level dynamics. The key features and processes, relevant to the Fortescue Marsh aquifer system, are presented in Figure 3-13 and can be summarised as follows:

- Regional aquifers include: the basement (fractured) aquifer(s) (mineralised Marra Mamba Formation in the Chichester Range and mineralised Brockman Iron Formation in the Hamersley Range; the Fortescue Valley aquifer (Tertiary Detritals and Wittenoom Formation); and the CID aquifers associated with major drainage lines within and at the foot of the Hamersley Range.
- The main components of groundwater recharge include infiltration of surface runoff and overland flows from uphill areas in the break of slope zone at the valley margins (Figure 3-13); occasional Marsh flood recharge, streambed infiltration along the main creeks within the Fortescue Valley and a small component of diffuse recharge that may reach the watertable in parts of the study area.
- The ultimate groundwater discharge point is the Marsh. The groundwater flow direction in the study area is towards the Marsh, originating from topographically-driven flow in the ranges in the northern and southern limits of the study area to the topographic low points in the Marsh floor.
- The main regional aquifer situated in the basin’s valley transmits water towards the Marsh; the shallow unconfined alluvial aquifer that is intermittently supported or sustained by surface water infiltration and the deeper confined section, which is a hydraulically connected regionally occurring calcrete/silcrete and weathered dolomite of the Wittenoom Formation.
- The throughflow contribution from the shallow section to the Marsh is considered negligible due to the low permeability of this generally clayey unit and the flat groundwater gradient. The confined aquifer component that is subject to upward leakage in the Marsh area is estimated to equate to about 28 GL/yr, with the majority of inflow incoming from the north of the Marsh. This value is consistent with the typical estimate of recharge in Pilbara as it equates to slightly over 1% of the area rainfall.
- The groundwater throughflow associated with the two largest surface water inflow components, the Fortescue River and the Weeli Wolli Creek is estimated at 2 and 8 to 10 GL/yr respectively. The estimate of the Weeli Wolli Creek throughflow is provided at its outflow point from the Fortescue Range.
- The groundwater flow component in the Marsh area is generally lost to soil evaporation and transpiration since the potential evapotranspiration rates greatly exceed the rate of upward flow. This process locks the salt load underneath the Marsh creating a hypersaline brine that migrates downward due to its higher density.

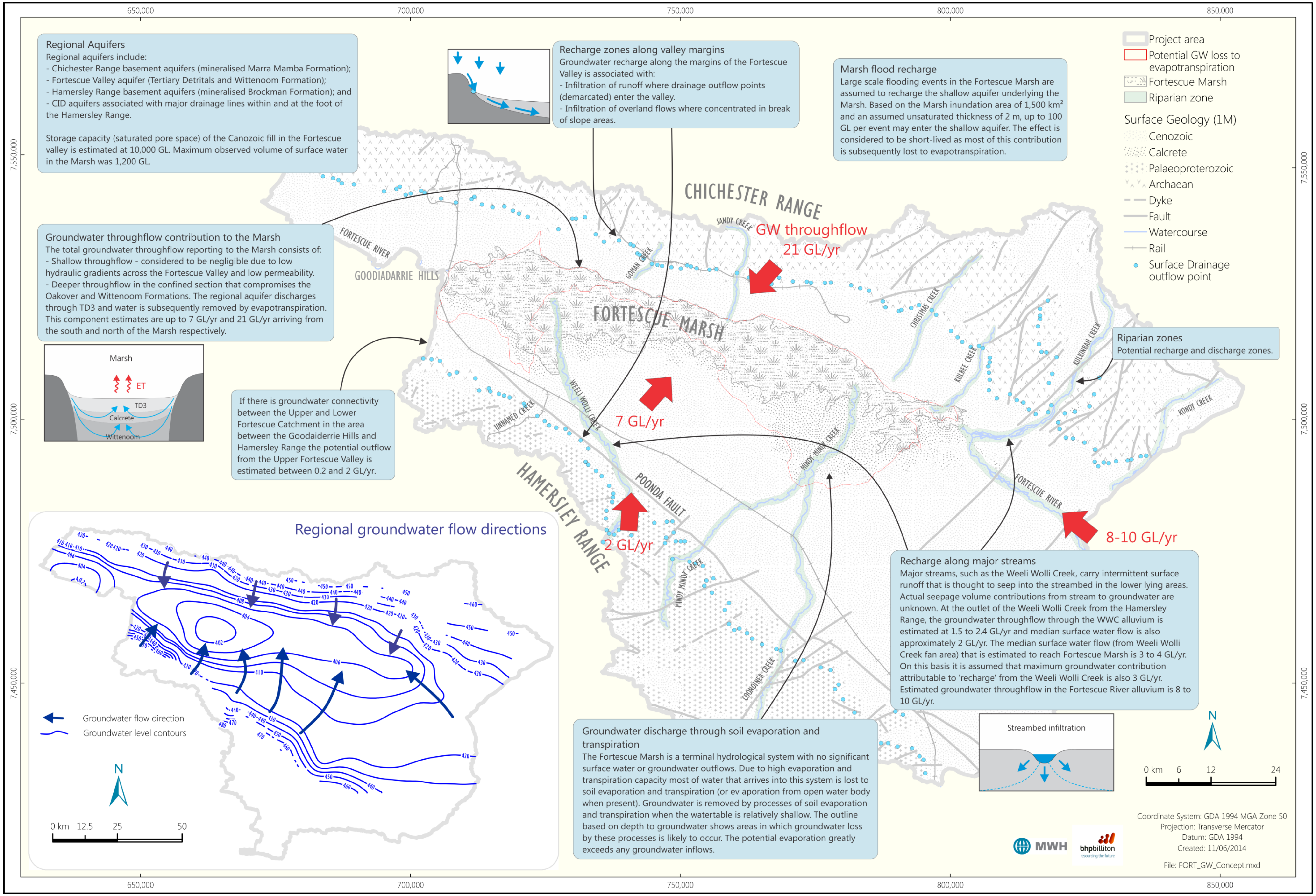


Figure 3-13: Hydrogeological conceptualisation of the Fortescue Marsh

4 Ecohydrological conceptualisation

4.1 Regional receptor assessment

4.1.1 Landscape EHUs

All nine EHUs are represented in the landscapes of the Fortescue Marsh study area as described in Section 1.3.3 (See also Table 4-1 and Map 4-01).

Upland areas (EHUs 1 and 2) are principally associated with the peaks, ridges and slopes of the Hamersley and Chichester Ranges. Within EHU 1, dendritic drainage networks emanating from the ranges aggregate into more substantial drainage floors (EHU 3) and channels (EHU 4). EHU 2 includes sloping land down-gradient from EHU 1, and also other low hills and rises across the Fortescue Valley. These areas are often dissected by ephemeral creeks with small drainage floors (EHUs 3 and 4), which may further coalesce before feeding into lowland areas. Lowland areas include the extensive alluvial flats of the Fortescue Valley (EHU 6), sandplains adjacent to the foothills of the Hamersley Range and western flank of the Upper Fortescue River (EHU 5), and calcrete plains abutting the margins of the Fortescue Marsh (EHU 7).

Major channel systems (EHU 8) are associated with the Upper Fortescue River, the Weeli Wolli, Mindy Mindy and Coondiner Creeks deriving from the Hamersley Range, and Kondy Creek deriving from the Chichester Range.

The Fortescue Marsh (EHU 9) is the vast terminus for surface inflows from the Upper Fortescue River and other creek systems. A number of small claypans (EHU 9) provide localised drainage termini on the extensive alluvial and calcrete flats south of the Fortescue Marsh. West of the Goodiadarrie Hills, a series of freshwater claypans (EHU 9) occur within the Coolibah Land System (EHU 8) proximal to Fortescue River.

In addition to the Marsh and Lake Bed Land System mapping units, additional EHU 9 areas were defined based on Quaternary Lacustrine (Ql) 1:250,000 geology mapping; and claypans associated with the Freshwater Claypans of the Fortescue Valley PEC. Within the study area, these alternative mapping units provide greater resolution of drainage termini than the land system mapping undertaken by Van Vreeswyk et al. (2004).

4.1.2 Identification of ecological receptors

Ecological assets in the study area which display a high level of connectivity are considered to be ecological receptors. These include Fortescue Marsh and the Freshwater Claypans of the Fortescue Valley PEC (Map 4-01 and Map 4-02). These are discussed in the following sections.

Ecological assets considered to have a low level of ecohydrological connectivity and therefore considered not to be ecological 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 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, the Fortescue Marsh and/or the Freshwater Claypans of the Fortescue Valley PEC. These include the Australian Bustard, Bilby, Bush Stone-curlew, Mulgara, Northern Quoll and Western Pebble-mound Mouse.
- Fortescue Valley Sand Dunes PEC – principally associated with EHU 5, below the northern flanks of the Hamersley Range. The PEC includes red, linear sand dunes dominated by open shrubland vegetation communities that are atypical for the Pilbara. It does not receive significant surface inflows from beyond its boundaries. Groundwater is deep and disconnected from the surface ecosystem. Potential threatening processes include weed invasion (principally by Buffel Grass) and erosion.
- Mosquito Land System PEC - occurs in EHU 2 near the eastern boundary of the study area. It is distant from any current or future proposed BHP Billiton Iron Ore mining developments and therefore has not been considered further as a key receptor.

- Wona Land System PEC - occurs in EHU 2, on upland basaltic plains along the northern western fringe of the study area. It does not receive significant inflows from beyond its boundaries, and is up-gradient from BHP Billiton Iron Ore's Roy Hill mining tenements. Groundwater is deep and disconnected from the surface ecosystem. Potential threatening processes include weed invasion, grazing and changes in fire regime.
- Brockman Iron cracking clay communities of the Hamersley Range PEC - occurs in EHU 6; in the upper part of a small catchment area west of the Goodiadarrie Hills. Groundwater is deep and disconnected from the surface ecosystem. Although run-on from surrounding areas may be important for sustaining the Tussock grassland vegetation community in this PEC, the catchment source areas are localised and disconnected from any current or future proposed mining developments.

Table 4-1: Summary of EHUs within the study area

<table>
<tr><th>EHU</th><th>Percent study area</th><th>Distribution in study area</th><th>Component land systems</th></tr>
<tr><td>1</td><td>27%</td><td>The Hamersley Range along the southern margin of the study area (predominantly the Newman Land System).
The Chichester Range along the northern margin of the study area (predominantly the McKay Land System).</td><td>Capricorn; Granitic; McKay; Newman; Rocklea; Kumina; Robe; Laterite; Table</td></tr>
<tr><td>2</td><td>8%</td><td>Northern foot slopes of the Hamersley Range (predominantly the Boolgeeda Land System).
Eastern periphery of the Chichester Range (predominantly the Elimunna Land System).</td><td>Adrian; Billygoat; Bonney; Boolgeeda; Egerton; Elimunna; Mosquito; Platform; Wona</td></tr>
<tr><td>3</td><td>1%</td><td>Drainage floors within EHUs 1 and 2</td><td rowspan="2">Within EHU 1: Capricorn; Granitic; McKay; Newman; Rocklea; Kumina; Robe; Laterite; Table
Within EHU 2: Adrian; Billygoat; Bonney; Boolgeeda; Egerton; Elimunna; Mosquito; Platform; Wona
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.</td></tr>
<tr><td>4</td><td>1%</td><td>Major channels within EHUs 1 and 2</td></tr>
<tr><td>5</td><td>9%</td><td>Disjunct areas on the flats north of the Hamersley Range. Widespread occurrence in the east of the study area, south of the Fortescue River.</td><td>Divide</td></tr>
<tr><td>6</td><td>37%</td><td>Widespread on the alluvial flats of the Fortescue Valley, north (predominantly Cowra, Jamindie and Turee Land Systems) and south (predominantly Fan, Marillana and Turee Land Systems) of the Fortescue Marsh.</td><td>Brockman; Christmas; Cowra; Fan; Jamindie; Jurrawarrina; Marillana; Narbung; Pindering; Spearhole; Turee; Urandy; Wannamunna; Washplain</td></tr>
<tr><td>7</td><td>4%</td><td>Widespread along the southern margin of the Fortescue Marsh (predominantly the Calcrete Land System).</td><td>Calcrete; Warri</td></tr>
<tr><td>8</td><td>4%</td><td>Associated with major drainage lines existing the Hamersley Range (Weeli Wolli, Mindy Mindy, Coondiner creeks) and the Chichester Range (Kondy Creek in the north east). Also associated with the extensive floodplain of the Fortescue River upstream from the Fortescue Marsh.</td><td>Coolibah; Fortescue; River</td></tr>
<tr><td>9</td><td>8%</td><td>The Fortescue Marsh is the dominant feature.
Small claypans and ephemeral lakes classified as EHU 9 occur on the calcrete and alluvial flats south of the Fortescue Marsh, and west of the Goodiadarrie Hills.</td><td>Marsh; Lake Bed
Also includes Quaternary Lucustrine (Ql) 1:250,000 geology mapping units; and claypans associated with the Freshwater Claypans of the Fortescue Valley PEC.</td></tr>
</table>

4.2 Ecological receptor – Fortescue Marsh

While earlier sections have described aspects of the regional setting hydrology and ecology of the Fortescue Marsh, it is useful here to focus on, and restate, the specific attributes of the Marsh itself. The ecological values of the Marsh are presented in Sections 4.2.1 to 4.2.3. Hydrological and ecohydrological aspects are then discussed in later sections.

4.2.1 Overview

The Marsh is a brackish to saline, endorheic wetland formed in the drainage terminus of the Upper Fortescue River. It is a unique regional-scale landscape feature, extending for approximately 100 km along the Fortescue Valley with a width of typically 3 to 10 km.

The Marsh landform consists of sparsely vegetated, clay flats fringed by samphire vegetation communities (Figures 4-1 to 4-6). The Marsh boundary is approximately defined by the Marsh Land System described by van Vreeswyk et al. (2004). Bed levels in the Marsh lie between 400 m and 405 m AHD, and the samphire vegetation typically extends to about 407 to 408 m AHD.

The Marsh becomes inundated episodically in association with cyclonic rains, surface runoff and flooding. Following the largest events floodwaters may persist for several months, providing breeding and foraging habitat for waterbirds and other biota. Surface waterbodies in the Marsh rapidly evaporate, providing a mechanism for salt accumulation that has probably been occurring for hundreds of millennia (Skrzypek *et al.* 2013). Beneath the Marsh, the groundwater is hypersaline.

The Marsh bed comprises saline and sodic clays. Shallow calcrete and silcrete hardpans (within the upper 150 cm of the soil profile) are common in the vegetated Marsh periphery. The upper sediments support a shallow groundwater system, with the depth to watertable during inter-floods probably set by an evaporation extinction depth of a few metres. Deep Tertiary sediments beneath the Marsh host a series of variably connected aquifer systems, with heavier clay sequences functioning as aquitards.

The spatial scale of the Marsh is a key factor defining its ecohydrological attributes and potential susceptibility to hydrological change. The Marsh has a wide range of ecological values summarised as follows:

- classified as a wetland of national importance within the Directory of Important Wetlands in Australia;
- recognised as a nationally important Bird Area (Dutson *et al.* 2009); supporting multiple species subject to international treaties (e.g. JAMBA, CAMBA, ROKAMBA);
- the Marsh Land System is recognised as a Priority Ecological Community (Priority 1) by the Department of Parks and Wildlife (DPaW 2013);
- provides habitat for rare flora (endemic *Eremophila, Tecticornia* and other Priority species);
- provides habitat for rare vertebrate fauna (possibly including the critically endangered Night Parrot (*Pezoporus occidentalis*); and
- provides habitat for rare invertebrate fauna (locally restricted aquatic invertebrates).

These values collectively contribute to the Marsh's high conservation status. In 2013, the Environmental Protection Authority (EPA) published information and management guidance for protecting the water regime and ecological values of the Marsh (EPA Report 1484; EPA 2013). Further details on specific ecological values of the Marsh are provided in the EPA guidance document.

The Marsh has a history of pastoral land use since the late 19th century and remains accessible to cattle at present. However, large portions of the Marsh have been identified for transition into conservation tenure and management in relation to the expiry of Western Australian pastoral leases in 2015.

Figure 4-1: Saline clay flats in the Marsh interior (recently established samphire on the dry lake bed during a dry phase probably won't survive the next major inundation event) – photograph: D. Huxtable

Figure 4-2: A University of Western Australia research plot in samphire vegetation near the northern fringe of the Marsh – photograph: D. Huxtable

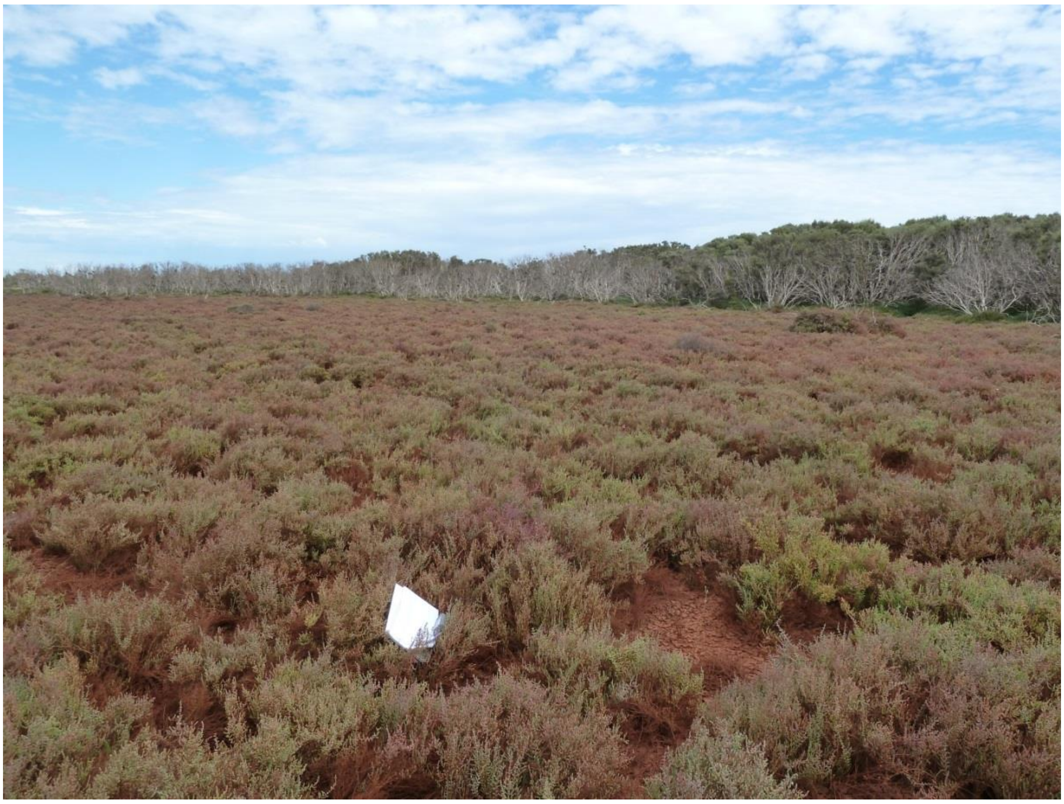


Figure 4-3: Samphire vegetation in the outer Marsh with a patch of *Melaleuca glomerata* woodland in the background – photograph: D. Huxtable

Figure 4-4: The boundary of samphire vegetation (in this case ≈407.5 m AHD) is typically abrupt and probably aligns with zones of seed dispersal by floods – photograph: D. Huxtable

Figure 4-5: Lignum (*Muehlenbeckia florulenta*) shrubland in the outer Fortescue Marsh – photograph: D. Huxtable

Figure 4-6: A drainage line fringed by Salt Water Couch entering the Fortescue Marsh – photograph: D. Huxtable

4.2.2 Previous work

Geology and groundwater investigations

Information on the stratigraphy beneath the Marsh is limited. The current hydrogeological conceptualisation is principally based on extrapolation of drilling information from the greater Fortescue Valley. Skrzypek et al. (2013) presented a conceptual geological model of the broader Fortescue Valley, as part of their recent study examining hydrological processes controlling groundwater salinity in the Marsh.

Fortescue Metals Group (FMG) is a key custodian of geological and hydrogeological information relevant to the Marsh. FMG has established a large bore network nested piezometers in areas north of the Marsh associated with the Cloudbreak and Christmas Creek mining operations. FMG has also undertaken investigations associated with the Nyidinghu project, south of the Marsh. Some of the information compiled by FMG is in the public domain as part of environmental impact assessment documentation (e.g. ENVIRON, 2005; FMG, 2011a; FMG, 2011b). This includes a Marsh hydrogeological conceptualisation that was included in EPA Report 1484 (EPA 2013).

Additional information relating to the eastern end of the Marsh has been gathered by Hancock Prospecting Pty Ltd (HPPL) for the Roy Hill project. Some data is available through environmental impact assessments such as MWH (2007); MWH (2009); ENVIRON (2009). A recommendation document by the EPA (2011) commented on Roy Hill project impacts on vegetation in the area. RHIO is currently developing groundwater resources in the eastern part of the study area; however, relevant information is not in the public domain.

Finally, Rio Tinto has recently undertaken a drilling program including areas of the Marsh in association with Australian Research Council (ARC) Linkage Project LP120100310 (refer to Section 4.2.2.3. below). The evaluation of results is on-going and not publically available.

Surface hydrology

An understanding of flood levels in the Marsh is limited to data from the Roy Hill streamflow gauging station (Ref. S708008), which operated during the period September 1973 to September 1986 and was located at the eastern edge of the Marsh (Map 3-01). This data has been augmented by anecdotal observations made by land managers. The main flow channel bed level at the gauging station was around 405.5 m AHD and during the 13 years of record, the maximum recorded water level was 408.75 m AHD, observed in February 1980 (Aquaterra, 2005). The gauged water level corresponded with a peak storage level of 406.5 m AHD in the Marsh (downstream) and occurred after two consecutive cyclones. Based on observations made by mining company personnel, large floods in the early 1970s caused Marsh inundation levels up to the level of the existing BHP Billiton Iron Ore railway track (Aquaterra 2005).

The impact of the Ophthalmia Dam on the flow regime of the Upper Fortescue Catchment was investigated by Payne and Mitchell (1999). The dam captures water from three of the 15 major tributaries of the Fortescue River, intercepting long term median inflows of about 30 GL. The dam does not prevent large flows from reaching downstream areas (Florentine, 1999), but has reduced flow volumes, peak flows, flooded width and frequency of flooding on the downstream floodplain (Payne and Mitchell, 1999). In particular it appears to have prevented or reduced medium-sized flows (recurrence interval of one to three years) from reaching the downstream floodplain. The effect of this flow attenuation diminishes with distance towards Roy Hill, but was detectable at the eastern edge of the Marsh near Roy Hill.

As a component of the Roy Hill Stage 1 Public Environmental Review (PER), Gilbert and Associates (2009) derived an indicative water balance for the Marsh, summarised as follows:

- estimated total basin capacity of the Marsh is 10,000 GL;
- estimated surface inflows to the Marsh in a median rainfall year is 300 GL;
- the storage capacity of the Marsh greatly exceeds inflows, even under extremely high rainfall scenarios;
- evaporation equals or exceeds runoff inflows in most months, such that in typical years inflows mostly evaporate within weeks to months (i.e. are not carried over the following dry season); and

- groundwater inflows were considered to be a small, insignificant component of the water balance (estimated to be 6 GL/yr based on analysis of data from gauged catchments in the eastern Pilbara).

ARC Linkage Projects relating to the Fortescue Marsh

In the period 2008 to 2011, an Australian Research Council (ARC) research project entitled “Ecophysiology of stem succulent halophytes subject to changes in salinity and water availability: distinguishing natural dynamics from potential mine related impacts” was undertaken by the UWA School of Plant Biology, in collaboration with the WA Herbarium and with industry funding support from Fortescue Metals Group (ARC Linkage Project LP0882350). The project was managed by Prof. Tim Colmer (UWA) and Prof. Erik Veneklaas (UWA), with the experimental work largely implemented by PhD student Louis Moir-Barnetson.

The project had the following objectives:

- identify the dominant samphire species that are present in the Marsh and environmental factors that explain their distribution pattern;
- relate samphire population dynamics with the dynamics of water availability (flooding and water deficit) and salinity, as related to weather conditions (rainfall, air temperature, and evaporative demand);
- relate key plant health indicators, including transpiration, water status, ionic relations, organic osmolytes, pigment composition (chlorophyll and photoprotective carotenoids) and chlorophyll fluorescence, with varying levels and combinations of stress factors (salinity, drought, flooding) under field conditions; and
- rigorously test, in controlled environments with defined treatments, hypotheses developed during the field work regarding physiological processes contributing to resistance of salinity, drought, and flooding, and also to ascertain reliable early-warning stress indicators.

Project work included the following components (pers. comm. Dan Huxtable, Equinox Environmental Pty Ltd 2014):

- Field observations of climatic, soil and samphire ecology/ecophysiology parameters conducted at two locations near the northern margin of the Marsh over a three year period (commencing in October 2008). At each location, a transect of replicated 20 x 20 m plots was established that spanned an ecological gradient with respect to soil water and salinity dynamics, depth to watertable and frequency of flooding within the Marsh ecosystem. Manual installation of shallow piezometers was attempted in the each of the plots; however impenetrable silcrete hardpans were invariably encountered within 120 cm of the surface.
- Controlled glasshouse experiments were undertaken to test the responses of major marsh samphire species to the individual and combined effects of salinity, water deficit, flooding.

Several journal papers related to the project have been published including:

- a major review of halophyte physiology and salinity tolerance (Flowers and Colmer, 2008);
- a review of halophyte flooding tolerance (Colmer and Flowers, 2008);
- a review of flooding tolerance in plants (Colmer and Voesenek, 2009); and
- taxonomic work with the formal description of two new samphire species from the Marsh (*Tecticornia globulifera* and *Tecticornia medusa*) (Shepherd and van Leeuwen, 2011).

Additional journal papers are at an advanced stage of preparation (pers. comm. E. Veneklass, UWA 2014). The proposed paper titles include:

- ‘Submergence tolerance in stem-succulent halophytes is associated with resistance to the osmotic swelling and rupturing of shoot tissues’;
- ‘The distribution and population dynamics of stem-succulent halophytic shrubs (*Tecticornia* species) at an ephemeral inland salt lake in arid-zone northwest Australia’;
- ‘Ecophysiological responses of *Tecticornia* species to seasonal changes at Fortescue Marshes’; and

- Drought tolerance of three *Tecticornia* stem succulent halophytes of an inland arid-zone salt lake system'.

In 2012, an Australian Research Council (ARC) research project entitled "Climate-related regime shifts in inland semi-arid ecosystems through ecohydrological proxies" was commenced by the UWA School of Plant Biology with industry funding support from Rio Tinto under ARC Linkage Project LP120100310. The project aims to investigate the dynamics of climate, especially rainfall, of the northwest of Australia over the last few thousand years through analysis of stable isotopes in surface water and groundwater, sediment cores (in the Marsh) and tree rings. The project has a 3-year duration.

As part of the project Rio Tinto has established a series of nested piezometers in and adjacent to the Marsh, which in combination with existing FMG bores provide pseudo-grid coverage along the east-west and north-south axes of the Marsh. The drilling methods have enabled the recovery of sediment cores from the upper profile of the Marsh for geochemical analysis.

To date a journal paper has been released discussing hydrological processes controlling the salinity of the Marsh (Skrzypek et al., 2013). Several additional journal papers are pending publication in 2014, including a paper addressing the flooding regime of the Marsh (pers. comm. Pauline Grierson, UWA 2014). This information is anticipated to greatly improve understanding of the Marsh flooding dynamics.

DPaW Marsh assessments

In April 2008, the then Department of Environment and Conservation (now DPaW) completed a resource condition assessment of selected wetlands of the Fortescue River system, including the Marsh, as part of the Department's Inland Aquatic Integrity Resource Condition Monitoring project (DEC, 2009).

Field investigations were carried out at three locations within the Marsh boundary (Fortescue Marsh West, Moorimoordinina Pool and Fortescue Marsh East). The assessment included:

- vegetation species and percentage cover;
- water quality of Moorimoordinina Pool (note that the other locations had no standing water at the time of sampling); and
- aquatic invertebrates in Moorimoordinina Pool.

In addition, DPaW has recently commenced a floristics survey of the Marsh, with funding support from a Fortescue Metals Group environmental offset. The survey is scheduled for completion in mid-2015 (pers. comm. Dr Stephen van Leeuwen, DPaW 2014) and no survey findings are available at the present time.

Vegetation, flora and fauna surveys by other parties

FMG is the only mining company to have commissioned vegetation and flora surveys over portions of the Marsh. This work has focused on the northern margins of the Marsh near the Cloudbreak and Christmas Creek project areas. The key survey reports in the public domain include:

- ENV Australia (2010) - *Christmas Creek Flora and Vegetation Assessment*, Prepared for Fortescue Metals Group Ltd, ENV Australia Pty Ltd, Perth.
- Mattiske Consulting Pty Ltd (2007) - *Flora and Vegetation near Fortescue Marshes*, Prepared for Fortescue Metals Group Ltd, Mattiske Consulting Pty Ltd, Perth.

These surveys found that the Marsh includes multiple samphire vegetation types, with zonal distribution patterns evident for the major samphire taxa. Small patches of *Melaleuca glomerata* woodland have also been noted south of Christmas Creek and along southern margins of the Marsh (Figure 4-3).

4.2.3 Ecological description

Wetland type

As detailed in Section 4.2.1 the Marsh is recognised as being a unique and extensive inland floodplain system within the Pilbara Region (McKenzie et al., 2009). The samphire shrubland is the largest ephemeral wetland in the Pilbara Bioregion.

In terms of a modified version of the international Ramsar Classification System for Wetland Type (Environment Australia, 2001), the Marsh includes two wetland types:

- Type B4: Riverine floodplains; includes river flats, flooded river basins, seasonally flooded grassland, savanna and palm savanna; and
- Type B6: Seasonal/intermittent freshwater lakes (>8 ha), floodplain lakes.

Vegetation and flora

Much of the interior of the Marsh consists of sparsely vegetated clay flats, within a series of low elevation flood basins. Vegetation recruitment may occur in these areas during dry phases; however, the frequency and depth of inundation events is a constraint to long term vegetation persistence.

In slightly more elevated areas fringing the bare flats, samphire (*Tecticornia* spp.) vegetation communities are prevalent. *Tecticornia medusa* (Priority 1) is prominent in down-gradient areas deep within the Marsh (about 1 to 1.5 km from the Marsh boundary). Further up-gradient *T. auriculata, T. sp.* Christmas Creek (K.A. Shepherd and T. Colmer et al. KS 1063) (Priority 1) and/or *T.* sp. Dennys Crossing (K.A. Shepherd and J. English KS 552) tend to be dominant taxa. *Tecticornia indica* subsp. *bidens* is the pre-eminent species in up-gradient areas near the Marsh ecophysiographic boundary, where it may grow in association with *Eremophila spongiocarpa* (Priority 1).

Patchy shrublands of Lignum (*Muehlenbeckia florulenta*) and False Lignum (*Muellerolimon salicorniaceum*) often grow in association with the samphire communities and *Atriplex flabelliformis* (Priority 3). These shrublands provide additional structural complexity. Small patches of *Melaleuca glomerata* woodland also occur, and may provide an important structural element for waterbird roosting and nesting (Figure 4-3).

Following large rain events and floods a variety of annual and ephemeral species emerge with some of elevated conservation status (e.g. *Nicotiana heterantha* - Priority 1; *Peplidium* sp. Fortescue Marsh (S. van Leeuwen 4865) – Priority 1). Salt Water Couch (*Sporobolus virginicus*) and Buffel Grass (**Cenchrus ciliaris*) also occur in places near the Marsh periphery, associated with drainages entering the Marsh.

The Marsh provides difficult growing conditions for vegetation owing to the combined stresses of seasonal drought, soil salinity, waterlogging and inundation. In some areas shallow hardpans also restrict samphire root depth. Flooding events dissolve and redistribute evaporitic salts that have concentrated during dry phases, creating dynamic conditions for vegetation with respect to salinity exposure.

