Water resource assessment for the Pilbara

A report to the Government of Western Australia and industry partners from the CSIRO Pilbara Water Resource Assessment

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Pilbara Water Resource Assessment acknowledgments

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The project was led by a Steering Committee that consisted of Greg Claydon (DoW, Chair), Blair Douglas (BHP Billiton), Warwick McDonald (CSIRO), Gary Humphreys (DoW), Paul Vanderwal (Water Corporation) and Gus Tampalini (PDC). People who served on the Committee in early stages of the project were Patrick Seares (DoW, Chair), Hamid Mohsenzedah (DoW), Glen Walker (CSIRO), Keith Anthonisz (DRDL, PDC), Kevin Lee (PDC), Paul Trotman (PDC) and Richard Bairstow (PDC).

We acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.
As the leading iron ore mining region of Australia and the base of some of the nation’s largest offshore oil and gas fields, the Pilbara has been undergoing significant growth and development.

With this economic growth has come an increased demand for water to support industry and a growing population.

The Pilbara economy is dominated by the extraction, processing and export of minerals and gas. Industrial water use includes dust suppression associated with bulk handling of ore and other uses at the coastal ports of Port Hedland, Dampier, Cape Lambert and Ashburton, and oil and gas, salt and ammonium nitrate production.

The Pilbara is also home to a number of groundwater-dependent ecosystems and riverine pools, which have enormous ecological, Aboriginal cultural, social and tourism values, given that they occupy less than half of one percent of a semi-arid area in one of the hottest parts of Australia.

The Western Australian Government is committed to delivering a sustainable water future that provides certainty for business investment in the Pilbara, and supports the Pilbara Regional Investment Blueprint objectives and Pilbara Cities vision of Karratha and Port Hedland transforming into regional centres of 50,000 people. It is also working to use water availability to lift the productivity of irrigated agriculture and livestock in the region by expanding existing precincts and starting new ones under the $40 million Royalties for Regions funded Water for Food initiative.

To do this, we need the confidence to set out how much water is available to support the region’s growth, as well as to meet the environmental needs of the Pilbara’s surface water and groundwater resources and their dependent values.

To date, groundwater investigations, water allocation planning and water supply planning have been undertaken about the water available in the Pilbara to meet sustainable development objectives of Pilbara coastal towns and industry.

Water use in the Pilbara is dominated by mining, with current water abstraction for the mining sector estimated to be around 550 GL/year, with around 250 GL/year of this water used for ore processing, dust suppression, consumption and other purposes. Through Pilbara water supply planning work undertaken by the Western Australian Department of Water, projected total water demand for the Pilbara region is expected to more than double by 2042 under a medium growth scenario.

The Pilbara has a highly variable climate with rain coming mainly from unpredictable thunderstorms and tropical cyclones over summer. The historical records show that there can be long periods of drought when summer rains fail and there is no wet season.

Understanding how future climate scenarios may change climatic conditions and consequently alter surface water volumes and groundwater recharge is an important piece to the jigsaw puzzle that will enable sustainable and effective management of water in the region.

The Department of Water, the Pilbara Development Commission and BHP Billiton agreed to partner with CSIRO to do this work and continue building the knowledge base to underpin future water resource management in the Pilbara. CSIRO had been involved in similar assessments throughout Australia, including in the south-west of Western Australia, so a nationally consistent, but regionally calibrated, approach was taken in this assessment. Funding for the $3.5 million project came from $1.5 million contributions each by CSIRO and the State Government through Royalties for Regions, and $0.5 million from BHP.

A Steering Committee consisting of representatives from the Department of Water, Pilbara Development Commission, BHP Billiton, CSIRO and Water Corporation, and several specialist technical committees,
provided substantial guidance to CSIRO throughout the project which had an assessment area of almost 300,000 km².

The Pilbara Water Resource Assessment project required several innovative assessment methods to be used, including remote sensing methods for groundwater-dependent ecosystems, hydrological interpretations, landscape and water resources characterisations, updated numerical modelling and the latest climate science.

The assessment indicates that the Pilbara is likely to be even hotter in the future, while rainfall patterns will continue to be highly variable with no clear wetting or drying trends. Even so, the assessment has increased our understanding of the climate and the water resources of the region in an otherwise uncertain environment and with otherwise uncertain changes to the climate.

Among other things, the reports and products from the assessment will be valuable for future decisions about water supplies and allocations in the region, and for carrying out strategic water and environmental assessments for new mining and other developments.

As Chairman of the Steering Committee of partners, I recommend these reports to you. The information will be helpful to the management of water in one of the hottest, driest and most economically important regions of Australia.

Greg Claydon
Chairman, Pilbara Water Resource Assessment Steering Committee
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<tr>
<td></td>
<td>PDC: Lisa Mayne, Rebecca Jarvis, Water Corporation: Emily Hunter</td>
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Note: all contributors are affiliated with CSIRO unless indicated otherwise. Activity Leaders are underlined. Many members contribute to more than one activity but are only listed once.
## Shortened forms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AGC</td>
<td>Australian Groundwater Consultants</td>
</tr>
<tr>
<td>AHD</td>
<td>Australian Height Datum</td>
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<tr>
<td>ASRIS</td>
<td>Australian Soil Resource Information System</td>
</tr>
<tr>
<td>AWRC</td>
<td>Australian Water Resources Council</td>
</tr>
<tr>
<td>BHP</td>
<td>Broken Hill Proprietary Company Limited</td>
</tr>
<tr>
<td>BHPB</td>
<td>BHP Billiton</td>
</tr>
<tr>
<td>BIF</td>
<td>Banded iron formation</td>
</tr>
<tr>
<td>BoM</td>
<td>Bureau of Meteorology</td>
</tr>
<tr>
<td>CID</td>
<td>Channel iron deposits</td>
</tr>
<tr>
<td>CMIP5</td>
<td>Fifth Coupled Model Intercomparison Project</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>COAG</td>
<td>Council of Australian Governments</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
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<tr>
<td>DEM</td>
<td>Digital elevation model</td>
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<tr>
<td>DoW</td>
<td>Western Australian Department of Water</td>
</tr>
<tr>
<td>DRDL</td>
<td>Department of Regional Development and Lands</td>
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<tr>
<td>ECC</td>
<td>Eastern Clay Conglomerate</td>
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<td>EPA</td>
<td>Environmental Protection Authority</td>
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<tr>
<td>ET</td>
<td>Evapotranspiration</td>
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<td>GCM</td>
<td>Global climate model</td>
</tr>
<tr>
<td>GDE</td>
<td>Groundwater-dependent ecosystem</td>
</tr>
<tr>
<td>GVL</td>
<td>Goethite Vitreous Lower</td>
</tr>
<tr>
<td>GVU</td>
<td>Goethite Vitreous Upper</td>
</tr>
<tr>
<td>IOCI</td>
<td>Indian Ocean Climate Initiative</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>IPCC AR5</td>
<td>The fifth assessment report of the Intergovernmental Panel on Climate Change</td>
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<tr>
<td>LGC</td>
<td>Limonite Goethite clay</td>
</tr>
<tr>
<td>mBGL</td>
<td>Metres below ground level</td>
</tr>
<tr>
<td>MMBF</td>
<td>Marra Mamba Banded Iron Formation</td>
</tr>
<tr>
<td>MrVBF</td>
<td>Multi-resolution valley bottom flatness</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalised Difference Vegetation Index</td>
</tr>
<tr>
<td>NDWI</td>
<td>Normalised Difference Wetness Index</td>
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<td>PDC</td>
<td>Pilbara Development Commission</td>
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<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>-------------</td>
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<tr>
<td>PE</td>
<td>Potential evaporation</td>
</tr>
<tr>
<td>PHADI</td>
<td>Pilbara Hinterland Agricultural Development Initiative</td>
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<td>RCP</td>
<td>Representative concentration pathways</td>
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<td>RS</td>
<td>Remote sensing</td>
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<tr>
<td>Sacramento</td>
<td>A rainfall-runoff model</td>
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<td>SILO</td>
<td>Queensland Government Climate database</td>
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<tr>
<td>SIMHYD</td>
<td>Simulated Hydrology, a rainfall-runoff model</td>
</tr>
<tr>
<td>SIMHYDGW</td>
<td>A modified version of SIMHYD, with additional parameters for groundwater</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
</tr>
<tr>
<td>TDS</td>
<td>Total dissolved solids</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>WARMS</td>
<td>Western Australian Rangelands Monitoring System</td>
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<td>Water Corp</td>
<td>Water Corporation of Western Australia</td>
</tr>
<tr>
<td>WCH</td>
<td>Weathered CID Horizon</td>
</tr>
<tr>
<td>WRM</td>
<td>Wetland Resource Management</td>
</tr>
<tr>
<td>WW</td>
<td>Weeli Wolli</td>
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# Units

<table>
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<tbody>
<tr>
<td>L</td>
<td>litre</td>
</tr>
<tr>
<td>kL</td>
<td>kilolitre (1,000 litres)</td>
</tr>
<tr>
<td>ML</td>
<td>megalitre or 1000 kilolitres (kL)</td>
</tr>
<tr>
<td>GL</td>
<td>gigalitre or 1000 megalitres (ML)</td>
</tr>
<tr>
<td>M</td>
<td>metres</td>
</tr>
<tr>
<td>Km</td>
<td>kilometres</td>
</tr>
<tr>
<td>m³/second</td>
<td>cubic metres per second or ‘cumecs’</td>
</tr>
<tr>
<td>Ma</td>
<td>million years</td>
</tr>
<tr>
<td>mAHD</td>
<td>metres above Australian Height Datum</td>
</tr>
<tr>
<td>mBGL</td>
<td>metres below ground level</td>
</tr>
<tr>
<td>Mt</td>
<td>mega tonne</td>
</tr>
<tr>
<td>W/m²</td>
<td>Watts per square metre. A measure of radiative forcing which is affected by greenhouse gases</td>
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Executive summary

About the Assessment

The Pilbara Water Resource Assessment aims to provide an overview of the current and future climate and water resources of the Pilbara to aid water planning and management and place local studies into a wider context.

It covers an area of 288,479 km² which is about 11% of the state of Western Australia but it contains only about 3% of its population (Figure 1). It is one of the world’s most important resource regions because of high grade deposits of iron ore and offshore gas processing facilities.

This water resource assessment examined the surface water and groundwater resources and their environmental significance at a regional level to assist water resource planning. While often based on detailed, local-scale investigations from around mine sites, it provides broad-scale contextual information developed from these localised investigations. Mine precincts constitute less than 1% of the region but they affect water resources as most modern mining is taking place below the watertable. There is also increasing interest in assessing the suitability of the region’s freshwater resources for irrigated agriculture to complement its long history of stock grazing. This requires knowledge of the region’s water resources and soils as well as projections of its future climate.

There are five main Australian Water Resource Council (AWRC) river basins in the Assessment area; Ashburton River, Onslow Coast, Fortescue River, Port Hedland Coast and De Grey River. Adjacent parts of the west Canning Basin and Great Sandy Desert were included to cover the most prospective groundwater resource in the area as well as adjacent copper, gold and uranium mines.

This report provides an overview of the whole Assessment area. More detailed assessments are provided in separate reports on four regions: Ashburton Robe, Upper Fortescue, Lower Fortescue Hedland and De Grey Canning. There are also technical reports on climate, and the methods used in the assessment.
Key findings

Hydrological characteristics of the Pilbara

- In different catchments, between 14 and 30 mm per rain event is required to generate streamflow. Infiltration excess causes most runoff and this threshold is not expected to change much in future because it depends largely on soil and landform characteristics. Similar thresholds have been reported for diffuse recharge of fractured rock aquifers.
- Potential evaporation exceeds annual rainfall by 6 to 14 times yet freshwater is common throughout the Pilbara, indicating that the regolith is flushed in major events.
- Between 6 and 50 mm of rainfall becomes runoff annually, leading to relatively short durations of river flow (20 to 150 days per year, spread over about 3 to 5 events).
• Streamflow exceeds recharge volumes by five to six times. This difference is the result of very large flows during cyclonic events and tropical depressions exceeding the amount of water that can infiltrate during these events.

• Over 92% of rainfall is evaporated from plants and soil, the remainder either running off or becoming recharge.

• There are increasing linear trends of annual rainfall, extreme rainfall (e.g. 99th percentile daily rainfall), number of rainfall days and mean rain day intensity for the 1961 to 2012 period in the eastern half of the Assessment area, with opposing decreasing trends in the western third.

Water resources

• Groundwater is currently the main water resource in the Pilbara. Most aquifers are recharged by water infiltrating through streambeds during large rainfall events.

• Alluvial coastal aquifers, an important local drinking water supply, appear less sensitive to a hotter and drier climate because the reduction in recharge is considerably less than the reduction in runoff and number of flow days.

• The Wallal Sandstone is a valuable strategic resource as future drier climates are projected to have a limited impact on its potentiometric levels near the coast.

• Channel iron deposits and paleochannels contain important, and often underutilised, water resources, mainly recharged from overlying modern drainages.

• The potential of dolomite aquifers to provide long-term water supplies have not always been investigated in detail and they are highly variable in nature.

• Mineralised iron formations are significant local aquifers.

Climate change

• Rainfall results from both tropical and more temperate meteorological processes in the Pilbara making projections of future changes difficult because they vary in their response to higher concentrations of greenhouse gases.

• The 2030 and 2050 climate almost certainly will be hotter. While global climate models project both wetter and drier conditions, the drier projections are more extreme.

• Runoff is projected to reduce by between 39% and 61% under a dry future climate, increase by between 18% and 25% under a wet future climate and be within 10% of historical values under a median future climate.

• A 1% change in mean annual rainfall results in about a 3% change in mean annual runoff. Recharge, however, only changes by about 0.4% for a 1% change in runoff and flow days.

Groundwater-dependent ecosystems

• Due to climatic conditions, groundwater resources in the Pilbara have an important environmental value supporting multiple terrestrial ecosystems. Only a subset of GDEs were covered: terrestrial vegetation, river pools and springs.

• Groundwater-dependent terrestrial vegetation and river pools, marking groundwater discharge zones, occupy less than 0.5% of the Assessment area.

• A typology for groundwater-dependent ecosystems (GDEs) based on the type of groundwater resources supporting them was developed: regional aquifers, localised aquifers of various origins and groundwater systems which do not form aquifers. The sensitivity of groundwater to climate largely affects variations in the GDE’s area, greenness and wetness.
• Compared with other types, GDEs sustained by regional groundwater discharge are the least sensitive to climate variability. Their characteristics were constant between 1988 and 2011, except where GDEs were affected by groundwater extraction.

• GDEs sustained by groundwater discharge from local aquifers are sensitive to extreme climate variability, such as during 1990–1992 when annual rainfall was less than 200 mm and its low intensity limited recharge.

• The GDEs most sensitive to climate variability are those associated with groundwater systems which do not form aquifers (e.g. break–of–slope accumulations of water after rainfall, faults).

• The greatest variety of GDE types and variability between wet and dry periods occurs in the Hamersley Range. While GDEs expand in wet years and contract in dry years their numbers remain the same. While GDEs expand in wet years and contract in dry years their numbers stay the same.

Hydrogeological provinces

• Conceptual hydrological models and indicative water balances have been prepared for 13 hydrogeological provinces. The four most significant provinces are as follows:
  – The Granite Greenstone Terrane province has among the highest mean annual rainfall, runoff, rainfall-runoff ratio, streamflow and recharge of all provinces in the Assessment area; in part because of its size, but also because it is situated downstream of the Chichester Range and lies in the path of rain-bearing meteorological systems. It also has shallow soils and a relatively high drainage density.
  – The Hamersley Range province also has a high rainfall, but has relatively low runoff and rainfall-runoff ratios because it has high subsurface storage (paleovalleys including channel iron deposits, dolomite) and subsurface discharge to lower areas. It has a wide variety of GDEs, many of which are sensitive to climate variability.
  – The Lower Fortescue Valley province is underlain by a high transmissivity aquifer which buffers its hydrological response compared with other provinces. It has a high number of flow days but only moderate runoff and recharge. The main calcrete aquifer discharges through springs.
  – The Ashburton province has low rainfall, few aquifers and a low proportion of rainfall becoming runoff compared with other provinces. The aquifers within this province may receive some baseflow discharge from the adjacent Hamersley Range. Its main GDEs are river pools with associated alluvium which can be refilled by relatively low runoff events.

Overview of the Pilbara Assessment area

The Assessment area is located in Australia’s north-west with most lying just north of the Tropic of Capricorn (Figure 2). The main towns in the Pilbara are Karratha (population in the 2011 census of 16,475), Port Hedland (13,772), Newman (5,478), Tom Price (3,134), Paraburdoo (1,509), Pardoo (806), Onslow (667), Pannawonica (651) and Marble Bar (208). There were 7,210 Aboriginal people recorded in the 2011 census in the four main Pilbara shires, 12% of the Pilbara’s total population. Ashburton Shire had a 9.3% Aboriginal population, East Pilbara 17%, Port Hedland 15% and the most populous shire, Roebourne 9%. Transient worker accommodation beds in the Pilbara have been estimated to be 50,388, so the population at any one time is very variable.

The area is a world-leading iron ore province and also contains important deposits of gold, manganese, copper and uranium. It also provides on-shore support and processing areas for offshore natural gas deposits.

The main land uses are vacant crown land (55%), private grazing leases (25%), grazing leases managed by mining companies (5%), grazing leases managed by Indigenous groups (4%) and reserves for parks and wildlife (7%) or other purposes (4%). A very small area (0.03%) is privately-owned freehold land. Therefore the Western Australian Government manages almost all of the land and water resources in the area.
The Hamersley Range which is south of the Fortescue River contains three of the highest peaks in Western Australia, which are between 1128 and 1249 metres above sea level (Figure 2). The Fortescue River is contained to the north by the Chichester Range which is a major divide for rivers flowing north to the Indian Ocean. The area contains some of the oldest rocks in the world associated with greenstones and granites. Banded iron formations form extensive sedimentary deposits, most associated with the Hamersley Basin. Most iron ore deposits are associated with supergene mineralisation within the banded iron formations. Also of importance are those of the re-deposited detrital and channel iron deposits.

The Assessment provides an overview of the current and future climate and water resources of the Pilbara to aid water planning and management and to place local studies into a wider context.

![Figure 2 Surface elevation of the Pilbara Assessment area showing the Hamersley Range (green zone) between Newman and Pannawonica, the Fortescue River to the north and the Chichester Range which forms the headwaters of all north-flowing rivers](image)

**Historical and future climate**

The Pilbara is one of the hottest regions in Australia which creates a challenge for both industries and residents. Mean maximum temperatures exceed 35 °C between November and March with the lowest temperatures along the coast and in the Hamersley Range. Maximum temperatures are mild in winter (22 to 25 °C maxima).

Except where orographic rainfall occurs in the Hamersley Range, the area has a mean annual rainfall of less than 400 mm (Figure 3). There is a zone of higher rainfall inland from the north-east Pilbara coast which may result from evening thunderstorms generated from humid air brought in by daily sea breezes during...
the hottest months of the year. The higher rainfall on the coast in the north-east may be due to the influence from tropical monsoon and/or cyclonic activity as it is related to an increase in summer rainfall in the past 40 years. This wetting is starting to extend to the west Pilbara which has experienced a decline in its autumn and winter rainfall since the 1960s. Both factors are thought to result from meteorological systems expanding towards the south with winter cold fronts no longer extending as far north as the west Pilbara and tropical influences extending further south in summer. More details on factors affecting the climate of the Pilbara are in an accompanying technical report in this series.

Projected climate data for 2030 and 2050 were estimated from 18 global climate models (GCMs) under two greenhouse gas emission scenarios. The scenarios were compared against the historical climate, comprising the 52-year period between 1961 and 2012. A median future climate was estimated as well as wet (10% likelihood of being exceeded) and dry (90% likelihood of being exceeded) future scenarios to understand how the hydrology of the Pilbara may respond to these climates were they to eventuate. Scenarios were used because there is uncertainty in future climates making predictions unreliable.

The 2030 and 2050 temperatures are projected to be about 1.5 and 2.2 °C higher, respectively, than in the 1961 to 2012 period; which has a midpoint of 1988 (Table 1). Temperatures on the Pilbara coast have already increased by about 0.8 °C and 0.4 °C inland since 1970 and the rate of increase is projected to rise.

The 2030 mean annual rainfall ranges between an increase of about 3% (11 mm) and a decrease of about 13% (42 mm) (Table 1). By 2050 the range is projected to be between a 4.5% (15 mm) increase and a 17% (58 mm) decrease. Thus the estimates are weighted towards a decrease in future rainfall. Given the increase in temperature (resulting in a 3 to 7% increase in potential evaporation) all future projections suggest an increase in mean annual rainfall deficits (mean annual rainfall minus mean potential evaporation).

Unlike in south-western Australia, in the Pilbara there are some scenarios that show an increase in future rainfall, and the increased rainfall in recent decades may be the result of a changing climate. The performance of GCMs is poor when modelling cyclones and future cyclone frequency and intensity under
climate change is uncertain. An increased incidence of cyclones between 1995 and 2001 resulted in the Pilbara having an average 50% higher rainfall over this 7-year period. This period, and a dry period between 1988 and 1992, were used to infer how GDEs may respond to periods of consecutive wet and dry years in future.

Rainfall has increased in the east Pilbara since about 1960. The average annual rainfall in the 1990 to 2012 period is shown in Figure 4.

Table 1 Projected future temperature (top) and rainfall (bottom) in 2030 and 2050 under wet, median (mid) and dry scenarios and a median (RCP 4.5) and high (RCP 8.5) greenhouse gas emission scenario

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>SCENARIO C</th>
<th>RCP4.5 EMISSIONS SCENARIO</th>
<th>CHANGE (°C)</th>
<th>RCP8.5 EMISSIONS SCENARIO</th>
<th>CHANGE (°C)</th>
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<td>2030</td>
<td>C30wet</td>
<td>1.4</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>C30mid</td>
<td>1.5</td>
<td>1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>C30dry</td>
<td>1.6</td>
<td>1.8</td>
<td></td>
<td></td>
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<tr>
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<td>C50wet</td>
<td>1.8</td>
<td>2.1</td>
<td></td>
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</tr>
<tr>
<td>2050</td>
<td>C50mid</td>
<td>2.1</td>
<td>2.9</td>
<td></td>
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<tr>
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<td>C50dry</td>
<td>1.8</td>
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<table>
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<tr>
<th>PERIOD</th>
<th>SCENARIO C</th>
<th>RCP4.5 EMISSIONS SCENARIO</th>
<th>(%)</th>
<th>(mm)</th>
<th>RCP8.5 EMISSIONS SCENARIO</th>
<th>(%)</th>
<th>(mm)</th>
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<td>3.2</td>
<td>11</td>
<td>5.6</td>
<td>19</td>
<td></td>
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<tr>
<td>2030</td>
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<td>–14</td>
<td>–12.6</td>
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<td>2050</td>
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<td>15</td>
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<td>–2.5</td>
<td>–8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2050</td>
<td>C50dry</td>
<td>–5.9</td>
<td>–20</td>
<td>–17.4</td>
<td>–58</td>
<td></td>
<td></td>
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Note: RCP = representative concentration pathway
Analyses of rainfall and runoff in 22 catchments\(^1\) showed that between 8 and 30 mm of rain is required to initiate runoff and that runoff is mostly caused by rainfall intensity exceeding the infiltration capacity of soils rather than from soils becoming saturated. Soils dry rapidly between many events because the potential evaporation exceeds rainfall about six-fold in the Hamersley Range and up to 14-fold in the southeast. While the number of events that produce runoff may decrease in the dry future climate scenario, the amount of rainfall required to initiate runoff is not expected to substantially change. The threshold is affected more by topography and soils than the prior wetness of the soils in rainfall-excess processes.

Only 3% to 9% (or 6 to 50 mm) of mean annual rainfall becomes runoff in the Pilbara. Higher percentages of rainfall almost certainly run off in small headwater catchments with a lot of runoff infiltrating into streambeds and therefore failing to reach downstream gauging stations or the Indian Ocean (Figure 5). The De Grey catchment has the highest mean annual water yield (1167 GL/year). Rivers in the Ashburton, Robe and Fortescue River basins in the south and west of the Assessment area have runoff coefficients between 2% and 4% of rainfall, while rivers in the Yule and De Grey basins in the north and east have runoff coefficients between 7% and 13% of rainfall. The lower reaches of the Fortescue and Ashburton rivers’ gauges have a larger mean number of flow days than other gauges in the Pilbara.

Runoff is very variable in the Pilbara as indicated by a coefficient of variation (standard deviation x 100 / mean) of 56%. Changes in rainfall are amplified in runoff, such that a 1% change in rainfall results in a 2% to 4% change in runoff. This amplification, which is referred to as the elasticity of runoff to changes in rainfall, is consistent with values modelled in semi-arid areas elsewhere in Australia.

\(^1\) Estimates made for large hydrogeological provinces can give a slightly different range than those made for small sub-catchments.
Consequently under a wet future climate scenario (C50wet8.5) mean annual runoff is projected to increase by between 18 and 25% relative to the historical climate whereas under a dry future climate (C50dry8.5) mean annual runoff is projected to decrease by between 39% and 61% relative to this baseline. This is predominantly a reflection of the larger changes in rainfall under the dry scenario than the wet scenario. Runoff under the median future climate scenario was mostly within 10% of the runoff under the historical climate.

Relative to the historical climate, the mean number of days of flow per year is projected to increase under wet future scenario by between 12% and 20% and decrease by between 25% and 59% under a dry future scenario. It is within 10% of the historical value under a median future climate. The elasticity of recharge to changes in rainfall is considerably less than that modelled for runoff; where a 1% change in rainfall, on average, results in a 0.2% to 0.3% change in recharge.

There are two large surface water storages in the Assessment area: Harding Dam which supplies water to the West Pilbara Water Supply Scheme; and Ophthalmia Dam which provides water for recharge to aquifers near the town of Newman in the Upper Fortescue catchment. The projected mean annual streamflow in the Harding River catchment at the dam site under the historical scenario is 52 GL. Relative to the historical scenario, changes in mean annual streamflow under the future climate scenarios range from +16.5% (7.7 GL) under a C50wet8.5 scenario to –43.8% (–17.0 GL) under a C50dry8.5 scenario. The historical mean annual number of flow days in the Harding River is 114 days, which is projected to increase by 8 days under a wet scenario and decrease by 21 days under a dry scenario. Mean annual streamflow and mean annual number of flow days in the Harding River are not projected to change substantially under the median future climate.
Groundwater hydrology and resources

The high evaporation rates and variability in runoff in the Pilbara require surface water storages to be both large and deep to be reliable water supplies. Some areas, especially flat coastal areas where river discharge may be highest, also lack suitable dam sites. Groundwater is the main water resource in the Pilbara because of the high costs of building dams able to store water over several years and the ability to develop wellfields close to many water demands. Aquifers containing fresh groundwater are often overlain by rivers, and depend on episodic streamflow for recharge. Recharge resulting from direct rainfall (called diffuse recharge) is mainly significant for major aquifers in the west Canning Basin and to a lesser extent, the Carnarvon Basin. Elsewhere diffuse recharge is less important because evaporation rates are very high and soil profiles usually dry between events, requiring them to be re-wet each time. Many areas also contain rocky surfaces which shed water into streams where direct recharge predominates.

The main aquifer types in the Pilbara and their distribution are shown in Figure 6. The brown areas represent areas of bedrock of granite and metasediments which underlie the greater part of the Assessment area. It is generally poorly fractured, although useful supplies (e.g. 5–10 L/second) can be obtained with persistence and acceptance of a high failure rate for sufficient bore yields, and by targeting prospective rock types and fractures. Within the banded iron formation bedrock there are local mineralised...
zones within which high yields and limited groundwater storage can occur. These are important where mine dewatering is carried out. Groundwater within the banded iron formations usually has a low salinity and is discharged to the environment during mining, except adjacent to the Fortescue Marsh in the Chichester Range where saline water is reinjected.

The light green areas illustrate sandstone, volcanic, and sedimentary rocks in greenstone belts (ancient dark coloured igneous rocks and sediments). These rocks can have moderate yields where fractured. The dark green shows those areas where Proterozoic dolomite underlay valleys. Proterozoic dolomite can form good aquifers where dissolution has created karstic porosity. One example is at the Woodie Woodie manganese mine where water is dewatered from the underlying Proterozoic dolomite aquifer.

Undifferentiated sedimentary rocks in the north-east of the Pilbara include paleochannels of Permian glacials that can yield water of variable quality but are otherwise not very prospective. The Wallal Sandstone aquifer in the west Canning Basin is the major resource of low salinity water for the Assessment area. It is overlain by the more saline Broome Sandstone.

Inland valley aquifers and deeper paleovalley aquifers including channel iron deposits, calcrete and gravels are the most important local aquifers inland. The latter get recharged during streamflow with the paleovalley aquifer receiving water from the modern alluvial deposits in most cases. Surficial alluvial sediments associated with modern river valleys occur in coastal areas and constitute important water resources for coastal town water supplies. These coastal aquifers and the Canning Basin are the most easily investigated and utilised. As a result groundwater models were available and used as part of the Assessment to assess the impact of future wet and dry climate scenarios on groundwater levels and reliability of groundwater extraction.

The Canning Basin receives diffuse recharge from rainfall over the Great Sandy Desert in major events (Figure 6). A future drier climate is expected to reduce this recharge but the modelled impact on potentiometric heads in the coastal areas was small. The Canning Basin has been receiving increased rainfall in the past four or so decades but the cause of the increase in rainfall is still unclear.

The change in river recharge as a function of changes in runoff and flow days was estimated for five alluvial aquifers; Lower Robe, Lower Fortescue, Millstream, Lower Yule and Lower De Grey. This is a measure of sensitivity or elasticity. River recharge was found to decrease by 20% to 70% of both runoff and flow days. This may be due to large volumes of runoff discharging to the ocean in large events affecting the mean and runoff not having sufficient time to recharge in storm events or when aquifers near the stream are full.

The Carnarvon Basin in the most westerly coastal part of the Pilbara contains mainly saline groundwater (6,000 to 15,000 mg/L TDS), which is now being desalinated to produce freshwater for gas processing and Onslow town.
Groundwater-dependent ecosystems

Under Pilbara climatic conditions, groundwater resources have important environmental functions. As terrestrial GDEs (e.g. vegetation, springs, pools) ultimately mark groundwater discharge zones, their delineation and characterisation helps understand groundwater processes and their function.

The types of groundwater sources that support GDEs vary throughout the area; from large regional aquifers (such as hosted in sedimentary basins and dolomites) and localised aquifers (such as paleovalleys or mineralised BIF) to groundwater which doesn’t form an aquifer (such as thin alluvial systems or fault zones). A clear understanding of GDE typology in terms of hydrogeological setting greatly assists the decision-making process in groundwater management, as aquifer-dependent GDEs may be affected by groundwater abstraction.

GDE habitats were mapped based on consideration of geological, hydrogeological and hydrological settings; available information of mapped vegetation and their typical ecohydrological characteristics, and remotely-sensed data analysis. Vegetation was classified on the likelihood of its groundwater dependency: from highly dependent (i.e. high likelihood of GDE occurrence), to partly dependent (i.e. medium likelihood of GDE occurrence), to non-groundwater-dependent riparian vegetation (i.e. lowest likelihood of GDE occurrence). Some GDEs, particularly those with a high level of groundwater dependency (high likelihood)
were also associated with a persistent presence of water. Those areas were also classified according to the likelihood of water occurrence (Figure 7).

An assessment of historical GDE variability between 1988 and 2011, using over 1000 Landsat 5 images validated at more than 1000 locations, showed that throughout this period the areas identified as GDEs constituted less than 0.5% of the Assessment area. The majority of GDEs (but not all) are associated with the Pilbara’s current drainage network (Figure 8), where replenishment of groundwater resources can be enhanced by stream leakage during infrequent flow events.

Seasonal dynamics of remote sensing characteristics (greenness and wetness) of the majority of individual GDEs (such as pools or vegetation communities) remained relatively constant between 1988 and 2011. Although the total area of GDEs contracted in response to consecutive dry years (early 1990s) and expanded during consecutive wet years (late 1990s), identified GDE habitats were not lost and new GDEs were not created. This would indicate that GDEs in the Pilbara are relatively resilient to extremely dry periods of several years duration.

Where GDEs are highly dependent on groundwater (such as habitats of *Melaleuca argentea*), their characteristics (extent, greenness and wetness, derived from remote sensing analysis) were not dependent on climate parameters and they were not affected by the extreme dry period of the early 1990s.
Figure 8 Likelihood of groundwater dependency in the Pilbara Assessment area
Sensitivity of GDE characteristics to climate variability progressively increases when the likelihood of their dependency on groundwater reduces. Vegetation partly dependent on groundwater (such as some known habitats of *Eucalyptus camaldulensis* and to a less extent, *E. victrix*) was characterised as more sensitive to seasonal and inter-annual rainfall variability. It was also more affected by temperature, associated with shorter than seasonal time periods (preceding one or two months).

Where groundwater monitoring data were available, remote sensing indicated that the greenness of vegetation is largely unaffected by groundwater levels deeper than 10 m below ground. As there is evidence of some tree species being able to reach deeper groundwater, such observations indicate that groundwater in such cases is unlikely to be the dominant source of water, used by vegetation and influencing vegetation productivity.

In contrast with other riparian vegetation not dependent on groundwater, GDEs were also insensitive to both seasonal variations in river flow and individual flow events.

Significant changes in ecohydrological conditions (e.g. reduction in rainfall intensity or groundwater abstraction) manifested in delayed change in GDE greenness. The delay was between 2 to 3 years following the initial impact. Effects on GDE wetness are more immediate.

The area of GDEs in the Coastal Plain, Chichester Range, Lower Fortescue, Oakover and Granite Greenstone Terrane hydrogeological provinces varied by a factor of 2 to 3 between 1988 and 2012. GDEs in the Hamersley Range varied up to six-fold over the same period. This province contains the most types of GDEs with a large proportion associated with non-aquifer groundwater dependency, which are particularly sensitive to climate variability.

### Hydrogeological provinces

Provinces were defined so that discrete, local information on climate, surface water hydrology, groundwater hydrology and GDEs could be integrated, enabling trends and patterns to be identified, analysed and discussed across the entire Assessment area. Hydrogeological similarity was adopted as the basis for defining provinces due to the strong correlation between topography, geology and hydrology in the Pilbara (Figure 9). Thirteen hydrogeology provinces were defined for the Pilbara and the following information was generated for each one:

- a conceptual hydrological model for the area, depicted using schematic cross-sections
- water balance estimates of rainfall, runoff and recharge, estimated using the SIMHYDGW model.

Information on the most important water resource features in each province are summarised below.
Ashburton Hydrogeological Province

This is the largest province (20% of the Assessment area) but it lacks currently-identified major water resources because it has the lowest rainfall of all provinces, and most bedrock has a low permeability or weathers to form clay-rich material. Few groundwater investigations have been carried out because of a paucity of mineralisation so the potential of known dolomite and sandstone formations to produce water has been little evaluated. One sub-catchment has significant modelled recharge which may relate to these prospective aquifers. The main land use is pastoral grazing of native grasses within mulga scrub with water for stock pumped from fractures in hard rocks or available from persistent waterholes. GDEs are located along major drainage lines and seem able to withstand consecutive dry years, possibly because only small amounts of runoff are required to fill the shallow alluvial aquifers and waterholes. Under a future dry climate, runoff may decrease by 57% but recharge by only 6%.

Granite Greenstone Terrane Hydrogeological Province

This rainfall province (17.6% of the Assessment area) lies in the main path of cyclones, tropical depressions and thunderstorms. It has the largest annual runoff, streamflow and estimated recharge of all 13 provinces, with streamflow exceeding recharge by about seven-fold. Groundwater resources are limited to alluvial aquifers and fracture zones in greenstones. Located within this province is the Harding Dam (64 GL capacity, 45 GL supply capacity due to water quality issues) which together with Millstream aquifer supplies water to the West Pilbara Water Supply Scheme. A future dry climate may result in a reduction of inflows to the dam, increasing the risk that the dam may not be able to reliability meet demand.
Hamersley Range Hydrogeological Province

This high rainfall, elevated province (15.4% of the Assessment area) has relatively low mean annual streamflows because its valleys are often underlain by permeable aquifers comprising paleovalleys (including channel iron deposits) and karstic dolomite. Runoff and mine dewater discharges into alluvial fans at the break-of-slope within the Upper Fortescue Valley. Mineralised zones within fractured rocks also contain locally important groundwater supplies for mining operations. The province contains the highest number of different types of GDEs. The total area of GDEs in this province was measured to vary by six-fold between wet and dry years. Under a future dry climate, runoff may decrease by 53% and recharge by 23%.

Canning Basin Hydrogeological Province

This province (11.3% of the Assessment area) contains the Wallal and Broome sandstones, two regionally significant aquifers. It is unusual in that the province contains extensive water in these largely unconsolidated sandstones and most recharge comes directly from rain falling in the Great Sandy Desert in large, often cyclonic events rather than from infiltration through streambeds as is the case in most other provinces. The province also contains areas of brackish to saline groundwater which supports GDEs along the coastal fringes. Modelling indicates a drier future climate may only have a small impact, possibly because of the large distance between the recharge and discharge zones creating long lag times and the Wallal Sandstone being confined. Rainfall in this area has been increasing over the last four decades, possibly as tropical climate systems extend further south.

Paterson Hydrogeological Province

This province (9% of the Assessment area) located in the south-east of the Pilbara is characterised by not having any external drainage and groundwater being more saline than in most other provinces (with the exception of the Carnarvon Basin province and the Fortescue Marsh). Assessments of groundwater have been made around mineral deposits – gold and copper at Telfer, uranium at Kintyre and copper at Nifty. Productive groundwater is associated with paleodrainages filled with sediments of Permian and Cenozoic age. Telfer groundwater supplies are principally derived from weathered rock and karsts in the Proterozoic Puntapunta Formation. Groundwater-fed playa lakes are the main GDE in this province.

Oakover Hydrogeological Province

This province (7.6% of the Assessment area) forms around the valley of the Oakover River, the main tributary of the De Grey River. Several aquifer types and GDEs are associated with the river alluvium, paleovalleys and dolomite formations. The area of vegetation considered to have some dependence on groundwater comprises less than 0.5% of the area. However, the total area of GDEs can vary on a decadal basis by more than three-fold as a result of intra-decadal differences in rainfall. Under a future dry climate, runoff may decrease by 41% and recharge by 24%.