Little information is available on the population dynamics of the samphire vegetation communities; however, the following observations by UWA scientists involved in ARC Linkage Project LP0882350 are notable (pers. comm. Dan Huxtable, Equinox Environmental Pty Ltd 2014):

- The major samphire taxa appear to be slow growing and long lived.
- Samphire transpiration flux rates are low (i.e. relatively low water use), suggesting a conservative water use strategy limited by the difficult growing conditions.
- Seed dispersal and recruitment is likely to be controlled by the flood regime. Floodwaters are likely to contribute to samphire recruitment by providing favourable conditions for germination and seedling establishment. Inundation is also possibly a significant mortality factor for small plants.

Fauna

The Marsh provides important breeding and foraging habitat for waterbirds (McKenzie et al., 2009). Notable species that utilise the Marsh include the Australian Pelican (*Pelecanus conspicillatus*) and Black Swan (*Cygnus atratus*). According to DPaW, there were between 260,000 and 276,000 individuals from 47 species of wetland birds observed when the Marsh was inundated in 1999 and 2003 (pers. comm. Dr Stephen van Leeuwen DPaW).

Between 2005 and 2009, Birds Australia undertook an assessment of Australian locations with global significance for bird conservation (Dutson *et al.* 2009). These locations are referred to as “important bird areas” (IBAs). The Marsh was one of 314 Australian sites classified as an IBA. The findings of the assessment included the statement “*The Fortescue Marsh IBA in Western Australia floods about once every ten years and have supported more than one per cent of the world population of 14 waterbird species*”. Twenty-three globally-important bird species were reported to use the Marsh (Table 4-2) (Dutson et al. 2009).

The functionality of the Marsh as an important waterbird habitat needs to be considered in a regional and national context. From an ecological perspective, the Marsh is one component of a network of wetlands across Australia. As a collective of geographically dispersed wetlands, the network enables bird populations to be sustained from year to year, despite much longer scale flooding and drought cycles in individual wetlands. This concept is well described by Olsen and Weston (2004), restated as follows:

"*Improved knowledge of waterbird distributions in Australia is showing that the arid zone is an important nursery for waterbirds, something that was poorly recognised as recently as 25 years ago. The use of arid zone wetlands in Western Australia is in the early stages of documentation, but Lake Gregory, Fortescue Marsh and Mandora Marsh in the north, together support over a million waterbirds during the late dry season in some years and are important breeding sites. However, it must be emphasised that Fortescue and Mandora Marsh flood only occasionally, so that waterbird populations are maintained only if other suitable wetlands in the arid zone, or elsewhere, are flooded when these lakes are dry. Thus, it is important to ensure that a network of big wetlands with high waterbird carrying capacity, throughout the arid zone and elsewhere, is conserved*"

Contemporary records have been made of the Critically Endangered[16] Night Parrot (*Pezoporus occidentalis*) near the Marsh (David and Metcalf, 2008). The low halophytic samphire shrubland habitat provided by the Marsh, in combination with surrounding hummock grasslands, may provide favourable habitat for this species (McDougall *et al.* 2009). The Australian Bustard (*Ardeotis australis*) is also found at the margins of the Marsh (Davis *et al.* 2005).

A number of conservationally significant fauna species have been recorded in areas fringing the Marsh including the Bilby (*Macrotis lagotis*), Northern Quoll (*Dasyurus hallucatus*) and Mulgara (*Dasycercus cristicauda*) (Davis *et al.* 2005). The significance of the Marsh habitat for these species is unclear; however, it may contribute to their foraging range.

The Marsh hosts aquatic invertebrate assemblages of conservation interest, and several endemic taxa of macro-invertebrates are known only from the Marsh. As part of the Pilbara Biological Survey[17], two areas near the western and eastern ends of the Marsh respectively were sampled for aquatic invertebrates in the period 2003 to 2006 (Pinder et al., 2010). Several potentially endemic species were collected including a variant of the rotifer *Brachionus angularis*, a new *Alona* cladoceran and a new *Ainudrilus* oligochaete. Additional taxa recorded at the Marsh were only collected from one other location at Weelarrana Salt Marsh including a new *Mytilocypris* ostracod and *Coxiella* snails. No information is available on the ecological requirement of these taxa.

The Marsh has not been sampled for stygofauna owing to a lack of bores. However, areas north of the Marsh associated with FMG Chichester Projects have been sampled (Bennelongia 2007), and also areas east of the Marsh associated with Roy Hill Project (HPPL, 2009). Several stygofauna and troglobiotic taxa were collected in these studies. In each case, the subterranean fauna communities were found to be relatively poorly developed in comparison with other locations in the Pilbara. None of the taxa collected and identified at these locations were regarded as having conservation significance.

The Marsh includes a number of persistent pools associated with drainage scours along the Fortescue River channel and other major channel inflows. These are probably sustained by storage in the surriounding Marsh sediments after flood events. The pools could potentially function as refugia for some aquatic fauna species during interfloods.

[16] Under both the *Wildlife Conservation Act 1950* and the *Environment Protection and Biodiversity Conservation Act 1999*.
[17] Further detail on the Pilbara Biological Survey is provided in MWH, 2014.

Table 4-2: Globally-important bird populations in the Fortescue Marsh Important Bird Area

Source: Atlas of Australian Birds – Birds Australia <http://www.birdata.com.au/iba.vm>

Scientific Name	Common Name	Conservation status (WA)	Population (no. of individuals)	Season	Monitoring Period
Acanthiza robustirostris	Slaty-backed Thornbill	none		resident	2008 - 2008
Anas gracilis	Grey Teal	none	0 – 28,312	unknown	1999 - 2003
Anas superciliosa	Pacific Black Duck	none	0 – 63,560	unknown	1999 - 2003
Anhinga novaehollandiae	Australian Darter	none	0 – 1,474	unknown	1999 - 2003
Ardea pacifica	White-necked Heron	none	0 – 2,148	resident	1999 - 2003
Ardeotis australis	Australian Bustard	Priority 4 (WA)		resident	1998 - 2008
Aythya australis	Hardhead	none	0 – 76,746	resident	1999 - 2003
Burhinus grallarius	Bush Stonecurlew	Priority 4 (WA)		resident	1998 - 2008
Chlidonias hybrida	Whiskered Tern	none	0 – 19,601	unknown	1999 - 2003
Conopophila whitei	Grey Honeyeater	none		resident	2008 - 2008
Cygnus atratus	Black Swan	none	0 – 17,535 i	resident	1999 - 2003
Dendrocygna eytoni	Plumed Whistling-duck	none	0 – 17,500	resident	1999 - 2003
Emblema pictum	Painted Firetail	none		resident	2008 - 2008
Eremiornis carteri	Spinifexbird	none		resident	2008 - 2008
Falco hypoleucos	Grey Falcon	Schedule 1 (WA)		resident	1998 - 2008
Himantopus leucocephalus	White-headed Stilt	none	0 – 24,837	unknown	1999 - 2003
Malacorhynchus membranaceus	Pink-eared Duck	none	0 – 11,157	unknown	1999 - 2003
Neopsephotus bourkii	Bourke's Parrot	none		resident	2008 - 2008
Pezoporus occidentalis	Night Parrot	Schedule 1 (WA)[18]		unknown	2005 - 2005
Phalacrocorax melanoleucos	Little Pied Cormorant	none	0 – 5,991	unknown	1999 - 2003
Phalacrocorax sulcirostris	Little Black Cormorant	none	0 – 27,630	unknown	1999 - 2003
Poliocephalus poliocephalus	Hoary-headed Grebe	none	0 – 12,673	unknown	1999 - 2003
Threskiornis spinicollis	Straw-necked Ibis	none	0 – 16,947	unknown	1999 - 2003

4.2.4 Surface water catchments

Catchment areas contributing flows to the Marsh include (Map 4-01):

- downstream portions of the Fortescue River catchment. The majority of this catchment extends beyond the study area;
- downstream portions of the Weeli Wolli Creek catchment, on the alluvial fan of this creek system. The majority of this catchment extends beyond the study area;
- Koodaideri Creek;
- Chuckalong Creek, located between the Weeli Wolli Creek to the west and Mindy Mindy Creek to the east;
- Coondiner Creek and Mindy Mindy Creek;
- BHP Billiton Iron Ore Roy Hill East;
- Goman/ Sandy Creek;
- Christmas Creek;
- Kulbee Creek; and
- Kulkinbah Creek.

The Marsh itself consists of two basin areas (east and west) separated by a slightly more elevated divide.

For each of these catchments, the relative contribution of different EHUs to the catchment area provides an indication of surface water processes (source, transfer and receiving) operating within the catchment (Map 4-01). This also provides a basis for comparing different catchments. For example, the Weeli Wolli Alluvial Fan sub-catchment to the south of the Marsh comprises mostly lowland sandplains, with gently undulating surfaces, significant infiltration losses and low surface water runoff. In contrast, the Goman/Sandy Creek sub-catchment to the north of the Marsh includes a combination of upland source and transitional areas with short flowpaths and high runoff, and lowland alluvial plains with higher infiltration and lower surface runoff.

Each of the study area catchments are described in more detail as follows.

Catchments contributing to the eastern fringe of the Fortescue Marsh

A relatively small portion of the Fortescue River catchment, being 2,152 km^2 of the total catchment area of 16,281 km^2, lies within the study area to the east of the Marsh (Map 4-01). This area can be partitioned into two distinct sub-areas, north and south of the Fortescue River respectively. The northern sub-area contains areas of EHUs 1 and 2 - upland source areas comprising hills and dissected slopes and plains. Surface water runoff from these areas is directed via dendritic drainage networks through short flow paths that terminate in the Fortescue River. The southern sub-area consists of lowland alluvial plains and sandplains (EHUs 5 and 6), which constitute part of the Fortescue River alluvial fan. These EHUs are associated with poorly defined drainage patterns, high infiltration rates and minimal runoff; although, some local scale surface water redistribution may occur. The Fortescue River including its associated floodplain is classified as a lowland major channel system (EHU 8).

Catchments contributing to the southern fringe of the Fortescue Marsh

Catchments that lie on the southern fringe of the Marsh include the Koodaideri Creek, Weeli Wolli Alluvial Fan, Chuckalong and Mindy Mindy/Coondiner Creek sub-catchments. These sub-catchments drain from the Hamersley Range and extend across the wide, flat plains between the base of the Hamersley Range and the Marsh. The Chuckalong catchment is a small catchment between the Weeli Wolli Alluvial Fan catchment and the Mindy Mindy / Coondiner Creek catchment. Examination of the 5 m DEM revealed that the Mindy Mindy Creek catchment is a sub-catchment of the Coondiner Creek catchment, with Mindy Mindy Creek flowing into the Coondiner Creek downstream of Coondiner Pool.

Each of these catchments includes upland source areas of the Hamersley Range (EHUs 1 and 2) in association with upland drainage floors and channel networks (EHUs 3 and 4); however the proportional contribution of these units varies considerably between the catchments.

[18] Also a listed species under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)

Upon exiting the Hamersley Range, channel flows are dissipated across the lowland plains. Drainage through these areas can be complex and consists of low-energy channels, channel breakouts and depressions. Areas of sheetflow may also occur as dictated by surface types and gradients. Within the lowland sandplains, drainage is poorly organised and infiltration rates are high. Along the fringes of the marsh, the calcrete plains (EHU 7) have numerous localised drainage termini which can collect runoff, in addition to drainages extending into the Marsh.

One of the most significant features to the south of the Marsh is the Weeli Wolli alluvial fan (Map 4-01). The distribution of flow between the channels within the alluvial fan area varies with the intensity of the event. For example, during low flow events, flow will be confined exclusively to the main Weeli Wolli Creek channel; whereas, during large events the flow within the main channel would only represent a small proportion of the total flow across the alluvial fan.

Surface water runoff from the Mindy Mindy / Coondiner Creek sub-catchment, with an area of 3,205 km^2, flows in a north-easterly direction from the Hamersley Range into the Fortescue Valley. Coondiner Creek flows through Eagle Rock Pool and Eagle Rock Falls in the upper reaches of the catchment, and Coondiner Pool at the base of the creek system (Map 3-01). Coondiner Pool occupies an area of approximately 0.09 km^2 and is classified as a shallow, semi-permanent claypan area/wetland. It is underlain by low permeability, fine to medium-grained alluvium.

The Wanna Munna sub-catchment lies to the southwest of Coondiner Creek sub-catchment, outside the study area. It is a relatively small catchment with an area of 502 km^2 and is bound by the Fortescue River, Weeli Wolli Creek and Coondiner Creek sub-catchments. The Wanna Munna sub-catchment is believed to respond primarily as an internally draining catchment during minor and average rainfall events. However, following significant rainfall events the internal capacity of this catchment may be exceeded with flows spilling over into Coondiner Creek. It is not known whether there is any significant groundwater outflow from the Wanna Munna area into the study area.

Catchments contributing to northern fringes of the Fortescue Marsh

Drainage from the Chichester Range flows towards the Marsh via a series of floodplains, alluvial fans and incised ephemeral creeks. These drainage features extend along the northern edge of the Marsh, between 5 and 10 km from the base of the Chichester Range and sloping at around 0.3%.

Catchments lying to the north of the Marsh include the BHP Billiton Iron Ore Roy Hill East, Goman/ Sandy Creek, Christmas Creek, Kulbee Creek and Kulkinbah Creek catchments (Map 4-01). These catchments include a relatively even distribution of upland source areas (EHU 1 and 2 within the Chichester Range) and lowland alluvial plains (EHU 6).

The upland areas drain into a series of relatively well-defined, parallel drainage channels. Moving further south, the topography becomes flat and the drainages become narrower and more divergent. A number of drainages penetrate into the Marsh, where they further distribute into splay channels and marsh playas. Areas of sheetflow may occur in the interdrainage zones. In comparison with the catchments located on the southern fringes of the marsh, flow distances from the upland to lowland areas on the northern fringes of the Marsh are shorter and cross a narrower alluvial plain.

In some locations the drainages from these northern catchments feed into semi-permanent waterbodies on the fringes of the Marsh, possibly associated with channel remnants and scours. These waterbodies are referred to as Yintas and have cultural significance to Traditional Owners.

Fortescue Marsh Basin

The Marsh (EHU 9) is the terminus for all surrounding catchments. Runoff from the surrounding catchments is influenced by surface detention, vegetation uptake, seepage and other removal processes before reaching the Marsh basin.

Examination of the 5 m DEM suggests that flood waters can pond up to 8 m in depth in the lowest elevation portions of the marsh following significant flood events. Water stored in the Marsh will slowly dissipate via seepage and evaporation. As these dissipation processes progress, the extent of the Marsh waterbody decreases and separates into a series of pools as controlled by basin topography until the surface completely dries. During the evaporation process, surface water salinity increases and traces of precipitated salt can be seen as floodwaters recede. During the seepage process, a proportion of the increasingly saline waterbody percolates into the deep, valley floor alluvium.

Based on comparison between Landsat and surface topographic data, flood peak elevations of up to 407 m AHD have occurred in the Marsh area in the past several decades. Spillover from the Marsh beyond the Goodiadarrie Hills requires Marsh flood elevations in excess of 412 m AHD, suggesting that this is a very rare event under the prevailing climate regime.

Examination of the 5 m DEM, together with aerial photographs, shows that the Marsh can be partitioned into two internal catchment areas (Figure 4-7). These eastern and western basins interconnect during and following large flood events and wet periods, but may remain disconnected with lower inflows. The eastern basin is likely to spillover into the western basin at a level of around 406 m AHD. While the east-west divide is evident from the 5 m DEM and satellite imagery of flood inundation areas, field investigation and groundtruthing would be required to understand the process and explaination for formation of the divide.

Satellite imagery of the Marsh (Figure 4-7 top frame) clearly illustrates this east-west divide, showing inundation of the eastern basin whilst the western basin remains dry. This situation was likely due to inflow from the upper Fortescue River catchment, following a localised rainfall event. The bottom frame in Figure 4-7 shows the Marsh basin elevations based on the 5 m DEM, with lower elevations to the east of the divide.

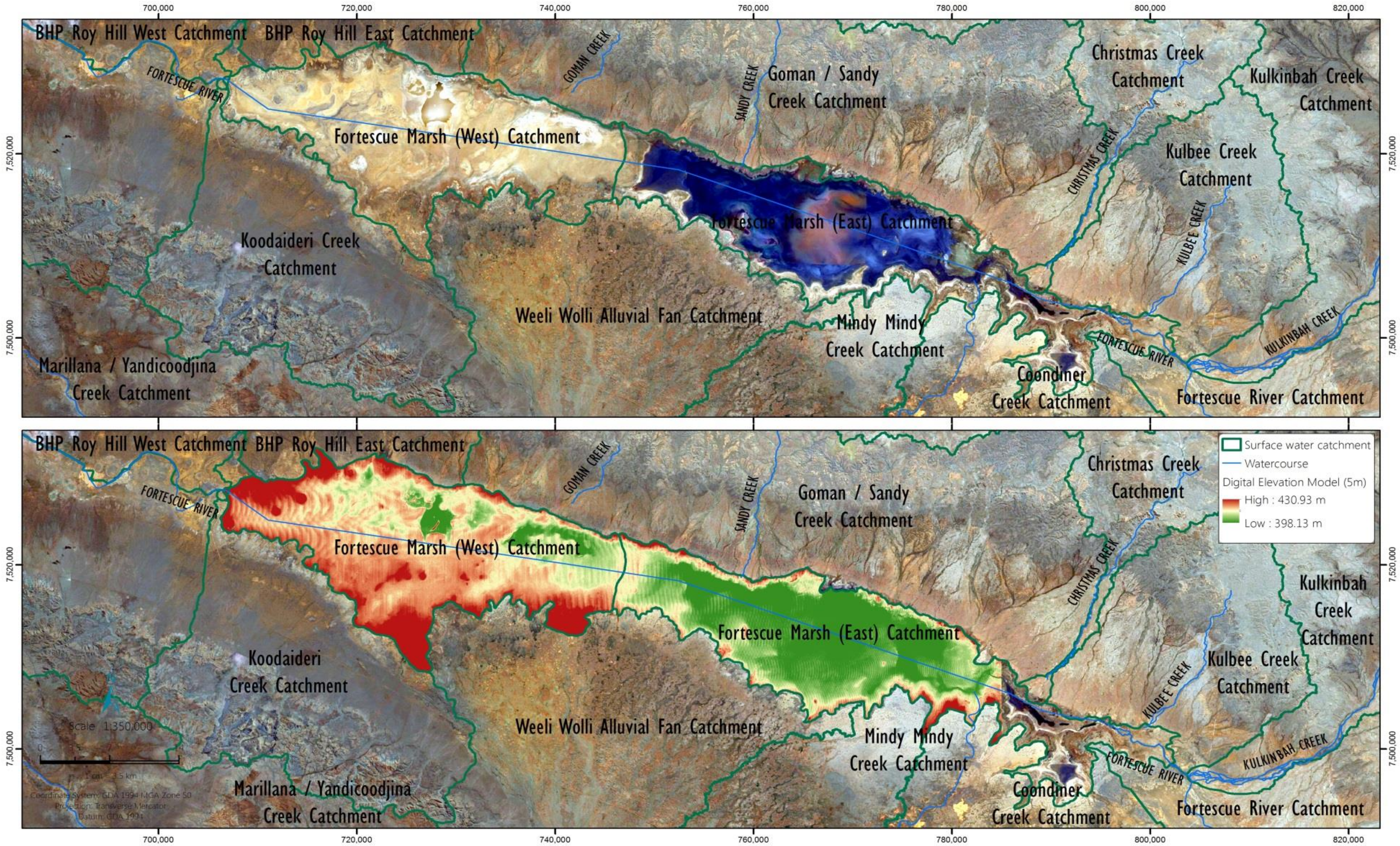


Figure 4-7: Fortescue Marsh internal catchment delineation as indicated by: inundulation of the west catchment only in early 2012 (Top) and by elevation differences between the east and west basins (Bottom)

4.2.5 Flood regime

Surface water expression is intermittent across the majority of the Marsh. Flooding of the Marsh corresponds with episodic surface flow events.

Little data are available to quantify the flood regime of the Marsh. Flooding of the Marsh results from direct rainfall, runoff from the surrounding catchments and inflow from the Upper Fortescue River and Weeli Wolli Creek. Large surface water inflows to the Marsh are generally associated with large-scale cyclonic events in the summer months, with a mean recurrence interval of about five to seven years (DEC 2009).

Historical flooding patterns of the Marsh can be inferred from Landsat imagery. The combination of Landsat imagery and high resolution DEM information can be used to improve the estimates of flooding depths and extents. A baseline flooding history dataset has been generated by UWA PhD candidate Alex Rouillard based on a review of historic Landsat images, but is yet to be published. This data would be useful to validate outputs from the conceptual water balance model (Section 4.2.6), which suggested a maximum (simulated) flooding extent of just more than 50% of the total Marsh area, and occurred only once over a 27 year simulation period (further detail provided in Section 4.2.7).

Rainfall measured at the BOM Wittenoom rainfall gauge (BOM station number 5026) shows a largely drying cycle (Figure 4-8) for most of the period from 1950 to the mid 1990s. This period is followed by a wet period to the early 2000s, with clear indications of a drying period since 2001/02.

A conceptual depiction of the dynamics of flooding and drying scenarios observed in the Marsh over the past three decades is shown in Figure 4-8. During the drought period from 1980 to around 1993, surface water inflows to the Marsh were well below the longe term average, with low volumes of water captured in the Marsh resulting in the Marsh being dry for extended periods. The Marsh acts as a groundwater sink although the net groundwater contribution to the Marsh is minimal, owing to the removal of shallow groundwater by evapotranspiration.

A much wetter period followed between 1999 and 2002, with a number of cyclones resulting in high inflows into the Marsh and extended periods of ponding. This wetter phase facilitated groundwater recharge and rise of the watertable. The nature of groundwater flow during mounding events is still radial with respect to the Marsh basin, however the flow directions may be reversed (i.e. away from the Marsh) for short periods until the groundwater system re-equilibrates.

The current period (post 2002) has seen a reduction in rainfall and runoff into the Marsh. The reduction in inflows and ponding events has contributed to a general drying trend compared to the 1999 to 2002 wet period.

Outputs from the Marsh conceptual water balance model (Figure 4.13 and Figure 4.14) support the contention that the Marsh experiences long term (interannual to decadal) drying and wetting cycles in response to climatic conditions.

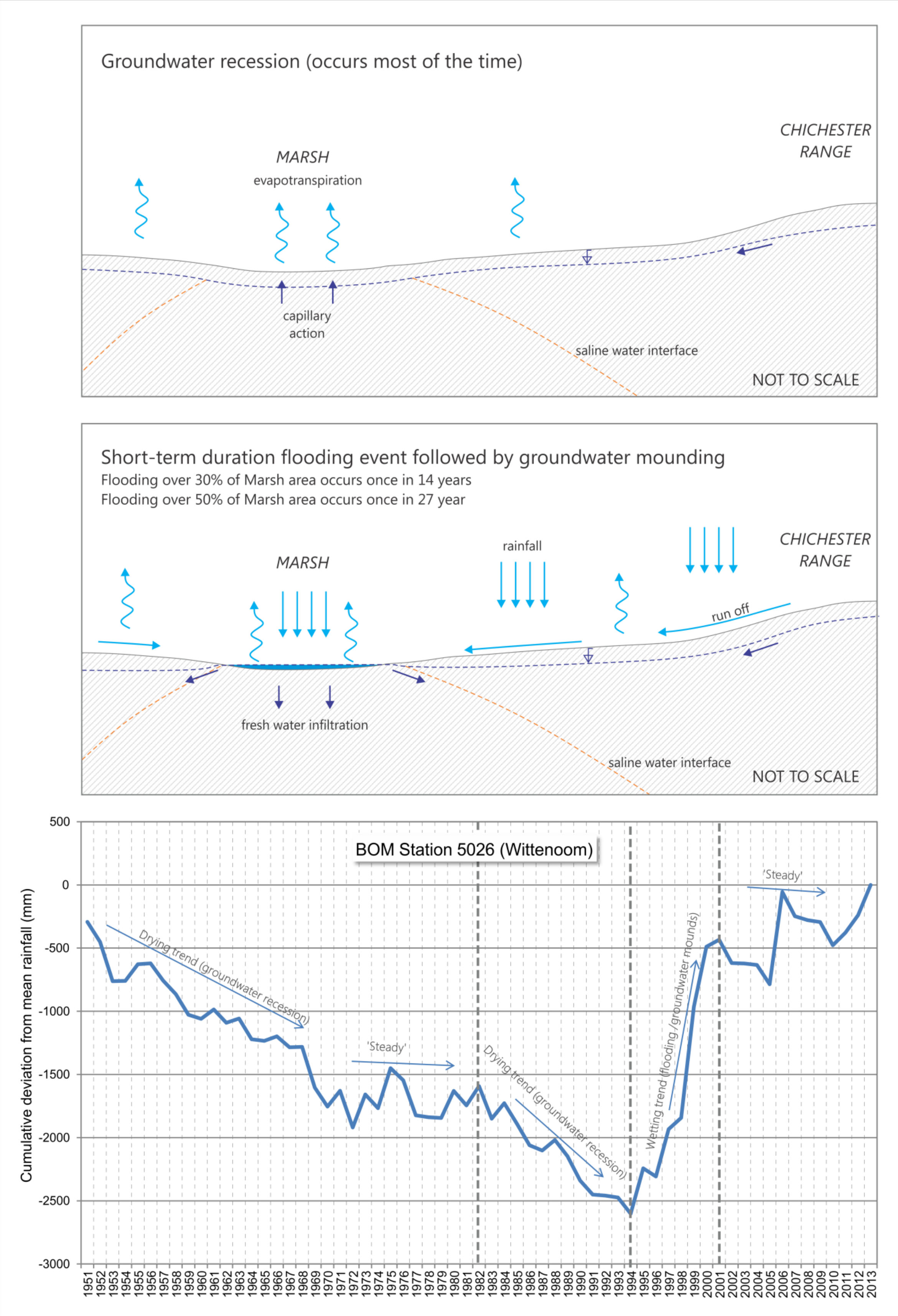


Figure 4-8: Conceptual flooding and drying dynamics of the Fortescue Marsh groundwater with rainfall cumulative deviation plot (BOM Wittenoom gauge)

4.2.6 Hydrogeological setting

As detailed in Section 2, the Fortescue Valley is underlain by a flat-lying, complex sequence of Quaternary and Tertiary alluvial, colluvial and lacustrine sediments. The saturated thickness of sediments beneath the Marsh which overlie sedimentary rocks of the Wittenoom Formation is on average 40 m (can be deeper, up to 70 m bgl, at places).

Hydrostratigraphy

The Marsh's aquifer system (Figure 4-9) is associated with the following general hydrostratigraphic sequence:

- Alluvial and colluvial deposits, consisting mainly of fine grained material but with occasional courser grained components such as those associated with outwash fans. The permeability of the alluvium is reported to be in the order of 0.1 to 1 m/day, with coarser material exhibiting higher permeability (FMG 2005a). The alluvium is the product of complex formation processes and is likely to be highly variable physically and with respect to its hydraulic properties. In places the Marsh bed includes shallow hardpans with very low permeability.
- Tertiary Detritals (TD3 unit). A mix of complex lacustrine deposits, with textural variations from sandy silt to a silty clay, generally texturally finest at the Marsh, with very low permeability (less than 0.1 to 0.01 m/day), effectively an aquitard. Pisolitic gravel may be present in places at the base of the TD3 unit forming localised aquifers.
- Calcrete layers associated with ancient watertable levels. Although referred to as calcrete this unit may contain significant silcrete and ferricrete horizons as the new drilling work undertaken in 2013 and 2014 by UWA shows that this unit underwent further significant silicification or iron enrichment at places. In the Mount Lewin area, the hydraulic conductivity of the calcrete unit has been determined to be in the range of 3 m/day to 20 m/day, with an average of approximately 10 m/day (Aquaterra, 2005c). The permeability of the calcrete in the area north of the Marsh is significantly higher, FMG (2010) reporting values over 100 m/day. There may be other calcretisation horizons within the Fortescue Valley, as it is not clear whether the calcrete outcrops to the south of the Fortescue Marsh belong to Oakover Formation. The recent UWA work confirms that in parts of the Marsh, particularly along the southern perimeter of the Marsh and further south of that perimeter, outcropping calcrete extends to a depth of approximately 16 to 25 m bgl. Calcrete is an important part of the regional aquifer under the Fortescue Marsh.
- Brecciated siliceous caprock has also been identified as a potential aquifer within the alluvial/colluvial deposits in the Fortescue Valley area (MWH 2009).
- On the northern flanks of the Marsh, the mineralised Marra Mamba Formation (a member of the Hamersley Group) dips and intersects the alluvium and Wittenoom Formation. The permeability of the Marra Mamba Formation is reported to be in the order of 3 m/day (Aquaterra 2005c).
- The Wittenoom Formation dolomite at depth under the Marsh. Weathered sections of the Wittenoom dolomite tend to have relatively high transmissivities (in the order of 20 m/day or more) due to the karstification (MWH 2009).

Beneath the Marsh the aquifer system hosts saline to hypersaline (in the order of TDS 10,000 to 75,000 mg/L) water and the deeper aquifers are saturated with hypersaline water (in the order of TDS 75,000 to 160,000 mg/L) (FMG 2005a; FMG 2009a). The hypersalinity is a consequence of the downward density-driven migration of salt due to the increased density of the solution.

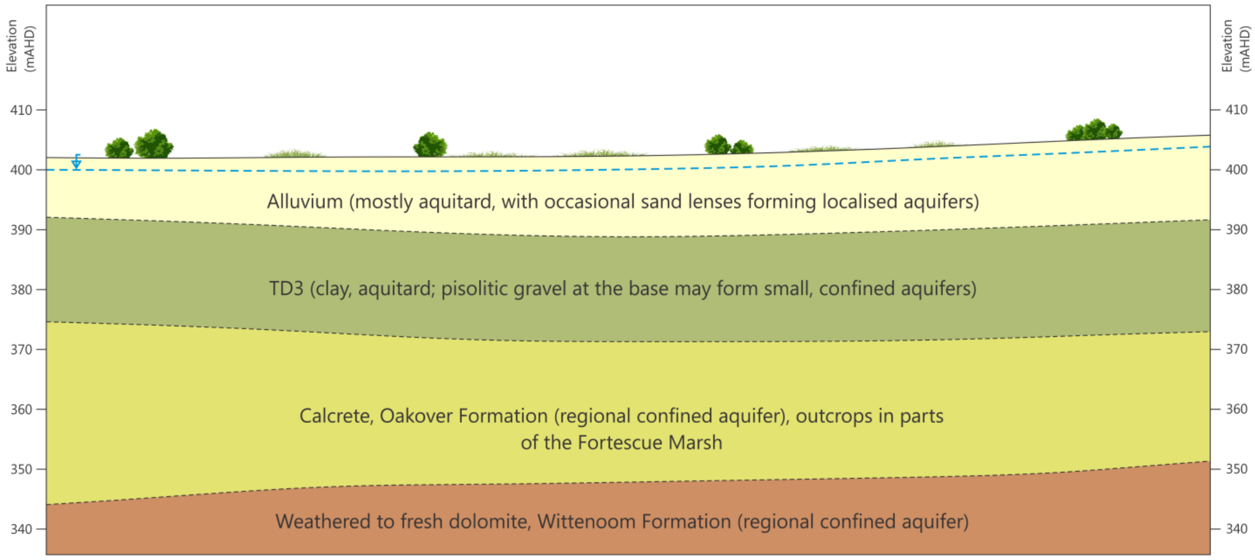


Figure 4-9: A typical hydrostratigraphical sequence under the Fortescue Marsh

Groundwater levels and flow

Soil moisture in the shallow alluvium of the Marsh is replenished by rainfall and surface inflows, and to a much lesser extent groundwater inflows. Shallow watertables are maintained by an interplay of flood recharge events, groundwater inflow and evapotranspiration. Net recharge is limited due to the low thickness of the unsaturated zone and competing effect of evapotranspiration.