Chichester Range Hydrogeological Province

While relatively low in elevation, this province (6.9% of the Assessment area) forms a very important watershed for north-draining rivers in the Assessment area. It has a higher mean annual runoff (18 mm/year) than the much more elevated Hamersley Range (12 mm/year) because valleys are incised and they are underlain by relatively low permeable material. Local aquifers are associated with mineralised zones in the Marra Mamba Iron Formation. Groundwater salinity increases with proximity to the hypersaline Fortescue Marsh. Under a future dry climate, runoff may decrease by 39% but recharge by only 10%.
Upper Fortescue Valley Hydrogeological Province

This flat, low-rainfall province (3.5% of the Assessment area) has relatively little runoff and recharge to its underlying aquifers, which are mainly modern alluvium and paleochannels, but include dolomite in the lower reaches. The hypersaline Fortescue Marsh is considered to be an important ecological asset in the Pilbara, supporting abundant bird life when flooded. The spatial extent of GDEs appears to be relatively stable, even over consecutive dry and wet years. Under a future dry climate scenario, both runoff and recharge are modelled to decrease by 40% to 50%.

Carnarvon Basin Hydrogeological Province

In this province (2.5% of the Assessment area), the large Carnarvon Basin extends into the west of the Assessment area where it underlies the flat coastal plain which contains modern alluvial deposits. Within the shallow alluvium of the Cane, Robe and Lower Fortescue rivers is fresh groundwater, which has local importance. Within the Birdrong Sandstone, saline confined groundwater is being desalinated to supply water for gas processing and Onslow town.

Coastal Plain Hydrogeological Province

In this province (1.8% of the Assessment area), water within the Yule and De Grey rivers recharges underlying alluvial aquifers and paleochannels, from which freshwater is pumped to supply the East Pilbara Water Supply Scheme. Modelling of the systems, as well as the Robe and Lower Fortescue alluvial systems, indicates that recharge will reduce by 20% to 70% the reduction in runoff and in the number of flow days. Excess runoff is discharged to the Indian Ocean so a future drier climate will not have as large an impact on water supplies as may be expected from projected changes in runoff.

Lower Fortescue Valley Hydrogeological Province

This small province (1.7% of the Assessment area) has several unusual features associated with its calcrete aquifer which buffers changes in river flow and recharge under most wet and dry climate scenarios. Groundwater modelling indicates that groundwater levels remain less affected by low rainfall periods and extraction than would be expected in less transmissive systems. The province contains valuable GDEs associated with Millstream pools which remote sensing has shown to have remained relatively stable between 1988 and 2012. The Millstream aquifer supplies water to the West Pilbara Water Supply Scheme.

Sylvania Dome Hydrogeological Province

This province (1.6% of the Assessment area) is associated with granitic plutons and mainly thin sandy aquifers although there is at least one major paleovalley containing groundwater which is recharged via streambed infiltration during infrequent runoff. Median annual streamflow is currently estimated to be about 28 GL/year and recharge 3 GL/year. If the future climate is appreciably drier, runoff may halve and recharge may decrease by about a sixth – a common response given leakage from streambeds in dry periods is projected to be high. As in many of the provinces, GDEs associated with modern drainages appeared to contract during low rainfall years but recovered without permanent loss in extent (if not species) when conditions become wetter.

East Upper Fortescue Hydrogeological Province

Relatively little is known about the water resources in this small inland low-rainfall province (only 1.2% of the Assessment area). The volcanic and clayey sediments that comprise the bedrock do not form aquifers. Modern alluvium is very thin. Pastoral bores rely on fractured rock aquifers.
Basis for the Assessment

Weather observations were more plentiful and widespread in the 1950s and 1960s when there were sheep stations throughout the Assessment area. More recently, mining companies have been recording climate data (e.g. from Telfer) and streamflows at some mine sites. However, these latter monitoring data are not yet long term and may not have the longevity of gauging in the past if they cease when mining moves or ceases altogether. Long-term surface water gauging is especially limited outside the Granite Greenstone Terrane Hydrogeological Province.

Groundwater and GDE investigations are numerous and intensive at only a few locations as evidenced by reports to environment and water regulators. The most significant investigations are of groundwater resources in the West Canning Basin. Information and understanding in this area is changing rapidly.

The Assessment has used the available long-term data and specific studies to draw a regional picture to put more intensive studies into a broader context. Schematic cross-sections and estimated water balances are indicative only and groundwater systems are particularly complex and varied. These generalised relationships should therefore be used with appropriate caution. This is a regional assessment and should not be used for local decision making.

Satellite remote sensing is a cost-effective monitoring tool that could be used more systematically and extensively in the Pilbara, with digital aerial photography playing a role in intensively managed areas. This requires cross-company and government coordination to get economies of scale and consistency of data collection and analysis.
1 Introduction

Authors: Don McFarlane and Geoff Hodgson

1.1 Background

The Western Australian Department of Water developed a regional water plan for the Pilbara (DoW, 2010a, 2010b) which summarised the regional hydrological resources and recognised the possibility of either a drier or wetter future climate in the Pilbara in contrast to the more certain drier future climate in the south-west. Uncertainty about the future climate can affect planning and regulatory decisions. This Pilbara Water Resource Assessment (the Assessment) was developed to provide a comprehensive analysis of the Pilbara’s historical climate and hydrology and the potential future effects of climate at the regional scale.

A 2013 groundwater allocation plan for the Pilbara set allocation limits and management rules for target aquifers – alluvial and sedimentary – and set a policy framework for fractured rock areas (DoW, 2013). This plan focused on the key water resources likely to support development. The plan was based on over 3 years of scientific investigation and groundwater modelling of key aquifers required to help meet current and future water demands. It estimated future climate impacts by scaling the historical climate record. Through the Assessment, future planning and allocation decisions will be progressively refined using improved climate information from global climate models (GCMs) as developed through the latest work by the Intergovernmental Panel on Climate Change (IPCC, 2013) and from further analyses of historical hydrological data from both private and public reports and databases.

In recent years, iron ore mining companies have been asked by the Western Australian Environmental Protection Authority (EPA) to assess the likely cumulative impacts of discharging dewatering flows into rivers and aquifers when mining below the watertable. The EPA also requires individual companies to estimate long-term impacts of mining and mine closure on the hydrology of areas and dependent ecosystems, often up to 2030 or 2050. In discussions about the Assessment, the EPA expressed a desire for there to be standardised methods for assessing hydrological impacts of different mining operations in these future years, as well as a better understanding of the cumulative impacts of mine development.

Independent of regulatory requirements, mining companies are involved in carrying out Strategic Environmental Assessments under either the Western Australian Environmental Protection Act 1968 or the Commonwealth Environmental Protection and Biodiversity Conservation Act 1999. This requires a landscape and regional scale approach for evaluating relationships between climate, surface water hydrology, groundwater hydrology and groundwater-dependent ecosystems.

In 2010 the Western Australian Department of Water approached CSIRO to conduct a water resource assessment of the Pilbara similar to that which had been jointly carried out in the South-West Western Australia Sustainable Yields Project (CSIRO, 2009a, 2009b, 2009c) and in the Northern Australia Sustainable Yields Project (CSIRO, 2009d). In these projects, CSIRO used the best available estimates of future climates (including extrapolations of historical and recent climates) and changes in development, to estimate potential surface water and groundwater yields in 2030 on a catchment and aquifer basis. This determined the sensitivity of water resources to climate and developmental drivers and indicated whether future water demands (environmental and consumptive) could be met. These projects produced models and methods that have been subsequently used for water and development planning. When the ideas for the Assessment were being developed, the projected demand for water exceeded the long-term reliable water supply for the West Pilbara scheme and it was approaching the reliable water supply in the East Pilbara (DoW, 2010a). Water demand in coastal centres in both the West and East Pilbara water supply schemes
have since been met by increased allocation limits and additional supplies becoming available, and by increased efficiencies in dust suppression and residential water use. Projected demands have not been realised and so considerable pressure has come off these schemes.

There has been increasing Western Australian government interest in developing irrigated agricultural industries in the Pilbara to utilise mine dewater and also water resources that have been identified while looking for supplies to meet drinking water needs in the East Pilbara especially (Water Corporation, 2012; DAFWA, 2014). The Assessment can provide input to assessments of future water supplies for agriculture.

The Assessment therefore aims to meet a number of different objectives held separately or jointly by state government departments, water service providers, mining companies and environmental agencies. Because there are uncertainties about the future climate of the Pilbara, scenarios that include base cases of extensions of the past climate sequences are included in the Assessment as well as current best estimates coming from the Intergovernmental Panel on Climate Change’s Fifth Assessment Report (IPCC, 2013) and the Indian Ocean Climate Initiative’s third phase (IOCI, 2012). Given that a future climate signal may not be clear in the Pilbara, and previous analyses of the historical climate and hydrology have been limited, the Assessment includes analyses of how the region’s hydrology has responded to past climate variability.

Given the regional nature of the Assessment it is only possible to consider how plant communities may respond to a future climate rather than impacts on specific species. Potential impacts on stygofauna which inhabit many aquifer systems in the Pilbara are not covered in the Assessment.

1.2 Geographic scope

While deciding the geographic scope of the Assessment, the following were considered:

- Australian Water Resources Council (AWRC) Drainage Basins 706 to 710, inclusive
- the area covered by the Pilbara Groundwater Allocation Plan (DoW, 2013)
- the area likely to provide water to the Onslow, West Pilbara and East Pilbara water supply schemes
- areas with adjacent mining activity.

A combination of these was agreed as shown in Figure 1.1, which comprises an area of 288,480 km².

The Assessment area falls into seven local government areas, the four main ones being the Shire of East Pilbara (shire office located in Newman, population 8,113), the Shire of Ashburton (Onslow, 6,730), the Town of Port Hedland (Port Hedland, 14,624) and the Shire of Roebourne (Karratha, 19,143). Small parts of the shires of Upper Gascoyne, Meekatharra and Broome extend into the Assessment area but there are no towns within these local government areas inside the boundary.

For reporting reasons the Assessment area has been divided into four regions (Figure 1.2):

1. The Ashburton Robe region (94,043 km², 32.6% of total) covers the major drainage lines in the southern Pilbara including the towns of Onslow, Pannawonica, Tom Price and Paraburdoo.
2. The Upper Fortescue region (29,791 km², 10.3% of total) was considered a separate area for reporting because of its inland location, its importance for iron ore mining, and the fact that the Upper Fortescue catchment does not discharge into the Lower Fortescue because the Goodiadarrie Hills create a barrier to river flow. Newman is the main town in this region and there are several mining encampments.
3. The Lower Fortescue Hedland region (54,304 km², 18.8% of total) includes coastal drainages that discharge from the Hamersley and Chichester ranges. This region includes all of the water supplies for the West Pilbara Water Supply Scheme which provides water to Karratha, Roebourne, Wickham and Dampier. The region also includes Port Hedland town site and the Yule borefield which provides water to the East Pilbara Water Supply Scheme.
4. The De Grey Canning region (110,331 km\(^2\), 38.3% of total) includes the De Grey catchment which drains the granitic Archaean shield component of the Pilbara Craton and the southern parts of the Canning Basin and Great Sandy Desert. The main towns are Marble Bar and Nullagine. The region extends into the Great Sandy Desert to include mining interests in Woodie Woodie, Nifty, Telfer and Kintyre.

![Map of the De Grey Canning region with towns, main rivers, and local government areas](image)

**Figure 1.1** Assessment area in relation to towns, main rivers and local government areas
1.3 Objectives

The overall objective for the Assessment is to provide an authoritative analysis of current and future water resources of the Pilbara for use by state government agencies, water service providers and mining companies in water and land planning. This report analyses data from the entire Pilbara Assessment area.

The overall approach of the Assessment includes:

1. analysing and reporting on historical climate and hydrological trends
2. defining different climate scenarios (wet, median and dry) and generating time series of climate data to describe these scenarios
3. spatio-temporal modelling of the implications of these climate scenarios for catchment runoff and aquifer recharge
4. propagating the runoff/recharge implications through river and groundwater models including explicit consideration of the surface water – groundwater exchanges

5. assessing and reporting the findings so that they may be used to estimate current and future water resources by water managers and industry stakeholders.

1.4 Assessment reporting

This report is one of a series of reports that forms the Pilbara Water Resource Assessment (Table 1.1). The series includes technical reports (for a technical audience), regional reports (for a well-informed stakeholder audience), and summaries and factsheets (for a general public audience). The executive summaries of the regional reports (including the Assessment area report) are substantially the same as their respective summary reports.

In addition to reports, the Assessment has developed a number of datasets on future climate, hydrology and environmental variables in a format that takes account of their accessibility and usefulness for later use. Other outputs include new and updated rainfall-runoff and groundwater models. Wherever possible, generalised relationships have been developed to help explain the region’s water resources. Although representative of broad patterns and trends, these generalisations may not be valid under all circumstances.

Table 1.1 Reports that comprise the Pilbara Water Resource Assessment

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1.5 Report structure

An overview of the Pilbara Assessment area, including topography, climate, soils, geology, vegetation and land use is provided in Chapter 2 (Figure 1.3). This chapter also introduces the concept of hydrogeological provinces which is a means of unifying background material and new findings from the report. Chapter 3 outlines future possible climate scenarios in the Assessment area. The surface water hydrology of the Assessment area is analysed in Chapter 4, including a review of past work and rainfall-runoff modelling. Groundwater resources are identified and analysed in Chapter 5. This chapter also includes estimates of recharge to alluvial aquifers and analyses of groundwater models under historical and future climate scenarios. Remote-sensing methods are used to identify groundwater-dependent ecosystems and their trends in recent decades in Chapter 6. The information of the preceding chapters is integrated in Chapter 7 where the analytical results from chapters 4, 5 and 6 are assembled into the hydrogeological province framework.

The Executive Summary outlines the most important points from the Assessment but doesn’t include all conclusions for the sake of brevity and readability. Some conclusions are based on detailed analyses contained within the climate and four regional reports, which should be read by readers wanting more detail.

Figure 1.3 The flow of information between activities and chapters
1.6 References

CSIRO (2009a) Groundwater yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

CSIRO (2009b) Surface water yields in south-west Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.


2 Overview of the Pilbara

Authors: Don McFarlane, Geoff Hodgson, Phil Commander, Olga Barron, Richard Silberstein and Santosh Aryal

Key points

- The Pilbara constitutes about 11% of Western Australia but has only about 3% of its population, 12% of which are Indigenous.
- It contains the highest peaks in Western Australia and experiences some of the highest temperatures in Australia. It is also one of the world’s most important mineral provinces.
- Rainfall is often intense and spatially variable as a result of thunderstorms, tropical lows and cyclones.
- Soils are often rocky and thin, resulting in rapid runoff. High potential evaporation rates result in rapid drying between events and few areas remain wet to produce saturation-excess runoff.
- Much of the Pilbara is underlain by fractured rock aquifers which are recharged in large storms and are often deep.
- The most common aquifers are alluvial deposits associated with rivers, especially near their ocean outlets. There are also paleovalleys and two sedimentary basins – the Canning in the north-east and the Carnarvon in the north-west.
- Iron ore mineralised zones can form aquifers – either through in situ leaching of banded iron formations or in channel iron deposits.
- The most common land use of the area is pastoral leases, with some being managed by mining companies and others by Indigenous groups.
- There are common associations between geology, hydrology, hydrogeology, soils and groundwater-dependent ecosystems which have enabled the Assessment area to be divided into 13 hydrogeological provinces. The four largest provinces (Ashburton, Granite Greenstone Terrane, Hamersley Range and Canning Basin) occupy 54% of the Assessment area.

2.1 Towns and infrastructure

The Pilbara Assessment area covers an area of 288,479 km² (11.4% of the state of Western Australia). The population recorded in the 2011 census for the main Pilbara shires was 59,895 located in the four main shires of Roebourne (22,900), Port Hedland (15,044), East Pilbara (11,950) and Ashburton (10,001) (ABS, 2013).

There has been considerable growth in population since the 2011 census. In 2013 the resident population was estimated to have reached 66,298 people, a 4,521 person or 7.3% increase on 2011 (Pilbara Development Commission, 2015). Transient worker accommodation beds in the Pilbara have been estimated to be 50,388 so the population at any one time is very variable (Pilbara Development Commission, 2012).

The main towns in the Pilbara are Karratha (population of 16,475, in the 2011 census as reported by ABS, 2013), Port Hedland (13,772), Newman (5,478), Marble Bar (208), Nullagine (178), Pardoo (806), Paraburdoo (1,509), Pannawonica (651), Tom Price (3,134) and Onslow (667).

There are 21 Indigenous communities in the Assessment area (Department of Aboriginal Affairs, 2015). There were 7,210 Aboriginal people recorded in the 2011 census in the four main Pilbara shires (ABS,
2013), or 12% of the Pilbara’s total population. Ashburton Shire had a 9.3% Aboriginal population, East Pilbara 17%, Port Hedland 15%, and the most populous shire, Roebourne 9%.

The road and rail network in the Assessment area is strongly concentrated along the coast and in the main iron ore mining areas in the Hamersley and Chichester ranges (Figure 2.1). Most iron ore in the central and west Hamersley Range is exported from ports near Karratha while most in the east Hamersley and Chichester ranges are exported from Port Hedland.

While there are a number of large parks and reserves throughout the region (Figure 2.1), only two are major tourist attractions; Karijini and Millstream Chichester national parks. Parks and reserves comprise about 11% of the Assessment area.

There are two integrated water supply schemes in the Assessment area. The West Pilbara Water Supply Scheme supplies water to Karratha, Dampier, Roebourne, Wickham and Cape Lambert from Harding Dam, the Millstream aquifer and Bungaroo channel iron deposit. The East Pilbara Water Supply Scheme supplies Port Hedland and South Hedland from the Yule and De Grey wellfields. Smaller towns get local supplies from nearby water reserves, often in alluvial aquifers but also from fractured rocks.

Figure 2.1 Towns, infrastructure and locations mentioned in the Pilbara Assessment area
2.2 Climate

In the companion technical report, Charles et al. (2015) provides a detailed review of the hydroclimate of the Pilbara. This section summarises the Assessment area’s historical climate as defined by SILO data DataDrill (Jeffrey et al., 2001). Projections of the 2030 and 2050 climate are made in Chapter 3.

The Pilbara is one of the hottest regions in Australia which creates a challenge for both industries and residents. The mean monthly January temperature exceeds 35 °C throughout the region with the lowest temperatures along the coast and in the Hamersley Range (Figure 2.2). Mean temperatures in excess of 40 °C (with some days in the high 40s) occur in the Ashburton catchment and the East Pilbara with Marble Bar and Telfer being among the hottest settlements in Australia.

Figure 2.2 Monthly mean of January daily maximum temperature for the period 1911 to 2011

The main large-scale climate processes that impact on the Assessment area’s rainfall are:

1. Tropical cyclones and depressions – these systems provide a lot of variability in the rainfall of the region. The percentage of annual rainfall resulting from these intense summer systems depends on their frequency and the path they take across the region, but it can be a significant proportion of the annual rainfall total.

2. Heat lows and thunderstorms – the region is prone to thunderstorms between December and March and this mechanism can be a major contributor to rainfall, especially in drier years. The storms result from the heat low that forms over the interior between spring and autumn each year.

3. Subtropical ridge – the region is dominated by the location and strength of this ridge which affects how far north cold fronts can extend in winter, and how far south tropical systems can extend in summer. The Assessment area is subject to dry south-easterly trade winds for a large part of the year because of the ridge.
4. Cold fronts – the south-western part of the region can be affected by cold fronts between late autumn and early spring but these have decreased in recent decades as the subtropical ridge has moved further south. Cold fronts can also interact with mid-level moisture in the eastern Indian Ocean to produce north-west cloudbands. These may also have decreased in recent decades.

5. North-west cloudbands – these systems can bring significant amounts of rainfall in some years, usually in autumn or winter. The reason for their formation in the Indian Ocean is poorly understood and they can disappear for many years before reappearing.

More detail on rainfall mechanisms and trends can be found in Charles et al. (2015).

Except where orographic rainfall is projected to occur in the Hamersley Range, the area has an average annual rainfall of less than 400 mm (Figure 2.3). There is a zone of higher rainfall 70 to 120 km inland from the north-east Pilbara coast which may result from evening thunderstorms generated from humid air brought in by daily sea breezes during the hottest months of the year. The higher rainfall on the coast in the north-east may be due to the influence from the tropical monsoon and/or cyclonic activity as it is related to a relatively recent increase in rainfall for this part of the Assessment area (see later).

Figure 2.3 was generated using SILO estimates of rainfall interpolated between rainfall recording stations and ground elevations. It is possible that neither the projected rainfalls in the Hamersley Range are as high, nor the low rainfalls in the interior are as low as shown, because of the distribution of the recording sites.

![Figure 2.3 Average annual rainfall for the Pilbara Assessment area](image)

About 60% of the Assessment area’s rainfall occurs between January and March (Figure 2.4). While the entire Pilbara has a summer rainfall maximum, coastal areas in the west Pilbara (e.g. around Onslow) receive some rainfall in May and June which corresponds to cold fronts crossing southern Australia and occasional north-west cloudbands. Winter rainfall is more effective in making water available to plants because of the high potential evaporation rates over summer.
Figure 2.4 Pilbara Assessment area monthly rainfall (mm) for the period 1911 to 2012. Range is the 20th to 80th percentile monthly rainfall.

Annual average Class A pan evaporation exceeds 3 m over most of the region but is lower over the Hamersley Range and highest in the south-east interior (Figure 2.5). These estimates are approximate given the paucity of recording stations.

Figure 2.5 Mean annual Class A pan evaporation for the Pilbara Assessment area
The annual rainfall deficit (rainfall minus Class A pan potential evaporation) ranges from 2.3 m in the Hamersley Range to over 3.2 m in the south-east interior (Figure 2.6). The coincidence of low rainfall and high potential evaporation results in potential evaporation exceeding rainfall by 6 times in the Hamersley Range and by about 14 times in the north-east interior. While this is a large range, a 6-fold difference is very large and indicates that soil water storages will become rapidly depleted between most rainfall events. This has implications for rainfall-runoff mechanisms as discussed later in this report. It also shows how much irrigation water would be needed for plants to survive the very hot summers.

Figure 2.6 Mean annual rainfall deficit (mm/year) using Class A pan evaporation
2.3 Physiography and surface water drainage

2.3.1 Physiography

The Assessment area contains the highest peaks in Western Australia, Mount Meharry (1249 m), Mount Bruce (1234 m) and Mount Nameless (1128 m) in the Hamersley Range; all higher than the highest peak in the south-west, Bluff Knoll (1099 m). The importance of the Hamersley Range for forming the headwaters of rivers in the western Pilbara is apparent in Figure 2.7, as is the importance of the much lower Chichester Range for north-flowing rivers in the east Pilbara. The Chichester Range crosses almost the entire Pilbara and has a steep southern flank and a sloping northern flank. The range is important in separating different catchments with hydrological properties.

Figure 2.7 Elevation of the Pilbara Assessment area (vertical exaggeration 100 times applied to relief)
The higher density of streams in the Hamersley Range is evident in Figure 2.8. Rainfall and runoff relationships in the catchments defined by the black lines in this figure are analysed and modelled in Chapter 4 of this report.

Figure 2.8 Major catchments and rivers in the Pilbara Assessment area

Shallow groundwater in the region is associated with modern alluvial deposits and sometimes with older paleovalleys which are a product of drainage and topography. A multi-resolution valley bottom flatness (MrVBF) index was developed by Gallant and Dowling (2003) to identify areas of deposited material at a range of scales based on the observations that valley bottoms are low and flat relative to their surroundings and that large valley bottoms are flatter than smaller ones. In this index, erosional terrain has values which are less than 1 and larger values indicate progressively larger areas of deposition. Higher MrVBF values may correlate with an increased depth of deposited material and vice versa if the relationships between topography and streams’ abilities to entrain and deposit material are valid.

The MrVBF index for the Assessment area shows high values associated with the Hamersley and Chichester ranges, the Ashburton River and greenstone parts of the Granite Greenstone Terrane (Figure 2.9). The index highlights the underlying geological structures which mainly cause elevation differences. The coastal plains are shown as being narrower and more distinct using this index than is shown in the topographic map in Figure 2.7. The extreme flatness of the Upper Fortescue Valley (and associated Marsh) and parts of the Paterson province are apparent in Figure 2.9. Ancient drainage patterns are also apparent in the Canning Basin.
Pain et al. (2011) identified thirteen physiographic regions which relate closely to the underlying geology in the Assessment area (Figure 2.10). A description of each province is provided below (Pain et al., 2011):

<table>
<thead>
<tr>
<th>Region</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anketell Hills</td>
<td>Low mesas, buttes and stony rises of lateritised sandstone and shale among east–west longitudinal dunes and sandy plains</td>
</tr>
<tr>
<td>Augustus Ranges</td>
<td>Parallel ranges and dissected plateaus with intervening hardpan wash plains and stony plains</td>
</tr>
<tr>
<td>Chichester Range</td>
<td>Narrow range of hills and dissected plateaus on basalt and sedimentary rocks</td>
</tr>
<tr>
<td>De Grey Lowlands</td>
<td>Flood plains and deltaic plains with stony plains and sandplains; tidal flats and some metamorphic, volcanic and granitic hills and islands</td>
</tr>
<tr>
<td>Eighty Mile Plain</td>
<td>Coastal plains and dunes with some estuarine plains</td>
</tr>
<tr>
<td>Fortescue Valley</td>
<td>Mainly alluvial lowland with hardpan wash plains and sandplain, possibly a graben</td>
</tr>
<tr>
<td>Great Sandy Desert</td>
<td>East–west longitudinal dunes and minor salt lakes</td>
</tr>
<tr>
<td>Dunefield</td>
<td>Dissected bold plateaus and ranges of flat-lying or moderately folded sandstone, quartzite and volcanic rocks</td>
</tr>
<tr>
<td>Hamersley Plateaus</td>
<td>East–west longitudinal dunes and minor salt lakes</td>
</tr>
<tr>
<td>Little Sandy Desert</td>
<td>Dissected flat-topped hills of granitic, volcanic and metamorphic rocks; interspersed by stony plains on granite</td>
</tr>
<tr>
<td>Nullagine Hills</td>
<td>Alluvial, deltaic and littoral plains; some sandplain and coastal dunes; minor islands</td>
</tr>
<tr>
<td>Onslow Plain</td>
<td>Dissected low sandstone tablelands with hills and ranges on gneiss and intervening areas of sandplains.</td>
</tr>
<tr>
<td>Rudall Tablelands</td>
<td>Sandplain and south-north longitudinal dunes with intervening alluvial plains.</td>
</tr>
</tbody>
</table>

By incorporating hydrogeology these regions are later refined to form hydrogeological provinces that are useful for summarising hydrological and hydrogeological properties.
2.3.2 Australian Water Resources Council basins in the Pilbara Assessment area

There are five Australian Water Resources Council (AWRC) drainage basins within the Pilbara Water Resources Assessment area; Ashburton (706), Robe (707), Fortescue (708), Yule (709) and De Grey (710). For the four Pilbara regional assessment reports, some of the basins have been combined while the Fortescue River basin has been divided into an upper and lower Fortescue. A summary of each AWRC basin is given below; detailed characterisation of the basins can be found in the relevant regional reports.

Ashburton River basin

The Ashburton River basin (706) covers an area of about 77,000 km² drained by the Ashburton River and its tributaries. The Ashburton River is approximately 685 km long, flowing from the east to a north-easterly direction before discharging to the ocean via a fairly well-defined channel south of Onslow. All watercourses of the Ashburton River basin including major rivers are naturally ephemeral with the main Ashburton River at Nanutarra (706003) flowing on average for 94 days per year. However, there are permanent pools in reaches maintained by groundwater throughout the year. Both monthly and annual flow volumes are highly variable with larger rivers flowing for longer periods than smaller rivers. The mean annual discharge of the Ashburton River at Nanutarra is 813 GL.
Robe River basin

The Robe River basin (707) contains the Robe and the Cane rivers. The Robe River has two main tributaries in its headwaters, split by the Hamersley Range. The main channel downstream is braided and has only a minor outlet to the ocean. The river discharges mainly to marshy flats on the coastal plain north of Onslow, providing recharge to the underlying alluvial aquifer. There are several major pools on the Robe River, with mining near the main channel at Ngalooon Pool. The Robe River at Yarraloola (707002) has a catchment area of 7100 km² with mean annual discharge of 116 GL flowing on average for 75 days per year.

The Cane River lies mainly on the coastal plain, discharging almost entirely into marshy tidal flats. The catchment area at Toolunga (707005) is 2330 km² with a mean annual discharge of 81 GL flowing on average for 65 days per year. The Onslow Coast Drainage Basin contains many small creeks that originate on the coastal plain and many do not discharge to the ocean (Ruprecht and Ivanescu, 2000).

Fortescue River basin

The entire Fortescue River basin (708) has an area of 49,760 km² and consists of two main sections: upstream of Fortescue Marsh including the Ophthalmia Dam, and downstream of the Marsh to the coast. The river does not flow from upstream of the Marsh to downstream sections. In this Assessment, the upstream section including the Marsh is called the Upper Fortescue basin and downstream of the Marsh section is called the Lower Fortescue basin.

Upstream of Ethel Gorge in the Upper Fortescue, the river has a dendritic pattern with three major tributaries, and passes through Roy Hill Station into the eastern end of the Marsh. The Fortescue River at Newman (708011) has a catchment area of 2800 km² with mean annual discharge of 11 GL. The other main tributaries of the Fortescue River in the upper section are the Marillana and Weeli Wolli creeks flowing directly into the marsh.

The Fortescue River downstream of Goodiadarrie Crossing is braided and has many small creeks joining the river. The river reach between Goodiadarrie Crossing and Gregory Gorge includes Millstream and is a major groundwater discharge area, with permanent pools. In this reach the topography is very flat, the river is braided with a poorly defined main channel, and there are several important springs. The mean annual discharge of Fortescue River at Gregory Gorge (708002) is 220 GL and flows on average for 150 days per year. From Gregory Gorge to the coast, the stream channel is well-defined with a stream bed of coarse gravel. The river here is braided with many tributaries and pools. Harding Dam, on the Harding River, in the lower reaches of the basin, has a catchment area of 1071 km² and a storage capacity of 63.8 GL (Water Corporation, 2015). The mean annual flow in the Harding Catchment is 38 GL per year (Dames and Moore, 1982).

Yule River basin

The Yule River basin (709) contains a number of rivers, the largest of which is the Yule River, with mean annual discharge of 324 GL at Jelliabidina (709005) from a catchment area of 8400 km². The Yule River flows on average for 70 days per year and has its headwaters on the Abydos Plain bounded by the Chichester and Mungaroona ranges. The Sherlock River, with catchment area 4580 km², at Coonanarrina Pool (709003) flows parallel to the Yule River, also originates in the Abydos Plain and discharges largely in the coastal marshes and mangroves. The other rivers in the basin are the George, Maitland and Turner rivers which have reasonably well-defined braided drainage patterns. The Turner River has a highly braided main channel that splits on the coastal plain.

De Grey River basin

The De Grey River basin (710) has the second-largest gauged catchment in the Assessment area (50,010 km²) at Coolenar Pool (710003). It has the highest volume of mean annual discharge (1170 GL) of all rivers in the Pilbara and flows on average for 104 days per year. The other main rivers flowing intermittently to the northwest are the Coongan, Shaw, and Strelley (East and West branches) and Nullagine rivers. These are locally very wide and sandy and sometimes braided, with semi-permanent and permanent pools. The De Grey River is formed from several parallel tributaries. The upstream branches of the river are generally
braided containing both springs and pools. The Strelley River lies entirely on the coastal plain, the Shaw, Coongan and Nullagine rivers extend to the Chichester Range, while the Oakover River is bounded to the east by the Great Sandy Desert.

The De Grey, Oakover and Nullagine river system runs through a range of geological environments creating a complex hydrogeological system. Flow in the De Grey River system is the primary recharge into alluvial aquifers which are important water supplies for towns in the region. These rivers typically flow only two or three times during the summer, mostly following cyclonic and other major rainfall events.

2.4 Geology of the Pilbara Assessment area and its hydrogeological significance

2.4.1 Geology

The hydrogeology of the Pilbara is influenced by the geology of the region and the drainage, which is in turn influenced by the geology and geological history, particularly drainage diversion, landscape erosion and inversion.

The region (Figure 2.10) encompasses the whole of the Archaean-Proterozoic Pilbara Craton, parts of the adjoining Capricorn and Paterson orogens, small parts of the Neoproterozoic Officer Basin, and the Phanerozoic Carnarvon and Canning basins (GSWA, 1990).
The Pilbara Craton consists principally of the North Pilbara granite greenstone terrane and the volcano-sedimentary rocks of the Hamersley Basin. The craton has been exceptionally stable over geological time, as demonstrated by the flat-lying unconformity on the granite greenstone at the base of the Hamersley Basin sequence. The adjoining Capricorn and Paterson orogens consist of folded and faulted metamorphosed sedimentary rocks, with some igneous rocks in the Gascoyne and Rudall complexes. The sediments of the Carnarvon and Canning basins are largely shallow dipping and unmetamorphosed.

The North Pilbara granite greenstone terrane, the Sylvania Inlier and other smaller inliers in the Hamersley Basin are composed of greenstone sequences which envelop, or are intruded by, composite granitoid complexes (batholiths), that range in age from 3650 to 2850 Ma (Nelson et al., 1999). The greenstone sequence is composed of a variety of sedimentary and volcanic rocks, principally basalt, acid volcanics, schist, quartzite, chert and banded iron formation (BIF) which host gold, base metals, and the iron ore deposits at Goldsworthy, Shay Gap, Yarrie, Pardoo and Ridley. The greenstone sequences have been subdivided into the older 3530–3170 Ma Pilbara Supergroup, dominantly volcanic, overlain by a younger (3020–2930 Ma) mainly clastic sequence including banded iron formation, the De Grey Supergroup (Van Kranendonk et al., 2007).

The greenstones are preserved in folded and steeply dipping sequences enveloping the granite batholiths (Figure 2.11). Their major landforms are spine backed ridges formed by the more resistant chert and BIF in the greenstone belts, which surround relatively flat granite batholiths. The rocks are generally well exposed with a thin weathering profile.
The Hamersley Basin sequence covers the southern part of the Pilbara Craton and extends over an area of approximately 40,000 km². It comprises the Archaean to Paleoproterozoic (2770 to near 2350 Ma) Mount Bruce Supergroup, which consists of the volcanic sedimentary Fortescue, Hamersley and Turee Creek groups, dominantly basaltic and sedimentary rocks of very low metamorphic grade (GSWA, 1990) unconformably overlying the granite greenstone terrane.

The northern margin of the Hamersley Basin is the gently south dipping Fortescue Group which forms the 400 km long Chichester Range. The Hamersley Range is formed by a syncline in the Hamersley Group and folding increases towards the southern margin, with the Ashburton Basin resulting in a series of domes and synclines. The range forms the highest part of Western Australia with Mount Mearry at 1249 m. The southern margin of the Hamersley Basin, the Ophthalmia Foldbelt, has been folded into tight synclines and anticlines, with granite greenstone terrane exposed in the anticlinal cores.

The Fortescue Group is composed of a volcano-sedimentary sequence comprising about 6000 m of subaerial to shallow marine volcanic and sedimentary rock that is divided into a series of depositional sequences, the uppermost of which passes conformably into the overlying Hamersley Group. Deposition of
the Fortescue Group coincided with the emplacement of mafic to felsic sills and dykes which also intrude the granite greenstone terrane.

The 2500 m thick Hamersley Group conformably overlies the Fortescue Group. It is characterised by BIF, but also includes shale, chert, dolomite and volcanics. The Hamersley Group hosts most of the main iron ore deposits of Western Australia, contained within around 1000 m of laterally extensive BIF representing three major episodes. The base of the Hamersley Group marks a change from a dominantly volcanic to a chemical sedimentary environment with Marra Mamba Iron Formation. About 200 m thick, the Marra Mamba Iron Formation (2600 Ma) is separated from approximately 600 m thick Brockman Iron Formation by about 750 m of carbonate, shale and minor chert of the Wittenoom, Mount Sylvia and Mount McRae Shale Formations (2600 to 2480 Ma). This sequence is followed, after the Brockman Iron Formation, by the third phase of iron formation deposition, the 600 m thick Weeli Wolli Iron Formation. The major iron ore deposits at Tom Price, Newman, Marandoo, Hope Downs, and the Chichester Range deposits are contained in the Brockman and Marra Mamba iron formations. The Hamersley Group is dominated by BIFs, with lesser shale, undivided chert, jaspilite, dolomite, mudstone and siltstone. The succession has been intruded by the Woongarra Rhyolite and dolerite. The uppermost Turee Creek Group conformably overlies the Hamersley Group and consists of siltstone, greywacke, dolomite and quartzite, intruded by dolerite sills.

In the Oakover Valley area the Wittenoom Formation equivalent, the Carawine Dolomite, is extensively covered by the Pinjain Chert Breccia which is a residual and replacement deposit forming paleokarst features where the pre-existing dolomite has been dissolved.

The Ashburton Basin lies unconformably on the Hamersley Basin, and with increasing metamorphic grade, passes south-westwards into the Gascoyne Complex. Sediments of the Ashburton Basin, mainly the Wyloo Group, dip to the south forming a succession of parallel ranges which the Ashburton River follows. Granite of the Gascoyne Complex is exposed in the western edge of the region. The younger Mesoproterozoic Bangemall Basin lies in the core of the Capricorn Orogen, generally separating the Ashburton Basin and Gascoyne Complex.

The Ashburton Basin is defined by the outcrop of the Wyloo Group, and the younger Bresnahan and Mount Minnie groups. These sediments and volcanics unconformably overlie the Hamersley Basin, and consist of quartzite, basalt, dolomite and shale about 12,000 m thick. They are part of the northwest–southeast trending Capricorn Orogen, in which deformation and metamorphic grade increases to the west to merge with the Gascoyne Complex.

The Mesoproterozoic Bangemall Group occupies the southern part of the region, which is in the core of the Capricorn Orogen, separating the Ashburton Basin and Gascoyne Complex. In this region it is mainly represented by the Edmund Subgroup which consists of around 10,000 m of shale, sandstone and dolomite. These rocks form parallel ranges, followed by the Ashburton River and its tributaries.

In the east of the region, the Bangemall Basin (1300–1400 Ma) is represented by the Manganese Group which consists of shale, sandstone dolomite and minor conglomerate, unconformably overlying the paleokarst topography on the Pinjain Chert and Carawine Dolomite in the uppermost Fortescue Valley and in the Oakover Valley. Manganese deposits occur at the base of the sequence, commonly infilling cavities in the Carawine Dolomite and irregularities in the paleokarst surface of the Pinjain Chert, and are currently being mined at Woodie Woodie.

The Paterson Orogen in the east of the region includes sedimentary rocks of the Yeneena Basin believed to be younger than 900 Ma (Grey et al., 2005) and the older metamorphic rocks of the Mesoproterozoic Rudall Complex. The Yeneena Basin contains the Throssel Range and Lamill Groups (Grey et al., 2005), which have been metamorphosed by the Paterson Orogeny. The Throssel Range Group comprises the Coolbro Sandstone and the mainly shale Broadhurst and Pungkuli Formations. The 5000 m thick Lamill Group consists of the mainly sandstone Malu Formation, the dolomitic Puntapunta and Isdell Formations and the overlying sandstone Wilki Formation. The Lamill Group metasediments of the Yeneena Basin host the gold mineralisation at Telfer and copper mineralisation at Nifty. The uranium ore at Kintyre is contained in narrow high grade veins in the metamorphic rocks of the Rudall Complex.
The Neoproterozoic (700–850 Ma?) sandstones, shales and dolomites occupying the area between the Bangemall and Yeneena Basins are assigned to the Officer Basin (Grey et al., 2005). These have been subdivided into structurally distinct groups, separated by major northwest–southeast faults, as they have not yet been able to be correlated. The Officer Basin sequence (formerly the Savory Basin in this area, GSWA, 1990) includes the Sunbeam and Tarcunyah groups, Boondawari Formation and Disappointment Group. The sedimentary rocks of the Officer and Yeneena basins are poorly exposed in the region, being largely covered with sand dunes, and their relationships are not clear (Grey et al., 2005).

The northern part of the Carnarvon Basin extends into the region. It contains a basal Cretaceous sequence, overlaying an erosion surface on older sediments, and calcareous sediments of Miocene age. The Cretaceous and Cenozoic sequence in the Carnarvon Basin is mostly fine-grained, with the only significant sandstone occurring at the base of the Cretaceous. The basal Cretaceous sediments, Yarraloola Conglomerate and Nanutarra Formation, crop out as isolated mesas along the inland boundary of the Carnarvon Basin, unconformably overlying rocks of the Hamersley and Ashburton basins, and the Gascoyne Complex, and pass laterally into the Birdrong Sandstone. The Birdrong Sandstone is continuous throughout the basin and forms the only major aquifer. It unconformably overlies Proterozoic rocks along the basin margin, and Devonian to Permian sediments towards the coast. The base of the Cretaceous sequence rests on an uneven erosion surface characterised by paleochannels which host the Manyinge uranium deposit. The Birdrong Sandstone aquifer is confined by the Cretaceous Muderong Shale and Gearle Siltstone and calcareous sediments of Cretaceous to Miocene age. The uppermost unit is often the Trealla Limestone, which varies from calcareous marl to lithified limestone.

The region includes the south-western part of the Canning Basin, south of Mandora Marsh. The Canning Basin is Australia’s second-largest sedimentary basin, containing sediments ranging in age from Ordovician to Cretaceous. The part of the basin within the region contains basal sediments of Permian age in the east, unconformably over lain by a Jurassic to Early Cretaceous sequence, which lies directly on Precambrian rocks in the south and west.

North-trending paleochannels containing sediments referred to the Permian Paterson Formation have been identified in the Oakover Valley, mainly overlying the Hamersley Group, and in the Nifty–Telfer–Kintyre areas, overlying Neoproterozoic sediments and the Rudall Complex (English et al., 2012). These paleochannels are believed to be glacial features, either ice gouged or eroded by meltwater during the Permian glaciation, though the Oakover Valley also follows a syncline in the Hamersley Basin which may in turn be controlled by an underlying graben. The paleochannels are filled with a variety of sediments, ranging from clayey till to outwash sands.

The Jurassic-Cretaceous sequence crops out as isolated mesas along the inland margin surrounded by the dunes of the Great Sandy Desert, and dips gently northwards below the coastal plain, thickening to the north. Surface geological maps of the basin have used a number of local geological units, such as Callawa Formation, Parda Formation, Frezier Sandstone and Anketell Sandstone, which have previously been simplified in the hydrogeological literature (Leech, 1979; Haig, 2009) to a basal Jurassic unit, the Wallal Sandstone (maximum thickness 218 m; Leech, 1979), overlain by the Jarlemait Siltstone and the Broome Sandstone (71 m). WorleyParsons (2013) have recently subdivided Leech’s Broome Sandstone into an upper and lower Callawa Formation.

Valley-fill sediments ranging in age from Eocene to Recent are best preserved in the valleys of the Hamersley Range within an early Cenozoic landscape. This sequence has been subject to erosion in the middle to lower reaches of the Ashburton and Robe Rivers in the west of the region, and in the Oakover Valley in the east, resulting in an inverted topography of sinuous mesas of channel iron deposits, and mesas of eroded calcrete.

Unconsolidated sedimentary deposits as much as 150 m thick occur in the Hamersley Range, underlying both current valleys and paleovalleys (valleys not occupied by active drainage lines), and comprise basal ferruginous sediments assigned to the Robe Pisolite or Marillana Formation (Kneeshaw and Morris, 2014), informally known as channel iron deposits (CID). These are overlain by calcareous clay or marl which has commonly undergone conversion to calcrete (Oakover Formation), lacustrine clay, iron-rich colluvium (detrital iron deposits), and gravel associated with the current drainages.
The Cenozoic sequence is commonly floored by a basal clay, termed Munjina Member of the Marillana Formation (equivalent to Robe Pisolite) by Kneeshaw and Morris (2014). Overlying this is the CID, the iron-dominant facies which is a fluvial deposit of Oligocene to Miocene age (Morris et al., 1993). These sediments occupy generally meandering paleochannels cut into the Early to Mid-Tertiary Pilbara ferricrete (‘laterite’) paleosurface (Morris et al., 1993). The variably eroded deposits range from less than 1 m to 100 m in thickness with channel widths typically less than 1 km, but ranging up to several kilometres. The deposits are anomalously high in iron content, and goethite-hematite CIDs represent a major source of the iron ore mined in the Hamersley Province forming the ore in the Robe River deposits, Solomon Hub, and Yandi and Yandicoogina. CIDs provided around 40% of the total of 394 Mt of iron ore mined from the Hamersley Province in 2009, and the current CID resource is around 7 billion tonnes (Morris and Ramanaidou (2007).

The CID is overlain by the Oakover Formation, of Miocene age, which appears to be a calcareous clay or marl deposited in a lacustrine environment, and which has commonly undergone conversion to calcrete (Barnett and Commander, 1986). The formation is generally less than 10 m thick (but can be more than 40 m). Dissolution of calcrete leads to the development of secondary porosity, which makes this formation a potential aquifer where the formation thickness is sufficient. The Oakover Formation is present in valleys in the Hamersley Range but has almost completely been eroded from the Robe River catchment, and Oakover Valley.

Kneeshaw and Morris (2014) assign a Pliocene age to the scree or detrital iron deposits (DID) that occupy valleys and valley margins adjacent to parent bedded iron deposits. In the centre of the Hamersley Range, the Oakover Formation is overlain by lacustrine clay and silt with modern fine-grained alluvium at the surface.

Tilting and uplift since the Cretaceous and early Cenozoic has led to the current drainage pattern. The early Cenozoic drainage pattern in the Hamersley Range is shown by the distribution of the Robe Pisolite, and this drainage pattern has been modified by tilting, leaving dry valleys, with modern drainages cross-cutting the original valleys, many of which are developed along the strike of the Wittenoom Formation. The current Fortescue Valley previously drained in the direction of the present Robe River, but has now been diverted at Millstream by the lower Fortescue River, which exits the valley sediments to cut through bedrock. Tilting is also responsible for creating a surface water divide in the Fortescue Valley at the Goodiadarrie Hills, upstream of Wittenoom, with the upper part of the valley internally draining to the Fortescue Marsh. Youthful northward draining streams to the coast between Roebourne and Port Hedland are actively down cutting through the Chichester Range, commonly along faults or lines of dolerite dykes.

Former rivers in the Canning Basin during the early Cenozoic are represented by paleodrainage systems (van de Graaff et al., 1977). The Percival Paleoriver traverses the southern margin of the basin, and is marked by a discontinuous line of salt lakes. Similarly, the Mandora Paleoriver (English et al., 2012) drained the centre of the basin, connecting with the present day Mandora Marsh. The Wallal Paleodrainage (van de Graaff et al., 1977), a dry valley floored by sand dunes, occupies the area between the De Grey–Oakover and the Mandora Paleodrainage.

Sediments forming the current river beds and flood plains are considered to be Pliocene–Pleistocene to Recent in age and are actively being deposited. The type of sediments depends on the rocks being actively eroded in their catchments, and ranges from sands derived from granite to cobbles derived from Proterozoic sediments. Fine-grained flood plain deposits occur away from the river beds.

Major aquifers have been formed by the gravel bedload of the Robe, Fortescue and De Grey rivers, and by the sands of the Yule and Turner rivers, but the Ashburton River seems to have relatively fine-grained bedload sediments, though a paleochannel trending away from the river near Nanutarra contains a significant thickness of gravel (Yesertener and Prangley, 1997), and sands in the Cane River are thin. Away from the river channels, the coastal plain sediments are represented by silts and clays deposited in major floods.
2.4.2 Hydrogeology

The major groundwater resources are contained in the Jurassic and Cretaceous sandstones of the Canning Basin, in karstic Proterozoic dolomite, in Cenozoic channel iron deposits, calcrete and alluvium of the inland valleys, and in the alluvial fan deposits of the major rivers on the coastal plain. Minor, localised groundwater supplies are also sources from fractured Precambrian rocks.

The Wallal Sandstone is the major aquifer in the West Canning Basin containing fresh groundwater. Groundwater flow is into the region from the east, with local recharge inferred along the southern margin, and artesian conditions along the coastal plain.

The Carawine Dolomite and Wittenoom Formation, where they underlie valleys in the Hamersley Basin, commonly have solution cavities developed, resulting in high transmissivity and bore yields. Similarly at the Woodie Woodie mine, the dolomite below the ore zone is highly transmissive. At the Telfer mine, dolomite of the Puntapunta Formation is also vuggy and high yielding.

Channel iron deposits are vuggy and have high storage and transmissivity. Being the ore body, they are dewatered for mining at Mesa J in the Robe River, and at the Solomon area and in Marillana Creek in the Hamersley Range. A borefield has been developed for public supply from the Bungaroo Creek deposit.

Calcrete in the Fortescue Valley at Millstream is vuggy and highly transmissive close to the watertable, and has been developed for the West Pilbara Water Supply Scheme.

The alluvial fans of the Robe, Fortescue, Yule and Turner rivers, and alluvium along the De Grey River all contain major sand or gravel aquifers which are regularly replenished by river flow. Minor aquifers occur in the alluvium of the Ashburton and Cane rivers.

Local groundwater supplies for mining have been developed in a variety of fractured Precambrian rocks, usually with a poor success rate, however, significant amounts of groundwater (about 350 GL/year) are pumped to dewater permeable iron ore deposits in the course of mining. Sandstone, quartzite, chert, and banded iron formation are considered more likely to contain fractures, while dolerite, basalt, schist and shale are considered least prospective. Structural features such as shear zones and faults may also yield useful supplies.

The Birdrong Sandstone is the major aquifer in the Carnarvon Basin, but in this part of the basin the groundwater in the aquifer is generally brackish close to the basin margin, and becomes increasing saline towards the coast.

Groundwater in the alluvial and valley-fill aquifers and in fractured bedrock is generally fresh to brackish inland, becoming brackish towards the coastal plain. The internally draining Fortescue Marsh, Samphire Marsh and the Mandora Paleodrainage, and paleodrainages along the southern margin of the Canning Basin contain saline to hypersaline groundwater. Seawater interfaces occur in the coastal alluvial aquifers, the Broome Sandstone, and the extreme western edge of the Wallal Sandstone.

2.4.3 Surficial Deposits Mapped Throughout The Region

Shallow aquifers in superficial deposits can provide groundwater with a lower cost of extraction. Coloured areas in Figure 2.12 show where superficial deposits occur in the Assessment area. The main deposits are sandplains associated with the Canning and Carnarvon basins, and down gradient of large granite outcrops including east of Newman (Sylvania Dome granite). Sandplains are relatively rare in the area underlain by the Hamersley Basin because of the clayey and rocky nature of the weathering products.

Ancient drainages have formed surficial deposits (dark grey) and they can be substantial aquifers which can be recharged from overlying modern alluvium formed around existing drainage lines. Streamflow after heavy rainfall is the main recharge mechanism to both systems. Some paleochannels contain channel iron deposits (CIDs) which constitute significant aquifers because of their permeability and porosity. Both
modern drainage lines and paleochannels can also contain calcrete and dolostone when they are associated with the Wittenoom Formation in the Upper and Lower Fortescue Valley.

Figure 2.12 Surficial deposits in the Pilbara Assessment area that are usually aquifers

2.5 Soil-landforms

Soil textures and depth greatly affect runoff initiation, the amount of recharge, and the type of vegetation that can grow. This can be mapped as regolith (loose material above bedrock) or as soil types (the zone used by plant roots).

The regolith map for the Pilbara (Marnham and Morris, 2003; Figure 2.13) shows the following features:

- extensive areas of alluvium (material laid down by rivers) associated with the Fortescue Marsh, coastal plains and major rivers, especially the De Grey and Ashburton. Most inland rivers only have small alluvial areas in their valley bottoms. Some alluvial areas are important aquifers, although the Fortescue Marsh is saline and the Ashburton alluvial is generally clayey
- exposed rock with thin soils comprises much of the Pilbara. Runoff can be immediate although the rocks are often fractured and water can infiltrate to depth in heavy storms
- large areas of colluvium (loose rocks and soils deposited on hillslopes and their base by runoff or gradual creep under gravity). It is common for colluvium to be found between exposed rock on hilltops and alluvium in river valleys
- large sandplains associated with the Great and Little Sandy deserts which usually overlie sedimentary rocks comprise the north-eastern part of the Pilbara. There are also large sandplain areas in the Upper Fortescue and near Onslow associated with the Carnarvon Basin.
- residual landscapes (landscapes that contain soil profiles from a previous climatic period) occur in poorly eroded inland sites.
- lime (calcrete) materials occurs in river valleys formed from the weathering of upstream dolomites (Wittenoom, Carawine, Duck Creek) or over exposures of these formations. The most extensive ones are in the Fortescue River Valley and north of Kintrye and Telfer in the Little Sandy Desert.
- tidal flats occur where the coastal plain is low enough to be inundated by high tides.

**Figure 2.13 Regolith map of the Pilbara Assessment area**

Source: Marnham and Morris (2003)

The Australian Soil Resource Information System (ASRIS) summarises major soil types across Australia and McKenzie et al. (2012) outline how ASRIS material can be interpreted and these are reproduced below.

Soil type affects recharge rates as well as the ability to produce runoff. Thin skeletal soils with low water holding capacities, which are common in the region, do not support much vegetation and wetting fronts can penetrate deeply to become recharge to underlying aquifers. Improved soil mapping is being carried out by the Western Australian Department to Agriculture and Food as part of the Pilbara Hinterland Agricultural Development Initiative.

The most extensive soil orders in the region are the very rocky Tenosols on hillsides and slopes, and Sodosols which have a strong texture contrast between the A and B horizons and a sodic B horizon in lower
parts of the landscape (Figure 2.14). The latter are associated with underlying clayey sediments. These two soil orders occupy the majority of the Pilbara. Small areas of Rudosols, which have similar poor development to Tenosols, occur in the extreme north-east and south-east of the Assessment area.

Kandosol soils which lack texture contrast between the A and B horizons and are not calcareous throughout occur over the Carnarvon Basin, Fortescue Valley, in broad valleys in the Hamersley Range and are associated with the De Grey and Oakover rivers alluvium.

Soils containing lime throughout their profile (Calcarosols) occur in areas associated with dolomitic rocks and also along the coastline associated with Tamala Limestone. Those in the east are associated with the Carawine Dolomite, in the Fortescue Valley with the Wittenoom Formation and in the south by the Duck Creek Dolomite.

Thin occurrences of Vertosol (cracking clay) soils occur along the upper Fortescue Valley, the Ashburton River but are associated with paleovalley and alluvium in the Hamersley Range. These can be chemically fertile soils but hard to cultivate because they shrink and swell depending on their moisture content.

In summary, most soils are rocky with poorly developed soil profiles with the exception of those in lower landscape positions where they may be alkaline, saline or clayey.

Figure 2.14 Soil types in the Pilbara Assessment area
2.6 Land and water use

2.6.1 Land use

Most of the land in the Pilbara is vacant crown land (54.8%) and pastoral grazing leases (34.4%) (Figure 2.15). Of the leases, 75% are owned by commercial pastoralists, 14% by mining company near the Hamersley Range and 11% by Indigenous groups.

Land managed by the Department of Parks and Wildlife for the Conservation Commission of Western Australia occupies about 6.5% of the Assessment area. The main tourist attractions are Karijini and Millstream Chichester national parks. There are many small reserves scattered throughout the Assessment area and two main Indigenous reserves. Only land in the region’s towns is under freehold tenure (0.03% of the Assessment area).

The number of sheep grazing pastoral land in the Pilbara peaked in the 1930s and after a period of low stocking have been progressively replaced by cattle since the 1970s (Figure 2.16). Cattle have about seven times the grazing intensity of sheep which means that commercial grazing pressures in the Assessment area overall may now be at an all-time high. As has happened throughout the rangelands, the availability of watering points in pastoral stations has resulted in an increase in grazing by both native and introduced species.
Sheep grazing was controlled using fenced paddocks (to separate ewes from rams) which resulted in grazing pressures being more distributed over the stations. In contrast, cattle grazing tends to be less spatially managed and can concentrate along drainage lines where more groundwater-dependent ecosystems are located.

More recent data on cattle stocking rates for the four Landcare Conservation Districts that cover the Pilbara show that numbers increased until the late 2000s before falling in 2010, but are still substantially above those recorded in the 1990s (Figure 2.17). The Western Australian Department of Agriculture and Food (DAFWA, 2013) estimated the 2012 carrying capacity for the East Pilbara Landcare Conservation District was 1.0 cattle unit/km² and 43% of leases had stock numbers above this carrying capacity. The condition of pastures at selected sites on pastoral stations is measured in the Western Australian Rangelands Monitoring System (WARMS). The high stocking rates are reflected in declines in the frequency of desirable perennial grasses in the Pilbara (DAFWA, 2013). Some references to changes in land cover conditions based on Landsat TM images analysis are discussed in Chapter 6.

Figure 2.16 Sheep and cattle numbers in the Pilbara (a) between 1894 and 2002 and (b) expressed as equivalent cattle numbers

Source Van Vreeswyk et al. (2004)
2.6.2 Water use

There are no allocation limits set for surface water resources and groundwater is considered the dominant economic water source in the Pilbara (DoW, 2014). The sum of all groundwater allocation limits for 18 shallow aquifers in the Pilbara was 142.6 GL/year in 2014 (DoW 2014). Almost 39 GL/year or 27% was available for licensing at that time. Not all licensed water is used each year. For example Water Corporation was only using about half of their licensed allocation from the Yule and De Grey (Namagoorie) Borefields in 2015 (Paul Vanderwal, pers. comm. 2015).

The main shallow resources (representing about 96% of the resource) were identified by DoW (2014) to be:

1. East Pilbara groundwater sub-area; Wittenoom – Wittenoom aquifer: 50 GL/year
2. Ashburton groundwater sub-area; Wittenoom – Wittenoom aquifer: 20 GL/year
3. Ashburton groundwater sub-area; Millstream aquifer: 16.7 GL/year, or 6 GL/year as a standalone source
4. Ashburton groundwater sub-area; Pilbara Lower Yule Alluvial: 10.56 GL/year
5. Ashburton groundwater sub-area; Pilbara – Lower De Grey Alluvial: 10.15 GL/year
6. Ashburton groundwater sub-area; Lower Bungaroo Valley: 10 GL/year
7. Ashburton groundwater sub-area; Pilbara – Alluvial: 7 GL/year
8. Ashburton groundwater sub-area; Lower Fortescue Alluvial: 6.6 GL/year
9. Ashburton groundwater sub-area; Carnarvon – Lower Robe Alluvial: 5.09 GL/year.

The two highest yielding aquifers are in Wittenoom Formation and the Millstream Aquifer is within calcite weathered from dolomite and redeposited. All except the Lower Bungaroo Valley aquifer (which is within channel iron deposits) are alluvial deposits associated mainly with modern streams and sometimes connecting paleochannels.
The main deep groundwater resources in the Pilbara are the West Canning groundwater sub-area; Canning–Wallal aquifer with an allocation limit of 30 GL/year, and the West Canning-Pardoo groundwater sub-area Canning–Broome aquifer with an allocation limit of 10 GL/year, both of which have water available (DoW, 2013a).

No allocation limits are set for fractured rock aquifers which cover much of the Assessment area and all of the mining areas where dewatering is required. Licensing policy and individual licenses cover these groundwater resources.

Groundwater was seen by DoW (2014) as being in short supply near high demand areas, particularly around Karratha and Port Hedland.

Estimates of mine dewater have been made by several groups. MWH (2009) estimated that about 171 GL/year was then being dewatered but this may grow to 335 GL/year when all mines were developed. DoW (2013b, cited in DoW 2014) estimated surplus mine dewater to be about 160 GL/year. GHD (2015) have estimated about 199 GL/year may be dewatered in the central Pilbara with about 124 GL/year being discharged to the environment in some manner.

There are two surface water impoundments in the Pilbara: Harding Dam near Karratha, and Ophthalmia Dam near Newman. Harding Dam is used along with water from Bungaroo (resource 1 above in the Wittenoom-Wittenoom aquifer) to supply water to the West Pilbara Water Supply Scheme and Ophthalmia Dam is used to recharge alluvial and paleochannel aquifers for subsequent use.

Water from the Yule and De Grey alluvial deposits are used to provide water for the East Pilbara Water Supply Scheme. Small wellfields are used to supply water from the Cane River alluvials for Onslow, Upper Hardey and Southern Fortescue rivers for Tom Price, bores north, north-east and west of Newman to supply this town, Seven Mile and Bellary creeks for Paraburdoo, Nullagine River bores for Nullagine and a fractured rock aquifer for Marble Bar. Onslow’s water supply and nearby gas processing water needs are about to be augmented by desalination of saline water from the Birdrong Sandstone in the Carnarvon Basin.

DoW estimate that about 350 GL of water was abstracted for mining in 2013 (D Ferguson, 2015, pers. comm.), which is about 45% of the 778 GL of water that was licensed for mining in the Pilbara region in 2014. In a report for the Chamber of Minerals and Energy, Deloitte Access Economics (2014) estimated that only about 131 GL (38%) of the 350 GL that was extracted by the mining industry was consumed, the rest being disposed to the environment or reinjected. The Deloitte Access Economics (2014) estimate of about 219 GL per annum being discharged to the environment is slightly larger than the 199 GL per annum estimated by GHD (2015).

### 2.7 Vegetation

Vegetation units in the Pilbara are based largely on their upper storey (Eucalypts, Acacia and mulga – a type of Acacia) as well as their understorey (hummock grass, tussock grass or shrubs) (Figure 2.18). Hummock grasslands (*Triodia* spp., a type of spinifex) with few trees is the most common vegetation unit, occurring on rocky plains as well as on the lower slopes of rocky areas in the Fortescue and De Grey basins and in the Great Sandy Desert. Tussock grasses, including Mitchell Grass (*Astreleba* spp.), form valuable grazing lands along the coast as well as in the Fortescue Valley.

Rocky areas in the Hamersley Range and in the granite greenstone terrane often maintain arid to semi-arid Acacia low open woodlands and shrublands with either a herbaceous or hummock grass understorey.

Mulga (*Acacia aneura*) woodlands and other types of Acacia shrublands are most common on texture contrast soils in the Ashburton Basin where they are used extensively for stock grazing.

Open Eucalypt woodlands are most common in the Yule and lower De Grey catchments. Some vegetation types are restricted to specific soils, especially saltbush, bluebush, samphire and chenopods which can survive in very arid, often salty soils. They are palatable to both native and introduced grazing animals.
The Pilbara Biological Survey identified four geographically distinct biogeographic subregions in the Pilbara taking into account geology, landform, climate, vegetation and animal communities (DPaW, 2013):

1. **Chichester subregion**: in the granite greenstone terrane of the northern Pilbara Craton and the Chichester Plateau of the Hamersley Basin. The broader Chichester subregion has deeply weathered regolith and is dominated by spinifex (*Triodia* spp.) grassland with irregularly scattered shrubs. The Chichester Plateau borders the northern side of the Fortescue Valley and reflects the soil landscape and vegetation of the Hamersley Plateau.

2. **Fortescue subregion**: delineated by the Fortescue River Valley. This region consists of salt marshes, mulga-bunch and short grass communities, with eucalypt woodlands along flood plains and associated with permanent springs.

3. **Hamersley subregion**: skeletal soils over iron-rich sedimentary rocks support spinifex grassland with Mulga and Snappy Gum in the Hamersley Range.
4. **Roebourne subregion**: covers the mudflats and low dunes of the coastal plain and comprises alluvial and aeolian sediments, often with a cover of grasses and soft spinifex.

These subregions align well with some of the Hydrogeological Provinces identified in the final section of this chapter.

### 2.8 Groundwater-dependent environmental assets

GDEs are characterised by unusual biota and high levels of biodiversity. In Pilbara landscapes they are geographically restricted and in many instances have significant ecological and cultural values (Carwardine et al., 2014). For the purposes of the assessment, GDEs are defined to include groundwater-dependent terrestrial vegetation and river pools and ecosystems they support. Subterranean GDEs were not included in the assessment.

A series of locations where groundwater-dependent ecosystems occur has been identified for the Assessment area. This was based on a collation of available information on known GDEs locations (Equinox Environmental, 2013). Figure 2.19 shows the most important environmental assets, most of which were named and hence have some long-standing significance for the local communities.

The Pilbara is one of the World Wildlife Fund’s Global 200 Eco-regions, selected for its unique and rich biodiversity (DoW, 2009). In the Assessment area there are two Ramsar-listed wetlands: Eighty Mile Beach coastal wetlands and Mandora Salt Marsh (Davis et al., 2013, Halse et al. 2011).

In addition, two other wetlands are proposed to be included in Ramsar wetlands listing; they are Millstream Pools and the Fortescue Marsh, both located on the Fortescue River.

![Figure 2.19 Types of groundwater-dependent ecosystems in the Pilbara Assessment area](image)
Many other wetlands in the Assessment area are classified as nationally important, including the De Grey River wetland system, Karijini (Hamersley Range) gorges, Leslie (Port Hedland) Saltfields System, Lake Disappointment (Savory Creek) System, Kookhabinna Gorge, Cape Range Subterranean Waterways and Lake Dora (Rudall River) System. These are listed in the Directory of Important Wetlands in Australia (Environment Australia, 2001).

Due to the arid climate of the region, permanent and semi-permanent pools are of high ecological value. These pools and wetlands sustain populations of terrestrial and aquatic flora and fauna during times of drought and are refuge areas from which biota expand during times of flood. Permanent pools with recognised significance include those associated with the Turner, Yule, Sherlock, Harding, Maitland, and Fortescue coastal rivers (Kendrick and Stanley, 2001).

There are two Priority 1 wild rivers in Pilbara (Figure 2.19): Tanberry Creek and the Upper Robe River.

Pools and wetlands also have significant cultural value to the local Indigenous people. For instance, stories of ‘The Dreaming’ from the Millstream area provide the basis for the cultural practices of the Yindjibarndi and Ngarluma people (WAPC, 2009)

2.9 Hydrogeological provinces

Integrating the topographic, geological and hydrological data in the previous sections, thirteen hydrogeological provinces have been defined for the Pilbara Assessment area (Figure 2.20; Table 2.1).

There are strong associations in each province with soil-landforms, vegetation, drainages and hydrogeology which are associated with the underlying geology. This makes summarising their water resource potential much simpler.

Detailed hydrological and hydrogeological analyses described in the following three chapters provide in-depth information about each of these six provinces. This information is then integrated in Chapter 7.
Table 2.1 Characteristics of the hydrogeological provinces in the Pilbara Assessment area

<table>
<thead>
<tr>
<th>HYDROGEOLOGICAL PROVINCE</th>
<th>AREA (km²)</th>
<th>AREA (%)</th>
<th>CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashburton</td>
<td>57,590</td>
<td>20.0</td>
<td>Very poor water resources are associated with this low-lying province. Its landforms and soils have developed by weathering of clayey and volcanic rocks which form few aquifers. The province receives runoff from the nearby Hamersley Range but little water is retained. Small river pools sustain GDEs. Texture contrast soils support mulga vegetation used for stock grazing. One of the driest provinces.</td>
</tr>
<tr>
<td>Granite Greenstone Terrane</td>
<td>50,612</td>
<td>17.6</td>
<td>Flat granitic batholiths with associated sandy soils are interspersed with ridges of older greenstone containing gold, copper and other minerals. Alluvial deposits associated with the main creeklines sustain local water resources and important GDEs. Contains the Harding Dam, one of only two surface water resources in the Pilbara.</td>
</tr>
<tr>
<td>Hamersley Range</td>
<td>44,509</td>
<td>15.4</td>
<td>Lowest rainfall deficit because of relatively high rainfall and low potential evaporation. High peaks and valleys underlain by Archean and Proterozoic sediments including important iron ore deposits associated with channel iron deposits (CIDs) and in situ enriched ore zones. Mainly low yielding fractured rock aquifers except where associated with paleochannels, CIDs, calcrite and dolomite of the Wittenoom Formation. Mainly skeletal soils, open woodlands and hummock grasses with GDEs associated with valleys and gorges.</td>
</tr>
<tr>
<td>Canning Basin</td>
<td>32,432</td>
<td>11.3</td>
<td>Flat coastal plain overlain by sandy dunal soils. Major water resources associated with the confined Wallal Sandstone aquifer. GDEs associated with paleovalleys and the brackish to saline Broome Sandstone aquifer. Diffuse recharge in inland areas recharges these aquifers.</td>
</tr>
<tr>
<td>Paterson</td>
<td>25,876</td>
<td>9.0</td>
<td>Low rainfall and high potential evaporation sandy and rocky area with only a few known water resources in Proterozoic dolomite and Permian paleochannels. Poorly investigated except around the Telfer (gold) and Nifty (copper) mines and at the Kintyre (uranium) deposit.</td>
</tr>
<tr>
<td>Oakover</td>
<td>21,831</td>
<td>7.6</td>
<td>Alluvial aquifers and GDEs are associated with the Oakover River, the main tributary of the De Grey River. Potential large groundwater resources in karst Carawine Dolomite, which requires large amounts of dewatering at the Woodie Woodie manganese mine. Less mineralised and therefore investigated compared with most surrounding provinces.</td>
</tr>
<tr>
<td>Chichester Range</td>
<td>19,852</td>
<td>6.9</td>
<td>Lower elevation range across the Fortescue River Valley from the Hamersley Range. Forms the headwaters of rivers in the Port Hedland Coast Basin as well as defines the Fortescue Valley in the north. Local aquifers are associated with the Marra Mamba iron ore deposits, which are saline close to the Fortescue Marsh.</td>
</tr>
<tr>
<td>Upper Fortescue Valley</td>
<td>10,171</td>
<td>3.5</td>
<td>Area surrounds and includes the hypersaline Fortescue Marsh formed by a surface water divide at the Goodiadarrie Hills which prevents the Fortescue River from leaving the upper valley. Aquifers associated with paleochannels are recharged by flow in modern valleys and from recharge of impounded water from the Ophthalmia Dam. Contains sandplain areas as well as sandfire, bluebush and chenopod flats.</td>
</tr>
<tr>
<td>Carnarvon Basin</td>
<td>7,312</td>
<td>2.5</td>
<td>Mesozoic sediments overlain by coastal plain. The Birdrong Sandstone contains saline water which is freshest in inland areas where it is recharged. Contains small alluvial aquifers associated with the Cane, Lower Robe and Lower Fortescue rivers.</td>
</tr>
<tr>
<td>Coastal Plain</td>
<td>5,134</td>
<td>1.8</td>
<td>A low lying coastal plain extends west and east of Port Hedland. Coastal alluvial aquifers contain important water resources for the East Pilbara Water Supply Scheme where the Yule and De Grey rivers form coastal deltaic deposits.</td>
</tr>
<tr>
<td>HYDROGEOLOGICAL PROVINCE</td>
<td>AREA (km²)</td>
<td>AREA (%)</td>
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<tr>
<td>Lower Fortescue Valley</td>
<td>4,986</td>
<td>1.7</td>
<td>A narrow valley between the Hamersley and Chichester ranges, characterised by riverine calcrite formed from weathering of the dolomite of the Wittenoom Formation. The main water source is the Millstream aquifer which has been the main water source for the West Pilbara Water Supply Scheme until the Harding Dam was built and Bungaroo started supplying water from a CID.</td>
</tr>
<tr>
<td>Sylvania Dome</td>
<td>4,457</td>
<td>1.6</td>
<td>Granitic rock outcrops and thin sandy soils, shallow alluvial deposits and associated GDEs. The crystalline basement rocks contain few fractures and therefore poor aquifers.</td>
</tr>
<tr>
<td>East Upper Fortescue</td>
<td>3,449</td>
<td>1.2</td>
<td>An arid inland area with very high temperatures and potential evaporation rates. Like the Ashburton province, the basement rocks comprise fine textured sediments and volcanics which weather to form clayey regoliths and few aquifers. Poorly investigated due to the lack of mineralisation.</td>
</tr>
<tr>
<td>TOTAL</td>
<td>288,479</td>
<td>100.0</td>
<td>11.4% of Western Australia’s area and 3% of its population which contains the state’s highest elevations (Mounts Meharry, Bruce and Nameless), highest temperatures (Marble Bar, Telfer) and most important mineral province in terms of export income.</td>
</tr>
</tbody>
</table>

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3 Climate

Authors: Steve Charles, Guobin Fu, Freddie Mpelasoka, Richard Silberstein, Geoff Hodgson and Don McFarlane

Key points

The key findings of the climate analysis and scenario development for the Pilbara Assessment area are:

- The mean annual rainfall for the baseline period (water years 1961 to 2012) is 334 mm/year, compared to the long-term (1911 to 2012) mean of 299 mm/year.
- An exceptionally wet 7-year period from 1995 to 2001 had a mean annual rainfall of 500 mm/year. Western Australia experienced more tropical cyclones than average during this period.
- There are increasing linear trends of annual rainfall, extreme rainfall (e.g. 99th percentile daily rainfall), number of rainfall days and mean rain day intensity for the 1961 to 2012 period in the eastern half of the Assessment area, with opposing decreasing trends in the western half of the Assessment area.
- The median (Cmid) projected changes from 18 global climate models (GCMs) are small changes in annual rainfall for both projection periods (2030 and 2050) of −0.1% of the baseline mean for RCP4.5 and −1.8% to −2.5% for RCP8.5.
- The selected Cwet scenarios have projected annual rainfall increases ranging from 3.2% (2030, RCP4.5) to 7.8% (2050, RCP8.5).
- The selected Cdry scenarios have projected annual rainfall decreases ranging from −4.2% (2030, RCP4.5) to −17% (2050, RCP8.5).
- The corresponding projected areal potential evaporation (areal PE) changes range from annual increases of 3% to 4% for 2030 and from 4% to 7% for 2050.
- The mean annual daily mean temperature changes relative to Scenario A (mid-point in 1986) under the future climate scenarios are 1.5°C for 2030 and 2.2°C for 2050.
- Annual rainfall deficits increase for all Cwet, Cmid and Cdry scenarios, due to projected increases in areal PE (a caveat being the Morton's areal PE formulation used does not account for wind speed changes).

3.1 Introduction

The objectives of the climate component of the Assessment include:

1. providing a review of historical Pilbara climate averages and trends using Bureau of Meteorology data and the Stage 3 Indian Ocean Climate Initiative (IOCI) findings, including:
   a. drivers of changes to recent rainfall
   b. intensity and frequency of tropical cyclones
   c. climate extremes
2. developing 2030 and 2050 climate scenarios of daily rainfall and areal potential evaporation (areal PE) to run surface water and recharge/groundwater models
3. summarising the range of possible future climates of relevance to sectors outside hydrology (e.g. agriculture, mining, tourism) where possible.

The historical climate characteristics of the Assessment area were outlined in Section 2.2. This chapter focuses on the selection and development of climate scenarios for historical and future climates and the quantification of rainfall and areal PE projections resulting from the future climate scenarios, as simulated...
3.2 Historical climate scenario

3.2.1 Baseline selection

The Assessment uses a water year of 1 October to 30 September as this period corresponds (on average) with the end of the dry season and the start of the wet season. It is thus a more meaningful climatic period than the calendar year, which would ‘split’ the wet season. A baseline period, representative of the historical climate of the Assessment area, was selected as the 52-year period from 1 October 1960 (water year 1961) to 30 September 2012 (water year 2012) (Charles et al., 2015). The source of historical data is the SiLO Data Drill, consisting of Bureau of Meteorology station data interpolated to a regular 0.05° grid (Jeffrey et al., 2001).

Figure 3.1 shows that the Assessment area’s historical climate is highly variable, with 11-year and 51-year moving averages showing the decadal and long-term variability, respectively. Temporal trends at individual stations are shown as the time series of the cumulative difference from the mean for five high-quality stations (Figure 3.2). These highlight the progressive drying over the early part of the record followed by consistent and on-going wetting since the 1960s for most stations, with particularly rapid wetting since the 1990s for the inland east (Bonney Downs) and inland central (Mount Florance) stations. The wetting trends continue in the most recent years for three eastern and central stations (Bonney Downs, Roebourne and Mount Florance) whereas the two westerly stations (Mardie, on the coast, and Mount Augustus to the southwest) show recent declines.

For the 1961 to 2012 baseline period, the eastern half of the Assessment area shows increasing linear trends for annual rainfall, 99th percentile daily rainfall (as an example of extremes), number of rain days, and rainfall intensity (i.e. rainfall amount per rain day), with opposing decreasing linear trends in the western third to half of the region (Figure 3.3). These trends show annual rainfall has decreased by about 100 mm in the extreme west (−2 mm/year/year) and increased by about 200 mm in the east (+4 mm/year/year) over the 52-year baseline period. The western decrease is related to climate change resulting in cold fronts no longer penetrating as far north as in the past. The increase in the east may also be associated with a poleward expansion of climate systems, with more tropical rainfall now reaching the Pilbara. However, it could also be due to natural variability or increased aerosols from forest fires and atmospheric pollution in south-east Asia (Rotstayn et al., 2012).

The mean annual rainfall of the Assessment area for the 1961 to 2012 baseline period was 334 mm/year. An exceptionally wet 7-year period from 1995 to 2001, the result of a higher than average frequency of tropical cyclones impacting Western Australia (Charles et al., 2015), has a mean annual rainfall of 500 mm/year. The mean of the 1961 to 2012 period excluding this wet 7-year period was 308 mm/year, which is similar to the 299 mm/year mean of the full 1911 to 2012 period as plotted in Figure 3.1. The presence of the wet 7 years towards the end of the record contributes to the region-averaged trends. For example, the mean 1961 to 2012 trend in annual rainfall, averaged across the Assessment area, is 2.2 mm/year/year with removal of the 7-year wet period reducing this to a 0.9 mm/year/year trend. The magnitudes of the trends in 99th percentile daily rainfall, number of rain days and rainfall intensity are small when averaged across the Assessment area, as the increasing trends in the east are mostly cancelled out by the decreasing trends in the west.
Figure 3.1 Average annual total rainfall for the water years 1911 to 2012, with (a) 11-year and 51-year moving averages and (b) means for certain periods for the Assessment area.