There is limited bore data from areas in and around the Marsh in the public domain. The available information suggests that the shallow watertable beneath the Marsh is 2 m or more below ground level, consistent with the expected evapotranspiration extinction depth in the clayey Marsh sediments (Map 3-02 and 3-03). During flooding events, the depth to watertable may reduce locally but only for a relatively short time.

Groundwater recharge and discharge

The Marsh acts as a short-term recharge and long-term discharge area for the regional groundwater flow. The recharge events are limited to flooding occurrences in the Marsh. Connectivity pathways between ponded water in the Marsh and the underlying aquifer systems are considered to be complex and volume-limited. Recharge may be facilitated by preferred pathways or zones of higher permeability in what is otherwise a clay-formed or hardpan developed floor of the Marsh.

The Marsh is the terminal point of the regional groundwater flow within the study area. However, groundwater inflows are constrained by low hydraulic gradients (Dogramaci et al. 2012) and are a minor component of the overall Marsh water balance (refer to Section 4.2.7). Most of the groundwater flow originating from the surrounding Fortescue Valley is considered to be removed by evapotranspiration within and around the periphery of the Marsh (Figure 4-15) consistent with evapotranspiration extinction depth.

The unsaturated zone beneath the Marsh bed is assumed to be a few metres thick. Based on FMG (2010) observations the thickness of unsaturated zone in the Marsh is approximately 2 m. Approximately 50 to 100 GL of water is estimated to be temporarily stored in the previously unsaturated zone by filling up the unsaturated voids with seeping ponded water during a flood event.

The proportion of such a recharge input to the total volume presumably stored in the Tertiary Detrital (TD) aquifer system can be estimated by calculating the TD aquifer volume as follows: for an area of 1,500 km^2, average saturated thickness of 40 m and specific yield 0.05 the estimated groundwater storage is 3,000 GL.

Base on these calculations the proportion of flood recharge to water stored in the valley aquifer in the broad area of the Fortescue Marsh is in the order of 1.5% to 3%.

The rechare pulse originated from flooding events, which is considered to be the major groundwater recharge source for the Marsh, is of short duration (usually weeks) and low frequency (generally once in three to four years for the last 30 years). Preliminary analysis suggests that the frequency of flooding is higher in the eastern Marsh basin.

Water stored in the Marsh is removed through evapotranspiration and vertical seepage. Much of the groundwater recharge pulse to the aquifer underneath is assumed to be rapidly lost to evaporation following the flood dissipation. During the evapotranspiration process, the water salinity increases and as the flooded areas recede, salts precipitate on the Marsh surface. A proportion of the increasingly saline water is believed to seep, through a density-driven flow, to the base of Tertiary Detrital units and the underlying weathered basement (the Wittenoom Formation).

4.2.7 Fortescue Marsh water balance

An integrated landscape water balance was developed for the Marsh, taking into consideration the hydrological conceptualisation of the Marsh. The water balance is dominated by surface water inputs.

The water balance was undertaken for the period October 1985 to September 2012, coinciding with the Waterloo Bore flow record period (Weeli Wolli Creek external inflow). The water balance model includes the ten study area catchments. The surface water rainfall-runoff relationships, developed in Section 3.1.3 and shown in Figure 3-5, were used to generate runoff for ungauged sub-catchments and the Upper Fortescue River downstream of Ophthalmia Dam.

The relative EHU distribution in both the gauged catchments and study area catchments were taken into consideration to identify catchments of likely similar rainfall-runoff response. This comparison of EHU distributions was then used to inform the process of assigning the rainfall-runoff relationships from gauged catchments to ungauged catchments. It should be noted that rainfall-runoff relationships were applied on a catchment scale basis, hence assuming that all EHUs within a specific catchment will have the same runoff coefficient. While this may not be the case, this assumption was deemed appropriate for this concept level assessment.

Inflows to the study area from the external Weeli Wolli catchment were taken from the Waterloo Bore flow record. Likewise, flows for the Fortescue River (Newman) catchment upstream of Ophthalmia Dam were taken from recorded streamflow at Newman gauge.

The Flat Rocks rainfall-runoff relationship was applied to sub-catchments on the southern fringes of the Marsh as these sub-catchments display a similar EHU distribution to that of the Marillana Creek catchment. There is a similar distribution of upland source areas with low energy channels, longer flow distance than the catchments on the northern fringes of the Marsh and lowland sand plains and alluvial fans with high infiltration rates.

The Newman gauged catchment rainfall-runoff relationship was applied to the sub-catchments to the north of the Marsh as these catchments display an even distribution of upland source areas and lowland alluvial plains, similar to that of the Newman gauged catchment. Runoff from the upland source areas is directed to the lowlands via dendritic networks. By comparison with the catchments located on the southern fringes of the Marsh, flow distances from the upland to lowland areas on the northern fringes of the Marsh are shorter and the extent of alluvial plain areas is less. Comparatively higher rainfall-runoff response is therefore expected from these catchments. The rainfall-runoff curve was adjusted downwards (Figure 4-10) to be representative of median runoff response, recognising that the northern fringe catchments contain comparatively lower percentages of upland source areas, and hence flatter slopes, and larger lowland alluvial plains than the Fortescue River (Newman) catchment. The assumed runoff coefficient of 2% corresponds to the median annual runoff for Fortescue River at Newman (i.e. lower than the average annual runoff coefficient of 5.3%).

The Tarina rainfall-runoff relationship was applied to Fortescue River catchment between Ophthalmia Dam and the study area. This was done recognising that the physical catchment characteristics downstream of Fortescue River catchment Newman and Ophthalmia Dam changes to generally flatter slopes, dendritic flow networks, mostly low energy channels and alluvial fans.

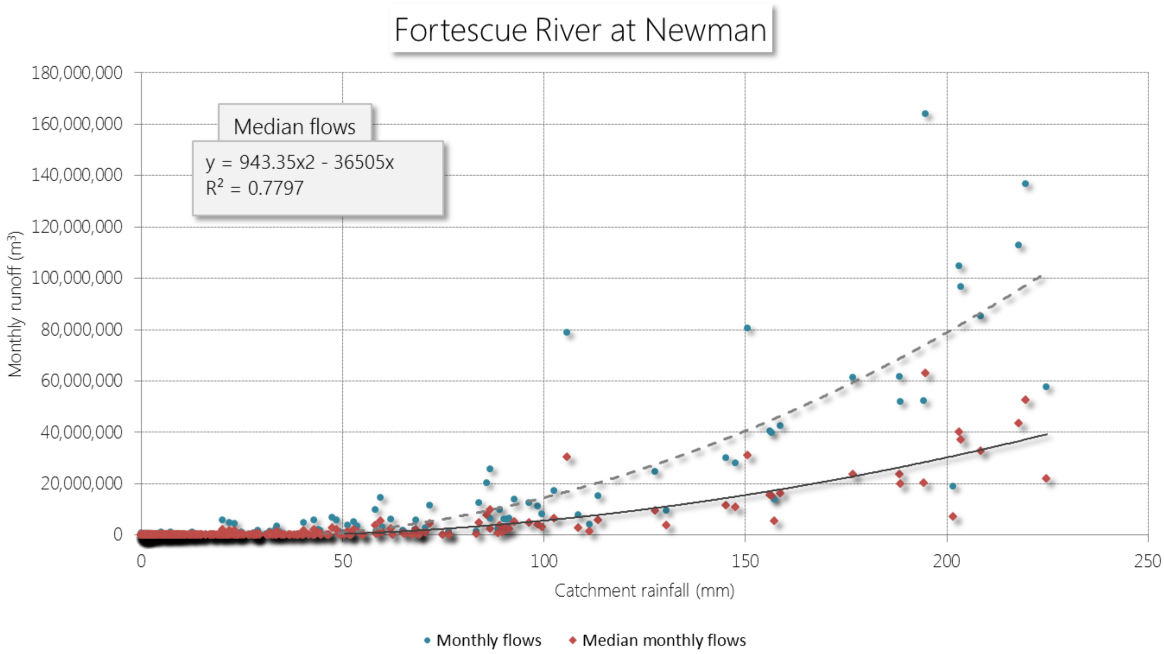


Figure 4-10: Newman catchment – rainfall versus runoff adjusted for application in Marsh northern fringing catchments

As discussed in Section 3.1.4, catchment rainfall-runoff response is event driven, with periods of high runoff followed by periods of little to no runoff. Runoff coefficients will therefore vary significantly from event to event. A single extreme event can skew the entire flow record, as shown to be the case for the Flat Rocks record. The rainfall-runoff relationships used to estimate surface runoff from the ungauged catchments are in the form of quadratic equations, i.e. not a constant runoff coefficient and are therefore deemed appropriate for application in the water balance.

In addition to assigning rainfall-runoff relationships to different study area catchments, different SILO rainfall gauges were used as rainfall inputs for the respective study area catchments. Differences in monthly rainfall between these gauges will therefore result in differences in simulated monthly runoff. This will result in the simulated rainfall-runoff response for study area catchments to be different to the gauged catchment runoff response.

Given the conceptual level approach and a lack of detailed soil and vegetation data for each of the study area catchments, infiltration, evaporation or evapotranspiration were not estimated in detail. The total volume of losses is that which is accounted for by the derived rainfall-runoff relationship.

In developing the model, the catchment runoff was directed to the east and west basins based on the 5 m DEM and aerial photography (Figure 4-7) as follows:

- The Goman-Sandy catchment runoff was split 2/3 and 1/3 east-west, respectively; and
- Weeli Wolli catchment runoff was assumed to flow into the west basin.

A stage-storage-area relationship was developed for the Marsh based on the 5 m DEM. From this relationship, the total storage volume of the Marsh is estimated at 8,000 GL, based on the assumption that the spill level of the Marsh would be approximately 412 m AHD. Simulated inflows, water levels, volumes and corresponding inundation (surface) areas from the integrated landscape water balance are shown in Figures 4-11 to 4-14, respectively.

As there is no historical water level data available for the Marsh, the simulated levels have been validated against water levels digitised from aerial photos of Marsh ponding events within the period September 1999 to March 2005 (FMG, 2010) (Figure 4-12). It should be noted that the levels interpreted from aerial photographs are single data points, i.e. representative of water levels in the Marsh for a specific day. While there is a relatively poor relationship between these interpreted levels and those simulated from the water balance model, the comparison suggests that the water balance model provides a reasonable representation of the Marsh flooding and drying regimes in the absence of additional data. Numerical models would be required to improve the overall water balance.

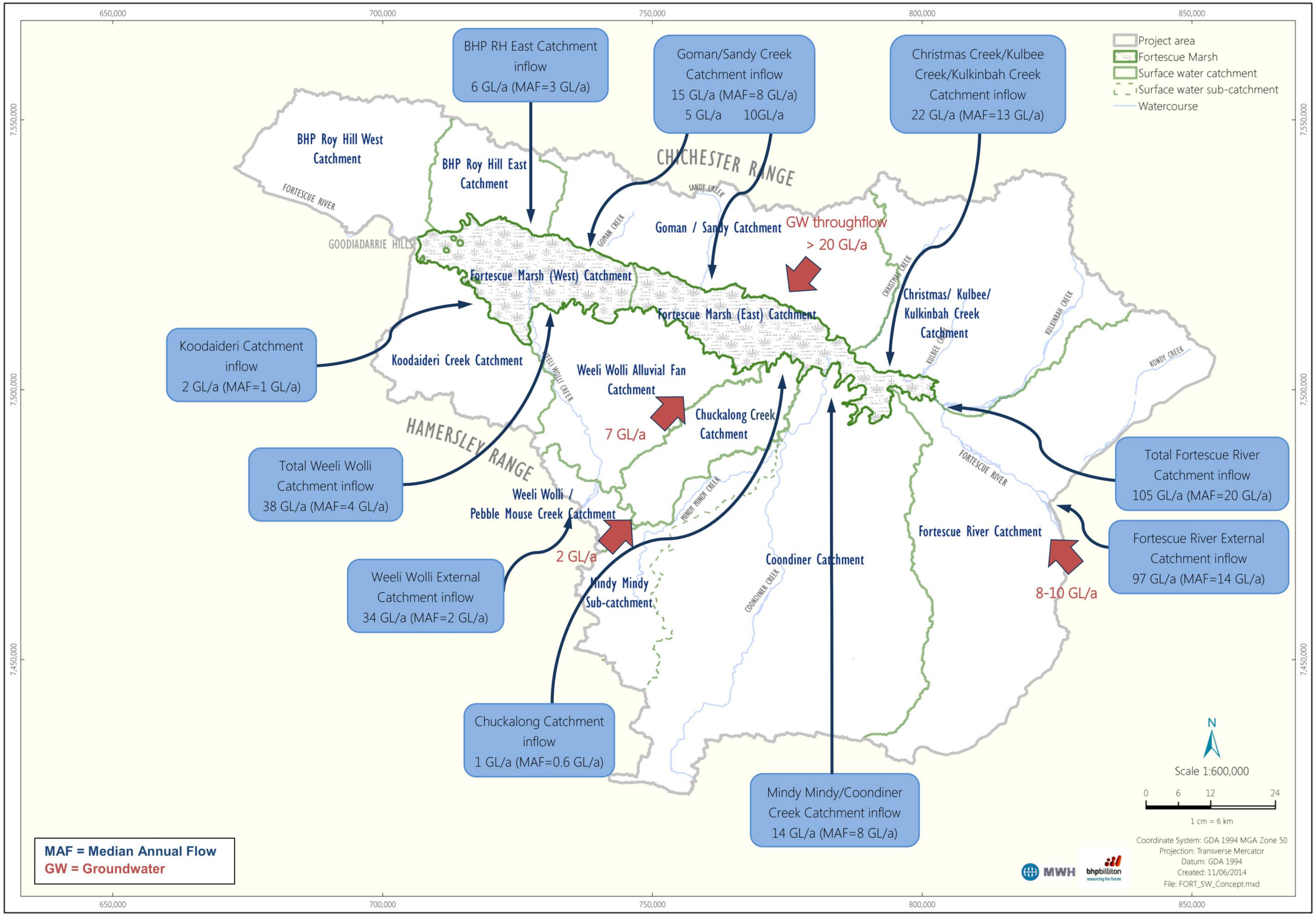


Figure 4-11: Mean annual inflows to the Fortescue Marsh from surrounding catchments and estimates of the regional groundwater throughflow

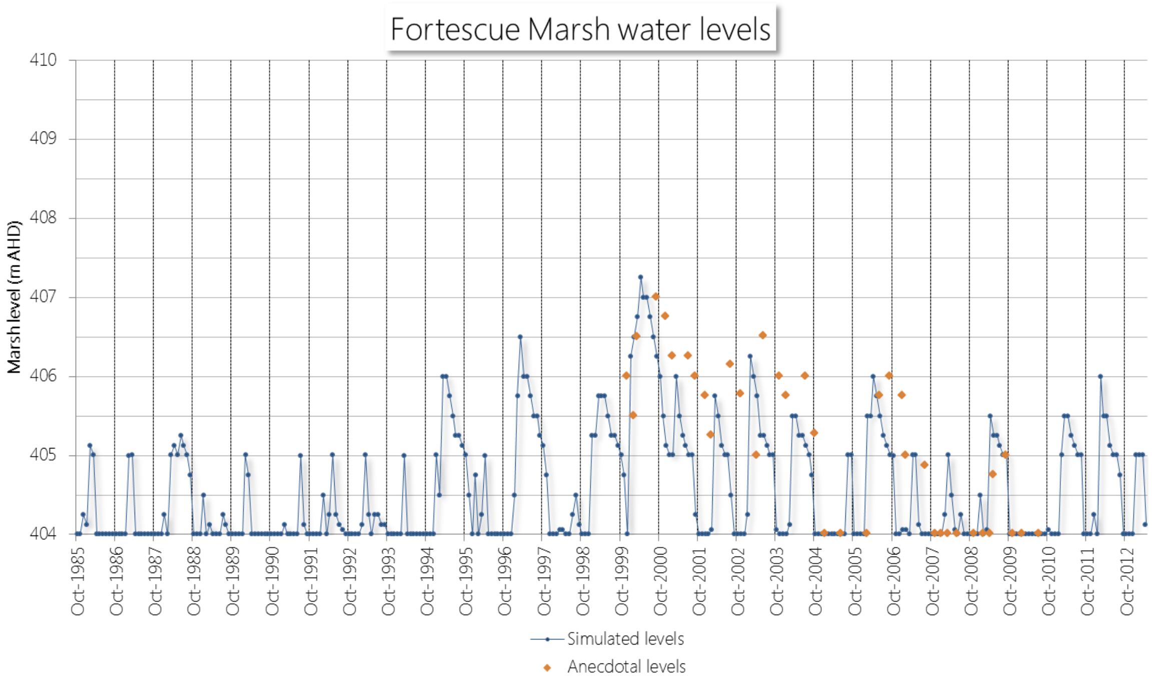


Figure 4-12: Fortescue Marsh simulated water levels, in comparison with anecdotal flood levels from aerial photos

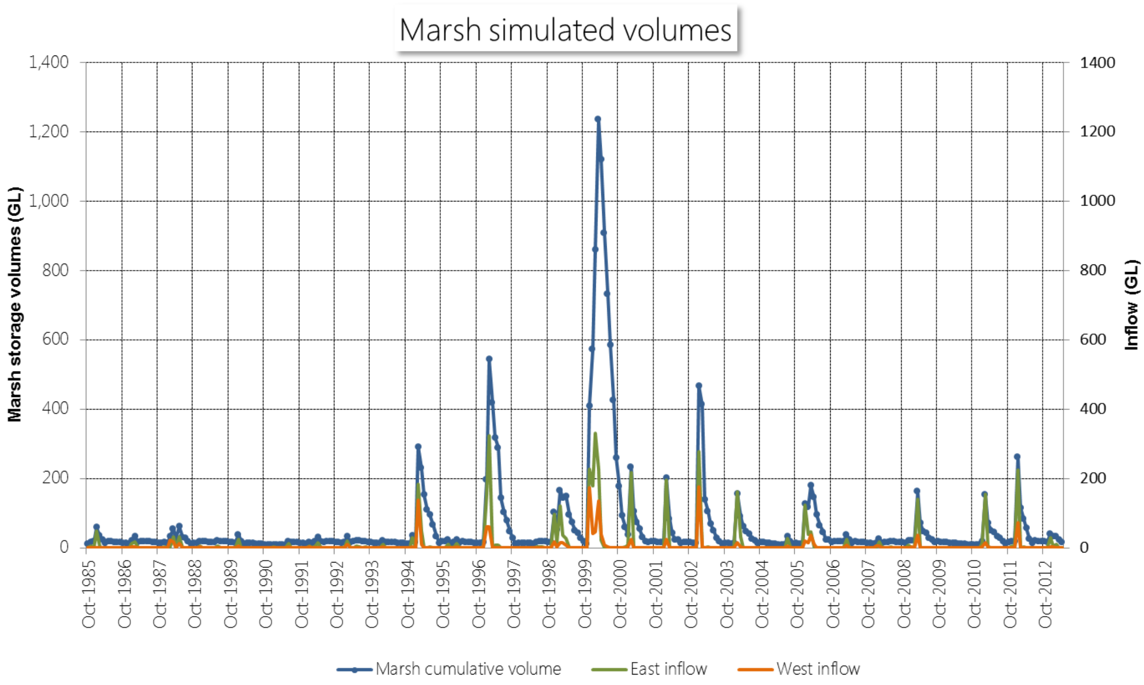


Figure 4-13: Fortescue Marsh simulated volumes, with inflows to the east and west basins

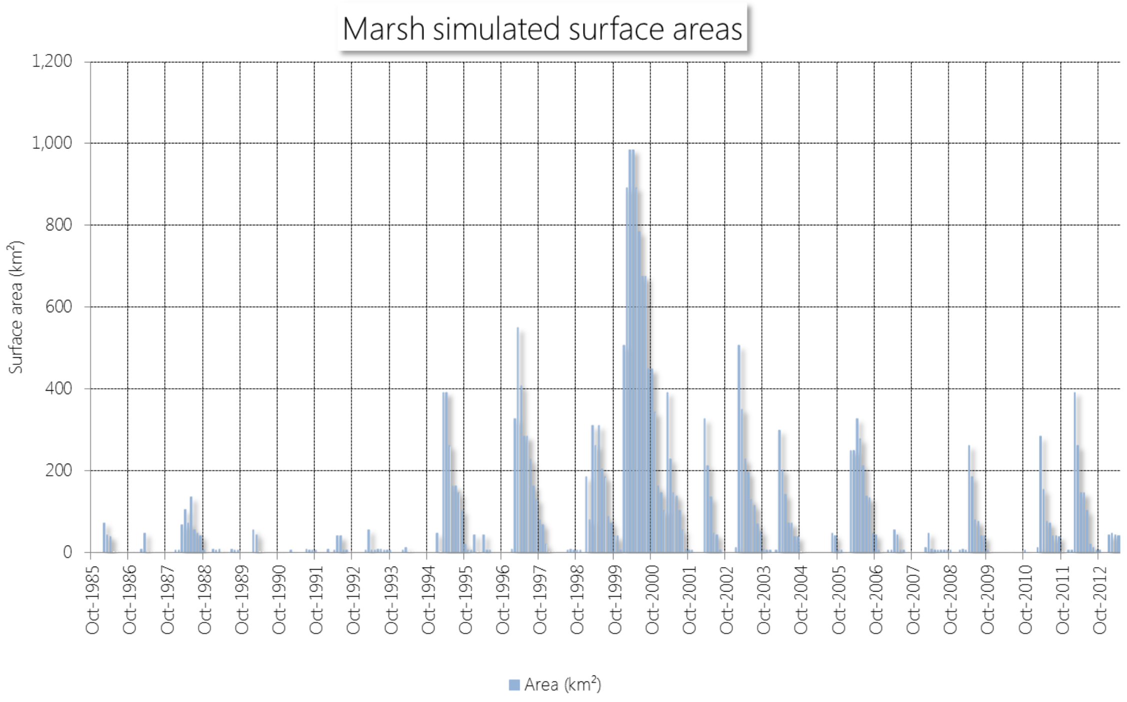


Figure 4-14: Fortescue Marsh simulated surface areas in response to simulated inflows

Results of the water balance model are presented in Table 4-3 with key findings summarised as follows:

- Modelled water levels ranged between zero (i.e. no water in the Marsh) to 407.25 m AHD.
- Based on a comparison between Landsat and surface topographic data between September 1999 and March 2005, water levels in the Marsh peaked at around 407 m AHD. The simulated water levels show reasonable correlation with the anecdotal water levels, and are consistent with the boundary of samphire fringing vegetation around the Marsh.
- A peak water level of 407.25 m AHD is equivalent to an inundation area of approximately 985 km², or 54% of the Marsh surface area.
- Maximum modelled Marsh water volumes range up to 1,236 GL, or 15% of the Marsh storage capacity.
- Spillover from the Marsh into the Lower Fortescue River catchment beyond the Goodiadarrie Hills would require Marsh flood elevations in excess of 412 m AHD; which has not occurred in recent history.
- Inflows from the Fortescue River and Weeli Wolli Creek contribute on average 52% and 19% of inflows, respectively. The remainder of inflows are from the study area sub-catchments.
- The event driven nature of streamflow is illustrated in the Marsh simulated inflows, with a limited number of runoff events driving the Marsh water balance. This is further demonstrated by:
    - the February 1997 simulated flows, where the Fortescue River and Weeli Wolli Creek contributed 78% and 14% of inflows, respectively, and the other sub-catchments only 8%.
    - the single largest monthly inflow (January 2003), when Fortescue River and Weeli Wolli Creek contributed 48% and 34%, respectively of inflows, and the other sub-catchments 18%.
- The hydrological information is useful to provide a broad understanding of the system and hydrological process, however, the variable nature of the hydrology, potentially skewed by single large events, limits the depth and extent of quantitative analysis that can be undertaken.

Table 4-3: Fortescue Marsh annual average water balance

Component	Unit	Value
Surface area • Internal study area catchments • Fortescue Marsh surface area	km²	10,313 1,818
Rainfall: • Internal study area catchments • Fortescue Marsh	GL	3,890 644
Runoff: • Internal study areas catchments • External inflow	GL	72 131
Evaporation and infiltration losses	GL	812
Groundwater throughflow to Marsh (Presumed lost to ET at the Marsh)	GL	6 to 7 (south) 21 (north)

Outputs from the conceptual water balance model for the Marsh were used to provide indicative flooding frequencies of the Marsh. The maximum simulated flooding extent was just more than 50% of the total Marsh area, and occurred only once over a 27 year simulation period (Table 4-4).

Table 4-4: Marsh indicative flooding frequency based on the conceptual water balance model

Variable	Observed/modelled range
Mean flooding frequency (20% Marsh area)	1 in 5 years
Mean flooding frequency (30% Marsh area)	1 in 14 years
Mean flooding frequency (50% Marsh area)	1 in 27 years
Maximum flooding extent (km²)	985 (April 2000)
Mean annual maximum flooding extent (km²)	210

4.2.8 Ecohydrological conceptualisation

The key features of the ecohydrological conceptualisation of the Marsh (Figure 4-15) are summarised as follows:

Surface and groundwater systems

- Inflows to the Marsh are dominated by the Fortescue River and Weeli Wolli Creek, contributing around 52% and 19% of mean annual inflows respectively. The catchment areas for these major drainages extend outside the study area. The remainder (29%) of inflows are from the catchments reporting directly to the Marsh.
- Flooding is generally associated with cyclonic rainfall and runoff in the summer months, with large-scale inundation events estimated to occur on average once every five to seven years. Inundation of east and west basins may be different for smaller events; however, large-scale inundation generally occurs across both east and west basins.
- Ponding in the Marsh is facilitated by the presence of relatively low permeability clay and silcrete/calcrete hardpans in the surficial sediments of the Marsh. More permeable material in the ponding surface is assumed to occur in some areas of the Marsh facilitating the seepage of flood waters into the sub-surface. It is postulated that most of the groundwater recharge within the

Marsh occurs in these zones of increased (vertical) permeability; however on-ground investigations are necessary to confirm this.

- A shallow, unconfined aquifer is situated in the top part of of the Marsh's surficial sediments. Groundwater levels range between 2 and 4 m bgl consistent with expected evapotranspiration extinction depth. The shallow watertable is maintained by a combination of flooding events, groundwater inflow, leakage from deeper confined units and evapotranspiration. Soil moisture in the shallow, generally unsaturated alluvium of the Marsh is replenished by rainfall and surface water and groundwater inflows. During flooding events, the depth to watertable may reduce locally but only for relatively short time.
- Calcrete of the Oakover Formation forms the regional-scale aquifer characterised by high permeability and storage. It is in direct hydraulic connection with the underlying weathered dolomite aquifer hosted in the Wittenoom Formation. Upward leakage through the aquitard units in Tertiary Detritals in the Marsh area - before evaporation from the shallow zone beneath the Marsh - is the main mechanism of the groundwater discharge from these units.
- The Fortescue Marsh is an internally draining surface water and groundwater basin. Groundwater level contours suggest radial groundwater flow to the Marsh from the margins of the Fortescue Valley. Groundwater gradients are flat within the Marsh suggesting low flows. Groundwater levels in the shallow alluvium within the Marsh are close to the surface, 2 to 5 m bgl (Map 3-02). Watertable rises during flood events are presumed to be 1 to 2 m, bringing watertable yet closer to the surface.
- Measurements of groundwater level dynamics during infrequent flooding of the Marsh are not available.
- The Marsh water balance is dominated by surface inputs (Figure 4-11). The major mechanism of groundwater recharge of the shallow aquifer is seepage of floodwaters. The upper end of recharge estimates to the shallow aquifer during the major cyclonic eevents is in the order of 50 to 100 GL per event, consistent with temporary refilling of 1 to 2 m of the unsaturated zone. Groundwater throughflow to the Marsh from the greater Fortescue Valley is minimal in the shallow unconfined aquifer due to assumed low hydraulic conductivity of the alluvium, and low hydraulic gradients. Groundwater mounding associated with flooding events may temporarily and locally reverse hydraulic gradients in and around the Marsh (i.e. directions away from the Marsh).
- Groundwater throughflow from the deeper confined aquifer (calcrete and weathered Wittenoom Formation) is estimated to be approximately 28 GL/yr. The throughflow discharges through upward leakage via TD3 unit in the Marsh area and is subsequently lost to soil evaporation and transpiration. The major shallow groundwater and surface water discharge mechanisms are direct evaporation of the post-flooding waterbody and exposed lake bed, soil evaporation from shallow watertable, and evapotranspiration from vegetated surfaces during interfloods.

Ecosystem components

- Much of the interior of the Marsh consists of sparsely vegetated clay flats within a series of low elevation flood basins. Vegetation recruitment may occur in these areas during dry phases; however, the frequency and depth of inundation events is a constraint to long term vegetation persistence.
- Fringing the lake bed areas are unique samphire vegetation communities including a number of rare flora taxa. Species zonation is evident and is considered to be a function of the combined stresses of seasonal drought, soil salinity, waterlogging and inundation. Structural complexity is provided by patches of *Muehlenbeckia florulenta, Muellerolimon salicorniaceum* and *Melaleuca glomerata*; the latter in particular may be important for providing roosting and nesting sites for waterbirds.
- Samphires exhibit conservative water use behaviour, and are probably reliant on pulses of fresh water associated with floods and stored soil moisture in the upper profile post-flooding. The flooding regime is likely to be a major factor influencing samphire recruitment and mortality.
- A number of fauna species with elevated conservation significance are present in areas fringing the Marsh including the Bilby (*Macrotis lagotis*), Northern Quoll (*Dasyurus hallucatus*), Mulgara

(*Dasycercus cristicauda*) and the Night Parrot (*Pezoporus occidentalis*). The Marsh habitat may contribute to the foraging range of these species.

- The Marsh supports aquatic invertebrate assemblages of conservation interest, including species known only from the Marsh. Little is known of the ecological requirements of these taxa.
- The Marsh has not been sampled for stygofauna owing to a lack of bores located on the Marsh. However; subterranean fauna communities in areas adjacent to the Marsh are relatively poorly developed in comparison with other locations in the Pilbara.
- A number of persistent pools are associated with associated with drainage scours along the Fortescue River channel and other major channel inflows. These are probably sustained by storage in the surrounding alluvium following flood events. The pools could potentially function as refugia for some aquatic fauna species during interfloods.

Existing and potential stressors

- Existing mining projects proximal to the Marsh include the FMG Cloudbreak and Christmas Creek operations along the northern margins. To the east, the RHIO Roy Hill project is under development with various early preparation works now completed. Additional mining proposals south of the Marsh including FMG Nyidinghu and Brockman Mining Limited Marillana. BHP Billiton Iron Ore and Rio Tinto have existing and proposed mines in upper catchment areas of the Weeli Wolli Creek.

Key indicators

Based on the ecohydrological conceptualisation of the Marsh, the following key indicators for the preservation of the ecological values of the Marsh are proposed:

- Volumes of surface and groundwater inflows to the Marsh.
- Flooding frequency, duration and spatial extent.
- Depth to watertable.
- Samphire vegetation health.
- Aquatic invertebrate assemblages (species diversity and abundance).
- Waterbird species diversity and abundance.