The 52-year 1961 to 2012 baseline period defines the historical ‘Scenario A’ against which all future scenarios (Scenario Cs) are compared. The future scenarios are termed ‘Scenario C’ for consistency with previous projects that included a ‘Scenario B’ representing the most recent decade, as in the Murray-Darling Basin Sustainable Yields Project (to represent the millennium drought) and the South-West Western Australia Sustainable Yields Project (to represent the continued recent drying trends). The Pilbara Water Resource Assessment comparison does not include a Scenario B.
Figure 3.2 Cumulative difference from the mean time series for five stations with high-quality long-term records. Locations of stations shown in bottom right panel.

Figure 3.3 Trends for 1961 to 2012 (a) annual rainfall, (b) 99th percentile daily rainfall, (c) number of rain days > 1mm, and (d) rainfall intensity for the Assessment area.
3.3 Future climate scenarios

3.3.1 Methodology

The methodology used to produce the Scenario C future climate time series of daily rainfall and areal PE is summarised here with full details reported in Chapter 4 of Charles et al. (2015). Scenarios of possible changes to the climate of the Assessment area by 2030 and 2050 were produced by scaling the historical (Scenario A) time series according to the long-term trends simulated by CMIP5 GCMs used in the IPCC AR5 (IPCC, 2013). These GCM simulations were forced by plausible scenarios of greenhouse gas emissions throughout the 21st century (Taylor et al., 2012).

The emissions scenarios used in AR5 are referred to as ‘representative concentration pathways’ (RCPs) (Van Vuuren et al., 2011). RCP8.5, a high-emissions scenario similar to the A1FI scenario in the previous IPCC AR4, and RCP4.5, a low-end scenario similar to B1, were used to assess a range of plausible changes. The RCP numbers refer to the approximate enhanced radiative forcing levels by 2100 (i.e. an additional 8.5 W/m² and 4.5 W/m² of radiative forcing at 2100 corresponding to equivalent CO₂ levels of ~1370 ppm and ~650 ppm, respectively). The RCP8.5 and RCP4.5 forced simulations do not diverge significantly until after 2050 (Knutti and Sedlacek, 2013) and thus the mean of the GCM ensemble is similar for 2030 and 2050. The GCM simulation producing the largest changes by 2030 could come from either RCP scenario, whereas by 2050 the RCP8.5 ensemble members produce the largest changes.

Eighteen GCMs were used as they provided the full set of output variables required for calculation of Scenario C daily time series (Table 3.1). Investigation of the ability of these GCMs to reproduce Pilbara regional climatology was not within the scope of this Assessment; however, other research has assessed the full set of AR5 GCMs within an Australian context (CSIRO and Bureau of Meteorology, 2015). An overall picture emerges that the GCMs projecting a drier future for the Pilbara region are more likely to be assessed poorer performers in terms of tropical climatology (monsoon, ENSO, MJO) compared to those that project wetter futures. However, there is still a role for assessing the full range of projected change, as is undertaken herein, whilst taking into account potential reduced confidence in those GCMs producing the dry scenarios.

The Scenario C daily time series were produced by scaling the Scenario A rainfall and areal PE series according to the projected GCM changes using a ‘daily scaling’ method based on Chiew et al. (2009) and Mpelasoka and Chiew (2009) as used in the CSIRO Murray-Darling Basin Sustainable Yields Project, Northern Australia Sustainable Yields Project and South-West Western Australia Sustainable Yields Project. This method is generally applicable to surface and groundwater climate change studies (Chiew et al., 2010; Crosbie et al., 2011) as it scales daily areal PE according to GCM-projected seasonal changes (on a December–January–February, March–April–May, June–July–August and September–October–November seasonal basis) and daily rainfall according to GCM-projected seasonal changes to daily rainfall on a percentile-class basis. That is, the rainfall scaling takes into account that projected changes in the higher intensity daily rainfalls may differ from moderate and low intensity events, and so the percentage changes as projected by the GCMs for the different percentile-bins are applied to the Scenario A rainfall amounts in the equivalent percentile-bins. This allows high intensity daily rainfall to increase even in cases where mean rainfall decreases. A limitation of this method is that the Scenario C series maintain the sequence of rainfall events as given by the Scenario A series, thus potential event frequency changes are not assessed.

Applying the scaling factor techniques to the Scenario A daily rainfall and areal PE time series produces an ensemble of 36 Scenario C time series for each projection period, i.e. 36 = 18 GCMs x 2 RCPs (RCP8.5 and RCP4.5) for projected-2030 and projected-2050 climates of the Pilbara. A summary set of three to represent a wet, median and dry future were selected from the 18 GCMs for each future period and RCP combination. The selection and properties of these selected scenarios are summarised for the Assessment area in the following section.
### Table 3.1 Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models and institutions

<table>
<thead>
<tr>
<th>GLOBAL CLIMATE MODEL</th>
<th>INSTITUTION</th>
<th>INSTITUTION ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCESS1.0</td>
<td>Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology (BOM), Australia</td>
<td>CSIRO-BOM</td>
</tr>
<tr>
<td>ACCESS1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCC-CSM1.1</td>
<td>Beijing Climate Center, China Meteorological Administration, China</td>
<td>BCC</td>
</tr>
<tr>
<td>CanESM2</td>
<td>Canadian Centre for Climate Modelling and Analysis, Canada</td>
<td>CCCMA</td>
</tr>
<tr>
<td>CCSM4</td>
<td>National Center for Atmospheric Research, USA</td>
<td>NCAR</td>
</tr>
<tr>
<td>CNRM-CM5</td>
<td>Centre National de Recherches Meteorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique, France</td>
<td>CNRM-CERFACS</td>
</tr>
<tr>
<td>CSIRO-Mk3.6.0</td>
<td>Commonwealth Scientific and Industrial Research Organisation in collaboration with Queensland Climate Change Centre of Excellence, Australia</td>
<td>CSIRO-QCCCE</td>
</tr>
<tr>
<td>GFDL-ESM2G</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory, USA</td>
<td>NOAA GFDL</td>
</tr>
<tr>
<td>GFDL-ESM2M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>Met Office Hadley Centre, UK</td>
<td>MOHC</td>
</tr>
<tr>
<td>IPSL-CM5A-LR</td>
<td>Institut Pierre-Simon Laplace, France</td>
<td>IPSL</td>
</tr>
<tr>
<td>IPSL-CM5A-MR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPSL-CM5B-LR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIROC-ESM</td>
<td>Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies, Japan</td>
<td>MIROC</td>
</tr>
<tr>
<td>MIROC-ESM-CHEM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIROC5</td>
<td>Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan</td>
<td>MIROC</td>
</tr>
<tr>
<td>MRI-CGCM3</td>
<td>Meteorological Research Institute, Japan</td>
<td>MRI</td>
</tr>
<tr>
<td>NorESM1-M</td>
<td>Norwegian Climate Centre, Norway</td>
<td>NCC</td>
</tr>
</tbody>
</table>

### 3.3.2 Scenario C selection

From the ensemble of Scenario C time series for 2030 and 2050, the RCP8.5 and RCP4.5 ensemble members that produced the 90th, 50th and 10th percentile rainfall changes for the Assessment area were initially identified as the Cwet, Cmid and Cdry scenarios (Charles et al., 2015). Evaluation of the spatial patterns associated with each of these initially selected scenarios determined cases where the initial selection had a spatial pattern that would not produce consistent results across the four reporting regions. For example, a Scenario Cmid selected on the basis that it produced the 50th percentile rainfall change when averaged over the entire Assessment area could have a spatial pattern consisting of two large opposing changes that cancel each other out to produce a small overall change. Thus selection of a different GCM with a more consistent spatial pattern and a similar overall rainfall change to that which was initially chosen was undertaken.

This approach resulted in the selection of the CNRM-CM5 GCM scenarios for Cwet, the ACCESS 1.0 GCM scenarios for the Cmid, and the IPSL-CM5A-MR GCM scenarios for the Cdry (for both RCP8.5 and RCP4.5). The Assessment area mean daily temperature changes simulated by these selected GCMs are summarised in Table 3.2. Note that whilst for 2030 the warming trends correlate with the magnitude of drying, this is not the case for 2050 as the Cmid GCM projects warmer trends than the Cdry GCM. This is not particularly surprising given that the Scenario C selection was based solely on projected rainfall changes.
Table 3.2 Mean annual daily mean temperature changes (relative to Scenario A) under Cwet, Cmid and Cdry future climate scenarios from 18 GCMs RCP4.5 and RCP8.5 emissions scenario projections for 2030 and 2050 for the Assessment area

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>SCENARIO C</th>
<th>RCP4.5 EMISSIONS SCENARIO CHANGE (°C)</th>
<th>RCP8.5 EMISSIONS SCENARIO CHANGE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2030</td>
<td>C30wet</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>2030</td>
<td>C30mid</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>2030</td>
<td>C30dry</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>2050</td>
<td>C50wet</td>
<td>1.8</td>
<td>2.1</td>
</tr>
<tr>
<td>2050</td>
<td>C50mid</td>
<td>2.1</td>
<td>2.9</td>
</tr>
<tr>
<td>2050</td>
<td>C50dry</td>
<td>1.8</td>
<td>2.7</td>
</tr>
</tbody>
</table>

The resulting Assessment area rainfall changes for these scenarios are summarised in Table 3.3, with the associated areal PE changes summarised in Table 3.4. Whilst rainfall in the future scenarios falls each side of a continuation of the current historical rainfall, the magnitude of change for the dry projections are up to 10% greater than those of the wet projections (i.e. the largest increase is 7.8% in contrast to the largest decrease of ~17.4%). In addition, the across-the-board increases in areal PE mean that even the Cwet and Cmid scenarios experience increased annual rainfall deficits. The spatial patterns of projected mean annual rainfall and areal PE change, for the Cwet, Cmid and Cdry scenarios, are shown in Figure 3.4 and Figure 3.6 respectively. The projected changes to 99th percentile daily rainfall are of similar magnitude to the annual changes (Figure 3.5). The spatial discontinuities result from changes in scaling factors across GCM grid boundaries.

Whilst on balance future projections indicate a slightly higher likelihood that the future climate will be both hotter and drier, with rainfall deficits and therefore soil moisture deficits correspondingly higher, as mentioned above the wet scenarios should not be discounted given that there is possibly lower confidence in the performance of the GCMs projecting a drier future (CSIRO and Bureau of Meteorology, 2015). Consideration of the wet scenarios is also important given observed trends of increased summer rainfall in the north-west of Australia.

There are several hypothesised drivers of the observed north-west Australian rainfall trends. Rotstayn et al. (2012) used a GCM (CSIRO Mk3.6) to model the role that aerosols (more specifically, the Asian aerosol haze) may have had on north-west Australian rainfall trends, proposing a mechanism by which the cooling effect of aerosols across the south-east Asian region increases cyclonic (clockwise) circulation over the Indian Ocean, leading to more moisture being transported towards north-west Australia by strengthened monsoonal winds. However, given the results were only based on one GCM, they state this interpretation should be treated as a hypothesis at this stage until tested by multiple models.

Lin and Li (2012) suggest that the observed increase in north-west Australian summer rainfall may be partially explained by a remote teleconnection with the tropical Atlantic. The mechanism involves increased tropical Atlantic sea surface temperatures producing enhanced atmospheric ascent, promoting the south-eastward propagation of a Rossby wave train that produces anomalies in upper tropospheric geopotential heights over Australia. This results in enhanced ascent and convergence in the lower troposphere over Australia, with associated increased rainfall in north-west Australia. In addition to this tropical Atlantic teleconnection, a relationship has also been proposed between warming sea surface temperatures in the tropical western Pacific to the north of Australia and north-west Australian summer rainfall increases since 1979 (Li et al., 2013). In this process, tropical western Pacific sea surface temperature warming results in the formation of a large cyclonic anomaly across the whole of northern Australia with the resulting low sea level pressure correlated with more rainfall, cloud and surface evaporation (and hence land surface cooling) over the region. Li et al. (2013) conclude that this increase in tropical western Pacific sea surface
temperature is the dominant driver of increasing northern Australia summer rainfall trends over the 1979 to 2010 period. As yet there is no clear understanding as to how these proposed driving factors have combined to produce the observed trends, or which are likely to dominate in the future (Cai et al., 2011; Li et al., 2013; Lin and Li, 2012; Rotstayn et al., 2012).

An additional caveat applies to confidence in the areal PE projections, given that the Morton’s areal PE formulation used does not take account of wind speed changes and thus is not considered a physically based method by McVicar et al. (2012). The impacts of the Scenario C projected rainfall and areal PE changes on modelled surface water and groundwater changes are covered in Chapters 4 and 5, respectively.

Table 3.3 Mean annual rainfall changes (relative to Scenario A) under Cwet, Cmid and Cdry future climate scenarios from 18 GCMs RCP4.5 and RCP8.5 emissions scenario projections for 2030 and 2050 for the Assessment area

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>SCENARIO C</th>
<th>RCP4.5 EMISSIONS SCENARIO (%)</th>
<th>RCP4.5 EMISSIONS SCENARIO (mm)</th>
<th>RCP8.5 EMISSIONS SCENARIO (%)</th>
<th>RCP8.5 EMISSIONS SCENARIO (mm)</th>
</tr>
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<tbody>
<tr>
<td>2030</td>
<td>C30wet</td>
<td>3.2</td>
<td>11</td>
<td>5.6</td>
<td>19</td>
</tr>
<tr>
<td>2030</td>
<td>C30mid</td>
<td>–0.1</td>
<td>0</td>
<td>–1.8</td>
<td>–6</td>
</tr>
<tr>
<td>2030</td>
<td>C30dry</td>
<td>–4.2</td>
<td>–14</td>
<td>–12.6</td>
<td>–42</td>
</tr>
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<td>2050</td>
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<td>7.8</td>
<td>26</td>
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<tr>
<td>2050</td>
<td>C50mid</td>
<td>–0.1</td>
<td>0</td>
<td>–2.5</td>
<td>–8</td>
</tr>
<tr>
<td>2050</td>
<td>C50dry</td>
<td>–5.9</td>
<td>–20</td>
<td>–17.4</td>
<td>–58</td>
</tr>
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</table>

Table 3.4 Mean annual areal PE changes (relative to Scenario A) under Cwet, Cmid and Cdry future climate scenarios from 18 GCMs RCP4.5 and RCP8.5 emissions scenario projections for 2030 and 2050 for the Assessment area

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>SCENARIO C</th>
<th>RCP4.5 EMISSIONS SCENARIO (%)</th>
<th>RCP4.5 EMISSIONS SCENARIO (mm)</th>
<th>RCP8.5 EMISSIONS SCENARIO (%)</th>
<th>RCP8.5 EMISSIONS SCENARIO (mm)</th>
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</thead>
<tbody>
<tr>
<td>2030</td>
<td>C30wet</td>
<td>3.0</td>
<td>57</td>
<td>2.2</td>
<td>42</td>
</tr>
<tr>
<td>2030</td>
<td>C30mid</td>
<td>3.2</td>
<td>60</td>
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<td>59</td>
</tr>
<tr>
<td>2030</td>
<td>C30dry</td>
<td>3.8</td>
<td>72</td>
<td>3.8</td>
<td>72</td>
</tr>
<tr>
<td>2050</td>
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<td>4.0</td>
<td>76</td>
<td>4.1</td>
<td>77</td>
</tr>
<tr>
<td>2050</td>
<td>C50mid</td>
<td>4.7</td>
<td>89</td>
<td>6.6</td>
<td>125</td>
</tr>
<tr>
<td>2050</td>
<td>C50dry</td>
<td>4.4</td>
<td>83</td>
<td>6.5</td>
<td>123</td>
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</table>
Figure 3.4 Mean annual rainfall change (percentage, relative to Scenario A) for 2030 and 2050 RCP4.5 and RCP8.5 projections for Cwet, Cmid and Cdry scenarios for the Assessment area
Figure 3.5 99th percentile daily rainfall change (percentage, relative to Scenario A) for 2030 and 2050 RCP4.5 and RCP8.5 projections for Cwet, Cmid and Cdry scenarios for the Assessment Area
Figure 3.6 Mean annual areal PE change (percentage, relative to Scenario A) for 2030 and 2050 RCP4.5 and RCP8.5 projections for Cwet, Cmid and Cdry scenarios for the Assessment area.
Figure 3.7 presents the selected Scenario C changes in the context of those projected by all 18 GCMs, with each coloured bar giving the range between the RCP4.5 and RCP8.5 projected changes for each GCM, for 2030 (left) and 2050 (right), respectively.

Figure 3.7 Mean annual rainfall change (percentage, relative to Scenario A) for RCP4.5 and RCP8.5 projections from 18 CMIP5 GCMs for 2030 and 2050 for the Assessment area. The second wettest (driest) scenarios from RCP4.5 and RCP8.5 are designated Cwet (Cdry). The median, selected from the 9th and 10th ranked GCM closest to the respective RCP4.5 and RCP8.5 mean, is designated Cmid. Solid symbols are used for RCP8.5, open symbols for RCP4.5.

The median and 10th to 90th percentile range of monthly rainfall from the Scenario C ensemble for RCP8.5 are shown for 2030 in Figure 3.8 and for 2050 in Figure 3.9. The Scenario Cdry is dominated by the relatively large reductions in January and February rainfall, the wettest months. RCP4.5 ensemble ranges (not shown) are smaller. The monthly mean, median and range of the scaled 1911 to 2012 series (this period allows direct comparison with Figure 2.4 in Section 2.2) for the RCP8.5 2050 Cwet and Cdry scenarios are shown in Figure 3.10 and Figure 3.11, respectively. These plots also highlight that the largest absolute changes are for the wetter summer months.

Monthly projected areal PE results for the RCP8.5 Scenario C ensemble are shown in Figure 3.12 for 2030 and Figure 3.13 for 2050, with the increase between 2030 and 2050 driven predominantly by the continued warming in the GCM simulations. The monthly areal PE projections for RCP4.5 are similar although the changes between 2030 and 2050 are less.
Figure 3.8 Mean monthly rainfall for Scenario A (A mean) and 2030 RCP8.5 Scenario C median (C median) and range (C range, from 10th to 90th percentile seasonal changes of 18 GCMs) for the Assessment area

Figure 3.9 Mean monthly rainfall for Scenario A (A mean) and 2050 RCP8.5 Scenario C median (C median) and range (C range, from 10th to 90th percentile seasonal changes of 18 GCMs) for the Assessment area
Figure 3.10 Scenario Cwet 2050 RCP8.5 monthly rainfall (mean, median and 20th to 80th percentile monthly rainfall range) for the Assessment area (compare to Figure 2.4 in Section 2.2)

Figure 3.11 Scenario Cdry 2050 RCP8.5 monthly rainfall (mean, median and 20th to 80th percentile monthly rainfall range) for the Assessment area (compare to Figure 2.4 in Section 2.2)
Figure 3.12 Mean monthly areal PE for Scenario A (A mean) and 2030 RCP8.5 Scenario C median (C median) and range (C range, from 10th to 90th percentile seasonal changes of 18 GCMs) for the Assessment area

Figure 3.13 Mean monthly areal PE for Scenario A (A mean) and 2050 RCP8.5 Scenario C median (C median) and range (C range, from 10th to 90th percentile seasonal changes of 18 GCMs) for the Assessment area
3.4 References


4 Rainfall-runoff

Authors: Santosh Aryal, Richard Silberstein, Geoff Hodgson, Don McFarlane and Warrick Dawes

Key points

- Observed data shows that only 2 to 13% of mean annual rainfall becomes runoff.
- Under a wet future climate scenario (C50wet8.5) mean annual runoff is projected to increase by between 13 and 35% relative to the Historical climate.
- Under a dry future climate (C50dry8.5) mean annual runoff is projected to decrease by between 33 and 61% relative to the Historical climate.
- Relative to the Historical climate, the mean number of days of flow per year is projected to increase under a wet future scenario by 12 to 20% and decrease by 25 to 59% under a dry future scenario.
- Mean annual runoff is projected to change by 3.4 to 4.0 times the percentage change in mean annual rainfall under the 2030 scenarios and by between 2.3 and 3.0 under the 2050 scenarios.
- Catchments in the Fortescue River basin have the lowest mean annual runoff and runoff ratio of 12.9 and 0.034, respectively. The Nullagine River in the De Grey river basin has highest mean annual runoff (50 mm) and one of the highest runoff coefficients (0.122).
- With a mean annual flow of 1167 GL, the De Grey River also has the highest discharge in the Assessment area. However, it also has the longest no-flow period of 1274 days at gauging station 710003.
- Mostly between 8 and 30 mm rain is required in each rainfall event to initiate runoff across the Pilbara.
- The longest period of no flow is projected to vary from less than a year for the lower Fortescue River to more than three years for the De Grey River at the outlet.
- The percentage change in groundwater recharge under wet and dry future climates relative to the Historical climate is much smaller than the percentage change in number of flow days.
- Compared to other basins the Ashburton and Robe basins show a large decrease in the number of years which exceed the high flow (90th percentile historical flow) under a dry future climate. They also show a large increase in number of years less than the low flow (10th percentile historical flow) due to dry future climate.
- In the De Grey River there is practically no difference between the flood heights due to highest recorded and highest future peak daily flows.

4.1 Introduction

This chapter provides results of surface water analysis and modelling of the Assessment area to evaluate the possible impact of future climate scenarios on aspects of the surface water hydrology of the Pilbara. Illustrative results are included here, with more-detailed analysis in the respective regional reports for the four reporting regions: Upper Fortescue, Lower Fortescue Hedland, De Grey Canning and Ashburton Robe.

A summary of past climate is in Chapter 2 and projected future climate scenarios are described in Chapter 3. Although contributing about one-third of the total rainfall to the region, rainfall during tropical cyclones results in a larger proportion of streamflow and recharge events to aquifers. Streamflow response to cyclonic rainfall events is almost instantaneous, while groundwater level responses often have a one to two month time lag (URS, 2008).

Because of the high potential evaporation, soils dry between events and a large rainfall threshold (21 mm of rainfall per event) needs to be exceeded to initiate flow or recharge. There is also a strong correlation
between streamflow and total recharge to alluvial aquifers because the majority of recharge is thought to result from recharge through the streambed during flow events.

4.1.1 Objectives of surface water analysis and modelling

The surface water data analysis and modelling calculates runoff and estimates flood extent in the five river basins discussed in Chapter 2.

The objectives of this component of the Assessment are:

1. characterise the rainfall-runoff and streamflow generation across the Assessment area during the historical climate
2. estimate and characterise changes in streamflow quantity, frequency and duration across the Assessment area under future climate scenarios relative to a baseline scenario
3. estimate changes in flow frequency characteristics and streamflow recharge under projected climate change scenarios
4. estimate the width and duration of near-river channel inundation associated with major flow events.

4.2 Catchment characteristics

4.2.1 Introduction and review of previous studies

The Pilbara contains five major river basins: Ashburton, Robe, Fortescue, Yule and De Grey. Each of the major rivers has a number of other tributaries, most notably the Oakover and Nullagine, tributaries to the De Grey River.

In the Pilbara the majority of streamflow occurs between January and March following tropical cyclones or thunderstorms. In the west of the Assessment area, winter rainfall during low-pressure trough systems can produce small runoff events in June. The proportion of rainfall contributed by tropical cyclones ranges from 50% at Port Hedland to about 30% in the most south-easterly parts of the Assessment area (Charles et al., 2013).

All watercourses are naturally ephemeral and even the major rivers are dry for long periods each year (on average >80% of the time). However, there are permanent pools in reaches maintained by groundwater throughout the year. Monthly and annual flow volumes are highly variable, more so than rivers elsewhere in the world with the same climate type and mean annual flow (Petheram et al., 2008). Larger rivers in the Pilbara flow for longer periods of time than smaller rivers. URS (2008) state that on average only the Fortescue River flows at a rate greater than 1 ML/day for more than 50% of the year.

The Assessment area is shown in Figure 4.1. In the east of the Assessment area (Canning) surface drainage is uncoordinated and no stream network is evident.
4.3 Review of rainfall-runoff responses

While there are 53 stream gauges within the Assessment area, 20 have no rating curve and for 7 others the rating curve is poorly defined. There are 26 stream gauging stations which have adequate good quality data and these stations were used in this analysis. These stations are mostly managed by the Department of Water (Table 4.1), and records range in length from 7 to 48 years, with a mean of 33 years (Figure 4.2). There are another eight stream gauging stations for which stage height only is available without the rating curves with sufficient confidence to estimate flows.

Periods of flow and no-flow are shown in Figure 4.2. A selection of flow statistics is listed in Table 4.2. Rainfall from over 90 rain gauges in the region has been analysed. The daily rainfall and potential evaporation (following Morton, 1983) sequences from the SILO DataDrill (Jeffrey et al., 2001, <www.longpaddock.qld.gov.au/silo/>) is used to compile climate data sequences for each catchment. The results of that analysis are given in Charles et al. (2013).

For the analysis, all rainfall have been taken from the SILO DataDrill set, and compiled to make up catchment average totals for comparison with the streamflow gauges. As a consequence, some large catchments have rainfall recorded a long distance from the flow gauge.
Table 4.1 List of stream gauges used in the Assessment, with catchment area and dates of commencement and cessation (if closed).

<table>
<thead>
<tr>
<th>AUSTRALIAN WATER RESOURCES COUNCIL CODE</th>
<th>STATION NAME</th>
<th>CATCHMENT AREA (km²)</th>
<th>STATION COMMENCE</th>
<th>STATION CLOSE</th>
<th>LENGTH OF RECORD (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>706003</td>
<td>Ashburton River, Nanutarra</td>
<td>71,387</td>
<td>1/06/1972</td>
<td></td>
<td>41.4</td>
</tr>
<tr>
<td>706207</td>
<td>Hardey River, Mt Samson</td>
<td>250</td>
<td>1/12/1966</td>
<td>24/05/2001</td>
<td>34.5</td>
</tr>
<tr>
<td>706209</td>
<td>Ashburton River, Capricorn Range</td>
<td>43,098</td>
<td>1/01/1968</td>
<td></td>
<td>45.8</td>
</tr>
<tr>
<td>707002</td>
<td>Robe River, Yarraloola</td>
<td>7,104</td>
<td>1/01/1972</td>
<td></td>
<td>41.8</td>
</tr>
<tr>
<td>707005</td>
<td>Cane River, Toolunga</td>
<td>2,326</td>
<td>30/09/1986</td>
<td></td>
<td>27.0</td>
</tr>
<tr>
<td>708001</td>
<td>Marillana Creek, Flat Rocks</td>
<td>1,370</td>
<td>15/08/1967</td>
<td></td>
<td>46.2</td>
</tr>
<tr>
<td>708002</td>
<td>Fortescue River, Gregory Gorge</td>
<td>14,629</td>
<td>2/06/1965</td>
<td></td>
<td>48.4</td>
</tr>
<tr>
<td>708011</td>
<td>Fortescue River, Newman</td>
<td>2,822</td>
<td>9/01/1980</td>
<td></td>
<td>33.8</td>
</tr>
<tr>
<td>708013</td>
<td>Weeli Wolli Creek, Waterloo Bore</td>
<td>3,991</td>
<td>30/11/1984</td>
<td></td>
<td>28.9</td>
</tr>
<tr>
<td>708014</td>
<td>Weeli Wolli Creek, Tarina</td>
<td>1,512</td>
<td>10/05/1985</td>
<td></td>
<td>28.4</td>
</tr>
<tr>
<td>708015</td>
<td>Fortescue River, Bilanoo</td>
<td>18,402</td>
<td>11/12/1975</td>
<td></td>
<td>37.8</td>
</tr>
<tr>
<td>708223</td>
<td>Fortescue River, Doggers Gorge</td>
<td>14,639</td>
<td>1/12/1966</td>
<td>6/03/1981</td>
<td>14.3</td>
</tr>
<tr>
<td>708227</td>
<td>Portland River, Recorder Pool</td>
<td>553</td>
<td>1 Dec 1966</td>
<td>24 May 2001</td>
<td>34</td>
</tr>
<tr>
<td>709001</td>
<td>Harding River, Upstream Cooya Pooya</td>
<td>1,058</td>
<td>13/12/1965</td>
<td>30/01/1985</td>
<td>19.1</td>
</tr>
<tr>
<td>709003</td>
<td>Sherlock River, Coonanarra Pool</td>
<td>4,581</td>
<td>1/11/1967</td>
<td>19/03/1997</td>
<td>29.4</td>
</tr>
<tr>
<td>709004</td>
<td>Maitland River, Miaree Pool</td>
<td>1,948</td>
<td>1 Jan 1972</td>
<td></td>
<td>43</td>
</tr>
<tr>
<td>709005</td>
<td>Yule River, Jellabiidinwa Well</td>
<td>8,427</td>
<td>18/09/1972</td>
<td></td>
<td>41.1</td>
</tr>
<tr>
<td>709007</td>
<td>Harding River, Marmurrina Pool U-S</td>
<td>49</td>
<td>1 Sep 1974</td>
<td>6 May 1999</td>
<td>25</td>
</tr>
<tr>
<td>709010</td>
<td>Turner River, Pincunah</td>
<td>885</td>
<td>1 Jan 1985</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>710001</td>
<td>Shaw River, Upper North Pole</td>
<td>6,479</td>
<td>15/02/1967</td>
<td>22/10/1981</td>
<td>14.7</td>
</tr>
<tr>
<td>710003</td>
<td>De Grey River, Coolenar Pool</td>
<td>50,007</td>
<td>6/11/1974</td>
<td></td>
<td>38.9</td>
</tr>
<tr>
<td>710004</td>
<td>Nullagine River, Nullagine</td>
<td>875</td>
<td>13/03/1997</td>
<td></td>
<td>16.6</td>
</tr>
<tr>
<td>710204</td>
<td>Coongan River, Marble Bar</td>
<td>3,736</td>
<td>1/12/1966</td>
<td></td>
<td>46.9</td>
</tr>
<tr>
<td>710229</td>
<td>Shaw River, North Pole Mine</td>
<td>6,501</td>
<td>1/02/1967</td>
<td></td>
<td>46.7</td>
</tr>
<tr>
<td>Average</td>
<td>–</td>
<td>10391</td>
<td>01/01/1972</td>
<td></td>
<td>33.5</td>
</tr>
<tr>
<td>Median</td>
<td>–</td>
<td>3543</td>
<td>28/08/1973</td>
<td></td>
<td>34.2</td>
</tr>
</tbody>
</table>
Figure 4.2 Period of record, flow, missing record and zero flow of the stream gauges used in the Assessment
4.3.1 Conceptual model of runoff generation in the Pilbara

Averaged over the Assessment area, rainfall in excess of potential evaporation occurs for fewer than 20 days per year. The spatial variability of rainfall within individual storm events is high. As the infiltration capacity of the soil is a significant determinant of runoff generation, the texture and surface condition of the soil, land use and vegetation can all influence runoff generation thresholds, and consequently these thresholds may be spatially and temporally variable. The rainfall-runoff data were analysed to compare runoff coefficients and other hydrological responses with geomorphological and geological properties.

It is important that a suitable conceptual model be developed to underpin the analysis and to provide a check on the appropriate structure of the hydrological models used. While there is little, if any, direct measurement of runoff generation processes in the Pilbara, there is strong anecdotal evidence for the occurrence of a number of key hydrological processes. The key processes believed to underpin rainfall-runoff responses and streamflow generation in the Pilbara are outlined below.

Hortonian overland flow (Horton, 1933) occurs in high intensity rainfall events when the rainfall rate exceeds the infiltration capacity of the soil surface. This is also referred to as ‘infiltration excess’ runoff. Such conditions are likely on rock outcrops, and where the surface has crusted, is non-wetting, or the soil has a low permeability. There is strong anecdotal evidence that this is the main runoff generation process in the Pilbara because of the often short duration and high intensity rainfall events.

Groundwater ‘return flow’ can also contribute to streams and perennial pools in the Pilbara. This occurs when rainfall which has infiltrated upslope emerges as groundwater seepages and springs through fractures in the rock or paleochannels (including channel iron deposits). This mechanism has been observed and interpreted from groundwater observation bores. It, and baseflow which is groundwater discharge that occurs long after infiltrating as rainfall, is thought to be an important source of water for springs and maintains flow in perennial streams in the region. While rainfall is highly intermittent, the persistence of streamflow and pools indicates the importance of groundwater discharging to streams. Some of this water comes from up-gradient areas, and some is temporary bank storage which returns to rivers after large flow events.

4.3.2 Rainfall-runoff relationships – data analysis

In Figure 4.3 daily runoff is plotted with daily rainfall, along with total runoff and rainfall from all flow events for four selected gauges. These gauges were chosen on the basis of their location (that there was one in each of the major rivers in each drainage basin), their length of record (had a long record including the last ten years) and that they had a reasonably large catchment area, to ensure that there were relatively long periods of flow. These hydrographs illustrate the variability across the region.

As discussed in an earlier report (Charles et al., 2013), there is some subjectivity to selection of the event thresholds. Because the emphasis is on streamflow and recognising that many rainfall events do not generate flow at the gauges, these flow ‘events’ are defined as commencing when flow rises above a level equivalent to runoff of 0.001 mm/day. Figure 4.4 shows annual runoff against mean annual rainfall and mean event runoff against event rainfall. First column of Figure 4.4 shows that there is a certain commonality of minimum annual rainfall required to initiate flow, at about 200 mm rainfall on an annual basis. The concept of ‘minimum annual rainfall’ required to produce flow in the catchment is useful as a summary statistic to compare gross response of catchments.

The second column of Figure 4.4 shows the rainfall-runoff response on an event basis. No precise determination of threshold is feasible due to crowding of points but around or less than 50 mm of event rainfall seems to initiate flow. Further investigation for more accurate determination of runoff event thresholds is undertaken in Section 4.7.4. Similar data for all gauges in the Assessment area are shown in the respective regional reports.
Figure 4.3 Daily rainfall and flow hydrographs for stations 706003, 707002, 708015, 709005 and 710003, illustrating the variability across the region. These gauges are all among the largest catchment areas in their respective drainage basins (see Table 4.1)
Figure 4.4 Annual runoff against annual rainfall and event runoff against event rainfall for the same catchments as Figure 4.3.

Table 4.2 details summary statistics of observed data for the 26 gauging stations across the Assessment area with adequate length and quality data. All available data were used in the analysis. The mean annual discharge ranges from 1.3 GL for the Robe River at Palra Springs (174 km²) to nearly 1,170 GL for the De Grey River at Coolenar Pool (50,000 km²). The number of flow days also varies considerably between stations, ranging from 20 to 150 days. The longest period of no flow varies from less than 1 year in the
Fortescue River to more than 3 consecutive years (1274 days) for the De Grey River, which also has the largest mean annual flow.

Table 4.2 Summary statistics for the gauges in the Pilbara streams

<table>
<thead>
<tr>
<th>AUSTRALIAN WATER RESOURCES COUNCIL STATION CODE</th>
<th>MEAN ANNUAL RAINFALL (mm)</th>
<th>MEAN ANNUAL DISCHARGE (GL)</th>
<th>MEAN ANNUAL RUNOFF (mm)</th>
<th>MEAN ANNUAL RUNOFF COEFFICIENT</th>
<th>MAX DAILY FLOW (GL)</th>
<th>MEAN NUMBER OF FLOW DAYS PER YEAR (days)</th>
<th>LONGEST NO FLOW PERIOD (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>706003</td>
<td>284.7</td>
<td>812.9</td>
<td>11.4</td>
<td>0.040</td>
<td>886.4</td>
<td>94</td>
<td>516</td>
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<tr>
<td>706207</td>
<td>360.1</td>
<td>1.5</td>
<td>6.1</td>
<td>0.017</td>
<td>9.4</td>
<td>20</td>
<td>1008</td>
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<tr>
<td>706209</td>
<td>259.4</td>
<td>364.9</td>
<td>8.5</td>
<td>0.033</td>
<td>373.4</td>
<td>84</td>
<td>608</td>
</tr>
<tr>
<td>707001</td>
<td>382.9</td>
<td>1.3</td>
<td>7.6</td>
<td>0.020</td>
<td>2.0</td>
<td>119</td>
<td>340</td>
</tr>
<tr>
<td>707002</td>
<td>396.4</td>
<td>116.5</td>
<td>16.4</td>
<td>0.041</td>
<td>372.1</td>
<td>75</td>
<td>1035</td>
</tr>
<tr>
<td>707004</td>
<td>390.5</td>
<td>43.9</td>
<td>13.1</td>
<td>0.034</td>
<td>138.4</td>
<td>65</td>
<td>599</td>
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<td>81.1</td>
<td>34.8</td>
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<tr>
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<td>7.9</td>
<td>0.020</td>
<td>62.5</td>
<td>73</td>
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<tr>
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<td>417.0</td>
<td>217.0</td>
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<td>0.036</td>
<td>283.0</td>
<td>150</td>
<td>305</td>
</tr>
<tr>
<td>708011</td>
<td>332.4</td>
<td>52.0</td>
<td>18.4</td>
<td>0.055</td>
<td>87.3</td>
<td>46</td>
<td>375</td>
</tr>
<tr>
<td>708013</td>
<td>408.5</td>
<td>34.2</td>
<td>8.6</td>
<td>0.021</td>
<td>94.4</td>
<td>22</td>
<td>717</td>
</tr>
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<td>11.8</td>
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<td>49.3</td>
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<td>18.4</td>
<td>0.055</td>
<td>112.8</td>
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</tbody>
</table>

The spatial distribution of mean annual runoff and mean annual runoff coefficient are shown in Figure 4.5 and Figure 4.6, respectively. Mean annual runoff ranges from 6 to 51 mm (Table 4.2). The annual runoff coefficient (the percent of rainfall that becomes runoff) ranges between 2 and 13%. Rivers in the
Ashburton, Robe and Fortescue river basins in the south and west of the Assessment area have runoff coefficients between 2 and 4%, while rivers in the Yule and De Grey river basins in the north and east have runoff coefficients between 7 and 13% (Figure 4.6). The figure illustrates that, despite the higher rainfall in the higher elevation Hamersley Range between Tom Price and Newman, this region has a lower runoff coefficient than further west and north, towards the coast.

Figure 4.5 Observed mean annual runoff shown for each gauged catchment in the Assessment area. Areas with no reliable observed data are shown in grey.
Figure 4.6 Observed mean annual runoff coefficient shown for each gauged catchment in the Assessment area. Areas with no reliable observed data are grey

The average annual flow days across the Assessment area (Figure 4.7) does not reveal a spatial trend except for the lower reaches of the Fortescue and Ashburton rivers, which show a larger number of flow days than at other gauges, as would be expected because of their large contributing areas.