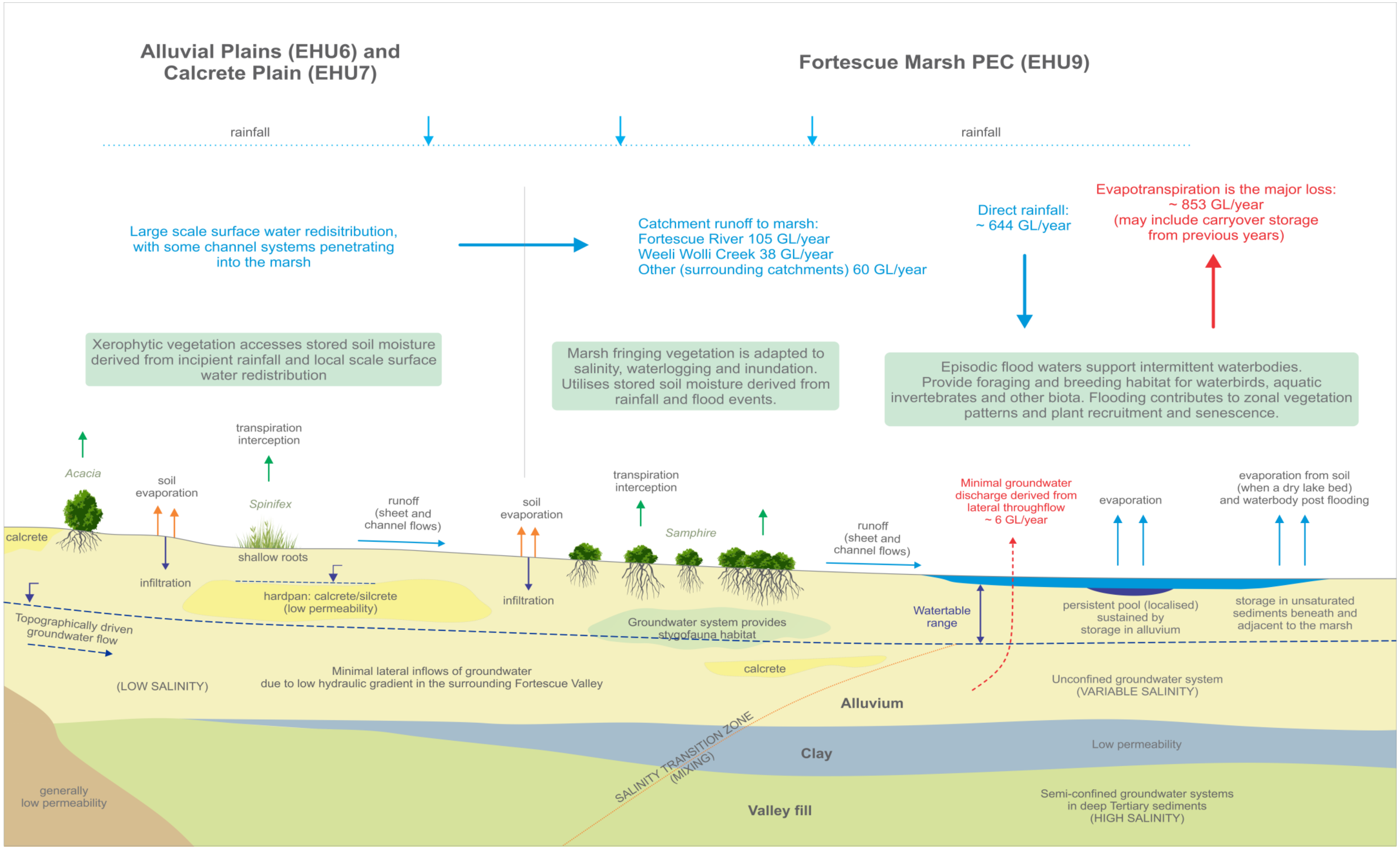


Figure 4-15: Ecohydrological conceptualisation of the Fortescue Marsh

4.3 Ecological receptor - Freshwater Claypans of the Fortescue Valley PEC (EHU 9)

This section of the report addresses the freshwater claypans of the Fortescue Valley PEC, including restating some information presented in earlier sections. Ecological information on the Freshwater Claypans is included in Sections 4.3.1 to 4.3.3, with hydrological and ecohydrological aspects presented in later sections.

4.3.1 Overview

The Freshwater Claypans of the Fortescue Valley is recognised as a Priority 1 Ecological Community (PEC) by the Department of Parks and Wildlife (DPaW) (DPaW, 2013). There are five occurrences of this PEC in the Fortescue Valley west of the Goodiadarrie Hills, with three in the study area summarised as follows (Map 4-02):

- East Claypan - located approximately 2 km west of the BHP Billiton Iron Ore railway line;
- Central Claypan - located 13 km west of the BHP Billiton Iron Ore railway line; and
- West Claypan - located approximately 4 km west of the Great Northern Highway.

All of these claypans are relatively small in size and are situated south of the BHP Billiton Iron Ore Roy Hill tenements (Map 4-02).

4.3.2 Previous work

There is little published information on the hydrology and ecology of the claypans constituting the freshwater claypans of the Fortescue Valley PEC. Between 2003 and 2006, Pinder et al. (2010) sampled water quality and aquatic invertebrates in the two PEC claypans west of the study area, as a component of the Pilbara Biological Survey (Table 4-5). A high diversity of aquatic invertebrates was observed, with major differences in assemblages between sampling dates (for each claypan respectively less than 15% of the total number of sampled taxa were collected on every sampling date).

Between 2004 and 2005, Halse et al. (2010) measured the depth to groundwater and sampled water quality in a station bore 2.5 km south west of the West Claypan (Table 4-6). The depth to groundwater was about 4 m and groundwater salinity around 4000 µs/cm EC.

4.3.3 Ecological description

The Freshwater Claypans of the Fortescue Valley PEC are important for waterbirds, invertebrates and some poorly collected plants (*Eriachne* spp, *Eragrostis* spp. grasslands) (DPaW, 2013). It is a unique community characterised by having relatively few Western Coolibah trees (*Eucalyptus victrix*) and expansive bare clay flats (Map 4-02).

The fringing Western Coolibah trees at the claypans, although at low density, may provide an important structural element for waterbird roosting and nesting. The flood regime may influence tree water use, through soil water replenishment and vegetation population dynamics (e.g. recruitment and senescence). 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 such wetland woodland communities requires sufficient recruitment/regeneration to compensate for adult tree mortality.

The ephemeral nature of the claypans is an important factor affecting aquatic invertebrate assemblages and use of the claypans by waterbirds. The high diversity of aquatic invertebrates may be related to high biotic diversity in riverine refugia, which promote high floodplain diversity following floods (Pinder et al., 2010). High turbidity may also be an important factor affecting the aquatic invertebrate species assemblages. Turbidity can limit macrophyte growth and affect algal production through light limitation, resulting in benthic primary productivity being largely restricted to the edge of the waterbody (Bunn et al., 2003; Fellows et al., 2007). Turbidity may assist some invertebrate species to more easily evade predation by waterbirds (Pinder et al., 2010).

The claypans and their surrounding catchments have been subjected to an extended period of pastoral land use, which is likely to have influenced catchment characteristics and vegetation communities.

Table 4-5: Data collected by Pinder et al. (2010) from freshwater claypans of the Fortescue Valley PEC located west of the study area

DPaW Site Code and Location	Units	PSW004 (652098E; 7549388N)			PSW005 (643987E; 7553451N)		
Sampling Date		24/05/2004	18/08/2003	30/08/2006	24/05/2004	18/08/2003	30/08/2006
Altitude	mASL	404	404	404	406	406	406
Turbidity	NTU	340	0.7	7	400	490	2.1
Total dissolved solids (TDS)	$mg.L^{-1}$	120	190	75	88	140	87
Maximum depth of invertebrate sample (Depth)	cm	62	35	60	104	70	150
Biomass of submerged macrophytes (SubMB)	$g.m^2$	0	87.1	4.5	0	0.8	17.4
% Cover of submerged macrophytes (SMC)	%	0	80	20	0	1	90
% Cover of emergent macrophytes (EMC)	%	0.5	0	0	2	0	0
pH	pH	8.1	9.33	9.21	7.72	8.09	9.13
Total filterable nitrogen (TFN)	$mg.L^{-1}$	0.84	1	0.43	0.39	1.7	0.57
Total filterable phosphorus (TFP)	$mg.L^{-1}$	0.03	0.01	0.02	0.02	0.21	0.02
Total chlorophyll (Chl)	$mg.L^{-1}$	0.0045	0.1495	0.002	0.0065	0.028	0.002
Water temperature (Temp)	ºC	24.7	25.6	23.9	28	22.5	24.4
Colour	TCU	37	13	15	37	17	11
Alkalinity	$mg.L^{-1}$	87	110	50	62	115	55
Hardness	$mg.L^{-1}$	23	25	20	22	359	19
Silica	$mg.L^{-1}$	11	15	3.1	7.8	11	7.9
Number of aquatic invertebrate taxa (diversity)		98	91	81	106	91	112

Table 4-6 Data collected by Halse et al. (2014) from a station bore located 2.5 km southwest of the West Claypan

Bore ID	Units	PSS284 Mulga1 (675434E; 7536782N; Altitude 411mASL)	
Sampling Date		23/06/2004	15/08/2005
Depth to water	m	3.8	4.25
Depth to bottom	m	5	5.85
Turbidity	NTU	22	0.7
Colour	TCU	2.5	2.5
TDS	mg/L	1.9	2.8
Alkalinity	mg/L	303	295
Hardness	mg/L	540	630
SiO_2	mg/L	71	94
Na	mg/L	614	692
Ca	mg/L	76.8	89.4
Mg	mg/L	83.8	99.8
K	mg/L	39	42.1
Mn	mg/L	0.0025	0.0005
Cl	mg/L	750	873
HCO_3	mg/L	369	360
CO_3	mg/L	1	1
NO_3	mg/L	5.8	9.1
SO_4	mg/L	485	577
Fe	mg/L	0.0025	0.0025
Sr	mg/L	0.55	0.67
EC	µS/cm	3757	4415
Field pH		6.81	6.79
TN	mg/L	6300	13000
TP	mg/L	30	5
Temp	°C	24.9	27.27
DO	%	41.1	61.9
DO	mg/L	3.1	4.9
Redox	mV	406	504

4.3.4 Surface water

The three freshwater claypans (East, Central and West) are located within the BHP Billiton Iron Ore Roy Hill West catchment (Map 4-02). This catchment occupies 725 km² of the Goodiadarrie Swamp catchment, which has a total area 4,138 km² (Map 3-01). Each claypan is associated with a discrete catchment area.

The catchment rainfall-runoff response and distribution of EHUs within the BHP Billiton Iron Ore Roy Hill West catchment are considered to be similar to those of the catchments located on the northern fringes of the Marsh. There is an even distribution of upland areas (EHU 1) and alluvial plains (EHU 6) in the catchment (Map 4-01, Map 4.02, and Figure 4-16).

Runoff from the eastern and central Claypan catchments flow directly into the East and Central claypans respectively; while the Western Claypan is located within a small localised catchment. Assessment of the 5m DEM levels suggests that runoff from the upstream surface water sub-catchments of the BHP Billiton Iron Ore Roy Hill West catchment will flow directly into the Fortescue River and do not contribute any surface water inflow to this claypan.

Based on similarities of catchment characteristics and EHU distributions in the Newman and Claypan catchments, the Newman catchment rainfall-runoff relationships, as discussed in Section 3.1.3, and adjusted for shorter flow distances and differences in alluvial plain areas (Section 4.2.6), have been applied to the claypan catchments to simulate runoff from these catchments. Similar to the Fortescue Marsh catchments, flooding is generally associated with cyclonic rainfall and runoff in the summer months. As shown in Figure 4-16, runoff into the claypans is estimated to be about 3% of annual rainfall, with significant catchment losses (infiltration, evaporation and evapotranspiration). The assumed runoff coefficient of around 3% corresponds to the median annual runoff for Fortescue River at Newman (i.e. lower than the average annual runoff coefficient of 5.3%).

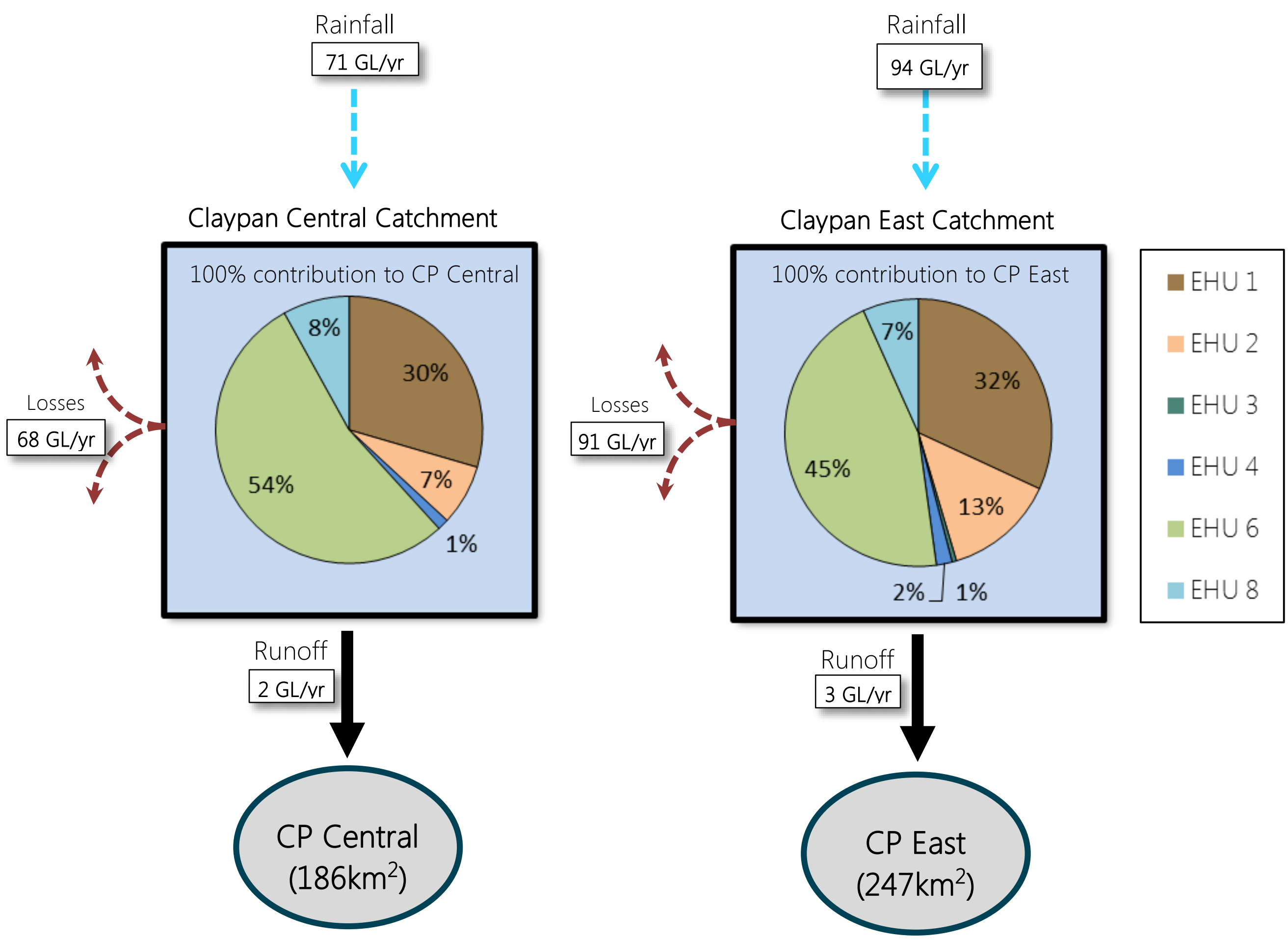


Figure 4-16: Conceptual water balance for the East and Central Claypans

4.3.5 Groundwater

The claypans are underlain by shallow alluvium and Tertiary Detritals, in a sequence presumed similar to the Fortescue Valley. The depth to watertable beneath the claypans is unknown, but considered likely to be in the range of two to four metres below ground level. The level of connectivity of the groundwater system with the surface environment is unknown.

The position of the watertable is maintained by the balance of groundwater inflow from the Chichester Range and evapotranspiration. Monitoring instrumentation needs to be installed to provide an understanding of the role groundwater has, if any, in the hydrological regime of the claypans.

4.3.6 Ecohydrological conceptualisation

The key features of the ecohydrological conceptualisation of the Freshwater Claypans of the Fortescue Valley PEC are depicted in Figure 4-17 and summarised as follows:

Surface and groundwater systems

- Surface water runoff from the surrounding catchments is attenuated in the internally draining low-relief landscape of the claypans. The estimated flooding frequency may be similar to the Fortescue Marsh and could range between 1 in 5 years to 1 in 27 years based on the hydrological analysis for the Marsh (Section 4.2). No information is available on flood levels/regimes that would be required to support the claypan ecosystems.
- Soil moisture in the shallow sediments of the claypans is replenished by a combination of rainfall and surface inflows.
- The ephemeral waterbodies of the claypans rapidly evaporate post flooding.
- Large floods exceed the storage volume of the claypans, and via flushing prevent significant accumulation of salts (in contrast with the Fortescue Marsh environment).
- Groundwater levels may range between 2 and 4 m bgl.
- Little is known of the hydrostratigraphy beneath the claypan surfaces. The claypans are assumed to be underlain by low permeability sediments, which may constitute a barrier to groundwater recharge and discharge. Further investigations are required to confirm this.

Ecosystem components

- The expansive bare clay flats are fringed with Western Coolibah and tussock grassland vegetation communities. The Western Coolibah trees may rely on stored soil moisture replenished by flooding to meet their water requirements.
- The claypans support diverse aquatic invertebrate assemblages during flood events. Waterbody ephemerality, turbidity and connectivity with the broader Fortescue River floodplain may be key factors affecting the species composition. These factors will vary interannually and between seasons.
- The claypans provide foraging habitat for waterbirds, and may also provide breeding habitat.

Existing and potential stressors

There are currently no mining activities in the catchments of the West, Central and East Claypans respectively.

Key Indicators

Based on the ecohydrological conceptualisation of the Freshwater Claypans of the Fortescue Valley PEC, the following key indicators for the preservation of the ecological values of the PEC are proposed:

1. Flooding frequency.
2. Depth to groundwater (unless shown to be disconnected from the surface environment).
3. Tree health (Western Coolibahs).
4. Aquatic invertebrate assemblages (species diversity and abundance).
5. Waterbird species diversity and abundance.

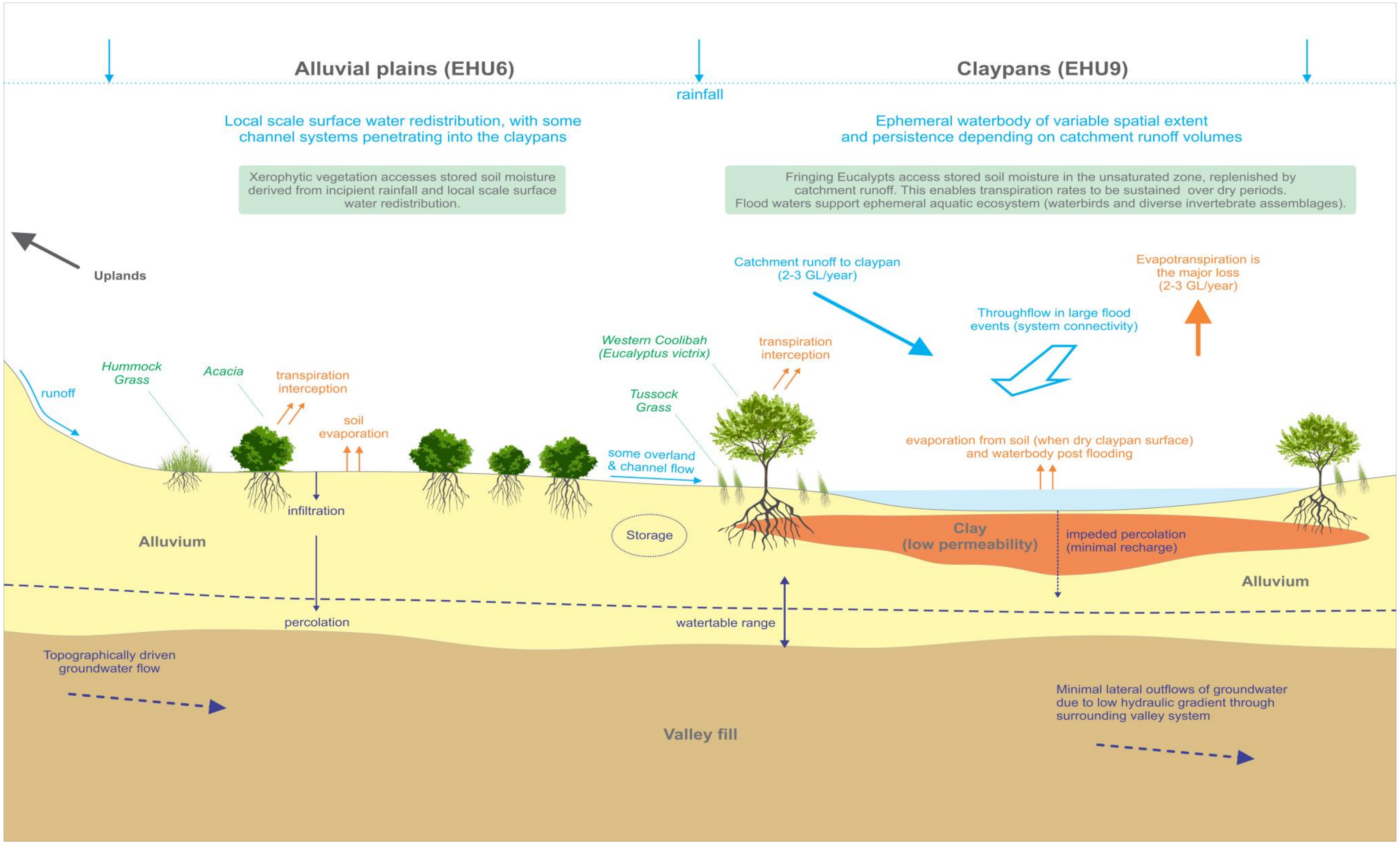


Figure 4-17: Ecohydrological conceptualisation of the Claypans

5 Stressors

5.1 Marillana

The BHP Billiton Iron Ore Marillana Iron Ore Project is approximately 100 km northwest of Newman and 16 km northeast of BHP Billiton Iron Ore's mining area at Yandi (Map 5-01), within the Upper Fortescue River Catchment along the northern edge of the Hamersley Range and southern side of the Fortescue River Valley. The project is approximately 9 km to the south of the closest part of the Fortescue Marsh.

The proposed project comprises fourteen open-cut pits (MA-A to MA-N), eight proposed OSAs (MA-1 to MA-8) and three proposed infrastructure areas (MI-1 to MI-3). The proposed study area plan also includes a conceptual railroad alignment (Map 5-01). The proposed footprint covers an area of 31 km^2 out of the total mining tenement M 270SA area of 115 km^2.

BHP Billiton Iron Ore have undertaken preliminary hydrogeological field investigations (RPS, 2012) enabling the development of a conceptual hydrogeological model. This has been incorporated into a numerical groundwater model that predicts groundwater response to dewatering scenarios related to a proposed mining plan and schedule (based on Preliminary_Mine_Sequence_hydrology.xlsx and 054 alignments.dxf).

No detailed surface water investigations have been undertaken to evaluate the potential impacts and influence of episodic flow events in the Weeli Wolli and Koodiaderi Creeks, as they discharge into the Fortescue River Valley and towards Fortescue Marsh.

Table 5-1 provides an overview of the Marillana orebody.

5.1.1 Conceptualisation

5.1.1.1 Surface water

The Weeli Wolli Creek is the main surface water feature that episodically flows through and adjacent to the south east corner of the tenement. The main creek channel flows in a north to north westerly direction terminating in the Fortescue Marsh.

At a regional scale, the Fortescue Marsh located to the north is the most significant surface water feature being an evaporative sink and regional termini for surface water catchments. There is no direct surface water flow from the Marillana deposit that reaches the Marsh.

5.1.1.2 Groundwater

The Marillana iron ore deposits consist of a combination of bedrock mineralisation within the Brockman Iron Formation members and localised overlying Tertiary detrital, scree, pisolite and CID deposits that occur along the northern flank of the Hamersley Range. An interpretive geological cross-section is presented in Figure 5-1.

The main bedrock aquifers are the mineralised orebodies within the Brockman Iron Formation (Dales Gorge Member, Whaleback Shale and Joffre Member), that have undergone preferential leaching resulting in enhanced secondary permeability within the ore zones and the associated partially mineralised halo zone. The unmineralised BIF and underlying shale units (Mt McRae Shale and Mount Sylvia Formation) have generally low permeability which restricts vertical and in some locations horizontal hydraulic connection.

To the north and outside the Marillana tenements, the Poonda Fault is concealed by the Tertiary sediments. This fault may contribute to hydraulic connection between orebody aquifers and the potentially highly weathered and cavernous dolomite of the Wittenoom Formation.

Aquifers within the Tertiary sedimentary sequence include localised, ephemerally saturated colluvium and detrital deposits generally marginal to the northern edge of the Hamersley Range (may be perched aquifers). Aquifers exist within the Weeli Wolli Creek alluvium, pisolites, gravels and CID deposits have highly variable extents and continuities. A broad scale calcrete aquifer, considered to be the Oakover Formation, is present within the Tertiary sediment sequence at or below the regional watertable extending from the south and outcropping near the edge of the Fortescue Marsh. These aquifers are expected to become increasingly confined with depth.

Groundwater flow is generally to the north towards the Fortescue Marsh, with water levels broadly mimicking topography. Depth to water potentially ranges from more than 150 m bgl at the top of Hamersley Range to about 20 m bgl in proximity to Weeli Wolli Creek.

The orebodies occurring at higher elevations in the Hamersley Range are likely to have limited or no hydrological connectivity with the detritals in the Fortescue Valley. Orebodies at lower elevations are likely to be at least partly connected with detritals in the Fortescue Valley.

Faults and dolerite dykes are known to propagate through the tenement and may act as conduits or barriers to groundwater flow. The Wittenoom Formation containing upper horizons of enhanced permeability may, in places, be in direct connection with orebody aquifers, notably where associated with the Poonda Fault.

Recharge contribution to the shallow aquifer from the Weeli Wolli Creek is expected to be small, given that median flows in the Weelli Wolli Creek within the Fortescue Valley are relatively small (2 to 4 GL/yr) and the depth to watertable is greater than 30 m bgl. High flows that occur infrequently have a greater potential to provide recharge to the underlying shallow aquifer.

Recharge from incidental rainfall, localised streamflow and sheetflow may occur along the foothills of the range into the detrital units (RPS, 2012).

Groundwater quality within the orebodies is generally fresh to brackish with salinity increasing slightly with depth. A significant regional saline-hydersaline groundwater body is known to exist to the north of the Marillana Project associated with the Fortescue Marsh, however its on impact on dewatering activities at Marillana is considered to be limited.

5.1.1.3 Generic mine type

Within the Marillana deposit, the majority of proposed pits comprising Brockman Iron Formation extend below the regional watertable, particularly those down dip and to the north of the Hamersley Range. These orebodies are typically overlain by saturated Tertiary sediments of detritals and CID. There is some uncertainty about the extent and degree of hydraulic connection between mineralised Brockman orebody aquifer and the Tertiary sequence and Wittenoom Formation to the north.

Most of the Marillana deposits occur along the valley margins (EHUs 3 and 4) and are of a “connected mine type” with at least one of the pit wall intersecting saturated detritals and / or geological structures resulting in potential hydraulic connection with the regional aquifer. Dewatering is likely to be high (10 to 20 ML/day) being strongly influenced by the potential strike length of the deposit and mining schedule. There is potential for drawdown propagation of connected mine types within the regional aquifer to extend for up to 15 km from the orebody (RPS, 2012).

Table 5-1: Marillana orebody overview

Orebody	MA-A	MA-B	MA-C	MA-D	MA-E	MA-F	MA-G	MA-H	MA-I	MA-J	MA-K	MA-L	MA-M	MA-N
Ore type	Detrital	Minor Detrital Brockman Iron Fm	Brockman Iron Fm	Detrital	Detrital Brockman Iron Fm	Detrital Brockman Iron Fm	Detrital	Brockman Iron Fm	Detrital Brockman Iron Fm	Detrital CID	Detrital	Detrital	Brockman Iron Fm	Detrital
Current status	Proposed mining. Exploration drilling and initial hydrogeological investigations (RPS 2012)													
Previous hydrological studies	RPS (2012) investigation and numerical groundwater modelling, supplemented by studies of other non-BHP Billiton Iron Ore projects in development nearby													
Ore below watertable (BWT)	90%	70%	30%	50%	40%	70%	50%	50%	50%	80%	50%	50%	70%	10%
Generic type	Detrital – partially connected. Low flows	Brockman connected. Mod flows	Brockman Potentially disconnected low flows	Detrital- partially connected. Low flows	Brockman connected Mod flows	Brockman connected Mod flows	Detrital- partially connected Low flows	Brockman connected Mod flows	Brockman connected Mod flows	Detrital- partially connected Low flows	Detrital- partially connected Low flows	Detrital partially connected Low flows	Brockman connected Mod flows	Detrital partially connected Low flows
Dewatering requirements (and basis)	Dewatering estimates of 2 to 16 GL/yr derived through numerical groundwater modelling (RPS, 2012) for the whole project (using a mining plan that slightly differs from the current design), but not per individual mining pit.													
Key dewatering drivers	Aquifer storage (dominant), lateral recharge, surface water runoff; Tertiary Detritals connection with some of the bedrock orebodies, such as MA-B, MA-E, MA-F and MA-I Hydraulic impact and influence of Poonda Fault along northern limit of deposits on groundwater flow from bedrock aquifers requires clarification – barrier or conduit?													
Interaction with Fortescue Marsh	Distance to Fortescue Marsh being19 to 23 km to north, except for MM-A which is 9 km away. Uncertainty of hydraulically connectivity with regional aquifer requires further investigation. Individual interception of surface water flow is minor (less than 0.1% of runoff).													

Important note: The contents of table 5.1 are conceptual only, of a general nature and do 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 this table.

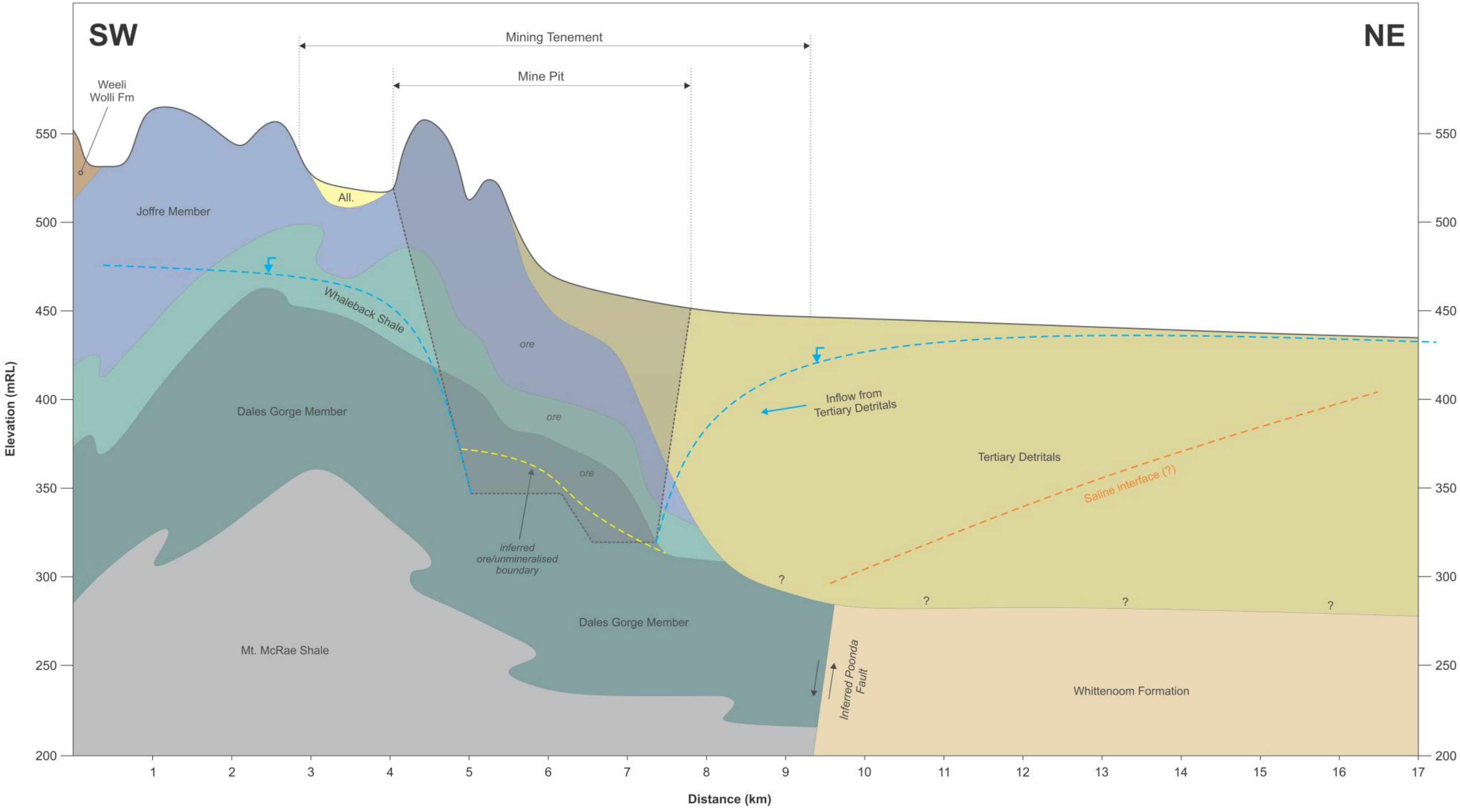


Figure 5-1: BHP Billiton Iron Ore Marillana orebody interpreted geological cross section A-A’

5.2 Mindy

The BHP Billiton Iron Ore Mindy Iron Ore Project is located approximately 60 km northwest of Newman and 30 km east of BHP Billiton Iron Ore's mining area at Yandi (Map 5-02). The Mindy deposits are in the Upper Fortescue River Catchment, along the northern flank of the Hamersley Range and corresponding with an eastern extension of the strike of the BHP Billiton Iron Ore Marillana deposit. FMG's Nyidinghu deposit is situated between the Mindy and Marillana deposits. The Mindy deposits are situated some 25 km southwest of the closest southern edge of the Fortescue Marsh.

The proposed project comprises three designated pits (MM-A to MM-C), nine associated waste rock dumps (OSA) (MM-1 to MM-9) and four infrastructure areas (MMI-1 to MMI-4) (Map 5-02). It also includes a conceptual railroad route connecting the proposed project to the BHP Billiton Iron Ore Newman to Port Hedland railroad to the north east.

The proposed Mindy project mine pits are located within mining tenements M 47/710 to 717 and M 47/725 to 728, and have a footprint of approximately 24 km^2 out of the total mineral tenement area of 65 km^2.

No hydrogeological investigations have been undertaken for the Mindy project to date.

Interpretations have been made using available drill data (GBIS) and information available in the public domain from similar types of deposits in nearby areas. As the BHP Billiton Iron Ore Marillana Deposit is located further along the strike of the Mindy deposits, many findings from that project including those detailed in RPS (2012) are directly relevant to the Mindy project.

No localised hydrological investigation has been carried out to date, to assess the potential influence or impact of episodic flow events associated with Mindy Mindy Creek, Weeli Wolli Creek, Chuckalong Creek and Coondiner Creek. Flows from these creeks are directed towards and potentially terminate in the Fortescue Marsh.

Table 5-2 provides an overview of the Mindy orebody.

5.2.1 Conceptualisation

5.2.1.1 Surface water

The Mindy proposed pits are between Weeli Wolli Creek catchment to the west and Mindy Mindy Creek catchment to the east, both draining to the north and terminating in the Fortescue Marsh.

The Weeli Wolli Creek is the main surface water feature that episodically flows adjacent to the western corner of the tenement, and potentially may impact pit MM-A. The main creek channel flows in a north-north westerly direction, terminating in the Fortescue Marsh.

The Mindy Mindy Creek catchment is relatively small and provides episodic flows between the eastern end of proposed pit MM-B and western edge of pit MM-C.

Potentially flowing through Pit MM-B is a small, ephemeral drainage system associated with the Chuckalong Creek catchment, which has the potential to affect the proposed mining operation.

5.2.1.2 Groundwater

The BHP Billiton Iron Ore Mindy deposits are hydrogeological similar to the nearby BHP Billiton Iron Ore Marillana deposits, with heterolithic Tertiary Detritals, comprised of CID, pisolites, chert, haematite and goethite overlying mineralised Brockman Iron Formation. Detritals abut the lower slopes of the Hamersley Range, and increase in thickness towards Fortescue Marsh. Interpreted geological cross-sections are presented in Figure 5-2 and Figure 5-3.

The mineralised Weeli Wolli and Brockman Iron Formations (Dales Gorge Member, Whaleback Shale and Joffre Member) form the main aquifers, with enhanced secondary porosity from fractures, ore-mineralisation, weathered horizons, joints and bedding planes.

The underlying Mt Sylvia Formation and Mt McRae shale form the main regional aquitards in the study area, along with the unmineralised sections of the Brockman Iron Formation which also serve to restrict permeability and act as an aquitard.

The Tertiary sedimentary sequence may contain a number of localised, potentially perched aquifers, located in colluvial and detrital deposits on the northern edge of the Hamersley Range. Additionally, aquifers are present in the Weeli Wolli alluvial sequence, comprised of pisolithic gravels and CID deposits, although the vertical and lateral extent of these aquifers is unknown.

Orebodies located in elevated areas of the Hamersley Range are unlikely to be hydraulically connected to the detritals in the Fortescue Valley. Orebodies in lower areas are likely to be at least partially connected with detritals in the Fortescue Valley.

The direction of groundwater flow is generally in a northeast direction, from the Hamersley Range ridgelines towards the Fortescue Marsh. The groundwater gradients are steep along the edge of the Hamersley Range, but flatten to the north towards the Fortescue Marsh. Depth to groundwater within the tenement area is significant and usually exceeds 20 m bgl.

Faults and dolerite dykes are known to propagate through the tenement. Permeability may increase where faults such as the Poonda Fault intersects the orebody aquifer. The Poonda Fault cuts across the northwest side Mindy Pit MM-B and may provide groundwater connectivity within the fractured or weathered dolomite of the Wittenoom Formation. However, the presence of faults and dolerite dykes may act as a barrier to groundwater flow and contribute to partial aquifer compartmentalisation.

Recharge to the groundwater system attributed to surface water is expected to be minimal given the depth to watertable. Episodic rainfall events generally result in sheet flow and localised flow through minor drainage channels reporting to the base of the Hamersley Range and into the detrital units (RPS, 2012). The groundwater throughflow through the Weelli Wolli alluvium was estimated at a about 2 GL/yr at the outlet from the Hamersley Range part of which is estimated to be captured by potential dewatering in the proposed MM-A pit.

Water quality data at the tenement is not available. Based on data from Nyidinghu and Marillana deposits, water quality is assumed to be fresher towards the Mindy Mindy Creek, becoming more saline away from the creek to the northwest.

Previous investigations at these sites indicate the presence of a regional saltwater interface to the north of the Mindy proposed pits. The saline groundwater mound is a result of surface water/groundwater interaction, evaporation processes, salt accumulation and density driven groundwater flow emulating from the Fortescue Marsh. It is unlikely that the saltwater interface will have a significant impact on dewatering operations at Mindy.

5.2.1.3 Generic mine type

All pits located within the Mindy project area will extend into the Brockman Iron Formation, and are estimated to extend well below the watertable.

All pits are expected to encounter some Tertiary sedimentary sequence overlying the Brockman Iron Formation units of varying depth, with the upper part of northern hanging wall likely to be made up of exposed Tertiary sediments.

Connectivity between the Tertiary Detritals and Wittenoom Formation, and the underlying Brockman Iron Formation, and what hydraulic role the Poonda Fault plays in this system is still ambiguous, as it depends largely on the aquifer extent and its characteristics.

All of the Mindy deposits are defined as being of the “connected” mine type, with some or all of the pits intersecting saturated horizons of Tertiary Detritals. Dewatering volumes are likely to be moderate to high, with an estimate of 10 to 20 ML/day dewatering required.

Based on analogy with Marillana deposit, there is potential for drawdown resulting from dewatering activities to extend up to 15 km to the north but not as far as the Fortescue Marsh.

Table 5-2: Mindy orebody overview

Orebody	MM-A	MM-B	MM-C
Ore type	Detritals Brockman Iron Formation	Brockman Iron Formation Detritals	Brockman Iron Formation Detritals
Current status	Proposed mining outline utilising SEA resource mining footprint Resource definition drilling only No actual design pit schedule and shell		
Previous hydrological studies	No hydrogeological investigation undertaken on resource area Hydrogeological investigations undertaken on adjacent project areas – FMG's Nyidinghu and BHP Billiton Iron Ore Marillana		
Ore below watertable (BWT)	50%	70%	40%
Generic type	Detritals/Brockman – connected Moderate flows	Detritals/Brockman – connected High flows	Detritals/Brockman – connected Moderate flows
Dewatering requirement basis	Likely to significant due to influence of the through flow associated with the Weeli Wolli Creek palaeochannel, estimated at over 3 to 8 GL/yr (analytical model)	Likely to be significant due to the size of the pit, up to 9 to 27 GL/yr (analytical model)	2 to 4 GL/yr (analytical model)
Interaction with Fortescue Marsh	Interaction with Fortescue Marsh negligible. Influence on and by Weeli Wolli Creek.	Interaction with Fortescue Marsh will be negligible; however the large footprint has local influence on surface runoff.	Interaction with Fortescue Marsh will be negligible. Influence on Mindy Mindy Creek is possible.

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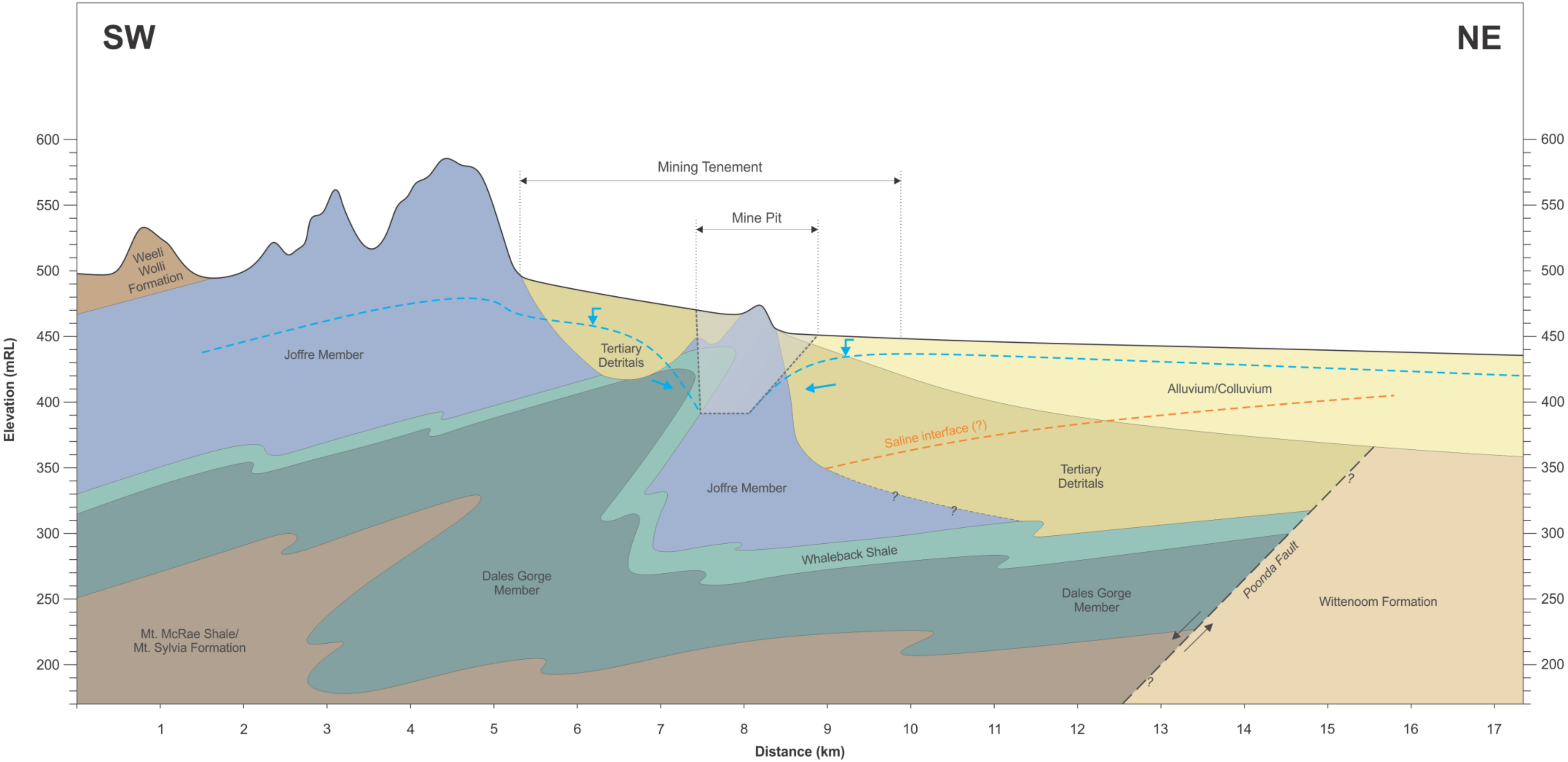

Figure 5-2: BHP Billiton Iron Ore Mindy orebody interpreted geological cross-section A-A'

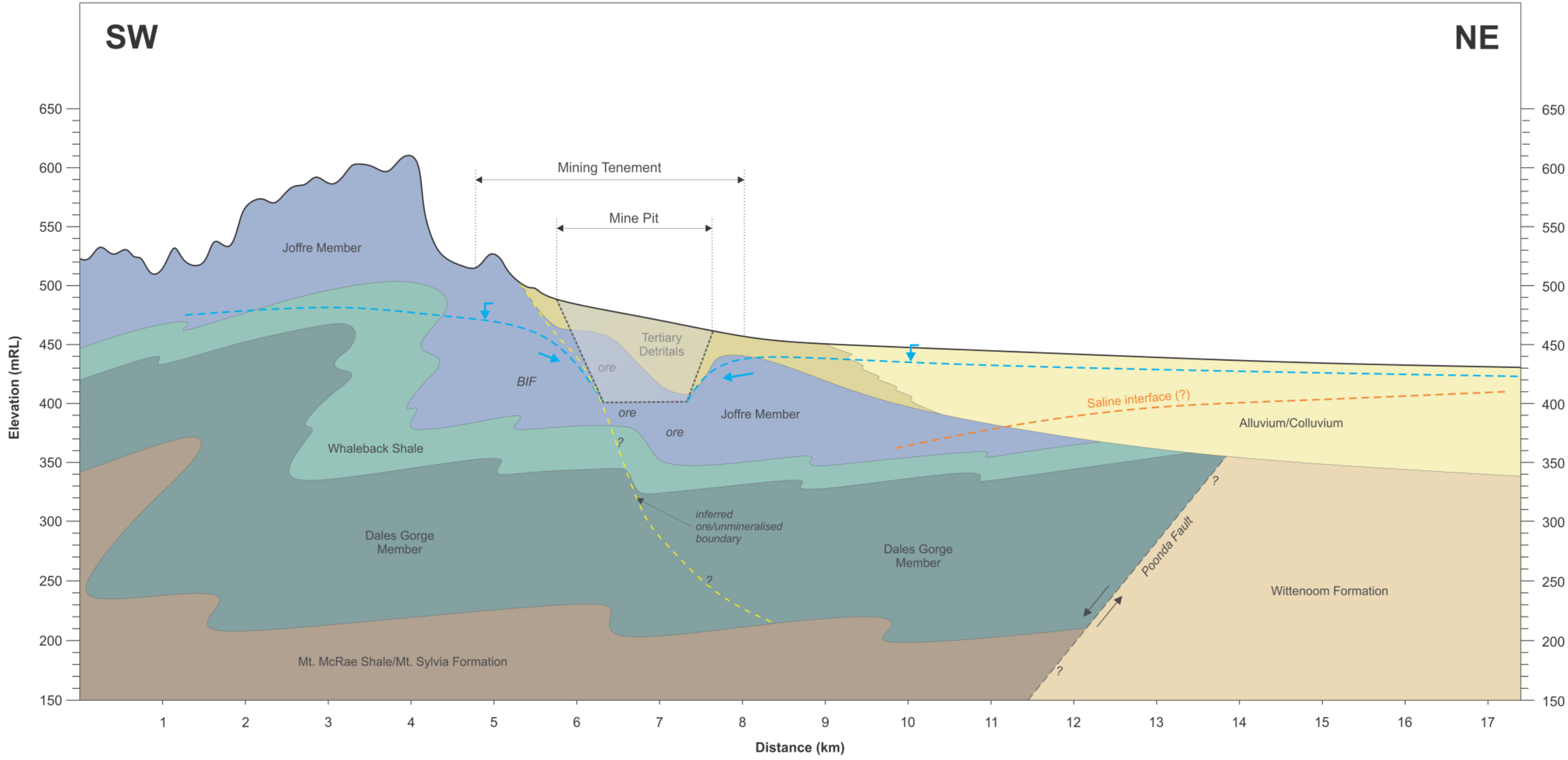

Figure 5-3: BHP Billiton Iron Ore Mindy orebody interpreted geological cross-section B-B'

5.3 Coondiner

The BHP Billiton Iron Ore Coondiner Iron Ore Project is located along the north-eastern flanks of the Hamersley Range and the southern side of the Fortescue River Valley within the Upper Fortescue River Catchment (Map 5-03). The proposed pits are approximately 50 km north of Newman and 40 km north of BHP Billiton Iron Ore's mining area at Mt Whaleback. The proposed mining area is located some 35 km south of the closest part of the Fortescue Marsh.

The Coondiner Project is located within the mining tenements M47/718 to 724 and M47/729 to 731 extending into the southern limits of the Fortescue Valley.

There are five proposed mining pits (CO-A to CO-E), six associated OSA's (CO-1 to CO-6) and five proposed infrastructure areas in the Coondiner area. In addition a proposed railroad route to the east of the tenement connects the Coondiner Project to the BHP Billiton Iron Ore Newman to Port Hedland Railroad. The footprint of the proposed pits covers an area of 11.6 km^2.

No hydrological and hydrogeological investigations of the Coondiner deposits have been undertaken to date.

A number of data sources were used to establish a conceptual interpretation for Coondiner, including resource definition drill data from GBIS, information from Strategic Environmental Assessment (SEA) Cumulative Impact Assessment Footprint, and exploration data from similar orebodies such as BHP Billiton Iron Ore's Marillana.

The Coondiner deposits are distant from other proposed mining projects including non-BHP Billiton Iron Ore projects.

Table 5-3 provides an overview of the Coondiner orebody.

5.3.1 Conceptualisation

5.3.1.1 Surface water

The entire Coondiner deposit lies within the Coondiner Creek Catchment. The Coondiner Creek dominates the hydrology of the area and runs through centre of the orebody area, ultimately discharging to the Fortescue Marsh approximately 35 km to the north.

Coondiner Creek is located along the alignment of a significant north eastern trending fault. Recharge via the creek bed alluviums into the fault zone is highly likely and may constitute a preferred flow path during recharge events. Further investigations are required to confirm this, though recharge is expected to be minimal given the depth to groundwater may be greater than 30 m bgl.

Episodic rainfall events, sheetflow and localised flow through minor drainage channels occur at the base of the Hamersley Range and into the detrital units (RPS, 2012). Fortescue Marsh is the end-point all local surface water flows, though only limited surface water contributions to the Marsh are expected from the Coondiner area.

5.3.1.2 Groundwater

The Coondiner deposits are hydrogeologically situated within Tertiary Detritals comprising CID, pisolites, chert, haematite and goethite overlying the Brockman Iron Formation. A location map of the area is presented in Map 5-03. A geological cross-section is presented in Figure 5-4, highlighting the key geological and structural relationships, proposed pit outlines, and inferred regional watertable in the Coondiner area.

The mineralised Joffre Member of the Brockman Iron Formation and Tertiary Detritals are considered to represent the main aquifer. The Brockman Iron Formation aquifer is formed through diagenetic processes resulting in significant secondary permeability in fracture zones and also areas with high mineralisation. The southern orebodies are mineralised zones within the Brockman and Boolgeeda Iron Formations in a synclinal structure. Theses mineralised zones are permeable and form local aquifers.

Additional regional aquifers are also present, including widespread interconnectivity of Tertiary Detritals from the toe of the escarpment of the Hamersley Range to the north as the southern part of the greater Fortescue Valley groundwater system. The Tertiary sequence deepens to the north. Localised aquifers of limited extent are also found within the sediments of the Tertiary sequence; including alluvium, calcrete, detritals and CID units. Weathered, cavernous Wittenoom Formation is also present, upthrust through the inferred extension of the Poonda Fault. Primary aquitards restricting permeability are unmineralised BIF units of the Brockman Iron Formation, Mt McRae Shale and Mt Sylvia Formation.

The Tertiary sedimentary sequence is underlain by the Wittenoom Formation, outcropping at the edge of Fortescue Marsh, which if weathered can contain cavities which may transmit and store significant quantities of water. The Mt Sylvia Formation is known to separate the Wittenoom Formation from mineralised sections of the Brockman Iron Formation functions in other parts of the Hamersely Range, and may similarly restrict permeability at some locations in the Coondiner area.

There is limited potential connectivity between the orebody aquifers and Tertiary Detritals, except were the mineralised orebodies intersect the Tertiary sediments below watertable. Pits located further north of the Hamersley Ranges have thicker Tertiary sequences, and therefore greater connectivity between the Brockman Iron Formation and the Tertiary Detritals is expected to occur.

Faults and dolerite dykes are present throughout the Coondiner area. Faults, such as the Poonda Fault, may either act as a groundwater conduit or a barrier to groundwater flow. In this area, however, the Poonda Fault, which is inferred to be close to but separated from the northern part of the orebody, is considered to have limited influence on groundwater flow.

The hydraulic gradient mimics topography with the steepest gradient at the Hamersley Range flattening out within the Tertiary sediments sequence in Fortescue Valley, flowing towards Fortescue Marsh. The depth to groundwater is greatest to the south along the crest of the Hamersley Range, with depth to water in these upper areas greater than 50 m. Depth to groundwater diminishes rapidly to the north of the Hamersley Range to less than 10 m below the floor of the Fortescue Valley within a short distance of the toe of the Hamersley Range escarpment.

Recharge to the Proterozoic basement is via direct rainfall infiltration. In the area overlain by the Coondiner Creek and associated fault zone, recharge would be via infiltration associated with flow events in Coondiner Creek via the river bed alluvium and potentially the fault zone.

Recharge to the regional Fortescue Valley aquifer system is via infiltration through the drainage lines and associated alluvium sequence during flow events. Additional diffuse recharge is considered to occur at the discharge area of the Proterozoic Basement outcrop and the colluvium/ detrital fans.

Water quality data in the Coondiner area is not available. However, given the orebody is located in a similar hydrogeological setting to the BHP Billiton Iron Ore’s Marillana Project, water quality has been assumed to be fresher towards the Coondiner Creek and become increasingly saline away from the creek. Salinity in the Tertiary Detritals at the tenement is likely to be less than 1,000 to 2,000 mg/L and generally below 1,000 mg/L in the orebody.

At the project tenement the saline interface extending into Tertiary Detritals from the Fortescue Marsh is estimated to be several kilometres northeast of orebodies CO-A and CO-B. Salinity at this location is likely to increase with depth, possibly to a concentration greater than 10,000 mg/L.

5.3.1.3 Generic mine type

Pit CO-D is entirely above the watertable, and is therefore not connected to regional groundwater. Most of the proposed pits, however, are located along valley fill lines, where at least one of the pit walls may intersect Tertiary Detritals which may furnish inflow into the pit.

Some connectivity between Tertiary Detritals and underlying Brockman Iron Formation is expected in CO-C, and is therefore classified as “connected”. Pit CO-E is also considered to be connected, though is expected to be detrital ore, rather than Brockman Iron Formation. Dewatering rates at “connected” pits are expected to be in the range of 10-20 ML/day. Pits located further north of the Hamersley Ranges (CO-A and CO-B) are classified as “fully connected”, as they are assumed to possess increased connectivity to the Brockman Iron Formation through a thicker Tertiary Detrital sequence. Dewatering requirements of these pits vary but for some of the pits (CO-B) are significant, and may exceed 20 ML/day.

Table 5-3: Coondiner orebody overview

Orebody	CO-A	CO-B	CO-C	CO-D	CO-E
Ore type	Detrital, CID, Brockman (?)	Detrital, CID, Brockman (?)	Detrital, CID	Brockman	Detrital (?)
Current status	Proposed mining Limited resource definition drilling No mining planned until after 2030	Proposed mining Limited resource definition drilling No mining planned until after 2030	Proposed mining Limited drilling resource definition No mining planned until after 2030	Proposed mining Limited drilling No mining planned until after 2030	Proposed mining No drilling to date No mining planned until after 2030
Previous hydrological studies	No previous groundwater or surface water studies undertaken to date				
Ore below watertable (BWT)	80% Inferred pit depth 70m but may have depth to mineralisation potential to 140 m	80% Inferred pit depth 70m but may have depth to mineralisation potential to 150 m	50% Inferred pit depth 30m	0 to 20% Inferred pit depth 60m, possibly dry	40% Inferred pit depth 25m
Generic type	Detritals/CID/Brockman – fully connected – moderate flows	Detritals/CID/Brockman – fully connected – moderate flows	Brockman – connected – moderate flows	Brockman – above watertable	Detritals – connected – low flows
Dewatering requirement basis	2 (6)[a] GL/yr (analytical model)	7 (32) [a] GL/yr (analytical model)	2 (8) [a] GL/yr (analytical model)	dry pit	1 (4) [a] GL/yr (analytical model)
Interaction with Fortescue Marsh	Localised reversal of GW flow not affecting the Marsh which is almost 40 km away	Localised reversal of GW flow not affecting the Marsh which is almost 40 km away	Localised reversal of GW flow not affecting the Marsh which is almost 40 km away	Negligible, if any	Localised reversal of GW flow not affecting the Marsh which is almost 40 km away

Note: – Analytical solution estimate with maximum estimated rate in brackets

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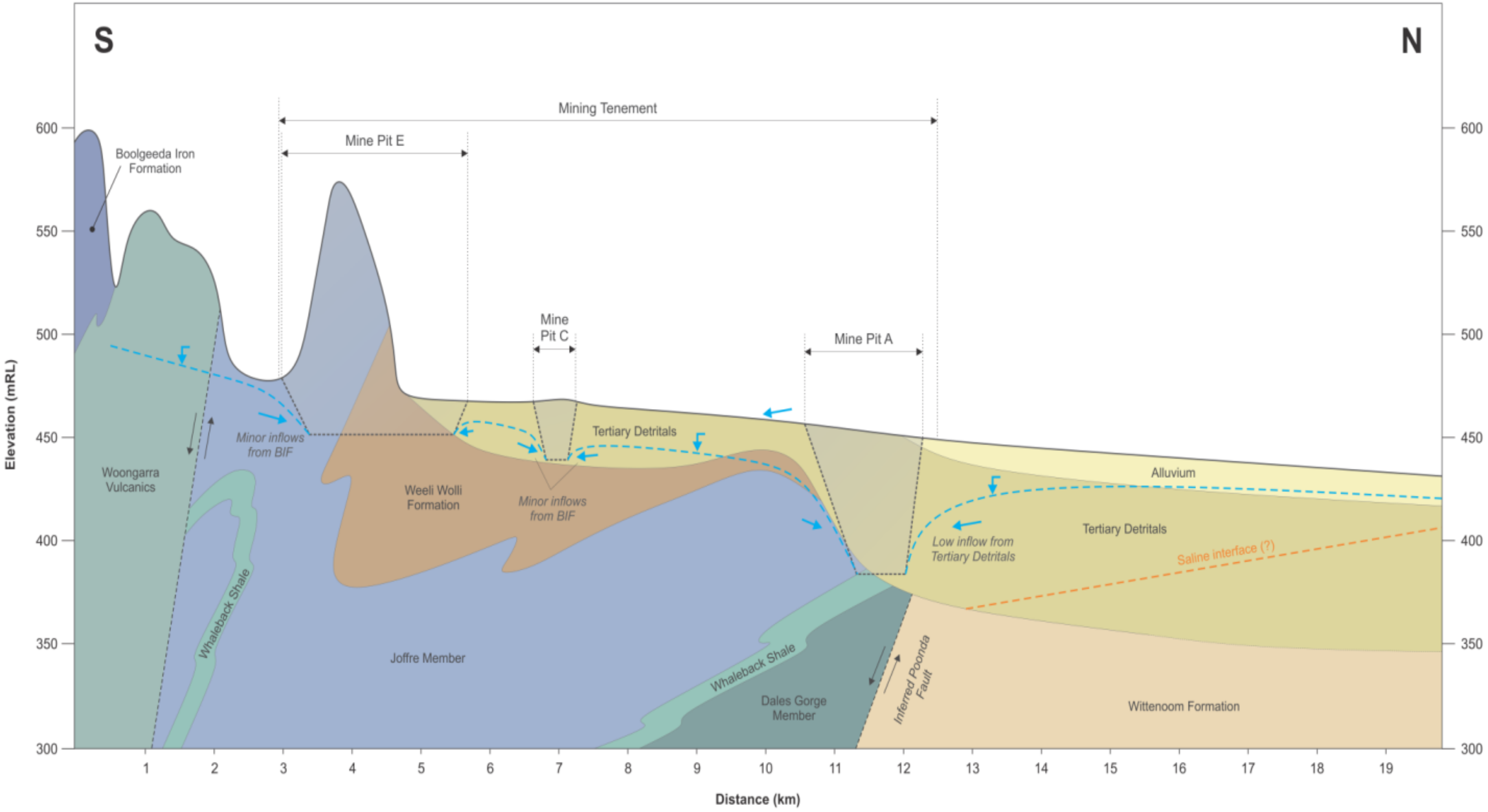

Figure 5-4: BHP Billiton Iron Ore Coondiner orebody interpreted geological cross-section A-A'

5.4 Roy Hill

The BHP Billiton Iron Ore Roy Hill Iron Ore Project is located approximately 250 km northwest of Newman and 25 km west of Fortescue Metal Group's (FMG's) current mining area at Cloudbreak. The proposed mining area is bound to the north by the Chichester Range and to the south by the Fortescue Marsh (for the eastern deposits) and Goodiadarrie Swamp (for the western deposits). The eastern deposits (Map 5-05) are located within the Upper Fortescue River Catchment, whilst the western deposits (Map 5-04) lie within the uppermost reaches of Lower Fortescue River Basin. These deposits are located within 5 to10 kms of the northern edge of the Fortcue Marsh and or Goodiaidarrie Swamp.

The BHP Billiton Iron Ore Roy Hill mining tenements consist of M45/1038 to M45/1065 and cover a total area of 261 km^2 of which the proposed pit footprint covers approximately 54 km^2.

The proposed project comprises of eleven proposed pit areas (RH-A to RH-K), seven associated mineral waste rock dumps (OSA) (RH-1 to RH-7) and nine infrastructure areas (RHI-1 to RHI- 9). It is inferred that railroad access will be available via the existing BHP Billiton Iron Ore Newman to Port Hedland Railway that bisects the deposits.

RH-A to RH-F are within the Goodiadarrie Swamp Catchment, while RH-G to RH-K are within the Upper Fortescue Marsh Catchment.

There is limited geological, hydrogeological and surface water information available for the BHP Billiton Iron Ore Roy Hill tenement.

Investigations undertaken on adjacent projects along the Chichester Range such as HPPL's Mulga Downs (MWH 2008, 2009 and 2013), FMG's Cloudbreak (Aquaterra, 2005) and FMG's Christmas Creek FMG (2010) and Aquaterra (2005), and BHP Billiton Iron Ore railroad water supply investigations (Bores T239 to T244), in conjunction with drill hole data from BHP Billiton Iron Ore's GBIS database has been utilised to conceptualise the groundwater system.