The distribution of runoff coefficient and other hydrological statistics are shown in Figure 4.8 and Figure 4.9 for all 26 calibrated catchments. These data can be used to help understand the hydrological behaviour across the region, check model calibrations, and assist to regionalise the model results and parameter estimation. For example, Figure 4.8 b shows the Upper Fortescue region has more rainfall than the median rainfall for the whole of the Pilbara but the runoff is less than median runoff for whole of the Pilbara while catchments in the De Grey Canning region have comparatively more runoff for a given rainfall. Figure 4.9 shows the trends and statistics related to runoff coefficient and flow event volume and duration.
Figure 4.7 Observed mean annual flow days per year for gauged catchments in the Assessment area. Areas with no reliable observed data are grey.
4.3.3 Data accuracy and spatial distribution of rain gauges

The spatial correlation of rainfall and streamflow gauging stations in the Assessment area is poor. This is a major issue for rainfall-runoff analysis, particularly where rainfall events have a short duration and large short-range spatial variability. This limits the identification of dominant hydrological processes and the quantification of hydrological responses. There is considerable anecdotal evidence that short-range, short-duration, intense thunderstorms can produce considerable flow events, and these are not accurately measured by the widely spaced rain gauge network in the Assessment area. This can make it challenging to accurately simulate individual runoff events.
The analysis used the SILO DataDrill (<http://www.longpaddock.qld.gov.au/silo>; Jeffery et al., 2001) surfaces, as these cover the entire area uniformly and are commonly used in hydrological modelling in Australia (e.g. Petheram et al., 2012a). The DataDrill surfaces have been compared to the more than 90 Bureau of Meteorology rain gauges and a good correspondence was found (Charles et al., 2013).

4.4 Rainfall-runoff modelling

A modification of the SIMHYD model (Chiew et al., 2002), SIMHYD GW, was used in which groundwater storage and recharge parameters were added to allow representation of recharge from the stream to alluvial aquifers. The modified model structure is shown in all regional reports.

4.4.1 Model application

Model simulations using the gridded rainfall and APET surfaces were undertaken and compared to simulations undertaken using catchment average climate sequence calculated from the gridded climate surfaces. Very small differences were found between the results, which is similar to findings by Petheram et al. (2012b) undertaken elsewhere in northern Australia. Therefore, rainfall-runoff modelling across the Assessment area was undertaken using the catchment average rainfall, and APET data across the catchments. This allowed representation of the spatial distribution of rainfall and APET across the catchments, and is more computationally efficient than undertaking a model calibration using gridded climate data.

4.4.2 Scenario definition

Daily runoff at defined catchment outflow points was estimated for the catchments listed in Table 4.2 for 52 water years under climate scenarios (see Chapter 3) comprising:

- Scenario A – the Historical climate (water years 1961 to 2012) with current development which was the base case
- Scenario C – future climate scenarios using climate sequences developed from 18 global climate models (GCMs) under medium (4.5) and high (8.5) representative concentration pathways (RCP, equivalent to warming scenarios) extended to two time periods, 2030 and 2050.

Future projections of rainfall from the 18 GCMs are variable, and which could be further amplified in terms of runoff. In order to capture the variability in future projections of rainfall and runoff, and keeping the reporting concise, results are presented for three scenarios for each of the two RCPs and for each of the two time periods. The three scenarios represent a future climate state: a wet future (Cwet, 90th percentile rainfall), a mid-range future (Cmid, median rainfall), and a dry future (Cdry, 10th percentile rainfall) (Chapter 3). These rainfall sequences were used to generate estimates of Cwet, Cmid and Cdry runoff. Results under Scenario A (called the ‘Historical’ scenario) form the baseline against which the other results are compared to assess the impacts of a changed climate on runoff.

4.4.3 Relationship between streamflow and inundation

One of the outputs of the surface water modelling is to determine the extent of overbank surface inundation if any, under future climate projections. The water depth and width in the river channel for each of the flood-prone reaches of rivers in Pilbara were determined using the Hydrologic Engineering Corps River Analysis System (HEC-RAS; USACE, 2014) flood plain modelling tool to investigate the relationship between streamflow and inundation.
4.5 Model input data and calibrations

4.5.1 Model calibration and parameter estimation

Model calibration

All hydrological models need calibration for a variety of reasons which involves selecting and adjusting model parameter values so that the model results agree with observed data to user-specified criteria. Since the number of stations and length of record with observed streamflow in the Pilbara region are limited, all the available streamflow data has been used for calibration to obtain a better estimate of parameter values. A 15-year warm-up period was used prior to calibration and for all simulations to ensure initial conditions are not a factor in the model output. The calibration period is a compromise between a recent shorter period that would better represent current conditions and climate, and a longer period that would better account for climate variability. It was found that streamflow in some of these catchments (e.g. Weeli Wolli Creek at Tarina (708014) since September 2005) included the effects of historical mine water discharges at some stage during the calibration period. In the calibration process those periods were excluded as the mine discharge data were not readily available.

Calibration objective function and automatic optimisation

The parameters of the SIMHYDGW rainfall-runoff model were optimised using an automated optimiser by maximising an objective function given by models fit to recorded data. Twelve alternative objective functions that may be suitable for the Pilbara have been tested. These are described in detail in Silberstein and Aryal (In prep). The simplest objective function used incorporates the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) of daily runoff together with the constraint that the total modelled runoff over the calibration period is within 5% of the total observed runoff (Silberstein et al., 2010). The other objective functions included combined values given by average of the NSE of the daily streamflow duration curve (FDC), the NSE of daily flow and NSE of the annual number of flow days.

The parameter set from the optimisation algorithm that gives the highest objective function value for each model was chosen to run scenario modelling. Model calibration used the shuffle complex evolution algorithm (Duan et al., 1992).

4.6 Rainfall-runoff results, synthesis and discussion

4.6.1 Model calibrations

Annual total runoff of the SIMHYDGW model and the observed sequences for four representative stations are given below (Figure 4.10). These are the same stations presented earlier in the event analysis in Figure 4.3. Except for a few years, these plots show a reasonably good fit with annual NSE ranging from 0.49 (one catchment in Upper Fortescue) to 0.96. The results for all other catchments are given in respective regional reports.
Figure 4.10 Annual modelled and observed runoff hydrographs of four representative stations that are discussed in Section 4.3.2

Scatter plots of observed and modelled annual runoff show the majority of catchments had a coefficient of determination ($r^2$) between 0.7 and 0.98, indicating good estimation of runoff in calibration (Figure 4.11). Comparisons of observed and modelled hydrological response functions such as flow duration curves, number of flow days, residual error and cumulative errors for all calibrated catchments were also determined and are shown and interpreted in the regional reports.
4.7 Simulation results under climate projections

The rainfall-runoff models were used to simulate runoff under the entire Historical climate (i.e. Scenario A, which is between 1 October 1960 to 30 September 2012) and under the projected future climates outlined in Section 4.4.2.

4.7.1 Spatial variability in runoff and number of flow days

Figure 4.12 shows the spatial distribution of mean annual runoff across the Assessment area under the Historical and six scenarios given by C30wet4.5, C30mid4.5, C30dry4.5, C50wet8.5, C50mid8.5 and C50dry8.5. Relative to the Historical scenario, the mean annual runoff mostly increases under the Cwet scenario both for the 2030 and 2050 conditions, whereas the runoff decreases under the Cdry scenario both for the 2030 and 2050 conditions.
The changes in mean annual runoff across the Assessment area under six future climate scenarios (Figure 4.13) shows that under the dry future scenarios for 2050 the mean annual runoff reduces by more than 25% all over the area and more than 50% in the Ashburton Robe and Upper Fortescue regions. For the wet future climate, the runoff increases throughout the Assessment area by 1% to more than 25%. The mid future climates are somewhat similar to the Historical climate and for most parts the results are within 10% difference (Figure 4.13).
Figure 4.13 Percentage change in spatial distribution of mean annual runoff across the Pilbara Assessment area under the Historical and six future climate scenarios.

Figure 4.14 shows the spatial distribution of mean annual number of flow days across the Assessment area under the Historical scenario and six scenarios given by C30wet4.5, C30mid4.5, C30dry4.5, C50wet8.5, C50mid8.5 and C50dry8.5. It shows that relative to the Historical scenario, the mean annual flow days mostly increase under the Cwet scenario for both 2030 and 2050 conditions, whereas they decrease under the Cdry scenario both for 2030 and 2050 conditions.
Figure 4.14 Spatial distribution of mean annual number of flow days across the Pilbara Assessment area under the Historical and six future climate scenarios

The number of flow days increases ranging from 4 to up to more than 50% in a few sub-catchments under the C50wet8.5 scenario relative to the Historical climate scenario (Figure 4.15). For the dry future climate C50dry8.5 the number of flows decrease by between 10 and 50% in most subcatchments. For the mid future climates the results are mostly within 10% of that for the Historical climate (Figure 4.15).
Figure 4.15 Percentage change in spatial distribution of number of flow days across the Pilbara Assessment area under the Historical and six future climate scenarios.
4.7.2 Spatial variability in runoff coefficients

Figure 4.16 shows that the runoff coefficient decreases across the Assessment area under a dry future climate (C50dry8.5) and increases under a wet future climate (C50wet8.5). For the mid future climates results are mostly within 5% of the difference (Figure 4.17).
The changes in runoff coefficient are shown in Figure 4.17. It shows that runoff coefficients change by between 10 and 50% under the dry future scenario (C50dry8.5) and between 5 and 50% under the wet future climate (C50wet8.5).

Figure 4.17 Percentage change in spatial distribution of mean annual runoff coefficient across the Pilbara Assessment area under the Historical and six future climate scenarios
4.7.3 Spatial variability of river derived recharge to groundwater

The ‘recharge’ term in the SIMHYDGW model provides the estimation of stream recharge to deep groundwater expressed as depth (mm) over catchments in the Assessment area. Figure 4.18 shows spatial variability of recharge to the groundwater in mm for the Historical and six scenarios mentioned above. In general, more recharge is estimated for Lower Fortescue Hedland in the Sherlock and Yule river catchments and lower Ashburton regions, possibly due to the presence of sandy alluvium and Duck Creek Dolomite, respectively. Less recharge is observed in the upper reaches of the Ashburton and middle reaches of the Fortescue River downstream of Fortescue Marsh, while the groundwater recharge for the catchment containing the Marsh is higher.

Figure 4.19 shows groundwater recharge (mm) decreases by between 10 and 25% in Upper and Lower Fortescue regions under a dry future climate while it increases or shows no change for a wet future climate throughout the Assessment area. The median changes in the groundwater recharge are less than ±3% for scenarios other than the C50dry8.5 scenario which is < -10%.
Figure 4.18 Spatial distribution of mean groundwater recharge across the Pilbara Assessment area under the Historical and six future climate scenarios
Figure 4.19 Percentage change in spatial distribution of mean annual groundwater recharge across the Pilbara Assessment area under the Historical and six future climate scenarios.

It is interesting to observe that, in most cases, sensitivity of the mean annual groundwater recharge to climate is much smaller than the sensitivity of mean annual runoff or number of flow days under dry and wet future climates. This is a very important finding showing how the surface and subsurface processes are affected differently by the future climates.
4.7.4 Impact of climate change on rainfall runoff thresholds

The changes in rainfall and other weather parameters due to future climate change, such as temperature and soil water deficits, have potential to impact runoff and other hydrological thresholds in the Assessment area. The pre-threshold behaviour for a natural process (e.g. surface flow) usually is much different to the post-threshold behaviour. For example until the threshold is reached a relatively large rainfall event may not produce any runoff, while a relatively small rainfall can generate runoff once the threshold has been exceeded. Effects of climate change that are limited to below-threshold behaviour may not be as severe as those changes that result in the threshold being exceeded. Therefore, the study of effects of climate change on hydrologic threshold behaviour is essential to understand the change in hydrologic processes in the catchment due to a change in climatic inputs.

Understanding the rainfall-runoff threshold helps identify streamflow initiation processes and their consequential impact on stream water dependent ecosystems, including recharge of alluvial aquifers that support groundwater-dependent ecosystems. Rainfall-runoff thresholds have never been thoroughly studied in the Pilbara. The amount and intensity of rain required to initiate runoff depends on antecedent soil moisture conditions, the structure and texture of the soil, infiltration capacities, vegetation, topography and surface properties such as micro-depressions that may impede overland flow reaching the stream. These thresholds, particularly in semi-arid areas such as the Pilbara, are strongly influenced by the fact that the PE over the region is much greater than rainfall over almost any time period other than around major rainfall events.

Figure 4.20 shows the rainfall threshold (mm) to runoff for events under the Historical and six scenarios. Overall, the number of events that produce runoff decreases under a dry future climate.

On a regional basis, the changes in thresholds due to future climates are less than ±15% for all except the De Grey Canning region (Table 4.3). Although the number of rainfall events that are greater than the threshold rainfall decreases in the dry future climate, the amount of rainfall to initiate the runoff does not change much.

<table>
<thead>
<tr>
<th>REGION</th>
<th>HISTORICAL THRESHOLD (mm)</th>
<th>PERCENT CHANGE IN THRESHOLD VALUES DUE TO</th>
<th>C30WET4.5</th>
<th>C30MID4.5</th>
<th>C30DRY4.5</th>
<th>C50WET8.5</th>
<th>C50DRY8.5</th>
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<td>Ashburton</td>
<td>20</td>
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<td>1.5</td>
<td>0.9</td>
<td>−2.0</td>
<td>10.0</td>
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<tr>
<td>De Grey Canning</td>
<td>24</td>
<td>9.1</td>
<td>2.9</td>
<td>−34.1</td>
<td>3.9</td>
<td>−16.8</td>
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</tr>
<tr>
<td>Lower Fortescue</td>
<td>22</td>
<td>2.3</td>
<td>10.1</td>
<td>−9.1</td>
<td>1.5</td>
<td>−1.4</td>
<td></td>
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<tr>
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</tr>
<tr>
<td>Upper Fortescue</td>
<td>14</td>
<td>1.6</td>
<td>8.3</td>
<td>1.3</td>
<td>−4.9</td>
<td>2.6</td>
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</tbody>
</table>
4.7.5 Low and high flow analysis

The frequency of occurrence of low flows in the historical period is compared with that for the two extreme wet and dry future climates given by C50wet8.5 and C50dry8.5. For the purpose of this report, low flow is defined as flow that is less than the 10th percentile annual flow and high flow is the flow that is more than the 90th percentile annual historical flow. By definition, flow less than 10th percentile flow occurs between 5 and 6 years out of the record period of 52, and flow in excess of the 90th percentile flow similarly.

Table 4.4 shows that for all catchments the instances of low flow decreased under wet future climate and increased under dry future climate while instances of high flow increased under wet future climate and decreased under dry future climate. As the low and high flows play a role in overall ecosystem health and function, such changes are likely to have implications for those. The most affected catchments are in the Ashburton/Robe basin showing a larger decrease in number of years exceeding the high flows as a result of a dry future climate. The effect of a wet future climate is relatively uniform across the Assessment area.
Table 4.4 Changes in occurrence of low and high flows due to Cwet and Cdry scenarios for 2050 and RCP 8.5

<table>
<thead>
<tr>
<th>STATION</th>
<th>YEARS LESS /MORE THAN HISTORICAL 10TH/90TH PERCENTILE FLOW HISTORICAL</th>
<th>YEARS LESS THAN HISTORICAL 10TH PERCENTILE FLOW C50WET8.5</th>
<th>YEARS LESS THAN HISTORICAL 10TH PERCENTILE FLOW C50DRY8.5</th>
<th>YEARS MORE THAN HISTORICAL 90TH PERCENTILE FLOW C50WET8.5</th>
<th>YEARS MORE THAN HISTORICAL 90TH PERCENTILE FLOW C50DRY8.5</th>
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4.7.6 Flood inundation depth and areas in Pilbara

Areas upstream of Gregory Gorge in the Fortescue River, upstream of Coolenar Pool in the De Grey River and reaches of Ashburton River between Nanutarra and its confluence with Henry River are prone to flooding (WALIA, 2007). The Hydrologic Engineering Corps River Analysis System (HEC-RAS; USACE, 2014) was used to estimate the river stage and flood inundation width for maximum recorded daily flows in these reaches. The stage and inundation width was also calculated for all future climate scenarios. In these reaches, the changes in flow width due to maximum (or minimum) future daily flows varied relative to the historical flows and were influence by the local topography. For example, the projected increase in flow width for the maximum future peak daily flow was only about 1.4% (80 m) greater than the maximum recorded daily flow in Ashburton. The difference in stage between the lowest and highest flows is less than 1 m at all cross-sections in De Grey River at Coolenar Pool with practically no difference between the highest future and historically recorded peak daily flow. For the modelled section of the Lower Fortescue River, relative to the peak historical daily flow the width of inundation is projected to increase by 10.8% (from 3032 m to 3414 m) and the flood height is projected to increase by 18.5% (2.75 m to 3.26 m). Note that the vertical cross-sections and horizontal distances of river reaches were derived from the currently available 1-second DEM which has much lower resolution than 1 m.

4.8 Knowledge and information gaps: regional monitoring needs

The availability of data from about 90 rainfall stations, 26 reliable stream gauges and additional stage-only gauges, as well as the length of record at these gauges, means that data availability remains the biggest need in assessing water resources in this area. The vast majority of many other streams of all sizes lack gauges. This is also true of the groundwater data and aquifer characterisation. It is recommended therefore, that urgent consideration be given to increasing the density of gauges across the region. Furthermore, there are a number of stream gauges for which there is a quite good stage record but no rating curve. It is also recommended that the gauges for which there is currently no rating curve be rated as soon as possible. There are also about a dozen stream gauges that have flow data but are not quality controlled and thus are unreliable. Errors due to the quality of the hydrological observation network are not discussed here. These errors affect the reliability of modelling results since the errors in parameter values can propagate from calibration to the future scenario projection.

The rainfall-runoff modelling was done on a large-scale regional basis using a lumped conceptual model, thus the outcome of the model needs to be evaluated on that basis. As mentioned earlier, the whole of the Pilbara had 26 reliable streamflow gauging stations available for the Assessment therefore runoff for large areas of the Assessment area were estimated using modelling with their parameters transferred from suitable nearby calibrated catchments. Furthermore, even a good reproduction of historical data in a calibration does not guarantee a reliable future projection, especially in a non-stationary climate regime, therefore runoff estimations from the ungauged catchments would have large uncertainty. The uncertainties of those estimation were not evaluated in the Assessment.

It is obvious that extending the network of rainfall and stream gauging stations can help overcome the issues to some extent. Two broad-based recommendations are:

- establish a network of gauging stations across the region (i) especially in parts of the Upper Fortescue, immediately downstream of Fortescue Marsh and further downstream along the Fortescue River; (ii) upstream of De Grey, Sherlock and Oakover rivers; and (iii) on tributaries of the Ashburton River
- establish a network of rainfall stations to record sub-daily events especially for small catchments to determine and help understand, among many processes, runoff-initiation thresholds.

Over recent years, there has been considerable small-scale monitoring work undertaken around sites of particular interest, such as mine pits and infrastructure. These studies could contribute much to the understanding of the hydrology of the region, but to date the results have had limited circulation. As these studies continue gathering valuable data at small scales and on short time scales, they help provide further
insights into the rainfall-runoff behaviours of catchments. Extending the data collection to monitor soil infiltration and other climate data (e.g. evapotranspiration) could lead to a significant improvement in understanding the hydrology of the region.

4.9 References


Horton RE (1933) The role of infiltration in the hydrologic cycle. Transactions of the American Geophysical Union 14, 446-460.


Silberstein RP and Aryal SK (In prep) Assessing the choice of objective function in optimising rainfall runoff modelling for ephemeral catchments.


5 Groundwater

Authors: Phil Commander, Rodrigo Rojas, Geoff Hodgson and Don McFarlane

Key points

- Major aquifers containing fresh groundwater are commonly associated with rivers and depend on streamflow for recharge. Direct rainfall recharge is only significant in the West Canning Basin.
- Main groundwater resources in the Assessment area are found in eight main hydrogeological systems:
  - coastal plain alluvial aquifers are the most easily investigated and presently utilised for supplying coastal towns
  - inland alluvial systems and paleovalley aquifers including CID, calcrete, and valley-fill are significant aquifers for local use
  - dolomites underlying inland valleys are commonly karstic and form a potential aquifer
  - Wallal Sandstone aquifer in the West Canning Basin is a major resource of low salinity water which is not fully allocated
  - Permian and Cenozoic paleochannels in the Paterson province show some potential as resource of low salinity water
  - the Carnarvon Basin contains mainly saline groundwater but can be suited to desalination
  - mineralised BIFs show locally high yields and limited storage, which are significant where mine dewatering is carried out. Low salinity groundwater from dewatering is either used for process water or discharged to the environment, whereas saline groundwater is reinjected
  - the bedrock of granite and metasediments which underlie the greater part of the region is generally poorly fractured, though useful supplies can be obtained by targeting prospective rock types and fractures.
- Modelling results suggest that changes in groundwater are projected to respond to changes in rainfall and river recharge patterns, with less water available under a drier climate.
- Decreases in streamflow and the number of flow days under a dry climate do not fully explain decreases in river recharge.
- Increases in river recharge under a wet climate is most likely the result of an increase in the number of flow days.
- Changes in the magnitude of water balance terms such as evaporation and soil water and the interplay with changes in the magnitude of streamflow and the number of flow days may explain the projected changes in river recharge.

5.1 Introduction

Groundwater in the Pilbara study area occurs in coastal plain sediments, in Cenozoic paleovalley and valley-fill sediments, in Phanerozoic artesian basins, and in fractured and fissured Archaean-Proterozoic basement rocks.

Apart from the Canning Basin, significant renewable groundwater resources are associated with the major rivers, and are recharged by periodic infiltration of flood water. Locally substantial low salinity groundwater resources may also be stored in channel iron deposits, fissured dolomite and in fractured rocks.

The major renewable groundwater resources are recharged by losing streams, which have a connection with the aquifer only when the rivers are in flood, generally for periods of 1–2 months following heavy
rainfall. Pools may persist in parts of the river beds which are over-deepened. The large pools at Millstream and Carawine Gorge are unique in the region, as they are maintained by perennial groundwater discharge.

The main hydrogeological systems identified in the Assessment area are detailed in Section 5.2. Section 0 presents the main results of the groundwater modelling in light of the projected climate change, whereas Section 5.3 presents a synthesis and discussion.

The alluvial aquifers support groundwater-dependent ecosystems (GDEs) which are discussed in Chapter 6, but are also closely related to streamflows, which are covered in Chapter 4. The combined consideration of all the above is discussed in Chapter 7.

The assessment and analysis in this chapter is based on available hydrogeological, hydrological and spatial information which is concentrated in areas which have undergone specific investigation of groundwater resources. These areas are widely spaced, and there is very little information on the greater part of the region. The heterogeneous geology makes it difficult to extrapolate information.

5.1.1 Geology

The Assessment area is mainly underlain by ancient Archaean-Proterozoic (3.3 to 1.4 Ga) rocks which have been variously metamorphosed and folded (Geological Survey of Western Australia, 1990). It encompasses the entire Archaean-Proterozoic Pilbara Craton, parts of the adjacent Proterozoic Ashburton Basin, Gascoyne Complex, Capricorn Orogen, Paterson Orogen and Officer Basin (Grey et al., 2005). The area is flanked by the gently dipping much younger Jurassic-Cretaceous sedimentary rocks (180–65 Ma) of the Carnarvon and Canning basins.

The Pilbara Craton includes the North Pilbara granite greenstone terrane, which is characterised by areas of low-relief granite surrounded by razor-backed ridges of vertically dipping greenstones (volcanic dominated metasediments and volcanics), and the Hamersley Basin, containing a sequence of basalts and volcanic rocks, sandstone, shale, banded iron formation (BIF) and dolomite which are flat lying to very gently dipping in the north along the Chichester Range, increasing in folding through the Hamersley Range towards the southern margin of the craton.

In the south of the study area, the sediments and volcanics of the Ashburton and Bangemall basins form ridges striking north–west to south–east, including small areas of the igneous and metamorphic Gascoyne Complex. In the east, the sediments of the Paterson Orogen and small areas of the Rudall Metamorphic Complex are poorly exposed and largely concealed beneath the dunes of the Great Sandy Desert.

The Jurassic and Cretaceous sediments of the Carnarvon and Canning basins crop out sporadically along the basin margins, but for the most part are concealed beneath the coastal plains.

Remnants of an early Cenozoic landscape are preserved by partly eroded channel iron deposits (CID), and covered by calcrete and late Cenozoic alluvial deposits. Quaternary deposits are represented by sand dunes and thin surficial deposits, and alluvium along the major rivers where they cross the coastal plain.

The Fortescue and Ashburton rivers, and to a certain extent, the Oakover River, follow the geological structure for most of their courses. The rivers draining the north Pilbara granite greenstone terrane are superimposed, passing through the greenstone ridges in prominent gorges. Drainage in the West Canning Basin is uncoordinated, though a paleodrainage network, partly obscured by sand dunes, is a remnant from previous wetter climates.

Change in drainage pattern is demonstrated by the eroded mesas of CIDs and the rejuvenation and capture of the Fortescue River at Millstream. Tilting of the Pilbara Craton is likely to be partly responsible for the subsidence in the upper Fortescue Valley forming the internally draining Fortescue Marsh, which is several metres below the surface water divide across the valley at the Goodiadarrie Hills.

The alluvial fans being built up by rivers on the coastal plain are currently active, with the river beds changing position periodically.
5.1.2 Hydrogeological setting

The fractured rocks of the Pilbara Craton and adjacent Proterozoic basins are flanked by the Carnarvon and Canning artesian basins, which have laterally extensive and gently dipping sandstone aquifers. The Archaean and Proterozoic rocks are generally poorly fractured and, with the exception of the fissured dolomites, only contain groundwater on a local scale such as mineralised zones in the BIF. Hence the major groundwater resources are in the overlying Cenozoic valley aquifers, principally in the alluvial fans of the major rivers on the coastal plain, in CIDs, calcrite, and inland alluvium.

Major renewable groundwater resources are generally associated with significant rivers, and are recharged periodically by infiltration of flood water. Significant low salinity groundwater resources may also be in storage in CIDs, fissured dolomite, and fractured rocks.

The alluvial aquifers on the coastal plain range from highly transmissive gravels along the De Grey, Fortescue and Robe rivers, to thin sands along the Lower Cane River. Highly transmissive gravels, containing brackish groundwater, occur in a paleochannel of the Ashburton River, but elsewhere along the river, the alluvium appears to be fine grained and generally not prospective for large supplies.

The major renewable groundwater resources are recharged by these losing surface water drainages, which have a connection with the aquifer only when the rivers are in flood, generally for periods of 1–2 months following heavy rainfall. Pools may persist in parts of the river beds. The large pools at Millstream and Carawine Gorge are unique in the region, as they are maintained by perennial springs.

The Hamersley Basin contains Cenozoic valley-fill sediments comprising major aquifers in CIDs and calcrite, recharged from surface flows. The calcrite aquifer in the Fortescue Valley at Millstream is the largest aquifer, supporting permanent pools and associated vegetation, and formerly supplying the West Pilbara Water Supply Scheme. The CID aquifers have only recently been developed for regional water supply and assessment of dewatering requirements is currently being undertaken prior to mining at a number of CID orebodies.

The karst dolomite of the Wittenoom Formation is the most important aquifer among the Archaean-Proterozoic rocks, and similar potential may exist in the Carawine and Duck Creek dolomites, although there has been no groundwater investigation of these units.

The Wallal Sandstone aquifer in the West Canning Basin contains a very large resource of low salinity groundwater (< 1,000 mg/L TDS (WorleyParsons, 2013)), recharged by rainfall on the basin margin, and receiving groundwater flow from the basin to the east of the study area. The aquifer is artesian on the coastal plain with natural potentiometric levels of up to 30 m above ground.

The Carnarvon Basin sediments are generally not prospective for fresh groundwater on account of the restricted recharge areas. The main aquifer, the Birdrong Sandstone is fresh only in small areas along the basin margin, and salinity rises to exceed 10,000 mg/L TDS along the coast.

Apart from the Carnarvon Basin, the internally draining Fortescue Marsh, and the salt lakes along the Paterson province – Canning Basin boundary, and the Mandora Marsh bounding the east of the Assessment area, groundwater is generally low salinity.
5.2 Aquifers

Groundwater resources in the Assessment area are found in eight main hydrogeological systems, which are further described in order of significance in the following sections and summarised in Figure 5.1.

5.2.1 Coastal alluvium

Important things to note about the coastal alluvium are:

- most major rivers have deposited coarse bedload material in alluvial fans where they enter the coastal plain, forming easily recharged and highly permeable aquifers
- aquifer material depends on the type and distance of the bedload source (sand being derived from granite, while cobbles are generated from hills of BIF and volcanics); sediments become finer with greater distance form source, with only clay deposited by the smaller rivers
- the size of the alluvial aquifer is strongly linked to the size of the river
- recharge depends on duration and magnitude of streamflow, and available storage in the aquifer
- groundwater salinity depends on the mean salinity of river (freshwater flood peak mostly discharges to the sea)
- groundwater-dependent vegetation along river banks are commonly associated with alluvial aquifers
- the aquifers are easily investigated and utilised.
Introduction

The alluvial aquifers of the coastal plain are spread along the region from the mouth of the Ashburton River near Onslow to the mouth of the De Grey River east of Port Hedland. Coastal alluvial aquifers have been the focus of a number of groundwater modelling studies across the Assessment area.

The major rivers have prominent alluvial fans, shown by the arcuate coastline built up by alluvial sediments, with the rivers shifting their courses and building up layers of interconnected permeable sediments. Away from the rivers, the coastal plain deposits are fine-grained flood plain silts and clay.

The type of alluvial sediments is largely controlled by their provenance. The Fortescue and Robe river bedloads are composed of cobbles derived from the volcanics and BIF of the Hamersley Basin, while the Cane, Yule and Turner rivers deposit sand derived from their granitic catchments. Mixed sediments occur along the Ashburton and De Grey. Other rivers, such as the Sherlock River which drains a Proterozoic dolerite and greenstone belt, have deposits mainly of silt and clay.

Recharge occurs rapidly through the river beds when streamflow commences and spreads out in the permeable layers away from the river. Generally the rivers flow for only a few weeks during the year, which is generally insufficient to completely fill the aquifers.

The groundwater salinity of the major aquifers reflects the salinity of the later flow, as the very fresh flood peak flows out to sea. Evidence from inland alluvial aquifers suggests that in wet years, a build-up of salt may be flushed in with initial flows (Commander et al., 2004).

Introduced mesquite (a small tree) grows exclusively on the Lower Fortescue alluvial aquifer, demonstrating their dependence on water from the aquifer.

Ashburton River alluvium

Relative to the other major Pilbara rivers, there are few low salinity pastoral wells adjacent to the Ashburton River. North-west of Nanutarra where the Ashburton River enters the coastal plain, a defined paleochannel containing coarse gravel 37 m thick, of which the lower 14 m are saturated, trends north-west away from the current river (Yesertener and Prangley, 1997). However, groundwater in the paleochannel gravels is brackish, ranging from 2000 to 8000 mg/L TDS, and increases in a north-westly direction. The gravels seem to be poorly connected with the river, as the near-surface strata near the river channel are clayey, hence the high salinity.

At Minderoo Homestead, following an aerial electromagnetic survey, three bores were drilled to a maximum depth of 45 m close to the river and intersected up to 40 m of silty sand, poorly sorted coarse sand, and weakly cemented basal gravel containing groundwater of 500–1200 mg/L TDS (Pennington Scott, 2010). The bores were tested at rates of 2500 kL/day and are used to irrigate fodder crops. The success of this geophysical investigation suggests that there may be potential to locate other local low salinity groundwater supplies in concealed permeable zones adjacent to the river.

Cane River alluvium

The Cane River borefield used for the Onslow town water supply is developed in relatively thin sands close to the river course (Martin, 1989). The alluvium consists of poorly sorted silt, sand and gravel up to 25 m thick, with lenses of sand and gravel limited to about 5 m thick. Martin (1989) also reports significant yields from the contact with the underlying Trealla Limestone, and where the limestone consists of alternating hard and soft layers. Yields are relatively low with 19 production bores producing about 630 kL/day (0.23 GL/year) (Haig, 2009). The salinity of the water supply is less than 300 mg/L TDS, but salinity has increased in some bores and also increases in very wet years, such as 1999–2001 when salinity peaked in some bores (Haig, 2009). The Water Corporation has announced that Onslow’s water supply will be supplemented with a new desalination plant, which is due for completion in 2016.
Robe River alluvium

The potential to extract groundwater from the Lower Robe River alluvium can be inferred by the presence of pastoral station wells of low salinity in the vicinity of the river (Davidson, 1975). Following installation of production bores for the Dampier–Perth gas pipeline, which were estimated to be capable of yielding up to 3000 kL/day, investigation proved the existence of a gravel aquifer, up to 10 m thick, extending 5 km away from the current river course (Commander, 1994b). Groundwater salinity is generally 500–800 mg/L TDS. Recharge to the aquifer occurs when the river flows, with groundwater levels rising by 4 m close to the river after a year of flow, and declining by the same amount after a year of no flow.

Lower Fortescue alluvium

The Lower Fortescue aquifer is composed of alluvial gravels deposited on the alluvial fan of the Fortescue River. The alluvial fan is around 30 m thick of which there is an aggregate maximum gravel thickness of 15 m, though it is generally 5–10 m thick close to the current river, with the balance silt and clay. The gravel generally occurs in an upper and a lower layer separated by silt and clay. The upper layer is not always saturated. Recharge to the alluvium is from localised recharge (stream leakage) during periods of river flow. The current course of the river is along the eastern margin of the fan, and groundwater flow is mostly across the fan to the northwest. The watertable rises after river flow by at least 6 m near the river, progressively diminishing farther away. The salinity of the groundwater reflects the salinity of the river water, and is about 500 mg/L TDS in the central area of the fan. Introduced mesquite has thrived to such an extent that forms impenetrable thickets where shallow groundwater exists.

No significant groundwater extraction is currently undertaken from this system at present.

Harding River alluvium

The thin alluvial and minor calcrete aquifer along the Harding River just south of Roebourne was used for the town supply up until the commissioning of the Harding Dam in 1985. Further investigation was carried out by Rockwater Pty Ltd (2006) reported in Haig (2009). The saturated thickness of the aquifer was found to be less than 8 m, and the maximum depth to basement was about 19 m. The salinity is relatively high, ranging from 790 to 1500 mg/L TDS. Haig (2009) noted that salinities in the borefield, when it was operating, were reported to increase with increased drawdown in years of low streamflow. Since 1985, the Harding River has been regulated by the Harding Dam, and therefore recharge conditions are controlled by dam release and overflow.

George and Sherlock rivers

Haig (2009) reviewed the previous assessments of groundwater prospects associated with the George and Sherlock rivers and estimated a potential yield of 2740 kL/day (1 GL/year) for the George River alluvium. However, there is no investigation information. The bedload of the rivers is mainly clay/silt, so it is unlikely that there are permeable sediments well connected to the rivers. Moreover, the regional pattern of groundwater salinity as shown by the pastoral station bores and wells (Davidson, 1975, reproduced in Haig, 2009) does not identify any groundwater less than 1000 mg/L TDS. While Haig (2009) recommends investigation, the prospects do not seem favourable.

Yule River alluvium

The Yule alluvial aquifer is a major aquifer developed to supply Port Hedland. It is composed of sand derived from the granitic catchment of the river interbedded with flood plain silt and clay. The sand, silts and clays are up to 60 m thick and extend 10 km away from the river. The current river channel broadly follows the paleovalley, the base of which slopes from +15 m at the North West Coastal Highway to −45 m close to the former highway alignment around 15 km from the coast. Groundwater recharge is from river flow, with groundwater flow principally away from the East Branch in both north–northeast and northwest directions. The groundwater salinity is less than 500 mg/L TDS in a belt 6 to 10 km wide, representing the distribution of sands, but rises near the former Roebourne-Port Hedland Road, which is close to the limit of spring tides. Discharge occurs along the river banks from phreatophytic river gums. The borefield supplying
Port Hedland runs for about 12 km along the east bank of the river. Current licenced extraction by the Water Corporation from this borefield is 23,290 kL/day (8.5 GL/year) to part of the supply to Port Hedland.

**Turner River alluvium**

The Turner River alluvium was developed for Port Hedland water supply following investigation in 1966, but has been subsequently replaced by the Yule River borefield. The original estimate of sustainable yield was less than 1 GL/year (Farbridge, 1967 quoted in Haig, 2009). The alluvial aquifer is a maximum of 43 m thick and composed of clay and sand with minor gravel. The sands are commonly carbonate cemented. Groundwater flow is away from the river, and groundwater of less than 1000 mg/L TDS only extends up to about 2 km from the river banks, and to a few kilometres north of the former Roebourne–Port Hedland Road.

**De Grey River alluvium**

The De Grey catchment, including the Oakover River, drains the Pilbara Craton and part of the Bangemall Basin. The De Grey alluvium has been investigated by the Geological Survey (Davidson, 1975) and by the Water Corporation since 1996 (Haig, 2009). The alluvium is composed of sand gravel and silt and reaches a saturated thickness of 70 m. The Water Corporation’s Namagoorie borefield, developed for Port Hedland water supply contains low salinity groundwater, less than 500 mg/L TDS, restricted to a narrow zone downstream of the confluence with the Shaw River. Currently, the Water Corporation has an extraction licence of 7 GL/year for use in Port Hedland.

Groundwater from the De Grey alluvium was formerly used for the Goldsworthy mine and town. Alluvium has been investigated farther upstream for supply to the Spinifex Ridge mine, reporting bore yields between 300 and 1,000 kL/d, and salinities between 1,000 and 3,000 mg/L TDS (Aquaterra, 2007a).

### 5.2.2 Channel iron deposits (CIDs)

**Introduction**

Channel iron deposits derived from the banded iron formations of the Hamersley Group were deposited in the valleys of the Hamersley Basin and extend into adjacent Ashburton Basin and Carnarvon Basin. These deposits underlie both current valleys and paleovalleys, and are also exposed as sinuous mesas, above the watertable. They comprise basal ferruginous sediments assigned to the Robe Pisolite or Marillana Formation (Kneeshaw and Morris, 2014), informally known as channel iron deposits (CID), which may have a basal clay (Munjina Member). These are overlain by calcareous clay or marl which has commonly undergone conversion to calcrete (Oakover Formation or Millstream Dolomite), lacustrine clay (Kangiangi Clay in the Fortescue Valley), iron rich colluvium (Detrital Iron Deposits), and gravel (Kumina Conglomerate) associated with the current drainages. Deeper paleochannel deposits, below the Robe Pisolite, consisting of gravel and clay have been found in some boreholes in the Fortescue Valley at the base of the Hamersley Range Scarp, but their age and relationships are unclear (Barnett and Commander, 1986).

The Cenozoic valley-fill sequence is commonly floored by a basal clay, termed Munjina Member of the Marillana Formation (equivalent to Robe Pisolite) by Kneeshaw and Morris (2014). Overlying this is the CID,
the iron-dominant facies which is a fluvial deposit of Oligocene to Miocene age (Morris et al., 1993). These sediments occupy generally meandering paleochannels cut into the Early to mid-Tertiary Pilbara ferricrete ('laterite') paleosurface (Morris et al., 1993). The variably eroded deposits range from less than 1 m to 100 m in thickness with channel widths typically less than 1 km, but ranging up to several kilometres. The deposits are anomalously high in iron content, and goethite-hematite CIDs represent a major source of the iron ore mined in the Hamersley Hydrogeological Province.