Table 5-4 and Table 5-5 provide an overview of the Roy Hill West and Roy Hill East orebodies.

5.4.1 Conceptualisation

5.4.1.1 Surface water

The Roy Hill orebodies are located along on the southern flank of the Chichester Range, with drainage in the elevated areas of the tenement being directed south through well-defined gullies and channels. In the lower sections, drainage would be via sheetflow in less defined channels towards the Fortescue Marsh and Goodiadarrie Swamp.

The hydrology in the area is dominated by a number of tributaries of the Fortescue River, with the eastern half of the tenement draining into the Fortescue Marsh and the western half draining towards the Fortescue River and the Goodiadarrie Swamp. Flow is generally in a southerly direction, and a multitude of smaller drainages from the range transport runoff following episodic rainfall events, which may contribute to focused groundwater recharge at the foot of the Chichester Range.

Groundwater recharge from tributaries of the Fortescue River after rainfall events is expected to be minimal, given that depth to water in the area is greater than 20 m bgl.

Aquifers are recharged predominantly via direct rainfall falling on the outcropping Tertiary Detritals and Nammuldi Member in the Chichester Range and via vertical leakage from the overlying Tertiary Detritals and focused infiltration from drainage lines. Incident rainfall also provides a smaller component of recharge within the Chichester Range over fractured outcrop or subcrop areas.

5.4.1.2 Groundwater

Quaternary alluvial deposits occur on the lower southern slopes of the Chichester Range. Tertiary Detrital deposits are also present, comprising colluvial and alluvial sediments and include goethitic materials with hematite and maghemite pisoliths. Figures 5-5 and 5-6 provide schematic geological cross sections through the orebody.

Tertiary calcrete (Oakover Formation) outcrops to the south, where it is deposited along drainage lines and within the Goodiadarrie Swamp and Fortescue Marsh. Dolomite of the Wittenoom Formation occurs to the south, overlying the Marra Mamba Formation and underlying Tertiary sequences in the Goodiadarrie Swamp and Fortescue Marsh.

The main aquifers at the BHP Billiton Iron Ore Roy Hill tenement are the alluvial/colluvial aquifer within the Tertiary and Quaternary deposits and the underlying mineralised or weathered Marra Mamba Iron Formation (the BIF aquifer). The BIF aquifer is a semi-confined aquifer within the slopes of the Chichester Range and an unconfined aquifer towards the upper parts of the Chichester Range where the Nammuldi Member of the Marra Mamba Formation outcrops. The permeability of the BIF aquifer is enhanced in mineralised zones of the upper Nammuldi Member, where mineralisation has increased the secondary porosity. In the lower unmineralised portion of the Nammuldi Member, permeability is enhanced along faults; however it is restricted within extensive shale units. Aquitards in the area are expected to be associated with the unmineralised Marra Mamba Iron Formation which consists of low-permeability shales.

Highly permeable Tertiary calcrete, potentially part of the Oakover Formation, outcrops towards the Goodiadarrie Swamp and Fortescue Marsh.

The dolomite of the Wittenoom Formation, which overlies the Marra Mamba Iron Formation, occurs south of the study area beneath the Marsh, Goodiadarrie Swamp, and much of Fortescue Valley, and likely exhibits low permeability where fresh and relatively unfractured. Fracturing and dissolution may enhance permeability.

Connectivity between the orebody aquifers and detrital units is considered to occur, although the detritals may only be partly saturated in certain pits. Of particular importance is the presence of calcrete horizons which are highly permeable based on information from mining at Cloudbreak to the east of the Roy Hill project area.

Faults and dolerite dykes are assumed to propagate through the tenement and may act as conduits or barriers to groundwater flow. The upper horizon of the Wittenoom Formation is not considered to be in direct connection with orebody aquifers.

Groundwater flow generally mimics topography and is generally in a southerly direction towards the Fortescue Marsh and Goodiadarrie Swamp areas. These internally draining surface water receptors also represent the groundwater termini or sinks in the area. In the western half of the ore body, to the west of the Goodiadarrie Hills, groundwater does not flow into the Fortescue Marsh, but instead flows into the Goodiadarrie Swamp.

A saline interface between saline water beneath the Goodiadarrie Swamp and Fortescue Marsh, and the brackish water to the south of the Roy Hill tenement area is inferred to exist. Based on water sampling at the Cloudbreak (RPS 2004) site directly east of the Roy Hill tenement, saline water (conductivity ranging from 2,000 to 5,000 mS/m) is encountered at depths as shallow as 40 m bgl.

5.4.1.3 Generic mine type

Pit RH-A, RH-E and and RH-F are entirely above the watertable, and are therefore not connected to the regional watertable.

Some connectivity is expected in RH-B, RH-C and RH-D (Roy Hill west), and is therefore classified as “connected”. Pits RH-G to RH-K (Roy Hill east) is classified as “connected”. Most of the proposed pits are located along valley fill lines, where at least one of the pit walls may intersect saturated horizons of Tertiary sediments which may furnish inflow into the pit. Despite this, there is some uncertainty regarding the degree of connection between the Tertiary Detritals and underlying Nummuldi BIF. Dewatering requirements for connected pits are expected to be in the range of 10-20 ML/day.

It should be noted that dewatering operations at FMG’s Cloudbreak have highlighted the fact that the original estimations of dewatering and saline water management (1 GL/yr) have been proven to be significantly underestimated compared to current actual dewatering and saline water management requirements (over 100 GL/yr)

The potential extent of drawdown, to the south towards the Fortescue Marsh and Goodiadarrie Swamp during dewatering activities is likely to be of the order of 2 to 5 kms.

Table 5-4: BHP Billiton Iron Ore Roy Hill orebody overview: western part, Goodiadarrie Swamp catchment

Orebody	RH-A	RH-B	RH-C	RH-D	RH-E	RH-F
Ore type	Tertiary Detritals overlying thin mineralised Nammuldi Member					
Current status	No active mining Wide spaced resource definition drilling only No proposed mining activity until beyond 2030					
Previous hydrological studies	None undertaken to date Hydrogeological investigations have been undertaken in the adjacent HPPL Murray Hills area to the west and construction water supply investigations associated with Newman to Port Hedland Railway Hydraulic gradient to the south towards the regional groundwater sink – Goodiadarrie Swamp Watertable mimic topography					
Ore below watertable (BWT)	0%	5%	5%	25%	0%	0%
Generic type	Nammuldi – Above watertable	Nammuldi – connected – Low flows	Nammuldi – connected – Low flows	Nammuldi – connected – Mod flows	Nammuldi – Above watertable	Nammuldi – Above watertable
Dewatering requirement basis	No dewatering required	Up to 1 GL/yr (analytical model)	Up to 3 to 4 GL/yr (analytical model)	Up to 5 GL/yr (analytical model)	No dewatering required	No dewatering required
Interaction with ecological receptors	Goodiadarrie Swamp is the terminus for groundwater and surface water flows, and it also an environmentally sensitive area. - Distance to the Swamp is approximately 8 km to the south - Intersection of groundwater throughflow to down-gradient receptors - Potential reversal of groundwater flow from receptor – considered to be localised due to the generally shallow depth of the pits - Saline interface drawn north through gradient reversal - considered to be localised due to the generally shallow depth of the pits					

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Table 5-5: BHP Billiton Iron Ore Roy Hill orebody overview: eastern part, Fortescue Marsh catchment

Orebody	RH-G	RH-H	RH-I	RH-J	RH-K
Ore type	Tertiary Detritals overlying thin mineralised Nammuldi Member				
Current status	No active mining Wide spaced resource definition drilling only No proposed mining activity until beyond 2030				
Previous hydrological studies	None undertaken to date Hydrogeological investigations have been undertaken in the adjacent FMG's Cloudbreak area to the east and construction water supply investigations associated with Newman to Port Hedland Railway Hydraulic gradient to the south towards the regional groundwater sink – Fortescue Marsh Watertable contours broadly mimic topography				
Ore below watertable (BWT)	30%	40%	40%	30%	30%
Generic type	Nammuldi – connected – Mod flows	Nammuldi – connected – Mod flows	Nammuldi – connected – Mod flows	Nammuldi – connected – Mod flows	Nammuldi – connected – Mod flows
Dewatering requirement Basis[5]	No dewatering required	Up to 4 GL/yr (analytical model)	Up to 10 to 13 GL/y (analytical model)r	Up to 6 to 7 GL/yr (analytical model)	Up to 7 to 9 GL/yr (analytical model)
Interaction with ecological receptor	Fortescue Marsh key receptor - distant - Intersection of through flow to receptor - Potential reversal of GW flow from receptor - saline interface drawn north through gradient reversal				

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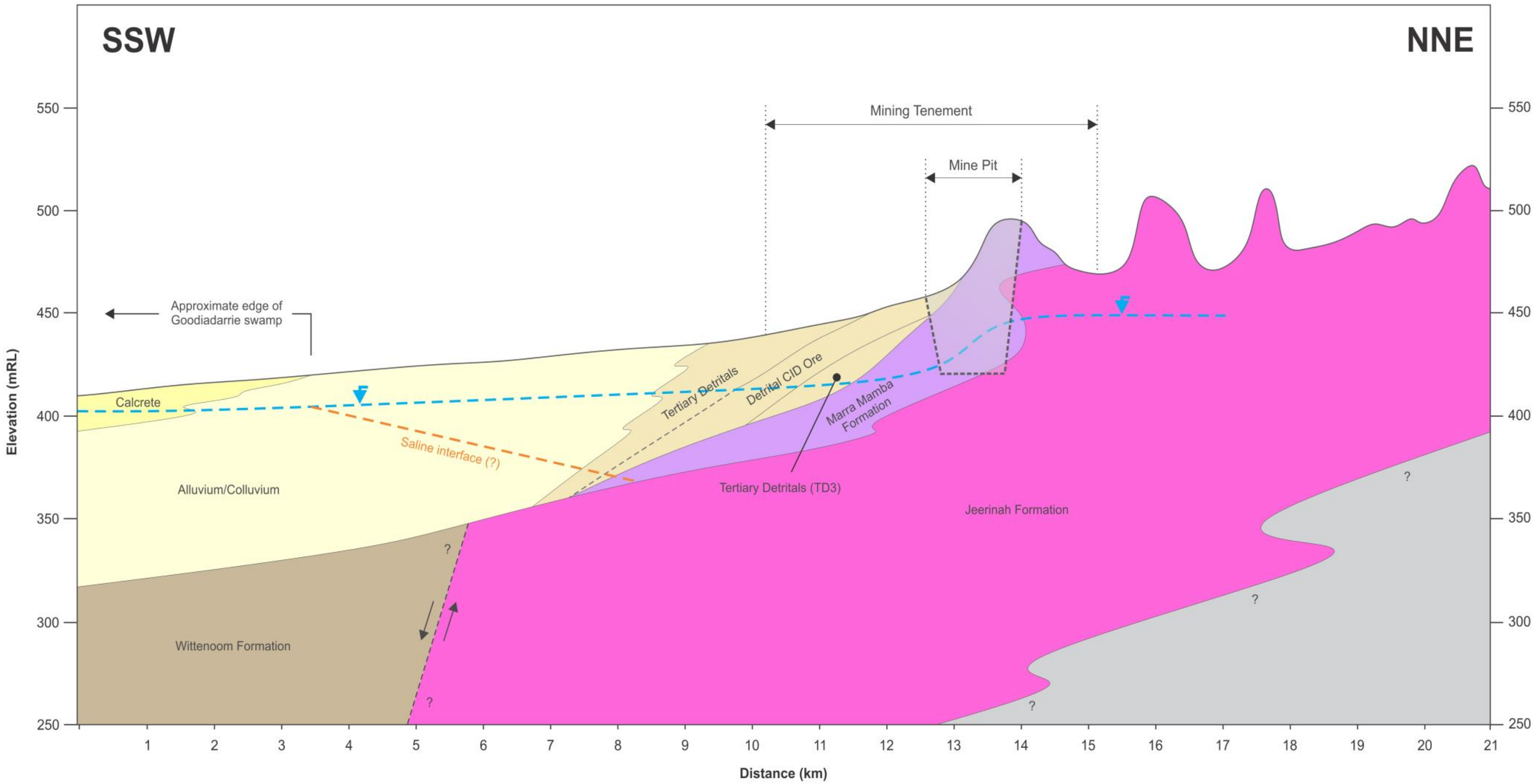

Figure 5-5: BHP Billiton Iron Ore Roy Hill orebody interpreted geological cross-section A - A'

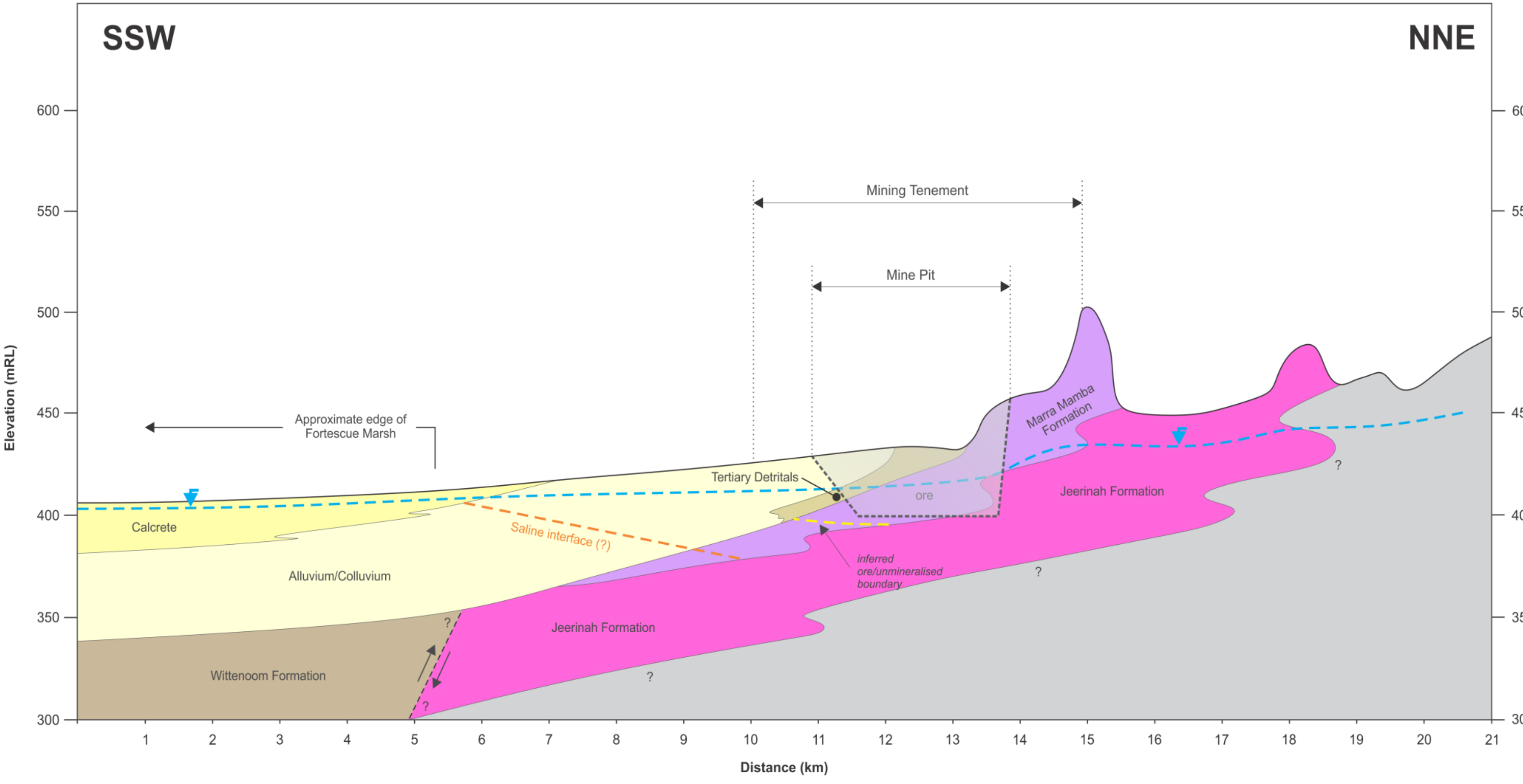

Figure 5-6: BHP Billiton Iron Ore Roy Hill orebody interpreted cross-section B-B'

5.5 Third-party stressors

This section addresses the potential influence of third-party operations on the ecohydrology of the Fortescue Marsh.

Map 5-06 presents the existing and planned mining operations by third parties within the Fortescue Marsh study area.

The Yandicoogina mining areas are presented in the report "Ecohydrological conceptualisation of the Marillana Creek Region".

5.5.1 FMG Cloudbreak

The Cloudbreak mine is located along the southern flanks of the Chichester Range and north of the Fortescue Marsh some 150 km north west of Newman and 263 km south of Port Hedland (Map 5-06). The mine is owned and operated by Fortescue Metals Group and commenced mining in October 2007. The mineralised Marra Mamba Formation is the primary source of the 40 Mtpa iron ore mining and processing operation, with a provisional mine life of 16 years. Over 90% of the iron ore resource is below water-table. The mining operations will extend along a strike length of approximately 40km.

FMG have undertaken several hydrogeological investigations on the Cloudbreak area related to the assessment, design, implementation and ongoing water management, and in particular to the dewatering, reinjection, saline water management issues and potential environmental impact assessment.

The Cloudbreak mining operations are located to the east of and mining the same geological sequence along strike from BHP Billiton Iron Ore's Roy Hill proposed mining areas. The Cloudbreak and Christmas Creek dewatering operations have the potential to influence groundwater conditions at BHP BIO's Roy Hill operations if they are operating in the same time period.

Cloudbreak conceptualisation

The main surface water flow paths through the Cloudbreak mining operations consist of relatively small catchments feeding north to south draining creek systems that have headwaters in the Chichester Range and terminate in the Fortescue Marsh. Whilst the catchment areas of these creek systems are relatively small, the potential for surface water impacting on mining operations requires careful management and implementation to avoid pit inundation events occurring such as those experienced at Cloudbreak in January 2012 associated with Cyclone "Heidi".

Pre-mining groundwater flow was via the regional aquifer systems (Tertiary detritals, Oakover Formation) and mineralised Marra Mamba Formation, with groundwater flow from the north, in the elevated Chichester Range, to the south with the groundwater terminus of the Fortescue Marsh. Mine dewatering is designed to ensure mining operations to depths of 90 m bgl can be sustained, with current dewatering rates approaching 100 GL/yr. A network of reinjection bores are being utilised to manage surplus to demand groundwater abstraction from the dewatering activities, also to mitigate the dewatering drawdown footprint and potential saline groundwater ingress. The reinjection borefields are located between the upgradient active mining areas and the downgradient Fortescue Marsh, targeting the Oakover Formation aquifer.

The Cloudbreak orebody is in direct hydraulic connection with the regional aquifers via the mineralised Marra Mamba Formation being in direct connection with the Tertiary Detritals and Oakover Formation.

Figure 5-7 presents a schematic cross section through the Cloudbreak orebody and illustrates the dewatering and reinjection borefields (DHI, 2012).

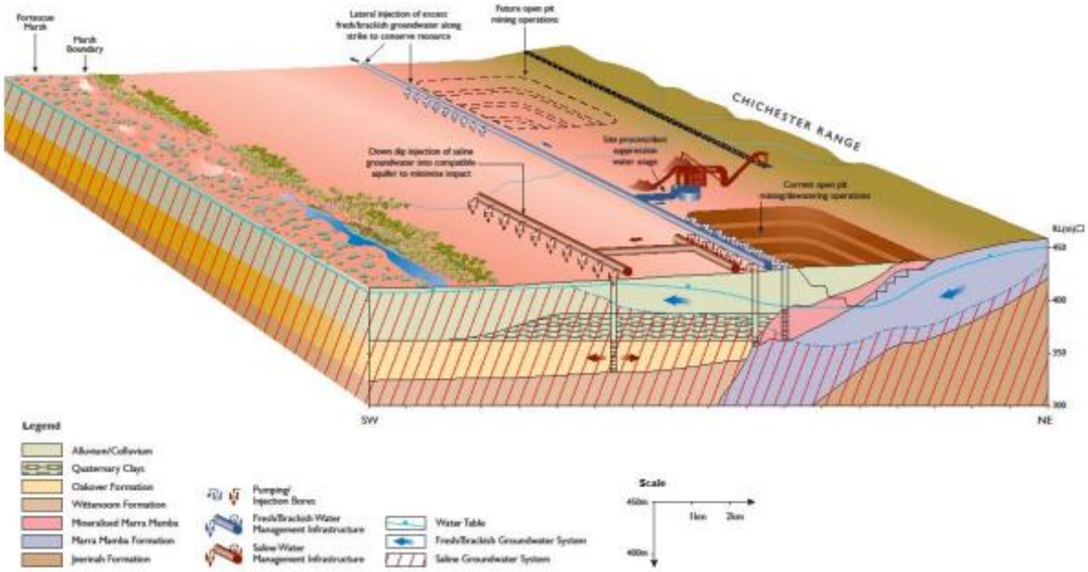

Figure 5-7: Conceptual cross section of Cloudbreak dewatering and reinjection operations (from DHI, 2012)

5.5.2 FMG Christmas Creek

The Christmas Creek mine is located along the southern flanks of the Chichester Range, some 50 km east of the FMG Cloudbreak operations, north of the Fortescue Marsh, some 110 km northwest of Newman and 325 km south east of Port Hedland (Map 5-06). The mine is owned and operated by Fortescue Metals Group. It commenced mining in May 2009. The mineralised Marra Mamba Formation is the primary source of the 50 Mtpa iron ore mining and processing operation, with a provisional mine life of 20 years. Over 68% of the iron ore resource is below water-table. The mining operations will extend along a strike length of approximately 30 km.

FMG undertook considerable hydrogeological investigations on the Christmas Creek and adjacent Cloudbreak areas focused on the assessment, design, implementation and ongoing water management related to the dewatering, reinjection, saline water management issues and environmental impact assessment.

The Christmas Creek mining operations are located to the east of and mining the same geological sequence along strike from Cloudbreak mining area. Dewatering at Cloudbreak and Christmas Creek operations have potential to influence groundwater conditions at BHP BIO’s Roy Hill operations if they are operating in the same time period.

Christmas Creek conceptualisation

The main surface water flowpaths through the Christmas Creek mining operations are via relatively small catchments, feeding north to south draining creek systems that have headwaters in the Chichester Range and terminate in the Fortescue Marsh. Whilst the catchment areas of these creek systems are relatively small, the potential for surface water impacting on mining operations requires careful management.

Pre-mining groundwater flow was via the regional aquifer (Tertiary Detritals, Oakover Formation) and mineralised Marra Mamba Formation, with groundwater flow from the north, in the elevated Chichester Range, to the south with the groundwater terminus of the Fortescue Marsh.

Mine dewatering is designed to ensure mining operations to depths of 50 m bgl can be sustained, with current planned dewatering rates approaching 50 GL/yr. To manage surplus to demand groundwater abstraction from the dewatering activities, also to mitigate the dewatering drawdown footprint and potential saline groundwater ingress, a network of reinjection bores are being utilised. The reinjection borefields are located between the up gradient active mining areas and the down gradient Fortescue Marsh, targeting the Oakover Formation aquifer.

The Christmas Creek orebody is in direct hydraulic connection with the regional aquifer via the mineralised Marra Mamba Formation being in direct connection with the Tertiary Detritals and Oakover Formation.

Figure 5-8 presents a schematic cross section through the Christmas Creek orebody and illustrates the dewatering and reinjection borefields (FMG, 2011).

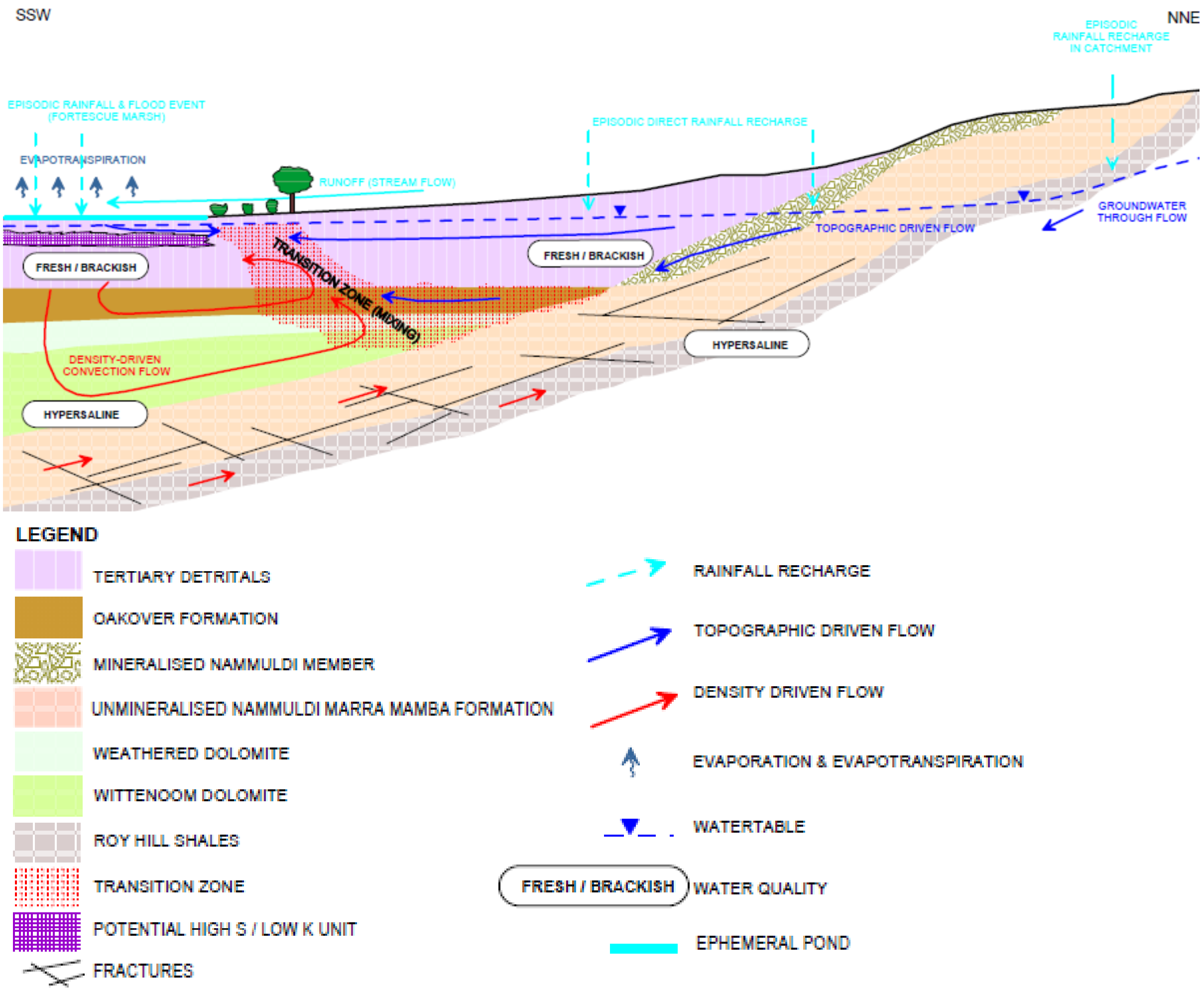

Figure 5-8: Conceptual hydrogeological cross-section of the Christmas Creek mining operation (after FMG, 2011)

5.5.3 FMG Nyidinghu

The Nyidinghu project is located along the northern flanks of the Hamersley Range, in proximity to the Weeli Wolli Creek, some 100 km northwest of Newman and 30 km south of the Fortescue Marsh (Map 5-06). The project is owned and managed by Fortescue Metals Group, and has a reported inferred iron ore resource of 2.46 Bt, with two proposed mining proposals:

- Iron Ore project - 4 year mining life, direct shipping ore (Brockman Ore) at a rate of 6 Mtpa to a maximum depth of 33 m, was anticipated to commence in 2015 but has been shelved. Mining would be above water-table with water supply from local small borefield (32 ML/a). (FMG, 2012)
- Greater Nyidinghu project – 2.46Bt (23 Mt measured and 1.86 Bt inferred, predominately mineralised Brockman Iron Formation (mainly Joffre Member) is the primary source of the deposit, with some minor detrital and CID mineralisation overlying the Brockman Formation resource. Proposed mining depths are greater than 200 m bgl, major dewatering requirements. PER expected to be submitted in mid 2017 with a proposed commencement of mining after 2018 (Nyidinghu Project Environmental Scoping Document).

There has been significant hydrogeological investigation undertaken by FMG (2008, 2012) on the Nyidinghu area related to the assessment, hydraulic testing, numerical modelling, implementation and ongoing water management related to the development of a dewatering and water supply borefield and potential environmental impact assessment. The Nyidinghu project is located immediately to the east of and in a similar geological sequence and along strike from the eastern edge of BHP Billiton Iron Ore's Marillana and IOH's Iron Valley proposed mining area. On the western edge of the Nyidinghu project area is the BHP Billiton Iron Ore Mindy mining area.

Nyidinghu conceptualisation

The main surface water feature in the Nyidinghu project area is the Weeli Wolli Creek which runs adjacent and through the project area, draining from the south to the north, before turning west at the exit point from the Hamersley Range before terminating in the Fortescue Marsh. Significant surface water management will be required for the Greater Nyidinghu proposed mining operations to proceed.

Pre-mining groundwater flow occurred via the regional aquifer system - Tertiary Detritals, Oakover Formation, CID, mineralised Brockman Iron Formation and karstic Wittenoom Formation, with the groundwater flow from the south to the north. The Fortescue Marsh is the groundwater terminus.

No mine dewatering is planned as proposed mining is currently understood to not proceed below the watertable. Numerical modelling for the Greater Nyidinghu project suggests significant drawdown and reversal of groundwater flow directions resulting from dewatering if the project goes below the watertable. Saline groundwater drawn the saltwater interface beneath the Fortescue Marsh has potential to migrate to the dewatering system and may require the establishment of a reinjection borefield to mitigate or minimise this impact.

The volumes of water considered for pit dewatering are estimated at a rate of up 90 GL/yr. According to the Nyidinghu Project Environmental Scoping Document up to 60 GL/yr of the surplus mine dewater will be discharged to Weeli Wolli Creek and up to 80 GL/yr will be reinjected into the aquifers within the Fortescue Marsh valley.

5.5.4 FMG Mindy Mindy

The FMG Mindy Mindy project is located immediately south and behind the northern flanks of the Hamersley Range, in proximity and to the east of the Weeli Wolli Creek, some 70 km north west of Newman and 25 km south of the Fortescue Marsh (Map 5-06). The project is owned and managed by a joint venture between FMG and Consolidate Minerals.

The Mindy Mindy project has a reported iron ore resource of 45 Mt, with an inferred resource of 107 Mt. The project has a proposed mining rate of 5 Mtpa for approximately 20-year mine life. The iron ore resource is contained within mineralised Channel Iron Deposit (CID), located within a minor, 12 km long, high order tributary of the Weeli Wolli CID system. The proposed mining program does not reportedly extend significantly below the watertable, with maximum depth of mining generally less than 40 m with only the northwestern extent of the channel being saturated

There have been some preliminary hydrogeological investigations undertaken by Aquaterra (2004).

Mindy Mindy conceptualisation

The main surface water feature in the Mindy Mindy project area is the Weeli Wolli Creek that runs along the western edge of the project, draining from the south to the north, before turning west at the exit point from the Hamersley Range and finally terminating in the Fortescue Marsh. The project is situated in one of the major eastern tributaries of the Weeli Wolli Creek before the latter exist the Hamersley Range.

This localised small catchment tributary draining to the west off the elevated range areas has the potential for minor surface water impacts, but little impact to the regional surface water regime.

Pre-mining groundwater flow occurs via the regional aquifer system. Groundwater flow takes place from the east to the west following the trend of the CID deposit, before joining into the Yandi CID aquifer system.

Only minor mine dewatering is planned as proposed mining is not proceeding significantly below water-table.