The CIDs are highly porous and permeable, and are capable of producing significant yields. They are hydrogeologically very significant in the Robe River valley, Marillana Creek, and the Solomon deposit area. They often have high transmissivity and are either directly or hydraulically connected with the surface water systems.

The CID is overlain by the Oakover Formation, of Miocene age, which appears to be a calcareous clay or marl deposited in a lacustrine environment, and which has commonly undergone conversion to calcrete. The formation is generally less than 10 m thick (but can be more than 40 m such as in the Millstream area). Dissolution of calcrete leads to the development of secondary porosity, which makes this formation a potential aquifer where the formation has sufficient thickness.

CID aquifers have been dewatered for mining in the Robe River area, Marillana Creek and at the Solomon and nearby deposits, and have been developed for the West Pilbara Water Supply Scheme at Bungaroo Creek.

**Robe River and Bungaroo Creek**

Aqurifer properties around Pannawonica and the Robe River area have been reported in Aquaterra (2004, 2007b), Rockwater Pty Ltd (2001), and Groundwater Resource Consultants (1988). Mesa J, at the confluence of the Robe River and Bungaroo Creek, is currently being mined for iron ore and is dewatered at a rate of 41,000 kL/day (15 GL/year), whereas the licenced extraction reaches 30 GL/year. The aquifer is 40 m thick and up to 4 km wide (HydroConcept, 2014).

The Bungaroo CID is upstream from the Mesa J deposit and is concealed by overlying valley-fill (Rio Tinto Iron Ore, 2011). The Bungaroo borefield is developed in CID in the valley of Jimmawurrrada Creek downstream from the confluence of Bungaroo Creek. Jimmawurrrada Creek occupies the ancestral Robe valley (a continuation of what is now the Fortescue Valley), along the strike of the Wittenoom Formation, whereas Bungaroo Creek is eroded into an anticline with Wittenoom Formation in the core. The Bungaroo borefield is now part of the West Pilbara Water Supply Scheme, with up to 27,400 kL/day (10 GL/year) piped to Millstream to join the pipeline to the Karratha–Roebourne area.

The CID rests in an uneven surface in the underlying dolomite of the Wittenoom Formation, with up to 160 m of CID and valley-fill sediments (HydroConcept, 2014). The valley-fill sediments up to 75 m thick include an exceptionally coarse shingle with boulders of BIF up to 1 m diameter in a clayey to silty matrix. The CID consists of an upper vitreous hardcap, a middle zone of pisolite and a basal clay and conglomerate. The pisolite is vuggy and permeable and up to 100 m thick.

HydroConcept (2014) identified the CID and gravels in upper Bungaroo Creek and the adjacent upstream Buckland area as having further potential for regional water supply.

**Weelumurra and Caliwingina creeks**

Weelumurra and Caliwingina creeks contain paleochannel systems developed in the axis of the Hamersley Range Syncline, and host extensive channel iron deposits. The upper part of the East Weelumurra paleovalley, which contains a number of CID ore bodies, including the Solomon CID deposit, is within the adjoining Kangeenarina Creek catchment. The three catchments drain out from the Hamersley Range northwards into the Fortescue Valley, and have formed large alluvial fans along the Hamersley Range Scarp.

The CID form a continuous aquifer in both catchments (HydroConcept, 2014), overlain by permeable valley-fill sediments. The CID is up to 50 m thick and can be divided into an upper layer of hard brown goethite and a lower layer of vuggy ochreous goethite separated by a stiff grey clay. The CID is locally underlain by a basal conglomerate overlying bedrock of Brockman Iron Formation, Mt Sylvia Formation or Wittenoom.
Formation. The CID is overlain by a discontinuous clay layer up to 30 m thick, a calcrete or silcrete layer up to 10 m thick with as much as 60 m of alluvial clay, silt and gravel and detrital iron deposits. The watertable appears to be generally within 10 m of the surface and both creeks contain pools which appear to be connected to groundwater. Bore yields of as much as 2,600 kL/day have been achieved from the CID aquifer (HydroConcept, 2014), and salinity ranges from 160 to 250 mg/L TDS in the Weelumurra West catchment, 530 to 660 mg/L TDS in the Weelumurra East catchment, and is less than 250 mg/L TDS in the Solomon Deposit.

Considerable hydrogeological investigations have been carried out at the Solomon Deposit to assess dewatering requirements (MWH, 2010c), but there has been little groundwater information collected elsewhere from ore exploration drilling. HydroConcept (2014) has assessed the two catchments as having significant groundwater resource potential, and has recommended groundwater investigation programs in the CID aquifer.

**Marillana and Weeli Wolli creeks**

The CID outcrops for 70 km along Marillana Creek, being covered by calcrete at the upper end of Marillana Creek, and underlying alluvium at the lower end below Weeli Wolli Creek. It ranges from 500 m to 1000 m wide and is up to 80 m thick, with a saturated thickness of 30–60 m. The current Marillana Creek crosses the sinuous outcrop of the CID in numerous places, allowing recharge from streamflow to take place.

The main aquifer horizon is the goethite ore zone, which overlies a basal clayey conglomerate, and is in places overlain by a clay conglomerate. Dewatering of the CID for mining at the BHPBIO Yandi and Rio Tinto Junction Central and Junction South East deposits is discharged to Marillana Creek giving rise to perennial flows in Weeli Wolli Creek which infiltrates to the alluvial fan at the base of the Hamersley Range Scarp.

**5.2.3 Valley-fill**

Important things to note about valley-fill sediments are:

- very high transmissivity and secondary porosity in calcrete
- readily recharged during surface water flow
- support spring-fed GDEs, e.g. Weeli Wolli, Millstream, Mindi Spring
- groundwater high in bicarbonate
- gravels, calcrete, CID and underlying dolomite aquifers potentially hydraulically connected and used together.

**Introduction**

Valley-fill sediments from the Hamersley Basin and adjacent areas have been studied and aquifer properties reported in previous studies. Sediments overlying the Fortescue Group and the granite greenstone terrane are generally very thin. There is little information in the Ashburton and Bangemall basins.

The valleys in the Hamersley Basin are mostly developed along geological weaknesses in the Wittenoom Formation, eroded in the dolomite, and have usually a common stratigraphic sequence, with CID at the base, overlain by calcrete (Oakover Formation) and then by lacustrine clay and varying alluvium from gravel adjacent to the hills to silts in the intervening flats. An upper layer of calcrete is commonly developed in the zone of watertable fluctuation.

Groundwater occurs in the interconnected dolomite, CID, calcrete and gravel aquifers. Recharge takes place to calcrete and CID outcrop from streamflow and sheet runoff, and through scree and fractured bedrock (including permeable ore zones) on the valley flanks.

**Lower Fortescue Valley**

The Fortescue Valley contains a variety of sediments, although the main aquifer is developed in calcrete. This is part of an extensive sedimentary deposit in the Fortescue Valley, equivalent to the Oakover
Formation of the East Pilbara, which appears to have been originally calcareous clay, but which has undergone progressive alteration to indurated crystalline dolomite (known as calcrete). In the Fortescue Valley, it was formally defined as the Millstream Dolomite by Barnett (1981) on account of its calcium-magnesium content. The calcrete is especially cavernous or vuggy close to the watertable, giving it a very high transmissivity and specific yield, hence it is very difficult to characterise. The calcrete aquifer is up to 40 m thick, and extends in an arc from at least 70 km upstream of Millstream, and 40 km westwards to Kumina Creek, close to the Robe River. The rise in watertable level in the calcrete where the Fortescue River flows over the outcrop, from 30 km upstream of Millstream, demonstrates that recharge from the river is a major component, but it also receives groundwater flow originating from farther up the valley, and from the valley flanks. While there is potential for direct rainfall recharge on the outcrop calcrete, this is considered to be a very small proportion of recharge.

Discharge from the aquifer takes place at Millstream where the Fortescue River leaves the Fortescue Valley to run through bedrock to the coastal plain. Discharge is principally through Deep Reach Pool, supporting vegetation and pools farther downstream. There appears to be an indirect connection, presumably through silt deposits, between the aquifer and Deep Reach Pool, as the pool level is 1.5 m below that of the watertable in the calcrete aquifer. There is also discharge from springs along the eroded northern margin of the calcrete at Chinderwarriner (formerly Crystal Pool), which supports vegetation in the Millstream delta, and smaller springs at Peters and Palm springs.

Despite there being demonstrated recharge from the Fortescue River over the outcrop of the calcrete, the salinity in bores in that area is higher than the salinity of the discharge water, implying that either the data are misleading, or the bore water is mixed with a source of lower salinity groundwater from the valley flanks. The salinity of the river where it flows over the calcrete has not been determined, and all data on river flow and salinity are inferred from measurements at Gregory Gorge, downstream from the Millstream pools.

The Millstream borefield commenced operation in 1969 to meet the required water supply for the West Pilbara Water Supply Scheme. By 1982 the borefield was suppling 27,400 kL/day (10 GL/year). In 1985 this reduced to 6 GL/year with the completion of Harding Dam. Water is currently sourced from the Millstream borefield when use of Harding Dam is constrained. A new water source has been established with the incorporation of the Bungaroo borefield (10 GL/year), which could potentially be utilised as a contingency water source option.

Upper Fortescue Valley

The Fortescue Marsh occupies an internally draining depression in the upper Fortescue Valley. The Marsh is underlain by dolomite of the Wittenoom Formation and chert breccia. Recent investigation of cores through the chert breccia have indicated that brecciation resulted from meteorite impact (Glikson and Hickman, 2014), though the extent of the impact is not clear. The Marsh is a groundwater sink, containing hypersaline groundwater, however the saline watertable is below ground. The Marsh periodically fills with freshwater from the upper Fortescue River. It is believed that saline groundwater extends westwards of the surface divide at the Goodiadarrie Hills, presumably contributing to groundwater salinity in the lower Fortescue Valley.

Hamersley Range

The valley-fill sequence adjacent to the Marandoo mine is typical of the major valleys in the Hamersley Range underlain by the Wittenoom Formation. The Marandoo dewatering extraction rate ranges from 2 to 36.6 GL/year. The iron ore deposit is in the north dipping Marra Mamba Iron Formation with the overlying karstic and dolomitic Paraburdoo Member of the Wittenoom Formation forming the base of the in-filled valley. The valley sediments are about 90 m thick consisting of the basal Robe Pisolite (CID), overlain by the Oakover Formation (calcrete), overlain by a thick sequence of lacustrine clay with 15 to 20 m of alluvium at the surface (Liquid Earth, 2005; Commander, 2009). An upper calcrete is developing in the zone of fluctuation at the current watertable, approximately 15–20 m below the surface. The main aquifer is formed by the karstic Wittenoom Formation, CID and Oakover Formation, which is also in contact with the
permeable ore zone. The bores supplying the mining operation are up to 100 m deep, and pumped at up to 860 kL/day, with a salinity of 500 to 550 mg/L TDS (Johnson and Wright, 2001).

This sequence is similar to that at the Southern Fortescue borefield, in the same valley to the west, and at the Brockman–Nammuldi and Silvergrass–Homestead deposit areas. The Southern Fortescue borefield has supplied Tom Price town and mine site with water since 1971, it consists of 10 production bores with a licenced extraction rate of 4.68 GL/year from a semi-confined aquifer system.

**Turee Creek Catchment**

Alluvial aquifers on the southern margin of the Hamersley Basin in the Turee Creek Catchment have generally been developed in conjunction with underlying CID and fractured bedrock. At Turee Creek East, the aquifer zone is 50–80 m thick, with up to 35 m of alluvium (Layton Groundwater Consultants, 1978; Aquaterra, 1999; North Ltd, 2002). Groundwater salinity ranges from 140–700 mg/L TDS.

In Turee Creek just to the south of the Channar iron ore mine (Johnson and Wright, 2001) there is an upper unconfined aquifer associated with the current creek, separated by a thick succession of low permeability valley-fill clay from a lower aquifer associated with paleodrainage gravels and karstic dolomitic units (Johnson and Wright, 2001). The nearby Mount Olympus borefield, which supplied the Mount Olympus gold mine in the Wyloo Group, utilises both shallow alluvium and karstic dolomite in the Duck Creek and Wittenoom formations. Groundwater in these aquifers ranges from 420 to 1100 mg/L TDS.

**Newman area**

There are up to 100 m of valley-fill sediments associated with the Fortescue River and the Whaleback and Homestead valleys near Newman (MNMC, 1980, 1981). The Fortescue River catchment upstream of Ethel Gorge mostly drains the granite of the Sylvania Inlier. MNMC (1981) divided the sediments into three sequences: an upper sequence of alluvium and calcrete, a middle argillaceous sequence, and a lower sand and gravel with minor silt and clay. Currently the Ophthalmia borefield has a licenced extraction rate of 10 GL/year of low salinity groundwater (generally <600 mg/L TDS). Enhanced recharge to the surface calcrete using water from the Ophthalmia Dam commenced in 1982, and has a designed annual infiltration rate of 7 GL/year.

**Oakover River**

Sumps in the river bed were used to provide water for the construction of the Marble Bar–Ripon Hills Road. Australian Bore Consultants (1999) reported that large resources of groundwater occur in the saturated sediments of the Oakover River. Owing to the discharge of dewatering from the Woodie Woodie mine, the river is now perennial, and some of the water is being used to irrigate fodder on Warrawagine Pastoral Lease.

**5.2.4 Dolomite**

Important things to note about dolomite are:

- it underlies the major valleys in the Hamersley Range and in the Oakover Valley
- it is locally karst and high yielding aquifers occur below valley-fill sediments
- large amount of dewatering is required where it is in hydraulic connection with mines
- local karst and weathered sequence of the Puntapunta Formation relevant for the Telfer water supply
- characteristics of Duck Creek and Carawine dolomites are relatively unknown
- perennial natural groundwater discharge to Carawine Pool supports GDEs
- in conjunction with overlying CID, calcrete and valley fill, dolomite systems are utilised for water supply
- dolomite in the Assessment area is highly variable in nature, and so is karst development.

The karst dolomite of the Wittenoom Formation, and the equivalent Carawine Dolomite, is the most important regional aquifer among the Archaean-Proterozoic rocks, being developed for water supply at Tom Price, Hope Downs, Area C, Orebody 18 and Jimblebar. Potential may exist in the Duck Creek Dolomite
of the Ashburton Basin, and the basal dolomite of the Bangemall Basin (variously mapped as Irregully Formation and Top Camp Formation, Geological Survey of Western Australia, 1990), though there has been no groundwater investigation of these units.

Karst development in the dolomitic Paraburdoo Member of the Wittenoom Formation seems to occur only in places below the valley-fill sediments and below the watertable; in outcrop, the dolomite is massive. Continuing karst development is indicated by the formation of sinkholes, which appeared during the 1980s in the Southern Fortescue borefield and near Roy Hill. By contrast, the Carawine Dolomite and associated Pinjian Chert of the Oakover Valley have numerous karst features such as sinkholes visible at the surface.

Large amounts of groundwater are pumped from the Carawine Dolomite at the Woodie Woodie mine to allow mining of the overlying manganese ore. The permanency of Carawine Pool, prior to additional inflows from mine dewatering indicates significant groundwater discharge from the dolomite aquifer.

Telfer gold mine uses the majority of the 29.7 GL/year of allocated groundwater from the weathered and karst features within the dolomites of the Puntapunta Formation. The groundwater is generally brackish (1500 to 3000 mg/L TDS).

5.2.5 Canning Basin

Important things to note about the Canning Basin are:

- south-western part of Australia’s second-largest artesian basin
- Wallal Sandstone aquifer contains low salinity water
- natural potentiometric levels are up to 30 m above the ground surface
- long groundwater flow times; Carbon-14 dates at thousands of years
- recharged by cyclonic rainfall on the Great Sandy Desert
- significant development potential; current usage relatively low.

The Canning Basin is Australia’s second-largest sedimentary basin, containing sediments ranging in age from Ordovician to Cretaceous. The part of the basin within the Assessment area contains basal sediments of Permian age in the east, unconformably overlain by a Jurassic to Early Cretaceous sequence, which lies directly on Precambrian rocks in the west. The stratigraphy has been simplified in the hydrogeological literature (Leech, 1979) to a basal Jurassic Unit, the Wallal Sandstone (confined aquifer), overlain by the Jarlemai Siltstone (aquiclude) and the Broome Sandstone (unconfined aquifer). WorleyParsons (2013) further subdivided the Broome Sandstone into an Upper and Lower Callawa Formation.

The Wallal Sandstone is a major aquifer containing groundwater of low salinity (240–500 mg/L TDS) east of Pardoo, and was originally investigated by the Geological Survey for supply to Port Hedland (Leech, 1979). The aquifer extends northwards of the Assessment area, but groundwater north of Mandora Marsh is brackish. Groundwater flow is from the east of the Assessment area, with a small contribution of recharge along the southern margin indicated by young Carbon-14 dates (Meredith, 2009). Groundwater along the coast has given Carbon-14 dates of over 40,000 years.

A production wellfield was established for the Shay Gap mine, and irrigation of fodder crops is being carried out on Pardoo and Wallal pastoral leases. Further investigation drilling has been carried out for the Water Corporation (WorleyParsons, 2013), for the Spinifex Ridge mine near the former Shay Gap borefield, and by the Department of Water to the east of the area investigated by the Geological Survey. The Broome Sandstone aquifer is saturated only in a narrow coastal strip about 20 km wide, and the salinity is relatively high, being less than 1000 mg/L TDS only to the south of the Great Northern Highway in the east of the region.
5.2.6 Permian and Cenozoic paleochannels in the Paterson province and Oakover Valley

Important things to note about Permian and Cenozoic paleochannels in the Paterson province and Oakover Valley are:

- concealed below sand dunes on the edge of the Great Sandy Desert and possibly underlying the Oakover Valley
- used as water supply for Nifty mine and Telfer access road
- presumed to underlie the chain of salt lakes between Lake Dora and Lake Waukarlycarly
- future water supply for Kintyre uranium deposit.

North-trending paleochannels containing sediments referred to the Permian Paterson Formation have been identified in the Oakover Valley, mainly overlying the Hamersley Group, and in the Nifty–Telfer–Kintyre areas, overlying Neoproterozoic sediments and the Rudall Complex (English et al., 2012). These paleochannels are believed to be glacial features, either ice-gouged or eroded by meltwater during the Permian glaciation, though the Oakover Valley also follows a syncline in the Hamersley Basin which may in turn be controlled by an underlying graben. The paleochannels are filled with a variety of sediments ranging from clayey till to outwash sands. The sands have been found to be useful aquifers, containing fresh to brackish water. Present day drainage lines follow some of these features and contribute recharge of low salinity water. Drilling at Nifty mine, along the Telfer access road, and at Kintyre has proven moderate yields of freshwater from the Permian sediments which are as much as 150 m deep. The Permian sediments in paleochannels are contiguous with equivalent sediments in the Canning Basin which are overlain by Jurassic and Cretaceous sandstones. Artesian flows are known from Permian aquifers along the basin margin (English et al., 2012).

A Cenozoic paleochannel, representing the course of the Percival Paleoriver is presumed to underlie the line of salt lakes from Lake Dora, south-east of Telfer, to Lake Waukarlycarly north of Nifty, and extend to the De Grey River near its confluence with the Oakover River (English et al., 2012). Extensive valley calcrite is mapped around Lake Waukarlycarly, and may have significant aquifer potential. By analogue with other paleochannels it is likely to contain sediments of Eocene to Pliocene age. However, there is no investigation data, and groundwater in the trunk drainages is likely to be highly saline.

The northern boundary of the region follows Salt Creek inland from Samphire Marsh, the infilled estuary to the Mandora Paleoriver which drained the centre of the Canning Basin as far back as Lake Gregory. Salt Creek contains a surface body of salt water with mangroves some 40 km inland, maintained by groundwater.

5.2.7 Carnarvon Basin

Important things to note about the Carnarvon Basin, limited only to the south-western part of the Assessment area, are:

- the Birdrong Sandstone is the only significant aquifer
- groundwater is generally brackish along the inland margin, and is saline at the coast
- artesian conditions occur over much of the coastal plain.

The Birdrong Sandstone is the only significant aquifer in the Carnarvon Basin sequence (Allen, 1987). Its equivalents, the Nanutarra Formation and Yarraloola Conglomerate, are mapped sporadically along the inland margin of the basin, overlying Proterozoic rocks, generally as isolated hills. In the subsurface, the Birdrong Sandstone rests on Proterozoic basement in the Peedamullah Shelf subdivision, and on Devonian to Permian sediments nearer to the coast (Hocking et al., 1987). The Birdrong Sandstone is generally up to 30 m thick and dips towards the coast, being around 400 m deep at Onslow. Artesian conditions are present over much of the coastal plain, and groundwater increases in salinity to exceed 10,000 mg/L TDS at the coast.

Investigation of the potential recharge area where the Cane River crosses the outcrop showed that the area of recharge to the Nanutarra Formation was very limited, and the Birdrong Sandstone was mostly confined
by the Muderong Shale (Yesertener and Prangley, 1996). Groundwater recharge along the river was indicated by the potentiometric levels which decline away from the river, but the salinity rose rapidly away from the river, indicating only a very limited area of fresh groundwater.

A substantial amount of exploration drilling has been carried out for uranium in the Birdrong Sandstone, resulting in the location of the Manyingee deposit (Minatome Australia Pty Ltd, 1982). The drilling has demonstrated the existence of paleochannels at the base of the Cretaceous sequence, similar to the lower Fortescue River area (Commander, 1994a), and resulted in a number of free-flowing brackish artesian bores. Trial in-situ leaching of uranium ore was carried out at Manyingee, where the groundwater is brackish, but it has not progressed to production.

Saline groundwater (13,000 mg/L TDS) from the Birdrong Sandstone has been developed for BHPBilliton’s Macedon project (Golder Associates, 2012), 16 km south of Onslow. Flows of saline groundwater have also been encountered in the Robe River oilfield at the mouth of the Robe River, where oil accumulations are present in the Mardie Greensand, which locally lies directly above the Birdrong Sandstone (Thomas, 1978).

5.2.8 Fractured rock

Important things to note about fractured rock are:

• occupy the greater part of the Pilbara, but do not generally contain regionally significant renewable groundwater resources, though large amounts are dewatered from storage in permeable mineralised iron ore zones
• high failure rate for sufficient bore yields
• more prospective rock units include quartz veins, chert, or prospective major fault zones
• locally used for mine water supply, railway and road construction water
• iron-enriched BIF ore deposits have well developed secondary permeability and need to be dewatered to mine
• generally fresh to brackish groundwater
• locally significant for springs and pools supporting GDEs.

Introduction

The only specific investigations of fractured rock aquifers in the region have been in the Harding River and upper Maitland River catchments near Roebourne, which were carried out for potential supply to the West Pilbara Water Supply Scheme. The first investigation carried out in the Harding catchment was in the volcanics and dolerite at Cooya Pooya (Barnes, 1973). Drilling carried out to depths of 245 m showed that the dolerite was unfractured, and that groundwater was limited to a thin weathered zone.

The drilling in volcanics of the lower Fortescue Group carried out for the Water Corporation by Rockwater Pty Ltd (2006) was summarised by Haig (2009). Targets near creeks where the rocks appeared to be well fractured produced airlift yields of up to 360 kL/day of water with a salinity up to 650 mg/L TDS.

Drilling was also carried out along the Sholl Shear Zone, identifying fracturing in the uppermost 30 m and obtaining airlift yields up to 430 kL/day, although the salinity ranged up to 2800 mg/L TDS. Rockwater Pty Ltd (2006) estimated that 3 GL/year of freshwater might be obtained from the Sholl Shear Zone, and a further 1 GL/year from the area investigated in the upper Harding catchment.

Drilling has been carried out by necessity at mining operations to obtain process water, and along roads and railway routes for construction water.

Allen (1966) reported on drilling at the Moolyella tinfield, but there are few reports of comprehensive assessment of fractured rock drilling.

Granite

Drilling at the Moolyella tinfield near Marble Bar reported by Allen (1966) found useful supplies in quartz veins, joints and pegmatites below the weathered zone at depths to 30 m. About one-third of the 30 bores
drilled below 20 m obtained supplies of greater than 100 kL/day. Groundwater salinity ranged from 480 to 770 mg/L TDS.

Groundwater Resource Consultants (1987) reported on a replacement borefield for the Bamboo Creek mine in granite at Eight Mile Creek yielding 790 kL/day from fractured granite, pegmatite and quartz veins. Rockwater Pty Ltd (1985) targeted a fracture zone visible on aerial photographs at Corunna Downs near Marble Bar. From four bores to a maximum of 51 m deep, yields of 500 to 900 kL/day were recommended. The supply for the Wodgina tantalite mine (Sons of Gwalia Ltd, 1999) was obtained from quartz veins near the Turner River, where the Main Roads Department had established a construction supply from a bore yielding 1000 kL/day.

The water supply for the construction of the Fortescue Metals Group railway was obtained mainly from granite areas (Aquaterra, 2007c). Bores were drilled to around 100 m with varying success rates. At Area 5, for instance, only two successful bores of 150–175 kL/day (1.5–2 L/s) resulted from 35 exploratory bores. At most sites, more than ten bores were drilled to achieve the required supply.

**Greenstone**

The rocks of the granite greenstone terrane are generally poorly fractured, and useful groundwater supplies are limited to siliceous units such as chert, banded iron formation, and quartz veins. Dolerite is generally considered to be unfractured and both basic and acid volcanics and schist are often weathered to clay.

Investigations for groundwater supplies include:
- chert at Lynas Find near Wodgina which yielded up to 800 kL/day (Mackie Martin PPK, 1993)
- acid volcanics, slate and quartz veins at Mons Cupri and Whim Creek (McPhar Geophysics, 1973) in which yields were less than 200 kL/day
- a dewatering bore in the Mallina Shear zone at the Indee gold project achieved a pumping rate of 390 kL/day (Aquaterra, 2006)
- at Bamboo Creek, Groundwater Resource Consultants (1987) reported on a maximum yield of 1350 kL/day from a program of 11 bores
- at Nullagine, a drilling campaign of 22 bores at 17 sites to a maximum depth of 40 m achieved a maximum yield of 610 kL/day, with 14 bores abandoned, and salinity range 1000–3000 mg/L TDS (KH Morgan & Associates, 1982)
- at Balla Balla, yields of 500–1500 kL/day were obtained from discrete fracture zones, margins of dolerite dykes, and lithological contacts (Groundwater Resource Management, 2008)
- bores in fractured acid volcanics near the Coongan River supply water for Marble Bar town
- Hamersley, Wyloo, Bangemall and Yeneena Basins.

Mineralised zones in the Marra Mamba and Brockman iron formations of the Hamersley Basin have developed high permeability, and dewatering is necessary to allow mining below the watertable. Mineralised, saturated and requiring dewatering deposits such as Atlas’s Pardoo, Mt Goldsworthy and Yarrie are within the Archean Cleaverville Iron Formation.

The orebody aquifers are generally limited along strike by the extent of mineralisation, though the Marra Mamba has hydraulic connection along 90 km of the Chichester Range, including both mineralised and un-mineralised portions. Both Brockman and Marra Mamba aquifers are bounded by impermeable shales, though the Marra Mamba ore bodies are commonly hydraulically connected to karst dolomite of the Wittenoom Formation. Groundwater in orebodies such as at Mt Whaleback, Tom Price and Paraburdoo are commonly compartmentalised by faults. Stand-alone water supplies have been developed from the ore bodies at Jimblebar and Orebody 18.

In the Paraburdoo borefield, bores are generally screened across both the weathered bedrock and the underlying fractured bedrock. The borefield consists of 11 production bores, 10 of which supply drinking water to the Paraburdoo town site, and 1 to the airport (Department of Water, 2013) and draws water from 2 aquifers beneath Seven Mile Creek and Bellary Creek. The upper aquifer is comprised of alluvium
and weathered bedrock which is collectively 30–70 m thick. The lower aquifer is unweathered and fractured bedrock. In most cases, the top of the screened interval is below the reported base of the alluvium.

Small to moderate yields (up to 500 kL/day) have been obtained from mineralised Fortescue Group at the Paulsens mine in the course of dewatering investigations (Quartz Water Australia Pty Ltd, 1999).

Groundwater Resource Consultants (1987) reported that the borefield at Bamboo Creek in Fortescue basalt and sandstone had declined in yield from 350 kL/day in 1983 to less than 100 kL/day by 1986.

Australian Bore Consultants (1999) reported yields from the Hardey Sandstone along the Marble Bar–Ripon Hills Road of up to 390 kL/day.

Moderate yields have been obtained from sheared and faulted metasediments of the Lamil Group in the Yeneena Basin along the Telfer access road, however, the basement rocks (other than dolomite and possibly sandstone) are not considered to be capable of large supplies.

### 5.2.9 Aquifers and hydrogeological provinces

In Chapter 2, thirteen hydrogeological provinces were introduced. They correspond to the integration of topographic, geological and hydrological features. There exist strong associations in each province with soil-landforms, vegetation, drainages and hydrogeology which are associated with the underlying geology. This makes summarising their water resource potential much simpler. Detailed hydrological and hydrogeological analyses is further described in Chapter 7.

Table 5.1 summarises the previously identified aquifers (water resources) in the Assessment area and their presence in the hydrogeological provinces identified in Chapter 2. Canning and Carnarvon basins have been grouped under the Sedimentary Basins column, whereas fractured rock aquifers have been sub-classified into areas where mineralised BIFs occur.

Fractured rock aquifers are predominant in most of the hydrogeological provinces. They are the main aquifer type identified in the Granite Greenstone Terrane, Chichester Range, Sylvania Dome and the East Upper Fortescue hydrogeological provinces. However, this type of resource is associated with local fractured systems with limited prospects to provide groundwater.

A combination of aquifer types/water resources is observed across all the remaining hydrogeological provinces. Prospects for groundwater resources exploitation will depend on local aquifer properties such as storage capacity, salinity, closeness to urban areas, among others, observed within each of these hydrogeological provinces.
Table 5.1 Main aquifers (groundwater resources) identified in the Pilbara region and their presence in the hydrogeological provinces. Hydrogeological provinces are listed by areal extension.

<table>
<thead>
<tr>
<th>HYDROGEOLOGICAL PROVINCE</th>
<th>COASTAL ALLUVIUM</th>
<th>CID</th>
<th>VALLEY-FILL</th>
<th>DOLOMITE</th>
<th>SEDIMENTARY BASINS*</th>
<th>PERMIAN/CENOZOIC PALEOCHANNELS</th>
<th>FRACTURED ROCK**</th>
<th>MIN BIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashburton</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Granite Greenstone Terrane</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hamersley Range</td>
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<td>-</td>
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</tr>
<tr>
<td>Canning Basin</td>
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</tr>
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<td>Paterson</td>
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<td>-</td>
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</tr>
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<td>Oakover</td>
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<td>✓</td>
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<td>✓</td>
<td>✓</td>
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<td>Chichester Range</td>
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<td>Upper Fortescue Valley</td>
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<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Carnarvon Basin</td>
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<td>✓</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Coastal Plain</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>✓</td>
<td>x</td>
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<tr>
<td>Lower Fortescue Valley</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Sylvania Dome</td>
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<td>-</td>
<td>-</td>
<td>✓</td>
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</tr>
<tr>
<td>East Upper Fortescue</td>
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<td>-</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

* Sedimentary Basins comprise Canning and Carnarvon basins
** A sub-classification of Fractured Rocks has been defined for areas with occurrence of Mineralised BIF

Groundwater modelling and climate change impacts

Numerous localised groundwater models have been developed throughout the Assessment area to meet the requirements of approvals for dewatering/water supply and environmental impact. These models have generally been developed by mining companies, with the results of the modelling outputs often reported in publicly available environmental approval documents. These models, although publically available for review, were not made available for the development of this assessment.

5.2.10 Groundwater models

The Assessment estimated the potential impacts of climate change on groundwater resources in six priority aquifers for which the Western Australian Department of Water have developed groundwater models. Details on the 2030 and 2050 climate scenarios that were used are in Chapter 3 of this report. The models are described and reviewed extensively in the regional reports as shown in Table 5.2.

The six priority aquifers included four coastal alluvial aquifers (23% of the modelled area), a dolomite/inland alluvial system at Millstream (4%), and the sedimentary West Canning Basin model. The latter comprises 73% of the modelling area. The total modelled area represents around 12% of the total Assessment area including the offshore area (Figure 5.2).
Table 5.2 Groundwater models used in the Assessment area, main water resources type and area modelled

<table>
<thead>
<tr>
<th>REGION</th>
<th>GROUNDWATER MODEL</th>
<th>AREA MODELLED (km²)</th>
<th>MAIN WATER RESOURCE TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Fortescue Hedland</td>
<td>• Millstream (SKM, 2009)</td>
<td>• 1,410</td>
<td>• Dolomites; inland alluvial systems</td>
</tr>
<tr>
<td></td>
<td>• Lower Fortescue (MWH, 2010a)</td>
<td>• 200</td>
<td>• Coastal alluvial aquifers</td>
</tr>
<tr>
<td></td>
<td>• Lower Yule (MWH, 2010b)</td>
<td>• 2,675</td>
<td>• Coastal alluvial aquifers</td>
</tr>
<tr>
<td>De Grey Canning</td>
<td>• West Canning Basin (Aquaterra, 2010)</td>
<td>• 26,100</td>
<td>• West Canning Basin (sedimentary)</td>
</tr>
<tr>
<td></td>
<td>• Lower De Grey (SKM, 2010a)</td>
<td>• 4,500</td>
<td>• Coastal alluvial aquifers</td>
</tr>
<tr>
<td>Ashburton Robe</td>
<td>• Lower Robe (SKM, 2010b)</td>
<td>• 714</td>
<td>• Coastal alluvial aquifers</td>
</tr>
<tr>
<td>Total modelled area</td>
<td>--</td>
<td>• 35,600</td>
<td>--</td>
</tr>
</tbody>
</table>

No formal classification in terms of confidence level was provided by the model developers. Only three models, namely, Lower De Grey (SKM, 2010b), Millstream (SKM, 2009), and Lower Robe (SKM, 2010b), have been classified as an ‘Impact Assessment Model’ in terms of model complexity given the MDBC (2000) modelling guidelines. These are defined as a “moderate complexity model, requiring more data and a better understanding of the groundwater system dynamics, and suitable for predicting the impacts of proposed developments of management policies” (MDBC, 2000).

In terms of target model confidence level and on the basis of the original modelling objectives, all six models used in the Assessment could be classified as Class 2 models following the Australian groundwater modelling guidelines (Barnett et al., 2012). This suggests that there is room for further model development and improvement/refinement. Revisiting, re-calibrating, re-validating, or performing a post-audit analysis to any of the models was beyond the scope of the Assessment and, as such, the models were used under an ‘as is’ basis.

There is inherent uncertainty to every groundwater modelling exercise arising from multiple sources (e.g. model parameters, model inputs, and model conceptualisations). All models used in the Assessment have been subjected to an uncertainty analysis as part of the modelling development. More confidence can be expected in describing potential impacts when reporting relative changes in groundwater balance components and groundwater levels compared to reporting absolute model outputs. Focusing on relative output changes largely removes potential model bias (Barnett et al., 2012).
5.2.11 Modelling results in the Assessment area

Changes in the water balance components (e.g. storage depletion/replenishment, localised and diffuse recharge, evapotranspiration, discharge) as well as projected groundwater levels were estimated for three climate scenarios; dry (C50dry8.5), median (C50mid8.5) and wet (C50wet8.5), for a 52-year simulation period starting on 1st October 2012 and defined in chapters 3 and 4. These scenarios were compared with a continuation of the historical scenario termed as Scenario A.

Table 5.3 shows the water balance components for each aquifer under the dry and wet scenarios for the 52-year simulation period. These represent the main components only so the numbers may not balance. Localised recharge from river leakage dominates the water balance for the coastal alluvial aquifers and Millstream, with the Lower De Grey, Lower Yule and Millstream aquifers receiving over 20 GL/year. Groundwater levels and salinity suggests that the resultant groundwater mound decreases with increasing distance from the river channels. At Millstream there is an apparent balance between river recharge and discharge at springs and into pools downstream of the main recharge zone, resulting in a balance. This suggests localised river recharge in this system has an important role supporting perennial springs and pools, and by association riparian vegetation. With the exception of the West Canning Basin groundwater model, all other models consider a recharge process associated with floodplain inundation when rivers are overflowing.
Table 5.3 Summary results for main groundwater flow components for six groundwater models for dry (C50dry8.5) and wet (C50wet8.5) climate scenarios. Values in parenthesis show relative change with respect to Scenario A.

<table>
<thead>
<tr>
<th>REGION</th>
<th>GROUNDWATER MODEL</th>
<th>SCENARIO</th>
<th>RIVER RECHARGE (GL/year)</th>
<th>RIVER GAINS/SPRINGS (GL/year)</th>
<th>RAINFALL RECHARGE (GL/year)</th>
<th>EVT (GL/year)</th>
<th>NET STORAGE (GL/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Fortescue</td>
<td>Millstream</td>
<td>C50dry8.5</td>
<td>20.6 (~16%)</td>
<td>21.2 (~15%)</td>
<td>4.0 (0%)</td>
<td>2.0 (+2%)</td>
<td>3.9 (+9%)</td>
</tr>
<tr>
<td>Lower Fortescue</td>
<td>Hedland</td>
<td>C50wet8.5</td>
<td>26.6 (+9%)</td>
<td>26.6 (+7%)</td>
<td>4.0 (0%)</td>
<td>2.1 (+5%)</td>
<td>3.2 (~9%)</td>
</tr>
<tr>
<td>Lower Yule</td>
<td>C50dry8.5</td>
<td>11.3 (~10%)</td>
<td>0</td>
<td>3.4 (~19%)</td>
<td>14.3 (~3%)</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C50wet8.5</td>
<td>13.2 (+5%)</td>
<td>0</td>
<td>4.6 (+7%)</td>
<td>15.8 (+7%)</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>De Grey</td>
<td>West Canning Basin</td>
<td>C50dry8.5</td>
<td>34.9 (~17%)</td>
<td>17.2 (~19%)</td>
<td>10.0 (~25%)</td>
<td>76.8 (0%)</td>
<td>-0.3 (~105%)</td>
</tr>
<tr>
<td></td>
<td>Lower De Grey</td>
<td>C50wet8.5</td>
<td>45.8 (+10%)</td>
<td>22.3 (+5%)</td>
<td>14.9 (~11%)</td>
<td>80.3 (+4%)</td>
<td>10.7 (+50%)</td>
</tr>
<tr>
<td>Ashburton</td>
<td>Lower Robe</td>
<td>C50dry8.5</td>
<td>10.9 (0%)</td>
<td>*</td>
<td>8.7 (~23%)</td>
<td>12.5 (~13%)</td>
<td>3.8 (+5%)</td>
</tr>
<tr>
<td></td>
<td>C50set8.5</td>
<td>10.9 (0%)</td>
<td>*</td>
<td>11.7 (~4%)</td>
<td>15.3 (+6%)</td>
<td>3.1 (~15%)</td>
<td></td>
</tr>
</tbody>
</table>

* Negligible values
** Apportioned from the total distributed recharge in the original model as 52% rainfall recharge and 48% river flood

Considering the length of the river reaches included in all modelled domains, river recharge for all models may vary between 270 and 1,600 ML/year/km. Observed records for the Millstream aquifer suggest an average of 30 days/year as effective river recharge events (1,325 days out of 16,345) (SKM, 2009), whereas for the Lower De Grey between 14 and 84 flow days are expected to recharge the alluvial aquifer (SKM, 2010a). This results in river leakage rates for the dry and wet scenario between 23 and 30 ML/km/flow day for the Millstream aquifer, and between 15 and 117 ML/km/flow day for the Lower De Grey alluvial aquifer. These values will differ from those presented in Chapter 4 as the ones shown here represent flow days effectively recharging the aquifers, which will vary from total flow days obtained in Chapter 4.