5.5.5 Iron Ore Holdings Iron Valley

The Iron Valley project is located along the northern flanks of the Hamersley Range in proximity and to the west of the Weeli Wolli Creek, some 90 km north west of Newman and 25 km south of the Fortescue Marsh (Map 5-06).

The project is owned and managed by Iron Ore Holdings and has a reported iron ore resource of 35 Mt, with a proposed mining rate of 5 Mtpa for a 7-year mine life. The mineralised Brockman Iron Formation (mainly Joffre Member) is the primary source of the deposit, with some minor detrital mineralisation along the northern extent of the deposit. The proposed three stage mining program does not reportedly extend below the water-table. A forecast project water demand of 0.36 GL/yr, is to be derived from a planned local borefield.

There have been some hydrogeological investigations undertaken by URS (2011, 2012) on the Iron Valley project area. They were focused on the assessment, hydraulic testing, numerical modelling, implementation and ongoing water management related to the development of a water supply borefield and environmental impact assessment.

The Iron Valley project is located immediately to the east of and in a similar geological sequence and along strike from the eastern edge of BHP Billiton Iron Ore's Marillana proposed mining area. On the western edge of the Iron Valley project area is the FMG's Nyidinghu project.

Iron Valley conceptualisation

The main surface water feature in the Iron Valley project area is the Weeli Wolli Creek that runs adjacent to the eastern edge of the project, draining from the south to the north, before turning west at the exit point from the Hamersley Range and terminating in the Fortescue Marsh. Localised small catchment tributaries draining out of the elevated range areas have the potential for minor surface water impacts to the proposed mining operations, but little impact to the regional surface water regime.

Pre mining groundwater flow is via the regional aquifer, in mineralised Brockman Iron Formation and overlying detritals. Groundwater flow originates from the south, within the elevated Hamersley Range and proceeds to the north, with the groundwater terminus being the Fortescue Marsh. Localised compartmentalisation due to presence of dolerite dykes may occur. No mine dewatering is planned as proposed mining is not proceeding below water-table.

No publically available schematic geological cross sections through the Iron Valley ore-body are available.

5.5.6 RTIO Koodaideri

The Koodaideri project is situated along the northern flanks of the Hamersley Range some 110 km west-northwest of Newman and 10 km south of the Fortescue Marsh (Map 5-06).

The project is owned and managed by Rio Tinto and has a reported iron ore resource capable of a mining rate of initially 35 Mtpa, ramping up to 70 Mtpa for a 30-year mine life. The mineralised, highly phosphorous Brockman Iron Formation is the primary source of the deposit. Four proposed pits are planned, of which three (K75W, K58W and K38W0) are stated to be 90% above water-table; however the fourth pit (K21W) is to extend to approximately 200 m bgl.

Dewatering of the pits is planned to be undertaken using the in-pit sumps. The forecast project water demand is:

- 6 GL/yr (2016 to 2023);
- 10 GL/yr (2023 to 2031) and
- 18 GL/yr beyond 2032 when wet processing is planned.

Some existing water local water supply bores will be utilised to supply the initial start-up water supply with a plan to utilise surplus dewatering discharge water from Rio Tinto's Junction Central and Junction South East operations.

Hydrogeological investigations were undertaken by PB (2011, 2012, and 2013). They incorporated the assessment of hydrogeological setting, hydraulic testing, conceptual hydrogeological modelling, and implementation and ongoing water management related to the development of a water supply borefield and environmental impact assessment.

The Koodaideri project is located immediately to the west of and in a similar geological sequence and along strike from the western edge of BHP Billiton Iron Ore's and Brockman Resources Marillana proposed mining areas.

Koodaideri conceptualisation

The main surface water feature in the Koodaideri project area is the Koodaideri Creek and Koodaideri Spring. Localised small catchment tributaries draining out of the elevated range areas have the potential for minor surface water impacts to the proposed mining operations, but little influence on the regional surface water regime (Worley Parsons, 2012).

Pre-mining groundwater flow is via the mineralised Brockman Iron Formation following on to the regional aquifer. Groundwater flow, inferred from hydraulic head data, is northward from elevated Dales Gorge Member aquifers towards the Cainozoic sediments of the valley fill which underlie the plain, and then towards the Fortescue Marsh.

Localised compartmentalisation due to the presence of dolerite dykes may occur.

Three main aquifer components within the Koodaideri project include:

- Fractured rock orebody aquifers of the mineralised Dales Gorge Member and the upper part of the Mount McRae Shale (where saturated).
- Fractured rock aquifers of weathered Wittenoom Formation that underlie the Cainozoic deposits in the Fortescue Valley.
- Unconsolidated sediment aquifers – the valley fill aquifer within Cainozoic sediments that underlie the Fortescue Valley

Figures 5-10 and 5-11 present a schematic cross-section through the Koodaideri orebody.

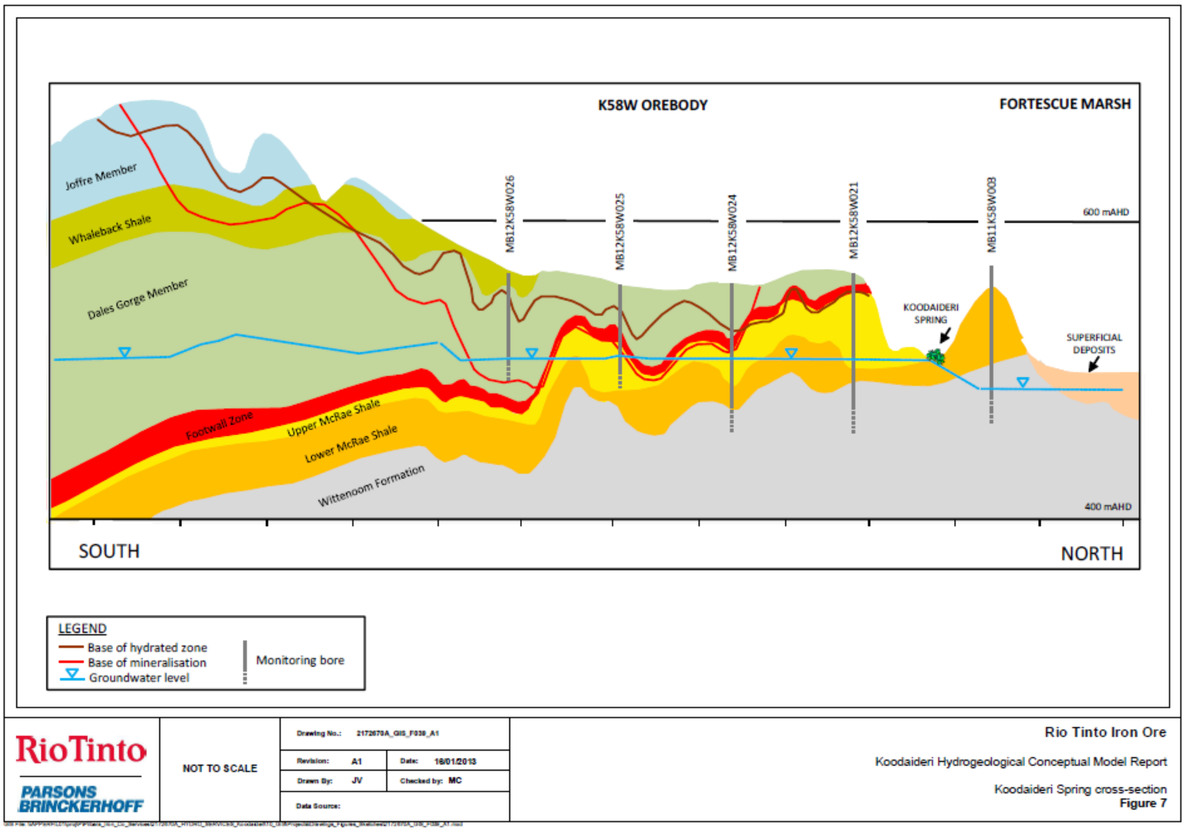

Figure 5-9: Geological cross-section of the Koodaideri deposit (after Parsons Brinckerhoff, 2013)

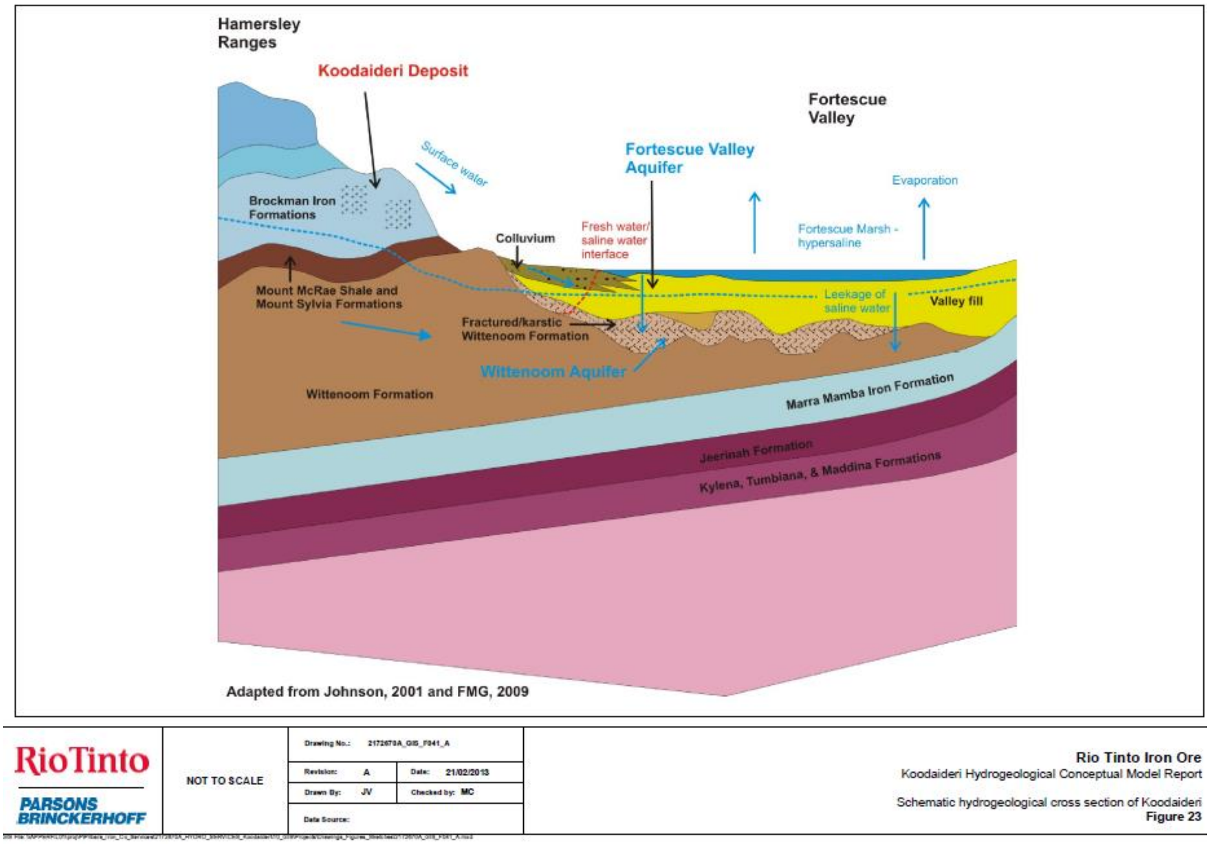

Figure 5-10: Conceptual hydrogeological cross-section of the Koodaideri deposit (after Parsons Brinckerhoff, 2013)

5.5.7 RTIO Koodaideri South

The Koodaideri South project is located to the south of the eastern end of the RTIO's Koodaideri deposit, south of the northern flanks of the Hamersley Range, some 110 km west north west of Newman and 15 km south of the Fortescue Marsh (Map 5-06).

The project is owned and managed by Rio Tinto (formerly owned by Iron Ore Holdings) and currently has an inferred resource of approximately 106 Mt. The mineralised highly-phosphorous Brockman Iron Formation is the primary source of the deposit. Three proposed resources have been identified to date – Kurrajura, Fingers and Bight.

No groundwater information is currently available, but considering the location and the size of the identified resources it is highly likely that the depth of any proposed pit would be above water-table.

The Koodaideri South project is located immediately south of the eastern end of Koodaideri deposit and in a similar geological sequence.

Koodaideri South conceptualisation

Localised small catchment tributaries draining out of the elevated range areas have the potential for minor surface water impacts to the proposed mining operations, but little impact to the regional surface water regime (Worley Parsons, 2012).

No water level monitoring has been documented to date. The location of the project area potential lies close to the inferred groundwater divide between the northward flowing system to the Fortescue Marsh and the southward flowing system of the Central Region area.

The main aquifer systems existing within Koodaideri South project are likely to be fractured rock orebody aquifers of the mineralised Dales Gorge Member.

No geological information is available to provide a hydrogeological cross-section for this project.

5.5.8 Brockman Resources Marillana

The Brockman Resources Marillana project is located along the northern flanks of the Hamersley Range some 100 km north west of Newman and 15 km south of the Fortescue Marsh (Map 5-06).

The project is owned and managed by Brockman Resources and has a reported iron ore resource of 700 to 750 Mt, with a planned process rate of 37 Mtpa production and 18 Mtpa of product, with a proposed 20-year mine life. The iron ore resource is reportedly detritals and the CID material. Two proposed pits are planned and are believed to extend to some 80 m bgl, with the depth to regional water-table being around 20 to 30 m bgl. A 2016 target commencing date has been indicated for this project.

Dewatering of the pits is planned to be undertaken using in-pit and ex-pit bores. The forecast project dewatering rate has been estimated at a peak of 32 ML/a, declining to around 5 ML/d towards the end of the mine life. Additional water supply will be sourced from an external borefield. Surplus dewatering volumes will be reinjected or returned to the groundwater system down gradient of the mining area via infiltration ponds (Aquaterra, 2010).

Hydrogeological investigation has been undertaken by Aquaterra (2010). They included hydrogeological drilling, hydraulic testing, conceptual hydrogeological modelling, numerical modelling and predictive simulations.

The Marillana project is located immediately to the down gradient and in a similar geological sequence to BHP Billiton Iron Ore’s Marillana proposed mining areas.

Brockman Resources Marillana conceptualisation

The main surface water feature in the Marillana project area is related to the Weeli Wolli Creek that flows just to the north of the proposed pits. Localised small catchment tributaries draining out of the elevated range areas have the potential for minor surface water impacts to the proposed mining operations, but little impact to the regional surface water regime (Ecologia, 2010). Diversion structures around the pits and infrastructure are proposed to deliver flow to the Weeli Wolli Creek.

Groundwater flow occurs within detritals, CID and calcrete aquifers, and the underlying karstic Wittenoom Formation aquifer. The direction of flow is from the south, in the elevated Hamersley Range, to the north, with the groundwater terminus being the Fortescue Marsh.

Dewatering is predicted to create a significant reversal of the groundwater flow towards the cone of depression, with modelling simulations suggesting impacts may extend to the edge of the Marsh. Reinjection and infiltration ponds are proposed to mitigate this impact to the north.

Figure 5-12 presents a schematic cross section through the Brockman Resources Marillana orebody.

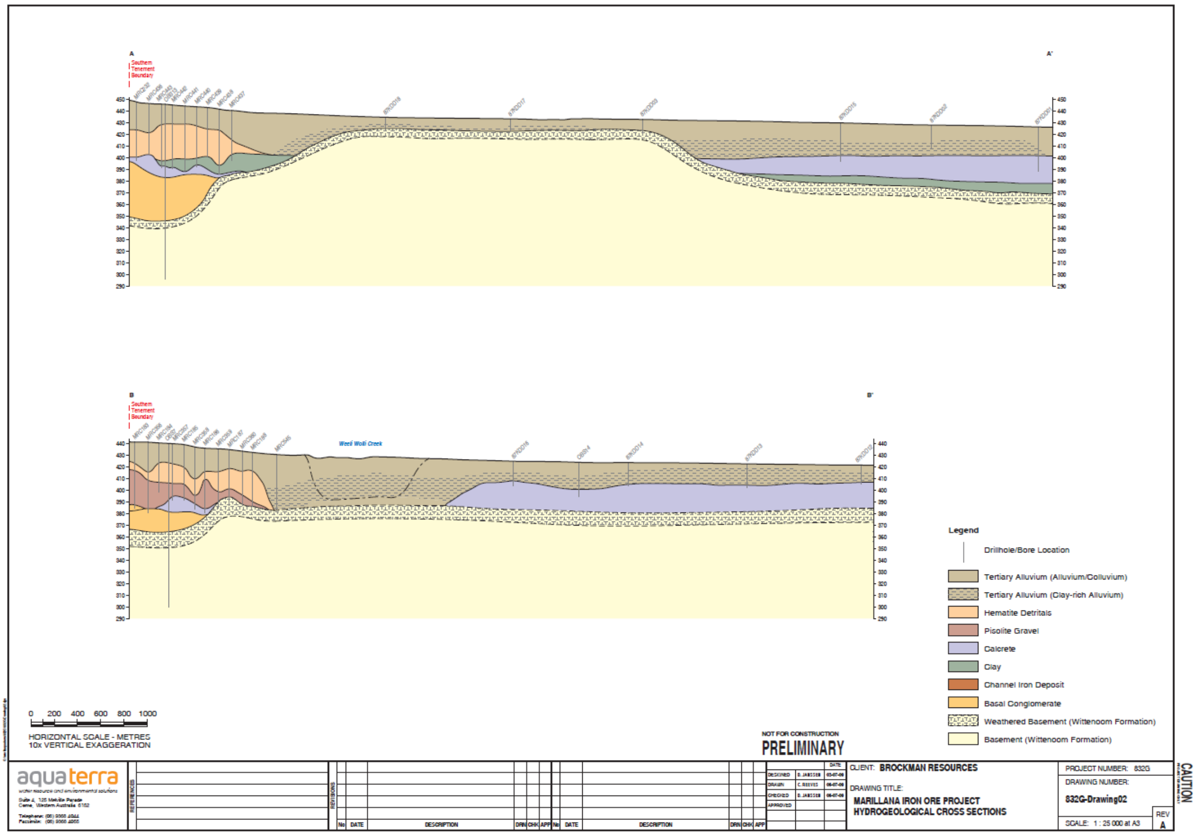

Figure 5-11: Geological cross-section of Brockman Resources Marillana project (after Aquaterra, 2010)

5.5.9 RHIO Roy Hill

The proposed Roy Hill mine is currently under construction with operations to commence September 2015. It is located along the southern flanks of the Chichester Range and north of and 4 km north- east of the eastern-most part of the Fortescue Marsh, and some 110km north of Newman (Map 5-06).

The mine is owned and operated by Roy Hill Iron Ore Pty Ltd. Pre-stripping commenced in late 2013. The mineralised Marra Mamba Formation is the primary source of the 65 Mtpa iron ore mining and processing operation, designed to produce 55 Mtpa of product with a provisional mine life of 18 years. A significant part of the iron ore resource is below the watertable. The mining operations will extend along a strike length of approximately 50 km and to a maximum depth of 100 m bgl.

MWH undertook extensive hydrogeological investigations (2005 to 2013) which addressed the assessment, design, implementation and ongoing water management related to the water supply, dewatering, saline water management issues and environmental impact assessment.

Current forecast water demand for the wet processing of the ore and operational requirements is 46 ML/d of brackish quality groundwater. Initial water supply for the project will be met by the Stage 1 Borefield (46 ML/d capacity), which has been developed within the proposed footprint of the mining activities and will be mined out by mining year 7. Dewatering borefields will be progressively developed to match mining requirements and become the priority water supply option.

A proposed Stage 2 Remote borefield has being identified, some 50 km to the south of the project area and to the south of the Fortescue Marsh should an additional brackish water source be required later in the mine life.

The Roy Hill mining operations are located to the east of, and mining the same geological sequence along strike from FMG's Cloudbreak and Christmas Creek operations. No BHP Billiton Iron Ore's projects are in close proximity to this operation.

Roy Hill conceptualisation

The main surface water drainage through the Roy Hill mining operations occur in several significant southward draining catchments that have headwaters in the Chichester Range and terminate in the Fortescue Marsh (No Name Creek, Kulbee Creek, Kulkinbah Creek and others).

Pre-mining groundwater flow was via the regional aquifer (Tertiary Detritals, Oakover Formation) and mineralised Marra Mamba Formation, with groundwater flow from the north, in the elevated Chichester Range, to the south and south west, with the groundwater terminus being the Fortescue Marsh.

Mine dewatering is principally being implemented via down-dip ex-pit dewatering bores which are designed to ensure mining operations to depths of 100 m bgl. These could be sustained with provisionally predicted dewatering rates approaching 100 ML/d. The saline interface associated with the Fortescue Marsh intersects some of the lower levels of the proposed mining areas, and as such saline to hypersaline groundwater is anticipated to be a significant component of the dewatering activity during periods of the mine life.

To manage surplus to demand, groundwater abstraction and the saline groundwater abstraction from the dewatering activities Roy Hill has adopted a disposal option via two large lined evaporation facilities to the south west of the operations and a brackish groundwater borefield to harvest the fresher groundwater. A significant localised cone of depression is expected to develop and move progressively along the strike of the orebody. Current groundwater modelling predicts only limited impacts to be observable near the edge of the Fortescue Marsh.

The Roy Hill orebody is in direct hydraulic connection with the regional aquifers via the mineralised Marra Mamba Formation being in direct connection with the Tertiary detritals and Oakover Formation, and potentially the regional karst aquifer of the Wittenoom Formation to the south.

Figure 5-13 presents a schematic cross section through the Roy Hill orebody.

5.5.10 Rio Tinto Hope Downs 4

The Hope Downs 4 mine commenced operations in 2013, and is located 30 km to the south of the northern flank of the Hamersley Range, at the headwaters of Coondiner Creek and some 30 km northwest of Newman (Map 5-06).

The mine is a joint venture between RTIO and HPPL, and is managed and operated by RTIO. The mineralised Brockman Iron Formation is the primary source of the 15 Mtpa iron ore mining and processing operation with a provisional mine life of 25 to 30 years. A significant part of the iron ore resource is below water-table (70%). The mining operations will consist of three separate mining pits to a maximum depth of 140 m bgl.

MWH (2005) carried out hydrogeological investigations which covered the assessment, design, implementation and ongoing water management related to the water supply, dewatering, water management issues and environmental impact assessment.

Current estimate of dewatering required for mining operations ranges between 4 GL/yr to 27 GL/yr, with an average of 10 GL/yr, over the life of the mine. A water surplus to requirement exists at this site with the approved initial surplus disposal option being discharge to the Kalgan Creek system some 16 km to the east or until Hope Downs 1 discharge to the environment to Weeli Wolli Creek ceases then the discharge will be directed to that area.

The Hope Downs 4 mining operations are located to the south of, and mining the same geological sequence as BHP Billiton Iron Ore's Coondiner project, however the operations are separated by over 30 km of relatively impermeable geological units.

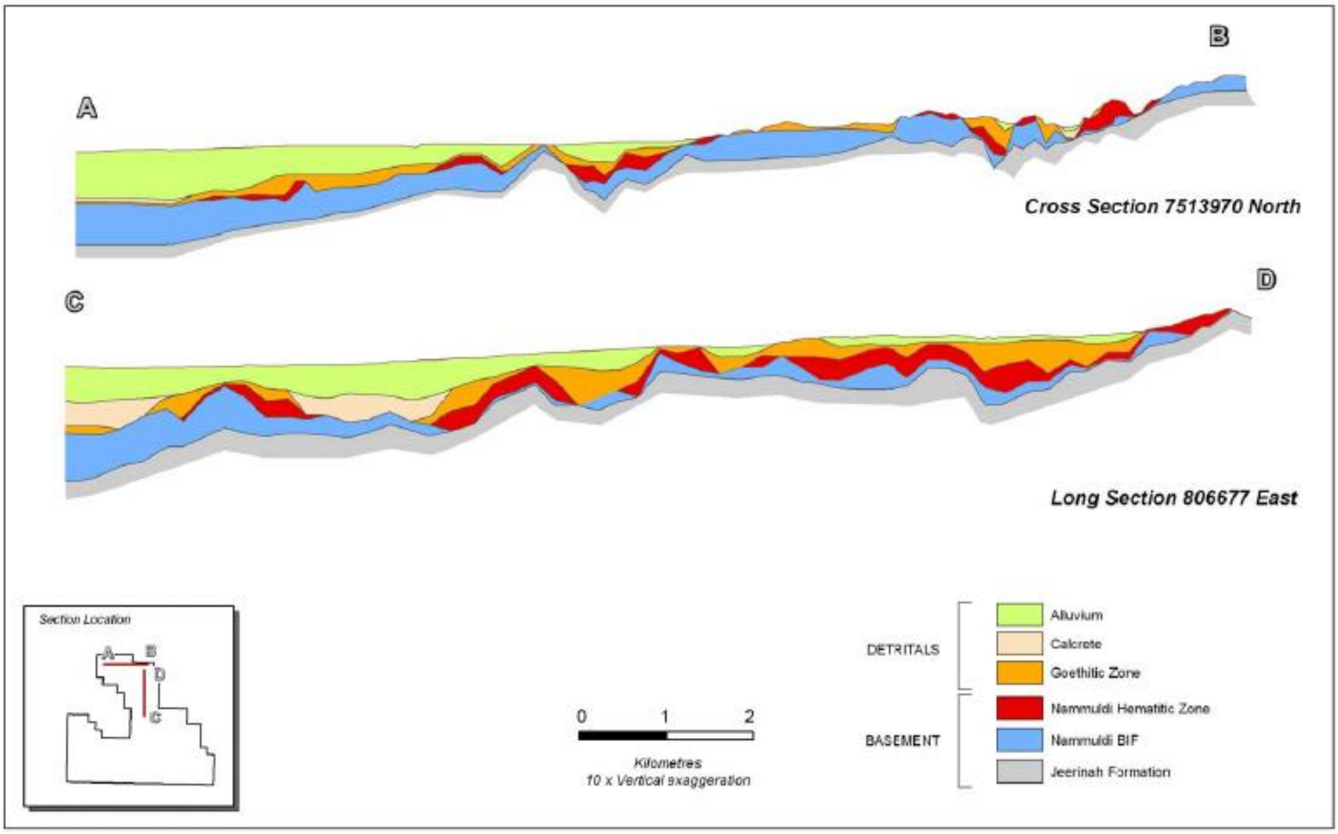

Figure 5-12: Typical geological cross-sections for RHIO Roy Hill project (after RHIO PER, 2009)

Hope Downs 4 conceptualisation

The surface water drainage paths through the Hope Downs 4 mining operations are in the headwaters of the Coondineer Creek the section of which 2.5 km long will be required to be realigned to bypass the mining and infrastructure at this site.

The un-mineralised sequence to the north and surrounding Hope Downs 4 behaves as a low-permeability barrier.

Mine dewatering is principally designed via down-dip ex-pit dewatering bores to ensure mining operations to depths of 140 m bgl can be sustained, with predicted dewatering rates approaching 27 GL/yr. A significant localised cone of depression is expected to develop within the mineralised orebody with minimal extension of the cone out into the low permeable bedrock.

6 Conclusions

The ecohydrological conceptualisation presented an understanding of the existing hydrological and ecological regimes in the vicinity of future BHP Billiton Iron Ore's mining and infrastructure development activities proximal to the Fortescue Marsh.

Based on the EHU development methodology, nine landscape ecohydrological units (EHUs) were defined within the study area. Based on an understanding of the existing environment, ecohydrological conceptualisations were developed for the two ecological receptors being the Fortescue Marsh and Freshwater Claypans (Figures 4-15 and 4-17).

Fortescue Marsh

The ecohydrological features of the Fortescue Marsh can be summarised as follows:

Surface and groundwater systems

- Inflows to the Marsh are dominated by the Fortescue River and Weeli Wolli Creek, contributing around 52% and 19% of mean annual inflows respectively. The catchment areas for these major drainages extend outside the study area. The remainder (29%) of inflows are from the catchments reporting directly to the Marsh.
- Flooding is generally associated with cyclonic rainfall and runoff in the summer months, with large-scale inundation events estimated to occur on average once every five to seven years. Inundation of east and west basins may be different for smaller events; however, large-scale inundation generally occurs across both east and west basins.
- Ponding in the Marsh is facilitated by the presence of relatively low permeability clay and silcrete/calcrete hardpans in the surficial sediments of the Marsh. More permeable material in the ponding surface is assumed to occur in some areas of the Marsh facilitating the seepage of flood waters into the sub-surface. It is postulated that most of the groundwater recharge within the Marsh occurs in these zones of increased (vertical) permeability; however on-ground investigations are necessary to confirm this.
- A shallow, unconfined aquifer is present within the upper surficial sediments. Groundwater levels range between 2 and 4 m bgl. The shallow watertable is maintained by a combination of flooding events, groundwater inflow, leakage from deeper confined units and evapotranspiration. Soil moisture within the Marsh is replenished by rainfall, and surface water and groundwater inflows. During flooding events, the watertable may locally increase but only for relatively short time.
- Deeper Tertiary sediments beneath the Marsh host a series of local-scale, variably connected aquifers, including clayey sequences that function as aquitards. Aquifer parameters are considered to be within the range of regional estimates.
- Calcrete of the Oakover Formation is an important part of the regional-scale aquifer characterised by generally high permeability and storage. It can be locally silicified or contain high iron contents forming silcretes and ferricretes. The unit is in direct hydraulic connection with the underlying weathered dolomite in the Wittenoom Formation. Evaporation from the shallow zone beneath the Marsh is the main mechanism of groundwater discharge.
- The Fortescue Marsh is an internally draining surface water and groundwater basin. Groundwater level contours suggest radial groundwater flow to the Marsh from the margins of the Fortescue Valley.
- Measurements of groundwater level dynamics during infrequent flooding of the Marsh are not available.
- The Marsh water balance is dominated by surface water contirbutions (Figure 4-1). The major mechanism of groundwater recharge of the shallow aquifer is seepage of floodwaters. The upper end of recharge estimates to the shallow aquifer during the major cyclonic eevents is in the order of 50 to 100 GL per event, consistent with temporary refilling of 1 to 2 m of the unsaturated zone. Groundwater throughflow to the Marsh from the greater Fortescue Valley is minimal in the shallow unconfined section due to limited overall recharge and low hydraulic gradients. Groundwater mounding associated with flooding events may temporarily and locally reverse hydraulic gradients in and around the Marsh (i.e. directions away from the Marsh).

- Groundwater throughflow from the deeper regional aquifer (calcrete and weathered Wittenoom Formation) is estimated to be approximately 28 GL/yr. Throughflow discharge through the Tertiary Detrital units is lost to soil evaporation and transpiration. The major surface water discharge mechanisms are direct evaporation of the post-flooding waterbody and exposed lake bed, and evapotranspiration from vegetated surfaces during interfloods.

Ecosystem components

- Much of the interior of the Marsh consists of sparsely vegetated clay flats within a series of low elevation flood basins. Vegetation recruitment may occur in these areas during dry phases; however, the frequency and depth of inundation events is a constraint to long term vegetation persistence.
- Fringing the lake bed areas are unique samphire vegetation communities including a number of rare flora taxa. Species zonation is evident and is considered to be a function of the combined stresses of seasonal drought, soil salinity, waterlogging and inundation. Structural complexity is provided by patches of *Muehlenbeckia florulenta, Muellerolimon salicorniaceum* and *Melaleuca glomerata*; the latter in particular may be important for providing roosting and nesting sites for waterbirds.
- Samphires exhibit conservative water use behaviour, and are probably reliant on pulses of fresh water associated with floods and stored soil moisture in the upper profile post-flooding. The flooding regime is likely to be a major factor influencing samphire recruitment and mortality.
- A number of fauna species with elevated conservation significance are present in areas fringing the Marsh including the Bilby (*Macrotis lagotis*), Northern Quoll (*Dasyurus hallucatus*), Mulgara (*Dasycercus cristicauda*) and the Night Parrot (*Pezoporus occidentalis*). The Marsh habitat may contribute to the foraging range of these species.
- The Marsh supports aquatic invertebrate assemblages of conservation interest, including species known only from the Marsh. Little is known of the ecological requirements of these taxa.
- The Marsh has not been sampled for stygofauna owing to a lack of bores located on the Marsh. However; subterranean fauna communities in areas adjacent to the Marsh are relatively poorly developed in comparison with other locations in the Pilbara.
- A number of persistent pools are associated with associated with drainage scours along the Fortescue River channel and other major channel inflows. These are probably sustained by storage in the surrounding alluvium following flood events. The pools could potentially function as refugia for some aquatic fauna species during interfloods.