Given the dimensions of the modelled domains, diffuse recharge through rainfall infiltration is of minor importance. However, in the West Canning Basin this mechanism is the main recharge process. This results from the large surface outcrop of this aquifer (one/two orders of magnitude larger) compared to the rest of the modelled domains (Table 5.2) and the paucity of streams.

Groundwater losses through evapotranspiration are dominant in coastal alluvial aquifers where groundwater levels are shallow and coastal riparian vegetation is common. The Lower De Grey aquifer has the highest evapotranspiration loss accounting for more than 80% of total outputs. This value is in agreement with evapotranspiration estimates for the Lower De Grey area prior to the commissioning of the Namagoorie borefield.

Relative changes in storage (last column in Table 5.3) are relatively important with respect to the historical scenario, especially for the West Canning Basin and Lower De Grey models, where fluctuations in net storage result from recharge declines under the dry climate. In terms of elasticity (i.e. ratio of proportional change in net storage contribution to proportional change in rainfall), however, relative changes are comparatively insensitive to changes in projected rainfall, with only the Lower De Grey and West Canning Basin showing elasticity values greater than 6. This suggests that, with the exception of these two models, all changes in net storage contribution are in agreement with projected changes in future rainfall.

Changes in water balance components are most pronounced under the dry scenario compared to the wet scenario. This agrees with the findings in Chapters 3 and 4, which indicate larger decreases in rainfall and runoff under the dry scenario compared to increases under the wet scenario. Also, higher temperatures and potential evaporation under the dry scenario will impact changes in the water balance under the dry scenario. Changes in groundwater recharge (localised and diffuse), however, are rather insensitive to changes in projected rainfall, with the recharge-rainfall elasticity ranging between 0.6 and 1.7 across all...
modelled domains. On the contrary, changes in the net contribution from storage show a larger sensitivity (up to 16.1 for the West Canning Basin aquifer), suggesting that groundwater reserves may be more impacted under a future drier climate. This model relies on diffuse recharge only given that regional throughflow and submarine discharge remains fairly constant under future climate scenario, even under a maximum extraction of 31 GL/year as defined in the Pilbara Groundwater Allocation Plan (DoW, 2013). Being deep and confined this aquifer has very large reserves and small areas of dependent GDEs compared with the small alluvial aquifers.

Figure 5.3 shows the elasticity of relative changes of river recharge to runoff and the number of flow days for the dry and wet climate scenarios in five different river gauge stations contained in the modelled domains. Under a dry scenario, no clear trend is identified signalling whether a decrease in runoff or the number of flow days dominate the decreases in river recharge. Thus, an interplay of both processes seems to explain the decreases in river recharge. Under a wet scenario, there is a clear trend showing that increases in the number of flow days will most likely play a major role in the increase of river recharge. These patterns could be explained by the interplay of projected changes in areal potential evaporation across the Assessment area, which remain fairly constant under dry and wet scenarios (Chapter 3), and changes in soil moisture content facilitating river recharge during river overflow, which is expected to increase under a wet scenario.

Apart from flow days in the De Grey River (710003, Coolenar Pool), river recharge reduces by only 20 to 60% the reduction in either runoff or flow days in these five aquifers. This means that these aquifers will be less impacted than may be expected from river measurements alone. Decreases in runoff may reduce outflows to the Indian Ocean without appreciably reducing river recharge amounts by the same proportion. The anomalous estimates for flow days in the De Grey Catchment are caused by a small change in the number of flow days in the denominator of the elasticity estimation; with the De Grey River having a much larger and permanent number of flow days during the year compared to other rivers. It should be noted that decreases in the number of flow days at the gauging stations depicted in Figure 5.3 are obtained from Chapter 4 of this report.

Simulated changes in groundwater levels (discussed under the regional reports) confirmed more pronounced impacts under a drier future climate compared to a wetter climate. Differences in groundwater levels between the dry and historical scenario for the 50th percentile are less than 1 m across all models. This suggests that changes in climate while maintaining all pumping equal results in changes in groundwater levels which are relatively small.

![Figure 5.3 Elasticity of river recharge to runoff and number of flow days for different river gauge stations contained in the five groundwater models presented in Table 5.1. 708015 – Lower Fortescue, 709005 – Lower Yule, 708002 – Millstream, 710003 – Lower De Grey, and 707002 – Lower Robe](image)
5.3 Synthesis and conclusions

The groundwater resources of the coastal alluvial aquifers are the most important in the region for supply to the coastal towns. These resources depend on river recharge and are easily accessible through borefields. Despite having a significant potential for water supply, management of coastal alluvial aquifers is somewhat constrained by the need to protect groundwater-dependent riverine vegetation which might have an increasing evapotranspirative demand under a drier climate.

An emerging major resource, not previously considered as a significant regional groundwater resource, are the concealed channel iron deposits (CID) present in the Pilbara region. The groundwater resources of the CIDs have not been extensively studied in the Assessment area, but recent evaluation suggests there is a large potential in the northwest Hamersley Range (e.g. upper Bungaroo in HydroConcept, 2014). Historically, surplus water resulting from mine dewatering has been discharged to the environment, but water resources planning could now account for potential use of the surplus water.

Inland groundwater resources such as alluvial systems associated with present-day drainage patterns, as well as karstified dolomite, show some potential as sources of fresh groundwater. Difficulties in assessing the opportunities for development are related to future predictions of increasing temperature and evaporation demands in the inland part of the Assessment area and the ephemeral nature of the river courses, thus limiting the effective localised recharge from rivers. Interconnection of the multiple aquifer systems present in inland groundwater systems (e.g. valley-fill, calcrite, CID, and karst dolomite) needs to be assessed as well as the quantification of the effective diffuse and localised recharge. Despite their relevance, inland groundwater resources are poorly studied and current assessments are limited to local conditions around mine sites and wellfields.

The major resource of groundwater in the East Pilbara coast is in the sedimentary aquifers of the West Canning Basin. The main aquifer (Wallal) has potential for extensive development as confirmed in the modelling results, though most of the allocated volume foreseen in the Pilbara Groundwater Allocation Plan (DoW, 2013) would come from storage. Research indicates that residence times are significant for this aquifer which is part of a larger regional groundwater system recharged by diffuse rainfall infiltration. Challenging aspects in the assessment of the potential for the West Canning Basin aquifer are a possible hydraulic connection with the Lower De Grey aquifer at the western limit and the quantification of the effective submarine discharge from the main confined Wallal aquifer.

Overall, results from the modelling of the different groundwater systems in the Assessment area are in agreement with results from other chapters detailing climate and surface hydrology. Impacts on groundwater resources are more significant under a drier, compared to a wetter future climate. This is explained by the more significant decreases in available water resources under the dry climate predicted by the global climate models (GCMs) used in the assessment.

In general, localised river recharge dominates the recharge mechanisms and full understanding of this process is required for a better quantification of the renewable groundwater resources. General figures on river recharge per kilometre length and flow days might differ from estimates in Chapter 4, as the latter considers total number of flow days, whereas estimates in this chapter are approximated using effective number of recharging flow days obtained from historical streamflow observations used during the calibration of the groundwater models. It is expected that localised recharge (expressed on a per kilometre basis) obtained from the SIMHYDGW model (Chapter 4) will be lower than estimates presented here, given that the former considers all days with simulated flows, including those not effectively recharging the aquifers.

When analysing localised river recharge under the future climate scenarios, it is apparent that the interplay of other variables such as evaporation and soil moisture content will impact this mechanism. Both increases and decreases in runoff and number of flow days might have a role inhibiting or enhancing this recharge process.
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6 Groundwater-dependent ecosystems

Authors: Olga Barron and Irina Emelyanova

Key points

- The developed methods, based on the combined analysis of geological, hydrogeological and ecohydrological data along with remote-sensing techniques, allowed delineating various types of actual and potential groundwater-dependent ecosystems (GDEs) in the Assessment area. The delineated GDEs, which cover less than 0.5% of land surface, include terrestrial vegetation and pools.
- GDEs were classified based on their dependency on various groundwater systems in the Assessment area, from regional bedrock aquifers to local aquifers to groundwater systems which do not form aquifers. GDE sensitivity to climate variability increases from the former to latter.
- The spatial extent and RS characteristics of the identified actual and potential GDEs remained relatively constant between 1988 and 2011, while larger variability occurred in non-GDE riparian vegetation.
- Vegetation considered to have a greater dependency on groundwater (GDEs) has a lower dependency on 11 climate parameters. Temperature, solar radiation and potential evaporation have more immediate effects on greenness (including GDEs), while seasonal rainfall variability has a significant effect on vegetation with low dependency on groundwater.
- GDE types considered to be dependent on some local aquifers or groundwater which does not form an aquifer show sensitivity to reduction in high-intensity rainfall, such as during a particularly dry period (1988 to 1992); however, they recover in subsequent years.
- The effect of groundwater depth on vegetation greenness is detectable when groundwater levels are less than 10 m below ground level. When groundwater level declines due to abstraction, the effect of water level changes on vegetation greenness is greater for vegetation with an initially high greenness. The changes are also influenced by the magnitude of the groundwater level decline. GDEs considered to be dependent on groundwater discharge from regional aquifers are very sensitive to changes in groundwater levels resulting from groundwater abstraction.
- Vegetation greenness shows more sensitivity to seasonal variations in river flow than to individual events.
- Significant changes in ecohydrological conditions (e.g. reduction in rainfall intensity or groundwater abstraction) manifest in changes of GDE greenness after the second hydrological cycle following the initial impact. Effect on GDE wetness is more immediate.
- Projected changes in rainfall and streamflow under future climate scenarios are less than has been recorded in the historical period at decadal (or greater time) scale. The main factors likely to affect future climate impacts on GDEs are changes in rainfall intensity and the frequency of high-intensity events; due to established relationships between high-intensity events and recharge (see Chapter 4).
- Spatio-temporal analysis of Landsat data allow potential and actual GDEs to be mapped and monitored as well as the spatial extent of riparian vegetation at regional and local scales. The method can be used to establish a baseline to overcome the challenge presented when site-specific baseline data are not available for long enough to characterise GDE response to climate and management.
- As the assessment was undertaken at a regional scale and is constrained to Landsat 5 spatial resolution (30 m by 30 m), it is recommended to support the reported results by site-specific investigations at individual locations of interest.
6.1 Introduction

As discussed in previous chapters, water resources and hence environmental water availability in the Pilbara are highly variable both spatially and temporally. High-intensity, low-frequency rainfall events and prolonged dry seasons have led to the development of unique ecological systems, which are well adapted to a mostly hot climate and sparse rainfall events which lead to water resources replenishment. One of these ecological system components is the so-called ‘groundwater-dependent ecosystem’ (GDE). Within the project, groundwater-dependent terrestrial vegetation and pools were considered. These GDEs provide refugia for many species and are crucial for their survival, and they have extremely high ecological value. Such locations are also likely to be important Indigenous sites (Carwardine et al., 2014). GDEs and their ecohydrological characteristics are also important for the estimation of groundwater sustainable yields, as GDE protection is one of the major sustainability measures when groundwater management options are considered.

The main objectives of the research within this activity of the Pilbara Water Resource Assessment are:

1. classification and delineation of potential and, where possible, actual GDEs at a regional scale
2. determination of their reliance on various water resources (groundwater, surface water, rainfall)
3. assessment of the sensitivity of potential and actual GDEs to historical climate variability, and potential impacts resulting from changes in water regimes driven by climate change.

To address these objectives at a regional scale, a combined analysis of geological, hydrogeological and ecohydrological data along with remote sensing (RS) techniques was carried out to define the spatial and temporal characteristics of GDEs. Due to the spatial resolution of available RS products with longer records (e.g. Landsat TM, 30 m by 30 m pixels), the developed methods are more suitable for vegetation community or habitat delineation and characterisation rather than for individual plants. RS-based characteristics of GDE habitats include the areas of GDE-related land cover classes, multispectral indices characterising greenness and wetness of such land cover classes, and their temporal and spatial patterns, which can be defined by derived RS products (e.g. the results of spatio-temporal statistical analysis).

It is important to mention that most of the reported analyses of GDEs were undertaken following the main project objective and hence were mainly focused on water resources characterisation. Even though information on vegetation and known pools were used for the carried-out analysis, ecological assessment, tree physiology or biodiversity characterisation fell outside the scope of this project. Still, the reported results provide a valuable basis for the follow-up research in GDEs within these research areas, which is also likely to add value to the reported outcomes.

This chapter describes the overall results of GDE delineation and typology and GDE dependency on water regimes, while more detailed results are presented in a series of regional reports. In the absence of a suitable groundwater model in the Assessment area, only a qualitative assessment of potential impacts from climate change and development on the GDEs is presented. The chapter provides comments on the limitations and uncertainty of the reported analysis, knowledge gaps and recommendations for future research.

6.1.1 Groundwater dependency: definition and types

GDEs are defined as those which require the presence or input of groundwater to maintain some or all of their ecological function, composition or structure (Eamus and Froend, 2006; Murray et al., 2006). Hatton and Evans (1998) identified four broad ecosystem classes within which groundwater plays an important role: terrestrial vegetation; river baseflow systems; aquifer and cave systems; and wetlands. These ecosystems were identified as being potentially vulnerable to groundwater abstraction and climate-induced hydrological change. Despite wide acceptance of this definition, the term GDE is known to have some shortcomings, particularly where the definition of ‘groundwater’ is concerned.
In order to meet the project objectives, it was important to develop a systematic approach to GDE delineation and analysis. Such an approach was based on a conceptual understanding of vegetation function in the Assessment area, various level of vegetation dependency on groundwater and types of groundwater systems. A systematic approach was particularly necessary due to deployment of mostly indirect information (e.g. derived from RS data) and the regional scale of the assessment.

Vegetation and landscape

As discussed in Page et al. (2011), characteristics such as ‘plant growth’ and ‘leaf area’ are commonly used to describe plant functional types including plant water use. Differences in leaf area and plant growth across communities and ecosystems have been extensively correlated with environmental gradients of resource availability including nutrients and water at regional or even global scale (e.g. Wright et al., 2004). While other factors are obviously of importance (e.g. nutrients, soil depth, fire regime), arid landscapes provide a relatively simple system of the relationship between forms and functions in plant traits (Page et al., 2011). While examining the prevailing vegetation communities and ecosystems in the Pilbara, Page et al. (2011) and Cullen et al. (2008) showed a strong landscape gradient from streamlines to flood plains to hill slopes. This gradient is largely controlled by water availability.

Under the arid and desert climate in the Pilbara, river valleys represent a part of the landscape where water, organic matter and fine soil materials accumulate during infrequent storm events, creating an environment more suited to plant growth. As was shown in Chapter 4, streamflow events occur on an annual basis, providing annual replenishment of water resources in the underlining formations whether they be soil profile, shallow alluvial sediments or aquifers. All such water resources, including groundwater, have significant ecological value as it supports riparian vegetation and river pools with significant conservation values.

Terrestrial GDEs generally include phreatophytic vegetation, consisting of plants which use groundwater to meet all or a proportion of their water use requirements. The groundwater resource may be available and used by vegetation persistently or on a transient basis. Importantly, phreatophytic behaviour seems to be more related to environmental conditions (e.g. adequate water availability from the vadose zone) than to the capabilities of a given plant species (Thomas, 2014). Furthermore, some species have a capacity to opportunistically use groundwater when available but may not be reliant on groundwater for growth and reproduction. In the Pilbara, several riparian tree species are considered to be indicators of vegetation that is potentially groundwater-dependent. *Melaleuca argentea* is restricted to sites with shallow and easily accessible groundwater and is generally regarded as having an obligate groundwater dependence (McLean, 2014). The dominant riparian tree species *E. camaldulensis* subsp. *refulgens* (River Red Gum) and *E. victrix* (Western Coolibah) use groundwater opportunistically. However, these species (particularly the former) also occur in habitats with deep watertables that may not be accessed by tree roots.

Groundwater-dependent vegetation tolerates frequent droughts, maintaining consistent access to groundwater resources. Where soil profiles are deep, as is commonly the case in proximity to drainage incisions, flood plains and valley systems, deep-rooted vegetation may also avoid drought stress by accessing deep soil water stores (i.e. vadose storage). Where information on depth to groundwater, soil water storage and vegetation water use is unavailable, it may be difficult to distinguish this type of vegetation from groundwater-dependent vegetation.

Groundwater systems

When the definition of GDE is discussed, confusion is commonly associated with the term ‘groundwater’. The definition of ‘groundwater’ varies from ‘water that is underground’ (<www.merriam-webster.com/dictionary/groundwater>) or ‘Groundwater is water located in the saturated zone below the earth’s surface’ (NWC, 2012), to ‘the water found underground in the cracks and spaces in soil, sand and rock. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers’ (<www.groundwater.org/get-informed/basics/groundwater>). Typically, groundwater practitioners dealing with water supply schemes or mining dewatering, focus on aquifers, or groundwater resources, which can be economically exploited due to their significant storage and yield.
Yet, other groundwater systems exist, which are characterised by low storage capacity or yield, such as fractured/weathered zones of bedrock formations and shallow thin alluvial deposits. Such groundwater systems are not considered to be aquifers, but such water resources can be sufficient to support seasonal environmental water demands and as such they have an important ecological function.

In addition, water stored in a soil profile above the watertable can also provide a sufficient water resource to support vegetation. However, and despite being ‘under the ground’, in this project such a water resource is not considered to be a ‘groundwater system’. In circumstances where vegetation can have access to both soil water and groundwater, assessment of their groundwater dependency can be challenging.

GDEs ultimately mark groundwater discharge zones, which could be related to diffuse discharge or localised discharge. Discharge may result from the expression of groundwater at the land surface (e.g. in connection with springs and permanent/persistent pools), from shallow watertables, or as groundwater uptake and transpiration by vegetation. In the latter case, depending on the vegetation root depth, discharge may be facilitated from watertables located some distance below the surface (Thomas, 2014). Hence GDE investigation supports better characterisation of groundwater systems.

**Groundwater quality**

The other consideration most relevant to classifying GDEs in the Assessment area is their tolerance to varying groundwater qualities, especially salinity. Groundwater in the Assessment area is mostly fresh. In a mostly arid climate with annual pan evaporation being 14 greater than annual rainfall, such an observation indicates that the watertable is relatively deep and that salt accumulation at the surface is not common. There are only a few exceptions to this regional pattern. Groundwater is highly saline in the Fortescue Marsh, which is an internal and terminal discharge zone for both groundwater and surface water in the Upper Fortescue region. As a result, the Marsh vegetation is dominated by samphire species. The other example is related to the Ramsar-listed Mandora Salt Marsh, which receives groundwater discharge from aquifers associated with the Canning Basin.

### 6.1.2 Remote sensing and GDEs

The specifics of GDE ecohydrological conditions results in their distinct signatures in remotely sensed surface reflectance images, which differ spatially and/or temporally from the surrounding areas. Remote sensing (RS) provides rapid and spatially extensive techniques for the assessment of vegetation structure and function, and can also provide insights into relationships among these and climate variables (Eamus et al., 2015). The distinct GDE signatures are manifested in plant density, greenness or spatial arrangement; given that plant density and by association leaf area index is positively correlated with water availability (Glenn et al., 2008).

Remotely sensed reflectance data allow analysis of ‘active greenness’ provided by time series of the Normalised Difference Vegetation Index (NDVI) (Tucker, 1986; Townshend and Justice, 1986; Tucker et al., 1991; Lambin and Strahler, 1994; Palmer and van Rooyen, 1998; Sobrino and Raissouni, 2000; Wallace et al., 2006; Sobrino et al., 2006; Donohue et al., 2008; Donohue et al., 2009).

Time series of RS data are well suited for exploration of differences in the vegetation ‘phenology’, or cyclical growth rate, of terrestrial vegetation with and without access to groundwater by using the time series of NDVI and NDWI (Normalised Difference Wetness Index) as indicators of vegetation greenness and wetness patterns over time, respectively (Bradley and Mustard, 2008; Barron et al., 2012).

Considering the specifics of Pilbara ecohydrological conditions and utilising remote-sensing techniques for their analysis, the following assumptions related to groundwater-dependent vegetation and pools in the Assessment area were made:

1. Vegetation communities are well adapted to the temporal variability of the water regime (seasonal, annual and decadal). Established plants are known to be tens to hundreds of years old and have been exposed to wetter and drier decades during their life-span, therefore, it is likely that their persistence
should be identified in RS data through time and across the landscape and changes in vegetation communities will be reflected in temporal patterns in RS data.

2. Different species are likely to have varying degrees of groundwater dependency. The habitats associated with some species are most often used as indicators of groundwater dependency (e.g. Melaleuca argentea and Eucalyptus camaldulensis). Others may have more episodic access to groundwater (Eucalyptus vitrix).

3. Greater availability of water to plants (such as consistent access to groundwater) is likely to result in a greater density of plants, greater leaf areas and/or canopy sizes. Therefore, areas with persistently high greenness and wetness indices indicate the high likelihood of groundwater-dependent vegetation occurrence.

4. A persistent presence of open water is indicative of groundwater discharge as rainfall and streamflow and is infrequent in the Assessment area. Rainfall events mainly occur between December and March, when evaporation demands are greater than rainfall.

5. Groundwater-dependent vegetation still experiences seasonal variability in leaf area or canopy size due to the impact of high temperatures during the wet period. However, such variability is less compared to other areas where vegetation does not have access to groundwater.

6. Annual plants opportunistically respond to rainfall and therefore influence the seasonal RS signature, which exhibits as high seasonal variation in those RS indices which characterise vegetation temporal dynamics. The effect of annual vegetation phenology may also have some effect on the greenness variability of areas dominated by trees.

6.1.3 Introduction to methods adapted for GDEs analysis

The collated publically available information on the major environmental assets in the Assessment area, which among others include actual and potential GDEs (Equinox Environmental, 2013) indicated that there are more than 800 sites in the Assessment area with well-recognised importance and such sites are commonly named. The majority of these sites are associated with groundwater-dependent pools and springs, e.g. Weeli Wolli Spring or Cathedral Pool (Figure 2.19, Chapter 2). In addition, Western Australian Department of Water and mining operators have made significant advancements in vegetation mapping, vegetation ecohydrological characterisation and their dependency on water regimes at selected locations (see a list of Western Australian Department of Water reports in the References section). When available, such information was used for establishing relationships between RS-based GDE characteristics and hydrological or hydrogeological observations (e.g. groundwater levels or river flow). These were also used for defining thresholds in RS-based GDE characteristics, indicative of material changes in GDE habitats resulting from changes in the local or regional water regime outside its historical variability. As GDEs mark areas of groundwater discharge, their characterisation along with the hydrogeological and groundwater-monitoring data provided additional information on groundwater processes.

Additionally, RS-based methods allow extrapolating local data on GDE characteristics to larger areas and to describe the cause–effect relationship between the hydrological cycle and vegetation/pool system responses at a regional scale. As RS data are available from the late 1980s, these data were used to establish background GDE conditions (baseline) in the Assessment area prior to the major mining operations, mainly started in the 2000s.

Known locations of key vegetation species and river pools were used to explore temporal variation of RS indices, the relationship between them and climatic parameters (and where possible with other water regime parameters, such as groundwater levels and river flow). Such information was further used to interpret (infer) the land cover as GDEs in other areas where such knowledge was not available. The results were validated utilising a database of actual and potential GDE locations collated by Equinox Environmental (2013) as well as personal on-ground knowledge of experts working in the Assessment area.

The long-term RS data were sufficient to explore the effect of climate historical variability on GDEs. During the period from 1986 to 2011 there were three periods with well-defined climatic conditions (Figure 6.2):
dry (1988–1992), wet (1995–1999) and median (2006–2011). This allowed exploring the sensitivity of GDEs’ RS characteristics to climate variability. Due to the project resources limitation, the methods developed for GDE delineation and characterisation were mainly confined to regions within six Landsat Tiles (Figure 6.1), selected in agreement with the project partners. This area comprises 55% of the Assessment area and RS data were available for more than 150 dates with overall more than 1000 scenes included in the analysis. The analysis of the remaining areas was simplified, using only three dates of RS data acquisition related to the end of the identified climatic periods (1992, 1999 and 2011).

AS groundwater in the Assessment area is largely fresh, the developed methods are most suitable for characterisation of freshwater ecological systems, though some analysis of spatial-temporal dynamics of land cover classes in the Fortescue Marsh was undertaken. The Ramsar-listed Mandora Salt Marsh was not included in detailed analysis as it is located outside the main study area (tile 111/74).

The method details are given in CSIRO (2012). Commercially available software (e.g. ArcGIS 10.2) and a series of codes were developed in IDL, Python and Matlab to implement the developed methodology.
Riparian vegetation

The presence of riparian vegetation is important for pool biota as it provides shelter, shading and organic matter input. It also constitutes zones of high productivity providing important food and structural resources for terrestrial biota. As discussed earlier, riparian vegetation in the Pilbara is a very distinctive land cover type which is consistently different to other landscapes. Due to such conditions, riparian vegetation is characterised by a very high contrast RS signature, persistent through time. Delineation of this land cover within the project was based on Principle Component Analysis of multiple dates of NDVI (Landsat 5). The first component (PC1) is most suitable to identify the invariant land cover classes.

This method allowed for mapping riparian vegetation across the entire Assessment area and the outcomes are shown in Figure 6.3. It is important to point out that this map does not represent the extent of GDEs. The undertaken analyses, discussed further in this chapter, indicate that only a small proportion of the riparian vegetation is likely to have some level on dependency on groundwater.

Figure 6.2 Annual rainfall (Marillana), including moving average over 5-year periods
6.3 GDE typology, based on their hydrogeological setting

The carried-out analysis along with other information generated or collated by the project led to the definition of GDE types, aiming to support water resource development or management. These GDE types were aligned with the water resources supporting them rather than their ecological significance.

As GDEs are maintained by groundwater associated with a variety of groundwater systems, they can be characterised by the origin of such systems and their scale. It was identified that the following GDE types are associated with groundwater systems of significant ecological function:

1) Ecosystems dependent on groundwater discharge from regional aquifers

Consistent groundwater discharge associated with such systems and controlled by regional groundwater gradients support the most persistent and spatially substantial GDEs. These GDEs are characterised by minimal temporal and spatial variability as they are supported by large (or relatively large) groundwater resources for which groundwater recharge and discharge zones are spatially separated. This group includes GDEs associated with groundwater discharge zones from bedrock aquifers hosted in:

- sedimentary basins (e.g. Canning Basin)
- karstified dolomite formations (mainly the Wittenoom Formation).

The former can be represented by the Ramsar-listed Mandora Salt Marsh, while the latter supports GDEs at many locations, such as Weeli Wolli Spring (Figure 6.4, Figure 6.5) or Millstream. The modern and historical discharge of groundwater from karstic dolomite formations is often marked by an occurrence of the calcrete formation. The spatially larger calcrete formations can also form an aquifer in their own right, such as in the area of Millstream.
2) Ecosystems dependent on groundwater discharge from local aquifers

GDEs of this type can be persistent temporally and are supported by the local aquifers mainly associated with secondary deposited formations:

- localised or diffuse discharge associated with CIDs, such as Yandi CID (Figure 6.4, Figure 6.6)
- persistent pools in the river bed underlined by the coastal alluvial aquifers and described as ‘windows’ to the aquifer, such as in the Coolenar Pool on the De Grey River (Figure 6.4, Figure 6.6)
- localised or diffuse discharge associated with other types of paleochannels (e.g. Ethel Gorge or Palm Springs on Caves Creek) (Figure 6.4, Figure 6.7).

Localised groundwater discharge associated with such groundwater systems can be controlled by catchment-scale groundwater gradients. Depending on the depth to groundwater, discharge can be diffuse: evaporation from pools, representing the watertable (as in coastal alluvial aquifers); and/or evapotranspiration by vegetation (e.g. Ethel Gorge).

These GDEs are spatially smaller than those dependent on regional aquifers, but they can be related to river pools and groundwater-dependent riparian vegetation.

In addition, a mineralised zone within the banded iron ore formations can form localised aquifers. However, these types of groundwater systems, which are particularly important to the mining industry, are not commonly associated with GDEs as the groundwater levels are commonly deep in these formations. Probably the most-known GDEs established in the area of direct groundwater discharge from BIF are the numerous gorges in the Hamersley Range (Hedley, 2009), e.g. Fortescue Falls and Circular Pool (Figure 6.4, Figure 6.8). However, some may argue that Brockman Formation in this area does not form an aquifer, but represents a fractured rock formation with limited groundwater storage.

![Figure 6.4 Locations of maps shown in Figure 6.5 to Figure 6.15](image-url)
Figure 6.5 GDEs associated with regional groundwater systems (aquifers): Weeli Wolli Spring (upper) and Millstream (lower) (box 1 and box 2 in Figure 6.4, respectively)
Figure 6.6 GDEs associated with local groundwater systems (local aquifers): Yandi CID (upper) and De Grey coastal alluvial aquifer (lower) (box 3 and box 4 in Figure 6.4, respectively)
Figure 6.7 GDEs associated with local groundwater systems (paleovalley, local aquifer): Ethel Gorge (Upper Fortescue, upper) and Palm Springs (Upper Ashburton, lower) (box 5 and box 6 in Figure 6.4, respectively)
3) Ecosystems dependent on groundwater which does not form an aquifer

At some locations, groundwater resources are not sufficient to be classified as aquifers but nevertheless are important for environmental water demands. GDEs associated with this group include:

- GDEs dependent on groundwater discharge from fractured rock formations, such as groundwater systems associated with localised fault/dyke zones (Figure 6.9). This GDE type is most clearly identified in the Granite Greenstone Terrane province, but can also be found in other provinces. Streams can be formed along the dykes (as shown in Figure 6.9) or faults, where streamlines are particularly straight and GDEs can be located along the stream channel. Streams can also cross faults zones where discharge from the fractured zone can be localised. GDEs of this type can be associated with terrestrial vegetation and some isolated relatively small pools.

- GDEs associated with shallow alluvial systems (Figure 6.10). These are more-often associated with vegetation with little or no surface expression of water.

- GDEs related to groundwater discharge zones along the bases of hill slopes (break-of-slope), which in the Pilbara are likely to be found along the edges of colluvial deposits formed below hills (seepage zones) and along the edge of the alluvial fans developed by current or ancient rivers. This GDE type is associated with groundwater seepage occurring due to a change in hydraulic conductivity, as colluvial or alluvial deposits are commonly underlain by less-permeable strata (Figure 6.11). These GDE types are associated with terrestrial vegetation while persistent presence of water is not detected.
Figure 6.9 GDEs supported by groundwater stored in fractured zone (dyke) (not aquifer): Sherlock River tributary (box 8 in Figure 6.4)

Figure 6.10 GDEs supported by groundwater stored in modern alluvial systems (not aquifer): Sherlock River (box 9 in Figure 6.4)
6.4 Other important environmental assets

6.4.1 Fortescue Marsh

The largest environmental asset in the region is Fortescue Marsh, listed as a ‘Nationally Important Wetland’ by the Department of Environment and Heritage and as an ‘Indicative Place’ on the Register of National Estate because of its significance as habitat for waterbirds (ENVIRON, 2005).

The Fortescue Marsh is an intermittent wetland developed on the valley floor, and is terminal internal drainage for the Upper Fortescue region. It receives discharge from the Fortescue River catchment from the east, stream discharge from the Chichester Range in the north and Hamersley Range from the south. The cycle of flooding and evaporation, over time, has resulted in the development of hypersaline groundwater beneath the Marsh. The water level below the Marsh is shallow, but can fall to 1.5 m below ground level after a prolonged dry period. Salt-tolerant samphire species dominate the vegetation cover of the Marsh.

Figure 6.12 shows the results of the carried-out analysis, including the extent of riparian vegetation in the proximity to the Marsh (Figure 6.12a) and ‘zoom-in’ views at two locations: the area where Weeli Wooli Creek flows into the Marsh (Figure 6.12b and c) and the eastern part of the Marsh downstream from the Fortescue River discharge area (Figure 6.12 d and e). Based on unpublished information from the Western Australian Department of Parks and Wildlife (DPaW, Stephen Van Leeuwin, pers. comm.), the identified area shown in Figure 6.12 (b and c) is related to an area of *Eucalyptus vitrix* habitat. The relatively low NDVI exceedance values (50% to 60%) for the high NDVI threshold (0.32, red colour in Figure 6.12 b), significant values of NDVI exceedance (70% to 80%) for the intermediate NDVI threshold (0.26) and absence of persistent water occurrence are consistent with the spectral signature detected for such habitats elsewhere. Persistent water occurrence is likely in the other selected location (Figure 6.12 e).
The Marsh boundary is marked by an area with characteristics dissimilar with the other Marsh area: it is persistently green, is identified as a unique land cover class by the Principal Components (PC) Analysis and shows a higher evapotranspiration (ET) values derived from CMRSET (MODIS based, 250 m by 250 m spatial resolution) with a low coefficient of variation of monthly ET (Figure 6.13 c). Combination of these evidences is likely to indicate groundwater discharge zones. This is consistent with a conceptual model of groundwater regime in this area described in Chapter 5, where groundwater flow follows the topographic gradient from the Chichester Range from the north and alluvial fans from the south. Due to high groundwater salinity below the Marsh, this fresh groundwater is likely to discharge along the Marsh boundary.
Figure 6.12 Fortescue Marsh: (a) riparian vegetation in the vicinity of the Marsh and NDVI (b, d) and NDWI (c, e) persistence analysis shown for two locations (indicated by red boxes in a)
Figure 6.13 Fortescue Marsh: (a) Composite of PC1, PC2 and PC3 of NDVI for the observed period, (b) main classes of the land cover; (d) monthly average evapotranspiration (CMRSET, 250 m by 250 m resolution) and (c) coefficient of variability in monthly evapotranspiration (CMRSET, 250 m by 250 m resolution); the area includes 2 km buffer zone around the Marsh.
6.4.2 Wild rivers

The Upper Robe River and Tanberry Creek are listed as Priority 1 wild rivers in the Pilbara. These assets are recognised in the Directory of Important Wetlands in Australia (Environment Australia, 2001). The Upper Robe River is located within the Ashburton region while Tanberry Creek forms a tributary of the Sherlock River in the Lower Fortescue Hedland region (see Figure 6.4).

The outcomes of the carried-out analysis for these rivers’ catchments are shown in Figure 6.14 and Figure 6.15. These include the extent of riparian vegetation (Figure 6.14a and b, and Figure 6.15a and b) as well as the extent of the identified groundwater-dependent vegetation (Figure 6.14c and Figure 6.15c). The figures also show the limited extent of the area with high NDWI persistence (Figure 6.14d and Figure 6.15d).

It appears that the area where there is a high likelihood of the GDE occurrence (red colour in Figure 6.14c and Figure 6.15c and blue colour in Figure 6.14d and Figure 6.15d) is greater along the Upper Robe River than along Tanberry Creek.
Figure 6.14 Upper Robe River: (a and b) riparian vegetation, (c) potential groundwater-dependent vegetation and (d) pools
Figure 6.15 Tanberry Creek: (a and b) riparian vegetation, (c) potential groundwater-dependent vegetation and (d) pools
6.5 Water regime and groundwater-dependent ecosystems

The undertaken analysis indicated that the sensitivity of GDEs to variation in the water balance is largely dependent on GDE typology, discussed above. It was shown that the vegetation which established in areas with substantial groundwater discharge has lower dependency on climate characteristics or river discharge.

6.5.1 Climate

The NDVI time series analysis at the locations where vegetation types have been mapped provided a basis for exploring the relationship between greenness and climate characteristics. It was shown that rainfall has a seasonal effect (>120 days) on vegetation greenness (Figure 6.16). Based on the estimated coefficient of correlation between rainfall and NDVI, the effect of rainfall progressively increases from vegetation with a potentially high level of dependency on groundwater (*M. argentea*) to a lower level of dependency (*E. camaldulensis* and *E. victrix*) to vegetation which is not likely to be dependent on groundwater water (Acacia Closed Scrub and Triodia Hummock Grassland). In other words, lower NDVI sensitivity to variations in rainfall in the areas with established *M. argentea* suggests a higher level of groundwater dependency. Conversely, the high sensitivity of the Acacia/Triodia communities to variations in rainfall is indicative of systems principally rainfall dependent.

Figure 6.16 Coefficient of correlation between selected climate parameters (rainfall, vapour pressure, relative humidity and temperature) and NDVI for selected vegetation type (data labels show the period of climate data aggregation, in days)
Other climate characteristics have a more immediate effect on vegetation greenness (Figure 6.16). *E. victrix* generally shows a slightly closer relationship of NDVI with climatic conditions than *E. camaldulensis*. These species commonly co-occur; however, while *E. camaldulensis* is mostly confined to the larger watercourses *E. victrix* occurs in a broader range of riparian and flood plain habitats. Greater dependency on climate parameters was inferred for Triodia Hummock Grassland, as coefficients of correlation between NDVI and climate parameters for these plant communities are higher than in the case of Acacia Closed Scrub.

### 6.5.2 Groundwater

As discussed in Chapter 4, groundwater-monitoring data in the Assessment area are sparse and are largely associated with aquifers used for water supply (e.g. coastal alluvial aquifers or Millstream) or other groundwater management areas (e.g. in mining precincts). Only the Western Australian Department of Water data related to the former are publically available. However, some groundwater-monitoring data were provided to the project by BHPBIO, partnering in this research. The bore data do not allow for independently defining the land cover type at the location of the bore.

Groundwater-monitoring data were used to explore the relationship between groundwater levels and vegetation greenness (NDVI) in the proximity of monitoring bores. Only RS data representing the end of the dry season (October and November) were used to avoid the effect of seasonal NDVI variability on such relationships. As the dates of RS and groundwater data acquisition did not coincide, groundwater levels were averaged over 30-day intervals centred on the time of Landsat data acquisition, on the assumption that changes in the groundwater levels at a given location within a single month are minimal. The data used for this analysis were associated with the area where historical variability of groundwater level was not affected by stressors other than climate.