Freshwater Claypans of the Fortescue Valley PEC

The key ecohydrological features of the Freshwater Claypans can be summarised as follows:

Surface and groundwater systems

- Surface water runoff from the surrounding catchments is attenuated in the internally draining low-relief landscape of the claypans. The estimated flooding frequency may be similar to the Fortescue Marsh and could range between 1 in 5 years to 1 in 27 years based on the hydrological analysis for the Marsh (Section 4.2). No information is available on flood levels/regimes that would be required to support the claypan ecosystems.
- Soil moisture in the shallow sediments of the claypans is replenished by a combination of rainfall and surface inflows.
- The ephemeral waterbodies of the claypans rapidly evaporate post flooding.
- Large floods exceed the storage volume of the claypans, and via flushing prevent significant accumulation of salts (in contrast with the Fortescue Marsh environment).
- Groundwater levels may range between 2 and 4 m bgl.
- Little is known of the hydrostratigraphy beneath the claypan surfaces. The claypans are assumed to be underlain by low permeability sediments, which may constitute a barrier to groundwater recharge and discharge. However, further investigations are required to confirm this.

Ecosystem components

- The expansive bare clay flats are fringed with Western Coolibah and tussock grassland vegetation communities. The Western Coolibah trees may rely on stored soil moisture replenished by flooding to meet their water requirements.
- The claypans support diverse aquatic invertebrate assemblages during flood events. Waterbody ephemerality, turbidity and connectivity with the broader Fortescue River floodplain may be key factors affecting the species composition. These factors will vary interannually and between seasons.
- The claypans provide foraging habitat for waterbirds, and may also provide breeding habitat for some species.

Stressors

BHP Billiton Iron Ore is planning to develop four potential mining areas adjacent to the Fortescue Valley in the future:

1. Marillana;
2. Mindy;
3. Coondiner; and
4. Roy Hill.

Marillana

The proposed BHP Billiton Iron Ore Marillana Iron Ore Project is located along and within the northern flank of the Hamersley Range, approximately 100 km northwest of Newman and 16 km northeast of BHP Billiton Iron Ore's mining area at Yandi. It is bound by Weeli Wolli Creek to the east, the BHP Billiton Iron Ore Yandi to Port Hedland Railroad to the west and the southern flank of the Fortescue Valley Basin to the north.

The Marillana mining tenement (ML270SA) covers an area of approximately 115 km^2. Included in the mining tenement are:

- Fourteen proposed pit areas (MA-A to MA-N);
- Eight associated mineral waste rock dumps (OSA) (MA-1 to MA-8);
- Three operational infrastructure areas (MI-1 to MI-3); and
- A proposed rail spur line connecting with the BHP Billiton Iron Ore's Newman to Port Hedland and MAC to Port Hedland railways located adjacent to the study area.

The proposed mine pits cover an area of approximately 31 km^2 within tenement M 270SA.

Mindy

The proposed BHP Billiton Iron Ore Mindy Iron Ore Project is located along the northern flanks of the Hamersley Range, approximately 60 km northwest of Newman and 30 km east of BHP Billiton Iron Ore's mining area at Yandi. It is bound by the Weeli Wooli Creek to the west, Mindy Mindy Creek to the east and the Fortescue Valley to the north.

The Mindy mining tenements (M47/710 to 717 and M47/725 to 728) cover an area of approximately 65 km^2. Included in the tenements are:

- Three proposed pit areas (MM-A to MM-C);
- Nine associated mineral waste rock dumps (OSA) (MM-1 to MM-9);
- Four operational infrastructure areas (MMI-1 to MMI-10); and
- A proposed rail spur line connecting with the BHP Billiton Iron Ore's Newman to Port Hedland railway located to the north of the study area.

The proposed mine pits cover an area of approximately 24 km^2 within the Mindy mining tenements.

Coondiner

The proposed BHP Billiton Iron Ore Coondiner Iron Ore Project is located along the northern flanks of the Hamersley Range and extending into the southern limits of the Fortescue Valley, approximately 50 km north of Newman and 40 km north of BHP Billiton Iron Ore's mining area at Mt Whaleback.

The Coondiner mining tenements (M47/718 to 724 and M47/729 to 731) cover an area of approximately 45 km^2. Included in the tenements are:

- Five potential mining pits (CO-A to CO-E)
- Six associated waste rock dumps (OSA) (CO-1 to CO-6)
- Three operational infrastructure areas
- A proposed railroad spur line that sits outside the Coondiner mineral tenements and connects to the existing BHP Billiton Iron Ore Newman to Port Hedland railroad has been planned.

The proposed mine pits cover an area of approximately 11.6 km^2 within the Coondiner mining tenements.

Roy Hill

The proposed BHP Billiton Iron Ore Coondiner Iron Ore Project is located along the southern flanks of the Chichester Range, approximately 250 km northwest of Newman and 25 km west of Fortescue Metals Group's (FMG's) mining area at Cloudbreak. It is bound by the Chichester Range to the north and the Fortescue Marsh and Goodiadarrie Swamp to the south. The deposits straddle the BHP Billiton Iron Ore Newman to Port Hedland railway.

The Roy Hill mining tenements (M45/1038 to 1065) cover an area of 261 km^2. Included in the tenements are:

- Eleven proposed pit areas (RH-A to RH-K) including:
  - RH-A to RH-F located within the Goodiadarrie Swamp catchment.
  - RH-G to RH-K located within the Fortescue Marsh catchment.
- Seven associated mineral waste rock dumps (OSA) (RH-1 to RH-7); and
- Ten operational infrastructure areas (RHI-1 to RHI-10).

It is anticipated that the existing Newman to Port Hedland BHP Billiton Iron Ore railway alignments and planned Chichester bypass route passing through the study area (Miscellaneous Licence L45/105 and L45/147) will be utilised.

Resource, hydrological and environmental assessment

All four project areas are at an early stage of exploration and resource definition. Ancillary investigations relating to likely water management needs are at an early stage. Resource, surface water, groundwater and ecological assessments undertaken by MWH have been based on available information, as summarised below.

- Of the four projects, assessment of the Marillana deposit is the most advanced. Work completed at Marillana includes:
  - the drilling and testing of one (1) test production bore, four (4) pilot holes converted to monitoring bores, forty (40) exploration monitoring bores drilled and cased to confirm aquifer presence and delineate aquifer extent. Testing of Falling head (13 bores), and constant head (15 bores) has been undertaken on the exploration monitoring bores to determine formation permeability values for various geological units.
  - Development of a conceptual groundwater model, followed by the construction of a numerical groundwater model.
- No hydrogeological or hydrological studies have yet been undertaken in the Mindy or the Coondiner project areas to date. Interpretations of the geological and hydrogeological features in the Mindy and Coondiner project areas have been made using available resource definition exploration drill data (GBIS) and information available in the public domain from similar types of deposits in adjacent areas.

- There is limited geological, hydrogeological and surface water information available for the BHP Billiton Iron Ore Roy Hill tenement. Investigations undertaken on adjacent projects along the Chichester Range provide confidence in local hydrogeology interpretations:
    - A total of 235 resource definition drillholes are reported within the BHP Billiton Iron Ore's GBIS data base for the BHP Billiton Iron Ore Roy Hill tenements, and provide a framework for establishing structure, geology, type of mineralisation and indicative depths of mineralisation.
    - Interpretations of the proposed mining areas have been made using available exploration data, geological maps and previous reports relating to nearby mining projects, such as FMG's Cloudbreak and Hancock Prospecting Pty Ltd's (HPPLs) Mulga Downs.

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Appendix A Data inventory and catalogue

This section describes the data compilation and collation effort in support of development of the Fortescue Marsh ecohydrological conceptualisation. Data have been sourced from publicly available records from past and on-going projects in the vicinity. These broadly include data from the following:

- Pre-feasibility and feasibility study reports
- Baseline studies
- Public environmental reports (PERs)
- Research publications
- Discrete data packages from BHP Billiton Iron Ore's projects (maps, bore logs, hydrochemical data, etc.)
- Department of Water (WA) online database
- Bureau of Meteorology online database
- Science Delivery Division of the Department of Science, Information Technology, Innovation and the Arts (DSITIA).

All data collected has been catalogued by discipline and custodial status of the data and compiled into the data catalogue: *Data catalogue*. The area disciplines and the custodians used in the data management system are shown below in Table A-1.

Table A - 1: Data Management System

Discipline		Custodian	
10	Hydrology, hydrogeology	BHP	BHP Billiton Iron Ore
20	Ecology	BRK	Brockman Resources Limited
30	Mining and mine closure	DEC	Department of Environment and Conservation
40	Heritage	DOA	Department of Agriculture
50	Environmental approvals	DOW	Department of Water
60	Geology, geomorphology, geochemistry, geotechnics	EPA	Environmental Protection Authority
70	Multidisciplinary	FMG	Fortescue Metals Group Limited
80	Ecohydrology	HPL	Hancock Prospecting Pty Ltd
		IOH	Iron Ore Holdings Ltd
		PIO	Pilbara Iron
		RIO	Rio Tinto
		RHI	Roy Hill Infrastructure Pty Ltd
		UWA	University of Western Australia
		WCP	Water Corporation
		VAR	Various

The volume of data available and collected permits a detailed review of only those data sets that are deemed relevant to this project. It is generally assumed that appropriate technical reviews, accuracy checks and verification of the data were completed prior to release into the public domain. As such, data review for the purpose of the compilation of the Fortescue Marsh ecohydrological conceptualisation has been limited to assessment of completeness and applicability of the data for the intended purpose.

Reports are available that describe partial aspects of the ecohydrology of the study area in adequate detail to inform the development of a regional conceptualisation.

Information used to develop the regional conceptualisation has been collated from multiple sources, as much of the information is localised with respect to specific mining projects and attendant surveys for the purposes of project approvals. For example, although these documents often discuss regional geology, the discussion is usually confined to the regional geology of the host range (i.e., either Chichester or Hamersley Range), or often limited to the likely extent of project-related impacts.

In addition to the publicly available data, much of the interpretation has been supplemented, where applicable, by intellectual knowledge acquired over the last 30 years of project work in the region by project team personnel, particularly Gary Clark (MWH).

Topography and drainage

A 5 m digital elevation model (DEM), commissioned by BHP Billiton Iron Ore was made available for part of the study area. The extent of this 5 m DEM is shown in Map A-01. This data greatly improves the accuracy of DEM processing required for the ecohydrological analysis of drainage related features. For the areas outside of the 5 m DEM extent, a 30m DEM was sourced from Geoscience Australia. The extent of this can also be seen on Map 2-01. These two surveys form a patchwork of topographical data across the study area which has been used as the basis for the topographical and draining interpretation for this study.

Climate

The closest Bureau of Meteorology (BOM) climate stations to the study area are in Newman and Wittenooom (Map 2-01) and their details are summarised in Table A - 2.

Table A - 2: Climate stations within the vicinity of study area

Gauge Number	Gauge Name	Managing Agency	Data Start	Data End
7151	Newman	BOM	01/01/1965	12/08/2003
5026	Wittenoom	BOM	30/10/1961	Present

To overcome the lack of historical climate data within the study area, other sources of data were investigated. Climate data was acquired from the Science Delivery Division of DSITIA. This data is referred to as SILO data and accesses a climate database containing synthetically generated data for Australia from 1889 to present. The length of these records is well suited to this study.

SILO data provides a daily historical time-series for specified locations. Eighteen locations across the study area were selected and climatic data sets were obtained for each of these locations. The location of these points is shown in Map 2-01. Climatic parameters extracted include temperature, rainfall, evaporation, radiation, vapour pressure, humidity, evapotranspiration, and sea level pressure.

Rainfall

To gain an understanding of the rainfall across the study area, rainfall data from stations within and immediately surrounding the study area was collected for both currently operating stations as well as closed stations. The location of these stations is shown in Map 2-01. The length and quality of rainfall records for each of these sites was evaluated, and is summarised in Table A-3.

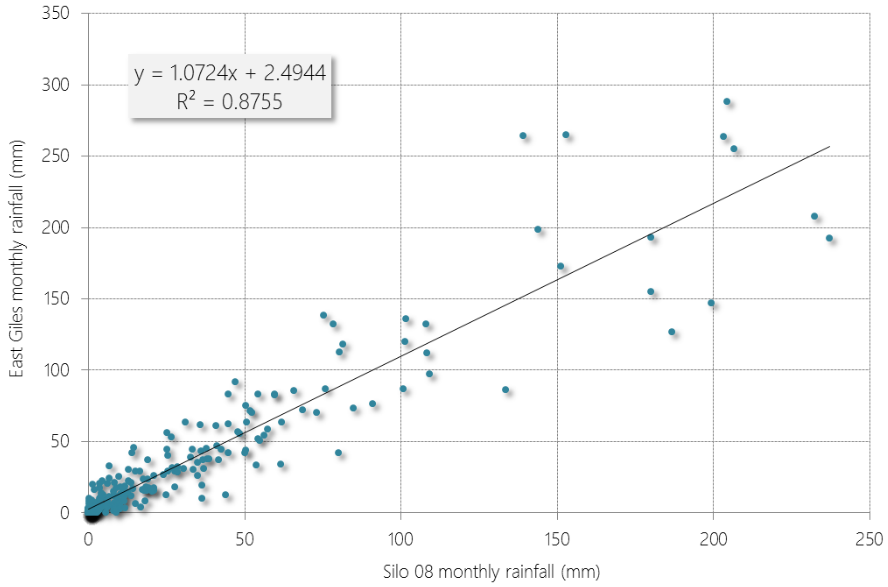
Table A - 3: Rainfall station summary

Gauge number	Gauge name	Managing agency	Data start	Data end	Record length	Data quality
13029	Billinooka	BOM	1960	1974	14 years	Not electronically available
13028	Walgun	BOM	30/10/1972	29-Dec-73	1 year	Not electronically available
13003	Jigalong	BOM	1/01/1913	9/01/1991	78 years	Good
7102	Murramunda	BOM	29/04/1915	29/12/1949	34 years	Good
7079	Sylvania	BOM	1/01/1950	1/03/2009	59 years	Average
7151	Newman	BOM	1/01/1965	12/08/2003	38 years	Good between 01/12/1965 - 31/08/1998
7176	Newman Aero	BOM	1/10/1971	30/06/1991	19 years	Good between 01/10/71 - 30/06/91
507005	Newman	DOW	8/02/1980	31/07/2013	33 years	Average
7172	Minderoo	BOM	1/01/1913	31/12/1931	18 years	Poor
5013	Minderoo	BOM	1/04/1912	31/05/2013	101 years	Poor
507009	Southern Fortescue	DOW	31/08/1980	21/05/2002	21 years	Average
507008	East Giles	DOW	1/01/1980	1/05/2002	22 years	Average
507007	South Giles	DOW	1/02/1980	1/05/2001	21 years	Average
507012	Wonmunna	DOW	28/11/1984	31/07/2013	28 years	Good
7169	Rhodes Ridge	BOM	30/01/1971	31/10/2011	40 years	Good between 01/02/1971 - 31/03/2003
505041	Waterloo Bore	DOW	1/07/1985	1/05/2013	27 years	Good
505040	Tarina	DOW	1/06/1985	1/04/2013	27 years	Good
505011	Flat Rocks	DOW	1/07/1972	1/01/2006	33 years	Good
5089	Packsaddle Camp	BOM	1/01/1989	30/06/2002	13 years	Good
505004	Munjina	DOW	1/02/1969	1/01/2004	34 years	Average
5003	Ethel Creek	BOM	1/01/1907	31/07/2013	106 years	Good up to 08/2003
505038	Poonda	DOW	1/01/1985	1/05/2013	28 years	Average
5064	Sand Hill	BOM	23/05/1971	31/07/1984	13 years	Good
5009	Marillana	BOM	1/12/1936	30/06/2013	76 years	Average
4026	Noreena Downs	BOM	1/01/1911	31/07/2013	102 years	Good
5025	Warrie	BOM	1/11/1927	31/05/1964	36 years	Good
5023	Roy Hill	BOM	1/08/1900	31/03/1990	89 years	Average
5047	Kediadary	BOM	1/01/1901	31/01/1910	9 years	Average

Although some of the stations show relatively extensive periods of data collection, most of the rainfall records are of a compromised quality, with periods of the records missing. This, together with the fact that the study area is extensive, does not provide a reliable understanding of long term rainfall across the study area.

To overcome the lack of data across the study area, rainfall data for each of the SILO locations (as described above and shown in Map 2-01) was obtained. Again, the length of this synthetically generated rainfall data is better suited to this study than the limited length of records from actual rainfall gauges in and surrounding the study area.

SILO rainfall data can, in some instances, reflect a higher number of wet days when compared to actual rainfall records. To ensure that the SILO data selected for this study was not overestimating the actual rainfall, it was correlated with actual rainfall records, for the same periods, for several of the gauges. Two such correlations are illustrated in Figure A-1, which shows a reasonably good correlation between the two data sets. Based on this relationship, as well as the fact that SILO provides good quality, long-term rainfall records across the entire study area, it was deemed appropriate that the SILO rainfall data be used for the purposes of this project.



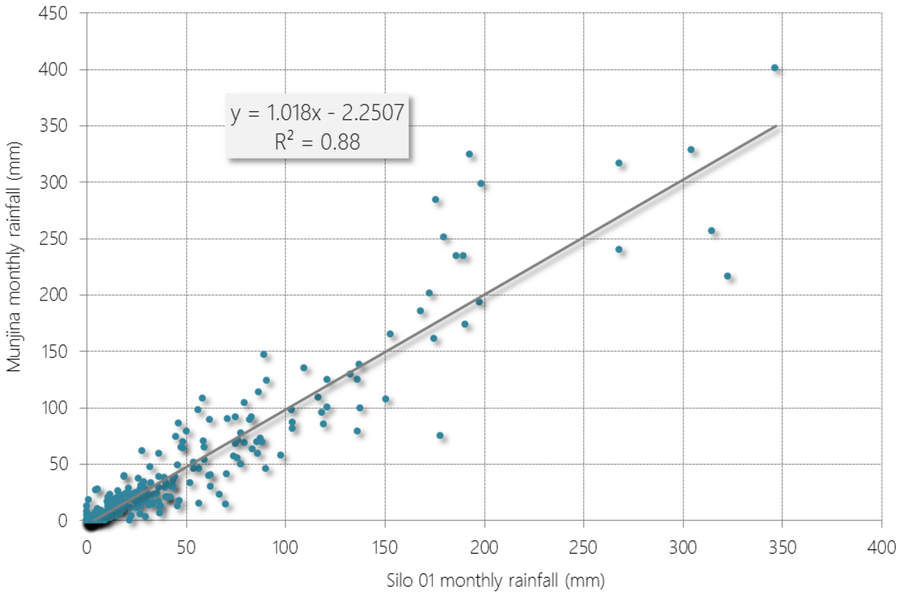


Figure A - 1: SILO vs recorded rainfall correlation

Geology and hydrogeology

Considerable information is generally available for the description of the geology, structure, hydrostratigraphy, regional water levels and hydraulic parameters in the northern portion of the study area, including the Chichester Range and northern reaches of the Fortescue Valley. A number of publications have been identified that contain valuable inputs for development of a conceptualisation for the study area. Locations of bores used to provide valuable hydrogeologic information for the area are presented in Map A-02.

The following documents provide relatively detailed and relevant information for the northern portion of the study area:

- 1:250,000 Roy Hill (SF50-12) and Balfour Downs (SF51-9) geological map sheets (Geological Survey of Western Australia);
- Hydrogeological Assessment for the Christmas Creek Water Management Scheme; FMG, October 2010;
- Hydrogeology Report for the Cloudbreak Public Environmental Review (PER); FMG, 2005;
- Stage 1 Public Environmental Review; HPPL Roy Hill, 2009.

Spatial coverage of data associated with Christmas Creek and Cloudbreak mine sites north of the Fortescue Marsh extends from the centreline of the Marsh to the interpreted surface water and groundwater divide within the Jeerinah Formation outcrops along the ridgeline of the Chichester Range. Hydraulic parameter data provided in the Christmas Creek hydrogeological report is based on testing of up to 25 bores completed in different stratigraphic units.

The following documents provide relevant information on geology and hydrogeology on the southern portion of the study area:

- Iron Ore Direct Shipping Ore Project – Referral and Supporting Information, FMG, 2012;
- Marillana Iron Ore Project – PER document, Brockman Resources, 2010;
- Koodaideri Hydrogeological Conceptual Model Report, Rio Tinto, 2013;
- Hydrogeological Investigation, BHP Billiton Iron Ore Marillana Iron Ore Project, BHP Billiton Iron Ore, 2012; and
- 1:250,000 Newman (SF50-10) and Robertson (SF51-13) geological map sheets (Geological Survey of Western Australia).

Spatial data coverage associated with project sites in the southern portion of the study area generally extends from the northern flanks of the Hamersley Range to the Munjina Roy Hill Road in the Fortescue Valley. The FMG (2012) report provides hydraulic parameter data derived from testing of a network of production and monitoring bores completed in different stratigraphic units within the Nyidinghu project area, which partly extends to the Fortescue Marsh. Water level contour maps are also presented and are based on data from monitoring bores within the Nyidinghu project area as well as a number of regional station bores within the Nyidinghu project area.

The recent Koodaideri report (Rio Tinto, 2013) includes preliminary drilling data (bore locations, water quality data) from site characterisation activities as well as surface and groundwater chemistry data within the Koodaideri Spring catchment.

In addition to descriptions of geology and hydrogeology in the above cited reports, stratigraphic bore logs have been collated from various sources and were used to create or update geological cross-sections along several transects across the study area. Data gaps in the spatial bore data are apparent, and these are discussed in more detail in Section 6.

Water level records were used to update water level contour maps. The current spatial coverage of the bore water level database is shown in Map A-03.

The level of detail and quality of the data is deemed acceptable for the intended purpose of providing informed inputs for development of a hydrogeological and ecohydrological conceptualisation. BHP Billiton Iron Ore has provided mineral resource definition geological data for the proposed mining areas – Roy

Hill, Mindy, Coondiner and Marillana prospects. In addition historical water bore drilling data was supplied by BHP Billiton Iron Ore for the Newman to Port Hedland railroad.

Geophysical data

Available geophysical data includes airborne transient electromagnetic (TEM) survey data reported in the Christmas Creek hydrogeological report (FMG, 2010) for assessment of spatial distribution of groundwater salinity at the watertable (Map 3-06). Spatial coverage included some 800 km^2 extending from the northern boundary of the Fortescue Marsh to the northern limit of saturated ore at Christmas Creek (which roughly coincides with the northern boundary of the study area), and from Christmas Creek in the east to Cloudbreak in the west. A TEM survey was also performed over the Cloudbreak mine area.

Airborne magnetics and airborne TEM surveys were also completed for the Roy Hill project to the west-northwest of the Marsh. The spatial coverage of the survey overlaps with the eastern edge of the study area.

Airborne magnetics and airborne TEM surveys were performed as part of the FMG Nyidinghu project and were used to define the extent of saline groundwater at 360m AHD (60 to 80 m below ground level at the proposed mine site) available in PER documents as shown in the data catalogue.

Hydrology

Surface Water

Historical flow data is available for one DoW streamflow gauging station within the study area - Waterloo Bore. An additional four streamflow gauging stations are located within the Upper Fortescue Catchment, within the sub-catchments reporting to the study area as shown on Map 3-01.

The quality of the data collected for each site varies and has therefore been used accordingly. Flow data and information, together with anecdotal evidence collated from reports as listed in the data catalogue, have supplemented the available data for these existing flow gauges and have informed our understanding of local and regional flow regimes.

Groundwater

Hydrochemistry data have been collated from a number of reports and data sources, and comprise the following:

- Bore water sample analytical results (typically major cations and anions), including samples collected during test pumping;
- Water quality parameters (pH, EC, temperature) collected during drilling and test pumping;
- Interpretation of salinity from airborne magnetics and TEM data; and
- Creek and surface water sampling, including creek pools (billabongs).

A hydrochemical database has been created by collating data from various reports and data sources, predominantly the Brockman Resources Marillana, FMG Nyidinghu, Christmas Creek and Cloudbreak project sites, and RHIO Roy Hill and also BHP Billiton Iron Ore’s Marillana project. Where reported, stratigraphic units or regional geologic formations within which the analytical samples were collected have been documented.

Salinity contours and profiles have also been generated for the above mentioned FMG and RHIO project sites, and the Brockman Resources Marillana and BHP Billiton Iron Ore’s Marillana projects at the southern extent of the study area. Spatial distribution of the hydrochemistry and salinity data is presented in Map 3-06 and Map A-04.

Data gaps apparent in the hydrochemistry data set are centred primarily on the region to the north-northwest of BHP Billiton Iron Ore Coondiner project towards the eastern edge of the Fortescue Marsh. Published geological maps indicate several station-owned bores within this region, and additional efforts to locate any existing data from those bores are on-going. There is also limited data for the Marsh itself, reportedly due to access constraints. Limited water quality samples are available for BHP Billiton Iron Ore railroad bores.

The three-dimensional element of groundwater quality data is under-represented. Most of the samples available are from a discrete interval within the bore. For ecohydrological purposes the most important samples appear to be from shallow groundwater although for mine dewatering purposes groundwater quality from deeper zones is equally important. The collection of samples portrayed on maps 3-04 and 3-05 is sourced from the shallowest horizon where feasible so that these are more suitable for ecohydrological purposes.

Data quality for most of the bores (as determined from ionic balance) is deemed to be acceptable (considering major cations and anions) as the majority of samples have ionic balances in the range of 5% to 10% or less.

From hydrogeochemical perspective the available samples typically do not report silica concentrations which could be an important parameter for hydrogeochemical modelling of groundwater chemistry evolution that involves important rock-forming silicate minerals.

Analyses of metals (where available) have been typically done after acid preservation but were not focused on determination of redox species (such as Fe^{III}/Fe^{II}, Mn^{IV}/Mn^{II}).

An additional hydrochemical dataset that also includes stable isotopes of ^{18}O and D has been recently published by Dogramaci and others (2012) and Skrzypek and others (2013).

Ecology

Land systems

The study area and surrounds was jointly surveyed by the Western Australian Departments of Agriculture, Land Administration and Land Information in the mid 1990's, as part of a wider rangeland resource survey for the Pilbara region (Van Vreeswyk et al. 2004). This included the delineation and description of land systems, broadly defined as "areas with a recurring pattern of topography, soils and vegetation". Over 100 land systems are recognised in the Pilbara region. Land system information is useful for broad scale assessment of surficial regolith characteristics (e.g. soil depth and composition), vegetation types and fauna habitat types. The land systems that occur across the study area are shown in Map 2-07.

The Pilbara land system mapping was principally based on interpretation of 1:50,000 aerial photographs, supplemented with other published data (*e.g.* geology, vegetation and previous land and soil surveys) and relatively limited field observations (Van Vreeswyk et al. 2004). This allowed the spatial extent of each land system to be defined. Descriptive information for each land system addresses:

- geology;
- geomorphology/landform;
- soils; and
- vegetation.

Within each land system a series of land units are described, including estimates of their proportional contribution to the land system spatial extent. Each unit is associated with ecological site types described according to their particular combination of topographic position, land surface, dominant plant species and vegetation formation.

Van Vreeswyk et al. 2004 also grouped the land systems into 18 land surface types according to a combination of more generic landforms, soils, vegetation and drainage patterns. This provides information more suitable for regional scale assessments.

Vegetation and flora

Considerable descriptive information for vegetation types and flora assemblages from sites within the study area is available. This has mainly been collected in association with mining and infrastructure projects. Over the past decade most surveys have been undertaken in accordance with EPA Guidance Statement 51, which provides minimum standards for different survey types (principally Level 1 and Level 2). The standards under which older surveys were conducted may be more variable.

At a broader scale vegetation was mapped at a scale of 1:1,000,000 in the 1970's (Beard 1975). The Beard (1975) mapping is available digitally, but in some cases may be offset from its true position. The land system mapping of Van Vreeswyk et al. (2004) is generally considered to better depict broad vegetation type boundaries.

Most survey reports include distribution maps for vegetation units and location data for species and vegetation communities of interest. Information relating to vegetation functional ecology (e.g., vegetation water use dynamics) is generally limited.

Fauna

The Pilbara Biological Survey was implemented in the period 2002-2007 to provide improved knowledge about the biodiversity of the Pilbara region in Western Australia. The Department of Parks and Wildlife (DPaW)[19] had a lead role in coordinating the implementation of the survey. Collation and interpretation of the survey data is ongoing.

The field component of the Pilbara Biological Survey included sampling relating to:

- Terrestrial flora and fauna;
- Aquatic ecology; and
- Subterranean fauna.

The locations of sampling sites are presented in Appendix B. Additional information about survey findings to date is published in Records of the Western Australian Museum, Supplement 78.

Terrestrial fauna

Considerable descriptive information for terrestrial fauna assemblages is available. This has mainly been collected in association with mining and infrastructure projects. Over the past decade most surveys were undertaken in accordance with EPA Guidance Statement 56 and associated guidance documents, which provide minimum standards for different survey types (principally Level 1 and Level 2). The standards under which older surveys were conducted may be more variable.

Most survey reports include information on habitat types (including their spatial extent) and fauna assemblages (species distribution and abundance). Information relating to fauna ecology is generally limited, although more in-depth assessments of the behaviour and habitat requirements of species of conversation significance are provided in some cases.

Aquatic fauna

The Pilbara Biological Survey included work targeting aquatic ecosystems. A summary of wetlands sampled in the survey is provided in the follo0wing publication:

- 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: 205–246.

A limited number of aquatic fauna assessments have also been completed, principally in association with Rio Tinto' Yandicoogina, Hope Downs and Koodaideri mining and infrastructure projects. Additional unpublished data is known to have been collected by mining companies in proximity to their project sites (e.g., Rio Tinto projects interfacing with the Weeli Wolli and Marillana creek systems). BHP Billiton Iron Ore has also commissioned a compilation of surface water assets in the Central Pilbara region by Edith Cowan University (Froend et al. 2013).

Subterranean fauna

Data relating to subterranean fauna (stygofauna and troglofauna) in the study area has been collated from the following sources:

- Technical reports, including publically available baseline environmental impact assessments (EIA) and monitoring reports;
- Published scientific journal articles;
- Western Australian Museum (WAM) subterranean fauna collection database; and
- Department of Environment and Conservation's (DEC) Threatened and Priority Ecological Communities (TEC's and PEC's) database.

The data sources relate to sites located within the study area as well as from neighbouring areas that are either within, or potentially connected with, the Fortescue valley system.

[19] Formerly the Department of Environment and Conservation (DEC)

Rare and Threatened Species and Communities

The DPaW maintains spatial databases of:

- Plant and animal taxa which are threatened with extinction (Declared Rare Flora and Threatened Fauna) represented spatially by point records;
- Plant and animal taxa that may be rare or threatened but for which there are insufficient survey data to accurately determine their status, or are regarded as rare but are not currently threatened (Priority flora and fauna) represented spatially by point records; and
- Threatened and priority ecological communities (TECs and PECs respectively), represented partially by buffered polygons.

Searches of DPaW databases were undertaken in July 2013 for Declared Rare Flora (DRF) and Priority Flora, Declared Rare Fauna and Priority Fauna, and TECs and PECs. Key findings are presented in Section 3.10.

Additional information on Rare and Threatened Species and Communities is contained in environmental impact assessment documentation for mining and infrastructure projects. This information is generally more detailed but is confined to conservation assets in specific study areas. Types of information include targeted surveys for particular species, more intensive and/or time series sampling programs, and impact prediction and assessment modelling. In some cases species records from these surveys may not be contained in the currently available DPaW databases.