Long-term mean NDVI values and mean depth to groundwater for over 150 bores (dark brown symbols) are shown in Figure 6.17 against all available data. The data scatter reflects the variability of groundwater level over time and between the monitoring sites. It also appears that historical variability in groundwater levels at individual sites is limited, particularly where groundwater is relatively deep.

![Figure 6.17 Scatter plot of NDVI and NDWI versus depth to groundwater](image-url)
Figure 6.17 indicates that the depth to groundwater has a particularly significant effect on vegetation greenness where the groundwater depth is less than about 8 to 10 mBGL, and most pronounced where groundwater depth is less than 5 mBGL. When groundwater is deeper, there is no discernible relationship between depth to groundwater and RS indices: the slope of the relationship between NDVI and depth to groundwater is two orders of magnitude less than for the areas with shallow groundwater (−0.0003 versus 0.037).

Low NDVI values (<0.2 overall and <0.15 on average) can be found at locations with all range of groundwater depths, but predominantly where the watertable is deeper. Such NDVI values are not commonly associated with GDE habitats. The effect of the groundwater depth on wetness (NDWI) appears to be marked within the same depth interval.

6.5.3 Surface water

As GDEs in the Assessment area predominantly occur along river channels, the relationship between streamflow and vegetation greenness provides a useful insight into the ecohydrological characteristics of riparian vegetation. Time series of NDVI and NDWI along with river discharge in the proximity of the available gauging stations were analysed for locations where multi-date RS data were available.

Where GDEs are concerned, the direct effect of streamflow on greenness associated with groundwater-dependent vegetation was not identified. Coefficients of correlation between NDVI and streamflow are generally low (R²<0.5) for both considered GDE types: terrestrial vegetation (NDVImean> 0.3) and pools (NDWImean≥0.1) (Figure 6.18).

As shown in the previous chapters, streamflow recharges to underlining alluvial (or other) groundwater systems. In such circumstances a low correlation between identified GDE greenness and streamflow indicates that groundwater resource replenishment is likely to be independent of overall river flow or is a low proportion of the streamflow volumes.

The higher R² values were observed for riparian vegetation which is not likely to be indicative of groundwater dependence (NDVImean< 0.2) for seasonal aggregation of stream discharge data (over 120 or 180 days). This is indicative of occasional inundation and seasonal water inflow to the root zone, which may include flood plains.

The higher R² values are also observed for NDVImean approximately equal to zero. Such a case is likely to represent the areas where water occurs seasonally and where NDVI varied between negative and positive values throughout the time (as the negative NDVI is associated with water presence). These locations commonly occur next to pools and mark the areas of spatial pool variability.

Spatially the effect of the streamflow on GDEs and other riparian vegetation can be illustrated for the Lower De Grey area (Figure 6.19). As the streamflow data was aggregated over a 120 day period for the gauge at Coolenar Pool, these data are likely to be representative of the overall effect of seasonality on terrestrial vegetation. The figure shows that correlation between streamflow and NDVI is not significant for GDEs but is significant for other riparian vegetation along De Grey River and its tributaries.
Figure 6.18 Coefficient of correlation between greenness and river flow which was aggregated over various periods of time (2 days to 360 days) for selected locations in proximity to the gauging station (708003); legend – mean NDVI at each location.
Figure 6.19 Correlation between streamflow (aggregated over a 120 day period) and NDVI in the area of riparian vegetation (d, with the extent of the riparian vegetation shown in b) and identified GDEs (f, with the extent of the GDEs shown in c)
6.6 The water regime alteration and GDEs

Sensitivity of GDEs (or other RS characteristics) to climate variability and groundwater abstraction is dependent on their typology, discussed in Section 6.3. As illustrated in Figure 6.20, sensitivity of GDEs to climate variability is lower when groundwater resources supporting them are large. The sensitivity to streamflow is not significant for all GDEs types which are located within proximity of the stream channels.

Figure 6.20 Sensitivity of various GDE types to climate variability and groundwater abstraction

6.6.1 Changes in climate and associated changes in streamflow

Smaller groundwater systems associated with shallow alluvial deposits are also resilient to changes in rainfall conditions. Even infrequent streamflow events, generated when daily rainfall exceeds certain thresholds (commonly greater than 16 mm, see Chapter 4) are sufficient to replenish their limited groundwater storage and hence sufficient to meet environmental water demands.

During 1987–2011 there was only one period when GDEs associated with local aquifers or non-aquifer groundwater systems showed substantial reduction in NDVI (shown by shaded areas in Figure 6.21 c). During 1990–1992 a reduction in high-intensity rainfall events led to a reduction in overall rainfall (shown by shaded areas in Figure 6.21 c). Total annual rainfall during these years was not the lowest during the observation period, but a sequence of 4 years of low annual rainfall with low rainfall intensity affected vegetation. This effect became evident during the second year of ‘drought’.
Figure 6.21 Cumulative deviation from mean for (a) the number of days with rainfall exceeding the identified thresholds and (b) total annual rainfall associated with the daily rainfall exceeding the identified thresholds; the shaded area indicates the period of particularly low rainfall of high intensity and, as illustrated in (c), particularly low NDVI in GDE types not sourcing water from regional and/or productive aquifers (two lines are related to two selected sites)
6.6.2 Changes in groundwater levels

Changes in the depth to groundwater do not seem to have an immediate impact on GDEs associated with terrestrial vegetation. At the locations where monitoring data were available, the greenness response to groundwater level drawdown is evident after two hydrological cycles.

Examples from the areas close to Newman show that the riparian vegetation of the Upper Fortescue River was impacted by groundwater drawdowns (Figure 6.22 and Figure 6.23). The effect of abstraction on groundwater level is evident from late 2004. Groundwater levels gradually declined from 3 mBGL to 16 mBGL by 2008, but reduction in NDVI was recorded only in 2007. However, changes in the wetness index were recorded sooner in 2006, which is likely to indicate a likely lower rate of evapotranspiration during the period and hence less vegetation access to water sources (Figure 6.22).

A similar response was observed at a number of locations, where there were also 2-year delays in NDVI response to groundwater drawdown. After the second year, NDVI falls outside the historical greenness variability (Figure 6.23).

At the same time the intensity of groundwater drawdown impact on vegetation greenness depends on (1) the initial vegetation greenness and (2) the changes in groundwater levels. Vegetation characterised by higher NDVI (>0.30) (most likely GDEs) appears to have higher sensitivity to changes in groundwater level. At such locations, reduction in greenness occurs even when the watertable does not change substantially (Figure 6.24). Vegetation with NDVI values <0.30 (which could be partly dependent on groundwater) appears to have moderate sensitivity to changes in groundwater level.

When the initial depth to groundwater was relatively shallow, the magnitude of changes in vegetation greenness depends on the magnitude of the changes in groundwater levels. At several locations with relatively shallow groundwater, some greenness recovery was noticed following the initial drop in NDVI values.

In some cases it was observed that greenness in the area affected by groundwater drawdown can somewhat increase over time (Figure 6.23). This may be indicative of a transition from vegetation communities dependent on groundwater to other vegetation communities. As the majority of identified GDEs are associated with river channels, seasonal streamflow can provide conditions for establishment of non-GDE-related riparian vegetation.

It is important to note that all the above discussion is solely based on RS-derived information. It would be most useful to examine on-ground observations to provide more physiological explanation of the reported changes. However, such information was not immediately available to the project.
Figure 6.22 Changes in depth to groundwater (top) and RS indices (bottom): blue line – groundwater abstraction commenced, purple – changes in NDWI; red – changes in NDVI
6.6.3 Increase in groundwater level

Additional recharge associated with mine water discharge or with climate variability can cause groundwater levels to rise and this can also have an impact on some GDEs.

Where mine water discharge is concerned, the Weeli Wolli Creek catchment is one of the most-known examples, where more than more than 50 GL is annually returned to the environment, mostly as direct discharge to creeks. Additional water availability has promoted vegetation establishment and growth (Figure 6.25 b). However, there is concern that it can also cause damage to vegetation dependent on deeper groundwater, such as *Eucalyptus camaldulensis*. This can be illustrated by Figure 6.25 c, where a red gum tree surrounded by newly established vegetation appears to be stressed.

Investigation of such transitions using RS techniques requires more-detailed local knowledge to clarify the use of NDVI as a measure of green biomass sensitive enough to detect such transitions at a Landsat resolution. However, this aspect was not investigated during the project.
6.7 Future projections of groundwater-dependent ecosystem status and condition (climate)

GDE sensitivity to climate variability within the historical range in the region was minimal. When climate change is concerned, in the absence of predictive modelling capability available to the project, only qualitative analysis of climate change on GDEs was carried out.

Projected changes in the Pilbara’s climatic conditions by 2050 are described in Charles et al. (2015) and Chapter 3. The changes in annual rainfall are projected to be from 7.8% (as maximum projected increase in annual rainfall) under Cwet scenarios (2050, RCP8.5) to –17.4% under Cdry scenarios (2050, RCP8.5) (as maximum projected reduction in annual rainfall). The mean annual daily mean temperature changes under the future climate scenarios are 1.2°C for 2030 (as minimum projected changes) and 2.9°C for 2050 (as maximum projected changes). The changes in runoff are projected to increase by +18% under a wet future climate scenario (C50wet8.5) and to reduce by –50% under a dry future climate (C50dry8.5).

The projected changes in rainfall and river flow and inferred changes in localised groundwater recharge appear to be smaller or comparable with their historical variability in this Assessment. Figure 6.26a illustrates that historical rainfall variability on a decadal basis or over greater time intervals (up to 50 years)
is less than the maximum values in projected rainfall changes (indicated by a dash line). Historical variability is expressed here as a difference between the 90th and 10th percentiles of annual mean rainfall estimated by moving average over 10, 20, 30 and 50-year intervals.

However, historical variability of temperature appears to be significantly lower than the predicted changes in temperature under future climate scenarios (Figure 6.26b). Such changes in temperature can lead to an increase in potential evaporation (Charles et al., 2015). Temperature increases and possible heat waves can be particularly damaging for vegetation in hot environments. The effect of such changes on GDEs requires further analysis.

Similarly to rainfall, historical variability of streamflow (also expressed as a difference between the 90th and 10th percentiles of annual river discharge estimated by moving average over 10, 15, 20 and 30-year intervals) is mostly greater than the projected changes in runoff under the future climate scenarios. The only exception is related to the Ashburton catchment (Figure 6.27b).

Figure 6.26 Historical variability in (a) annual rainfall and (b) maximum daily temptation (mean annual Tmax) at three selected climate stations (shown in legend), expressed as a difference between the 90th and 10th percentiles (in %), when annual rainfall and temperature are estimated by moving average over 10, 20, 30 and 50-year intervals

Figure 6.27 Historical variability in annual river discharge at selected gauging stations (shown in legend), expressed as a difference between the 90th and 10th percentiles (in %), when annual river discharge is estimated by moving average over 10, 15, 20 and 30-year intervals: (a) the gauging stations within the catchments where maximum reduction in runoff under future climate scenario is 25%; (b) the gauging stations within the catchments where maximum reduction in runoff under future climate scenario is less than 50 % (see Figure 4.17, Chapter 4)
6.8 Knowledge and information gaps

The assessment provides a basis for identifying actual and potential terrestrial GDEs associated with groundwater-dependent vegetation and surface expression of groundwater. At a limited number of locations the methodology was validated against available field data (less than 1000 locations over 288,479 km²), publications or expert knowledge; in these cases the methodology has shown 100% accuracy in representing local ecohydrological conditions. The developed methods allow identifying the areas with spectral characteristics and their temporal variability similar to those of known GDEs within the Pilbara region. However, the method does not allow the identification of how much groundwater is being used by terrestrial vegetation. Particularly in the case of GDEs dependent on groundwater which does not form an aquifer, additional site-specific hydrogeological and plant water use assessments are required to confirm the nature of any groundwater dependency. Note however, that GDEs of this type are the least likely to be affected by human use of aquifer resources.

Information gaps are mainly associated with the need to deploy the RS methodology at a finer scale to known locations. However, in this Assessment there is limited spatial coverage of climatic, surface water and groundwater data.

Climate data were available only for a few meteorological stations. Considering the high variability in rainfall across the Pilbara, this leads to uncertainty in the analysis of vegetation sensitivity to changes in climate parameters at some locations.

Temporal irregularity of Landsat data also limits the accuracy of statistical analyses. This may be improved by fusion of Landsat (16-days acquisition frequency) and MODIS data (daily acquisition), a process which is known as blending.

There were also discrepancies in georeferences of the ground-truth locations of known GDEs, which prevent the use of supervised classification algorithms to support GDE delineation.

The limited project time frame available for analysis and the project scope prevented greater data exploration, analysis and production of more ancillary products (in addition to fire and grazing maps). The Landsat data cube used for the project has great potential for use in environmental studies due to its containing vast amounts of information about landscape dynamics. As such, the method could be extended to other analyses of the landscape dynamics (vegetation, faults, hydrogeology, change detection, fire scaring, land cover monitoring, including GDEs and more), development of the environmental baseline for future development, and attribution of cumulative impact assessment to stressors.

6.9 References


Equinox Environmental (2013) Summary of groundwater dependent ecological assets in the assessment area of Pilbara Water Resources Assessment. A report to CSIRO.


**Western Australia Department of Water reports**


7 Integration and discussion

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Key points

- The 13 hydrogeological provinces identified in Chapter 2 provide a useful framework for discussing the hydrological and hydrogeological characteristic of the Pilbara, as well as how they may respond to a wetter and drier future climate.
- The provinces summarise surface water data collected on a catchment basis with groundwater information based on aquifers and groundwater dependent ecosystems (GDEs) based on discharge typologies.
- Recharge occurs primarily through stream leakage with only the Canning Basin and to a lesser extent the Paterson provinces having a lot of diffuse (direct rainfall) recharge through their sandy soils.
- The Ashburton province is the largest province in the Pilbara (20.0% by area) but has one of the lowest runoffs and stream leakages to groundwater. Stream leakage reduces by only 6% under a future dry climate, despite a 56% reduction in runoff.
- The Granite Greenstone Terrane province (17.6%) has the highest runoff, streamflow and recharge of all provinces. GDEs appear relatively stable in wet and dry periods and stream leakage reduces by only 7% under a future dry climate, despite a 39% reduction in runoff.
- The Hamersley Range province (15.4%) contains the highest peaks in Western Australia and the widest range in GDE types. Runoff is lower than would be expected because it infiltrates valleys underlain by paleochannels (including channel iron deposits) and dolomite. Of all the provinces, the area of GDE in the Hamersley Range is most sensitive to consecutive dry and wet years.
- The Canning Basin province (11.2%) consists of a flat coastal plain containing sandy dunal soil. Major water resources are associated with the confined Wallal Sandstone which receives diffuse recharge when tropical lows and cyclones cross the Great Sandy Desert. Modelling indicates that changes to potentiometric head in the Wallal Sandstone aquifer may be delayed under a future dry climate. The upper Broome Sandstone is saline.
- The Paterson province (9.0%) in the Little Sandy Desert has had little investigation or stream gauging. Unusually for the Pilbara, the groundwater is mainly brackish to saline and associated with Permian paleochannels and calcrite in low-lying areas.
- The Oakover province (7.6%) around the Oakover River has a relatively high runoff for the Pilbara which is initiated after rain events of about 30mm. A future drier climate would affect both runoff (-41%) and recharge (-24%). The Carawine Dolomite contains an important local groundwater resource.
- The Chichester Range province (6.9%) constitutes an important headwater for the north flowing streams in the Pilbara. The Range contains fractured rock aquifers and productive aquifers associated with mineralised areas in the Marra Mamba Formation. Groundwater becomes more saline with proximity to the Fortescue Marsh.
- The Upper Fortescue province (3.5%) contains fresh groundwater associated with paleochannels in the south and hypersaline groundwater associated with the Fortescue Marsh. A future drier climate is projected to reduce runoff by about 54% and recharge (mainly from streambed leakage) by 43% while the province has a runoff of only 5 mm per year.
• The Carnarvon Basin province (2.5%) contains fresh water in surface alluvial deposits associated with the Fortescue, Robe and Cane rivers but saline water associated with poorly flushed confined aquifers, especially the coastal Birdrong Sandstone. All of these aquifers provide useful groundwater resources, including the Birdrong, from which water is extracted for desalination.

• The Coastal Plain province (1.8%) constitutes low-lying areas that are not in either the Canning or Carnarvon basins. It includes the very important Yule and De Grey alluvial aquifers which supply the East Pilbara Water Supply Scheme. As for the Lower Robe and Lower Fortescue, recharge to these alluvial aquifers is projected to reduce by only 20 to 60% of the reduction in runoff or number of flow days under a future dry climate scenario.

• The Lower Fortescue province (1.7%) comprises the calcrete aquifer around Millstream and the Fortescue River valley to the east and west. The aquifer has a very high transmissivity making it less affected by climate variability and pumping than the Upper Fortescue. Some water is contributed from streams and aquifers in the Hamersley Range which makes this inland area comparatively water rich. Until the Harding Dam and Bungaroo CID water sources were developed Millstream was the main water supply for the West Pilbara Water Supply Scheme.

• The Sylvania Dome province (1.6%) is an inland variant of the Granite Greenstone Terrane province. It has both a low runoff and recharge which could decrease by 56% and 18% respectively under a future dry climate. GDEs associated with sandy alluvium change remain fairly constant through wet and dry periods.

• Finally the East Upper Fortescue province (1.2%) is similar to the Sylvania Dome in climate and landform but the volcanic and sedimentary bedrock weather to form low permeability clay rather than quartz-rich sands and clay. This province has limited mineralisation and is therefore little known. Fractured rock aquifers supply stock water for pastoral stations, as they do in many provinces.

7.1 Introduction

This chapter synthesises findings of surface water, groundwater and GDEs investigations for the 13 hydrogeological provinces defined in Chapter 2. Surface water characteristics are described in Chapter 4 on a sub-catchment basis, groundwater resources are described in Chapter 5 on an aquifer basis and GDEs in Chapter 6, are described on a typology basis. There are associations of differing strengths between these ways of summarising hydrology and the hydrogeological provinces. This chapter draws out these associations so that the water resources of the Pilbara can be understood through the interrelationships of climate, surface water, groundwater and GDEs for a reasonably small number of units – in this case thirteen.

Estimates from modelled sub-catchments were calculated on a hydrogeological province basis. This has the advantage of enabling SIMHYDGW estimates (such as recharge) to be related to underlying aquifers and to changes in area and number of GDE following consecutive wet years and dry years in the historical record.

To integrate the main findings from previous chapters schematic cross-sections across typical valleys in each of the 13 hydrogeological provinces were developed. The cross-sections show hydrogeological relationships which typify the province rather than being based on a specific location in the province. For example, common stratigraphic relationships show how leakage from rivers enters, via river alluvium, underlying formations. This water can then be transmitted to deeper geological units such as paleochannels, dolomite and fractured rock aquifers.

Where useful, sensitivities of modelled responses to future wet and dry climate scenarios are reported as ‘elasticities’, that is the proportional change in one parameter (e.g. runoff) for a given change in another (e.g. rainfall). Relative values and sensitivities may be a better guide than absolute values given the uncertainties in future climate projections and model accuracies.

Often limited data on water balance components is available for a hydrogeological province, and sometimes conclusions are drawn from multiple lines of evidence. Ideally, analyses are undertaken using a
combination of multiple river gauges and adjacent groundwater bore hydrographs. These are considered along with generalised SIMHYDGW model results and satellite remote sensing of discharge areas during dry and wet periods in the historical record to determine relationships. Often, however, key information is absent so results are inferred based on the hydrologic response of similar or nearby areas. Wherever possible the uncertainty in the estimate is indicated.

7.2 Rainfall, runoff and recharge estimates for hydrogeological provinces

There is reasonable coverage of streamflow gauging stations across six of the hydrogeological provinces (Granite Greenstone Terrane, Hamersley Range, Chichester Range, Ashburton, Lower Fortescue and Sylvania Dome), poor coverage across three of the provinces (Upper Fortescue, East Upper Fortescue and Oakover,) little or no coverage across the remaining four provinces (Coastal Plain, Canning Basin, Carnarvon Basin and Paterson) (Figure 7.1).

![Figure 7.1 Location of streamflow gauging stations within the hydrogeological provinces](image)

Low-yielding fractured rock aquifers (including in some cases high-yielding mineralised zones in major iron formations) are found in 11 of the 13 hydrogeological provinces; dolomite and valley fill are located in six provinces and channel iron deposits in five provinces (Table 7.1). The Ashburton, Hamersley Range, Oakover and Upper Fortescue Valley hydrogeological provinces contain four different types of groundwater resources (Table 7.1). The hydrogeological properties of these aquifers, and their relationship with landforms or adjacent strata that may receive water, helps explain the response of the provinces to future wet and dry climate scenarios.
Groundwater systems that support GDEs can be considered of three types – regional (productive) aquifers, local aquifers and ‘other’ groundwater systems (Table 7.2). These types vary greatly in their sensitivity to climate variability and groundwater extraction in close proximity to the GDE. GDEs associated with regional aquifers can be impacted by adjacent pumping but are less affected by climate variability given their large storage relative to the small size of the discharge zone. In contrast, small groundwater systems are greatly affected by seasonal and inter-annual rainfall variability as they have low storages and are not connected to aquifers that would be impacted by pumping. Local aquifers, which can be affected to some degree by both climate variability and pumping, are intermediate in response.

The relationship between the hydrogeological typology of GDEs and hydrogeological provinces (Table 7.2) indicates that GDEs associated with modern valleys are the most common, occurring in 10 of the 13 provinces. GDEs associated with paleovalleys and fractures zones (faults and dykes) occur in at least six provinces. The Hamersley Range province is by far the most diverse in having seven of the nine possible types.

<table>
<thead>
<tr>
<th>HYDROGEOLOGICAL PROVINCE</th>
<th>COASTAL ALLUVIUM</th>
<th>CID</th>
<th>VALLEY-FILL</th>
<th>DOLOMITE</th>
<th>SEDIMENTARY BASINS*</th>
<th>PERMIAN/CENOZOIC PALEOCHANNELS</th>
<th>FRACTURED ROCK**</th>
<th>MIN BIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashburton</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Granite Greenstone Terrane</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hamersley Range</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Canning Basin</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Paterson</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>Oakover</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Chichester Range</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Upper Fortescue Valley</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>Carnarvon Basin</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Coastal Plain</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>Lower Fortescue Valley</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Sylvania Dome</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>East Upper Fortescue</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

* Sedimentary Basins comprise Canning and Carnarvon basins
** A sub-classification of Fractured Rocks has been defined for areas with occurrence of Mineralised BIF

Table 7.1 The distribution of groundwater resources types in hydrogeological provinces
Table 7.2 Hydrogeological typology of GDEs in different hydrogeological provinces

<table>
<thead>
<tr>
<th>GROUNDWATER SYSTEMS SUPPORTING GDES</th>
<th>HYDROGEOLOGICAL PROVINCES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASH</td>
</tr>
<tr>
<td>Regional / productive aquifers</td>
<td></td>
</tr>
<tr>
<td>Sedimentary Basins</td>
<td>✓</td>
</tr>
<tr>
<td>Dolomites</td>
<td>✓</td>
</tr>
<tr>
<td>Paleovalleys</td>
<td>✓</td>
</tr>
<tr>
<td>Local aquifers</td>
<td></td>
</tr>
<tr>
<td>Chemical Iron Deposits</td>
<td>✓</td>
</tr>
<tr>
<td>Coastal alluvial aquifers</td>
<td>-</td>
</tr>
<tr>
<td>Other GW systems</td>
<td></td>
</tr>
<tr>
<td>Banded Iron formations and</td>
<td>✓</td>
</tr>
<tr>
<td>fractured rocks</td>
<td>✓</td>
</tr>
<tr>
<td>Modern Alluvium</td>
<td>✓</td>
</tr>
<tr>
<td>Break of slope</td>
<td>-</td>
</tr>
</tbody>
</table>

ASH = Ashburton; GGT = Granite Greenstone Terrane; HAR = Hamersley Range; CNB = Canning Basin; PAT = Paterson; OAK = Oakover; CHR = Chichester Range; UFV = Upper Fortescue Valley; CRB = Carnarvon Basin; COP = Coastal Plain; LFV = Lower Fortescue Valley; SID = Sylvania Dome; EUF = East Upper Fortescue

Bold names = analysed using multiple remote sensing images and therefore more reliable

7.2.1 Hydrological estimates under a continuation of the Historical climate

Rainfall thresholds to initiate runoff for the nine hydrogeological provinces, for which reliable data were available, ranged between 16 and 30 mm/event (Table 7.3). There is no strong spatial pattern in thresholds except that the catchments with the lowest thresholds are all in the Upper Fortescue region and have low annual rainfalls. The Lower Fortescue Valley is hydrogeologically similar to the Upper Fortescue Valley but has a high 70% higher threshold of 27 mm/event, possibly because of less rock outcrops and deeper soil profiles in the lower valley.

Median annual runoff exceeds 10 mm per year in only four provinces, Granite Greenstone Terrane, Oakover (which has limited data), Chichester Range and Hamersley Range. These are characterised by higher rainfall and either being elevated or receive runoff from elevated areas. This pattern is similar for runoff coefficients although the Hamersley Range has a much lower coefficient (3.1%) than the other three (Table 7.4).

The provinces in Table 7.3 are listed in decreasing order of size. The relevance of size is that streamflow is strongly correlated with catchment or contributing area. The much lower streamflow in the Ashburton province than the Granite Greenstone Terrane province, despite its larger area and similar thresholds to initiate runoff, results from the former’s lower rainfall. Streamflow in the four smallest, mainly inland, provinces is low (< 50 GL/year) because of their small area and low rainfall. Unless topographically favourable dam sites are available in these provinces, yields from surface water storages may be modest due to relatively low and highly variable inflows and high net evaporation (i.e. potential evaporation minus rainfall). An alternative to large surface water dams are dams for which the impounded water is used to recharge underlying aquifers, such as Ophthalmia Dam near Newman.

The specific hydrological responses to a future wet and dry climate between provinces are compared in the next section before Detailed analyses of the hydrological responses of individual provinces are contained in a later section, after their response to a future wet and dry climate has been examined. The SIMHYDGW model estimates both streamflow and recharge (Figure 7.2) which can be expressed on a volumetric basis for each province (Table 7.3). Mean recharge is less than streamflow in all provinces with the ratio of recharge to runoff ranging between about 10 and 30%. It is likely that large, often cyclonic, events result in...
large mean runoff volumes, some of which discharges to the ocean. Mean recharge is not as affected by these large events, being more related to period of flow than volume. The nine provinces shown in the table represent about 77% of the Assessment area and have a combined median annual streamflow of about 3230 GL and a combined median annual recharge of about 600 GL.

Under a continuation of the Historical climate the Granite Greenstone Terrain province has the highest runoff, streamflow and recharge (Table 7.3). This is the second largest province and while its rainfall is moderate (Figure 2.3), the soils are relatively thin and there is a dense stream network The headwaters for many rivers draining the Granite Greenstone Terrane are in the Chichester Range province (Figure 7.1), and as a result the relatively high runoff rates from the Chichester Range province (mean annual value of 17.8 mm) contribute to streamflow in many of the rivers in the Granite Greenstone Terrane province.

Median annual runoff in the Hamersley Range province (12.0 mm) is surprisingly low given the orographic enhancement of rainfall and steep river gradients that occur in parts of this province. Some valleys are underlain by deep paleochannels and dolomite in the Wittenoom Formation which are known to be recharged by runoff and mine dewater discharge in the Hamersley Range. Runoff is also low in the Lower Fortescue Valley (9.8 mm/year) which receives runoff from the Hamersley and Chichester Ranges. This province has karstic limestone and paleochannels both within the province and in up-gradient area. The relatively large number of flow days (median annual value of 85) in the Lower Fortescue Valley is a result of discharge from the Millstream calcrite aquifer. Because the groundwater discharge rates are small, it forms a very small proportion of total streamflow. Median annual runoff in the Ashburton province is low (9.2 mm) yet the median annual flow days is moderate (70). The reason for this is unclear, although it is possible that dolomite aquifers in this Ashburton province and paleovalley and dolomite aquifers in the Hamersley Range contribute baseflow for extended periods following the wet season. Both the Hamersley Range and Chichester Range provinces have a relatively high numbers of flow days (median annual values of 92 and 80 respectively) supporting the hypothesis that there is a slow release of groundwater from fractured rock, paleochannel and/or karstic aquifers to rivers within these provinces.
Detailed analyses of the hydrological responses of individual provinces are contained in a later section, after their response to a future wet and dry climate has been examined.

### Table 7.3 Hydrological responses for nine hydrogeological provinces under the Historical Climate

<table>
<thead>
<tr>
<th>HYDROGEOLOGICAL PROVINCE</th>
<th>RAINFALL THRESHOLD FOR RUNOFF (MM/EVENT)</th>
<th>MEDIAN RUNOFF (MM/Y)</th>
<th>MEDIAN ANNUAL FLOW DAYS</th>
<th>MEDIAN STREAMFLOW (GL/Y)</th>
<th>MEDIAN RECHARGE (GL/Y)</th>
<th>MEDIAN ANNUAL RECHARGE/MEDIAN ANNUAL STREAMFLOW (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashburton</td>
<td>26</td>
<td>9.2</td>
<td>70</td>
<td>534</td>
<td>83</td>
<td>15.6</td>
</tr>
<tr>
<td>Granite Greenstone Terrane</td>
<td>24</td>
<td>23.5</td>
<td>84</td>
<td>1187</td>
<td>173</td>
<td>14.6</td>
</tr>
<tr>
<td>Hamersley Range</td>
<td>23</td>
<td>12.0</td>
<td>92</td>
<td>532</td>
<td>110</td>
<td>20.7</td>
</tr>
<tr>
<td>Oakover#</td>
<td>30</td>
<td>19.0</td>
<td>74</td>
<td>382</td>
<td>45</td>
<td>11.6</td>
</tr>
<tr>
<td>Chichester Range</td>
<td>22</td>
<td>17.9</td>
<td>80</td>
<td>356</td>
<td>65</td>
<td>18.2</td>
</tr>
<tr>
<td>Upper Fortescue Valley#</td>
<td>16</td>
<td>5.4</td>
<td>23</td>
<td>55</td>
<td>14</td>
<td>25.2</td>
</tr>
<tr>
<td>Lower Fortescue Valley</td>
<td>27</td>
<td>9.8</td>
<td>85</td>
<td>49</td>
<td>8</td>
<td>17.0</td>
</tr>
<tr>
<td>Sylvania Dome</td>
<td>20</td>
<td>8.5</td>
<td>32</td>
<td>38</td>
<td>4</td>
<td>10.5</td>
</tr>
<tr>
<td>East Upper Fortescue#</td>
<td>20</td>
<td>8.3</td>
<td>28</td>
<td>28</td>
<td>3</td>
<td>10.7</td>
</tr>
</tbody>
</table>

# Less reliable data

Given the wide range in size of the 9 hydrogeological provinces, runoff and recharge are reported as an equivalent depth, and compared with the province median annual rainfall in Table 7.4.

The Lower Fortescue Valley has the highest median annual rainfall followed by the Granite Greenstone Terrane, the Hamersley Range and the Chichester Range. The Granite Greenstone Terrane has the highest median annual runoff and together with the Chichester Range, they have the highest runoff coefficients and median annual recharge as a proportion of median annual rainfall. Inland, low elevation provinces have low rainfalls and consequently also have low runoffs and recharge values, approximately one third to one half the values of the higher rainfall provinces.

While the median annual runoff ranges between 8 and 24 mm across the Assessment area, the SIMHYDYGW model estimates that median annual recharge ranges between 1 and 3.5 mm. Much of this recharge will occur through streambeds but these values are reported as an average over the whole province. Some recharge will later become runoff through baseflow although this is not a large component in dry catchments. In some but not all provinces the median numbers are less than the mean indicating the importance of high runoff and recharge events. These events are likely to be important for flushing salts from the Assessment area. About 92 to 95% of rainfall is evaporated across the Assessment area (Table 7.4).
Table 7.4 Median rainfall, runoff, runoff ratio, recharge and recharge ratio for nine hydrogeological provinces under the Historical Climate

<table>
<thead>
<tr>
<th>HYDROGEOLOGICAL PROVINCE</th>
<th>MEDIAN RAINFALL (MM/Y)</th>
<th>MEDIAN RUNOFF (MM/Y)</th>
<th>MEDIAN ANNUAL RUNOFF TO MEDIAN ANNUAL RAINFALL (%)</th>
<th>MEDIAN RECHARGE (MM/Y)</th>
<th>MEDIAN ANNUAL RECHARGE TO MEDIAN ANNUAL RAINFALL (%)</th>
<th>EVAPORATION (% OF RAINFALL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashburton</td>
<td>258</td>
<td>9.2</td>
<td>3.4</td>
<td>1.4</td>
<td>0.56</td>
<td>96.0</td>
</tr>
<tr>
<td>Granite Greenstone Terrane</td>
<td>345</td>
<td>24.0</td>
<td>6.8</td>
<td>3.4</td>
<td>0.99</td>
<td>92.2</td>
</tr>
<tr>
<td>Hamersley Range</td>
<td>340</td>
<td>12.0</td>
<td>3.1</td>
<td>2.5</td>
<td>0.73</td>
<td>96.2</td>
</tr>
<tr>
<td>Oakover</td>
<td>315</td>
<td>19.0</td>
<td>4.7</td>
<td>2.1</td>
<td>0.66</td>
<td>94.6</td>
</tr>
<tr>
<td>Chichester Range</td>
<td>321</td>
<td>18.0</td>
<td>5.2</td>
<td>3.3</td>
<td>1.02</td>
<td>93.8</td>
</tr>
<tr>
<td>Upper Fortescue Valley</td>
<td>283</td>
<td>5.4</td>
<td>1.9</td>
<td>1.4</td>
<td>0.49</td>
<td>97.6</td>
</tr>
<tr>
<td>Lower Fortescue Valley</td>
<td>394</td>
<td>9.8</td>
<td>2.7</td>
<td>1.7</td>
<td>0.42</td>
<td>96.9</td>
</tr>
<tr>
<td>Sylvania Dome</td>
<td>270</td>
<td>8.5</td>
<td>3.2</td>
<td>0.9</td>
<td>0.33</td>
<td>96.5</td>
</tr>
<tr>
<td>East Upper Fortescue</td>
<td>256</td>
<td>8.3</td>
<td>2.9</td>
<td>0.9</td>
<td>0.34</td>
<td>96.8</td>
</tr>
</tbody>
</table>

The median rainfalls for each province shown in Table 7.4 do not reflect the 102 year (1911 to 2012) mean rainfall distribution shown in Chapter 2. For example the Granite Greenstone Terrain province has a similar rainfall as the Hamersley Range which has a strong orographic effect in the long record. This difference results from the east Pilbara becoming significantly wetter in the past five decades (the Historical climate period) as shown in Figure 7.3 and for the period between 1990 and 2012 as shown in Figure 7.4.

This could be interpreted as the expansion of the tropical rainfall systems into the east Pilbara, especially given the cold fronts that used to affect the west Pilbara around Onslow have contracted to the south. However this wetting is not reflected in tropical eastern Australia as may be expected if it was a broad-scale phenomenon. The 18 GCMs do not project this wetting pattern to continuing until 2050 as has been discussed in Chapter 3 and the climate report (Charles et al. 2015). In this assessment we present data for wet, median and dry scenarios to overcome this lack of clarity. The wetting since about 1960 has raised the rainfall in all hydrogeological provinces compared with their long term average with those in the east the most affected to date.

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2 There are slight differences between Table 7.4 (median data from modelled catchments) and Figure 7.4 (mean rainfall data for the entire province) but they don’t change the overall relativities
Figure 7.3 Mean annual rainfall for the Historical (baseline) period between 1961 and 2012

Figure 7.4 Mean annual rainfall for the period between 1990 and 2012 showing wetting developing from the east
7.2.2 Hydrological estimates under future wet and dry climates

Runoff thresholds in each hydrogeological province under wet and dry climate scenarios were very similar to the Historical climate. This is to be expected if runoff is initiated by rainfall excess and there little residual soil water left between events. The characteristics of the soil and catchment define the runoff thresholds and these do not change under a future wetter or drier climate.

Two future climate projections are shown in all future climate figures – the lowest change expected (2030 and a 4.5 W/m² Representative Concentration Pathway, RCP) since it is sooner and has the lowest emission; and the highest change expected (2050 and an 8.5 W/m² RCP). All other projections are within this range.

The rainfall–runoff coefficient is projected to increase by between 1 and 10% under a C30wet4.5 climate scenario compared to the Historical climate, and to decrease by more than 50% in all provinces under a C50dry8.5 scenario (Figure 7.5). The names of the nine hydrogeological provinces for which data are available are shown in Figure 7.1. Significant reductions (10 to 25%) in the runoff coefficient may eventuate by 2030 under a dry future climate. Small reductions in runoff may also occur in inland provinces under a median future climate (C30mid4.5). The runoff coefficient in these areas is very low so even a small absolute change can result in a large proportional change.
Mean annual runoff as a function of mean annual rainfall under seven climate scenarios for the six provinces with the most reliable data are shown in Figure 7.6. The Ashburton province has a markedly lower rainfall than the other provinces. Two distinct groups of hydrogeological provinces are seen in terms of their runoff response; with the Granite Greenstone Terrane and Chichester Range having about 20 mm of runoff than the other three which receive more than 300mm of rainfall. The Lower Fortescue Valley appears anomalous in terms of its rainfall-runoff relationship because of its low runoff for its high
rainfall. In terms of its physical characteristics the Lower Fortescue Valley is unusual in that it has a simple drainage system and the Lower Fortescue River receives groundwater discharge from the highly transmissive Millstream calcrete aquifer, which results in this river having the highest number of flow days across the Assessment area (Table 7.3). In the Hamersley Range province stream leakage results in recharge into underlying paleovalleys and dolomite which may reduce its rainfall-runoff ratio. By contrast the Chichester Range and Granite Greenstone Terrane lack dolomite and paleochannel aquifers and a larger proportion of rainfall becomes runoff.

![Figure 7.6 Mean annual runoff (mm) as a function of projected mean annual rainfall (mm) scenarios for six Hydrogeological provinces](image)

Runoff under wet 2030 climate scenario (Cwet 2030 RCP4.5, Figure 7.7) is less than 10% lower than runoff under the Historical climate but is between 10% and 25% lower under a dry future climate and moderate RCP of 4.5 W/m² (i.e. Cdry 2030 RCP4.5). For median climate scenario the change is mostly less than ±10%.

Runoff under wet 2050 climate scenario (Cwet 2050 RCP8.5, Figure 7.7) is between 25 and 50% higher than under the Historical climate but a more than 25% decrease for all provinces under a dry scenario (Cdry 2050 RCP8.5) with provinces in the southern part of the Assessment area all projected to have a more than 50% decrease in runoff (Figure 7.7).

Province data for 2050 runoff under both a wet (Cwet8.5) and dry (Cd8.5) future climate and the higher RCP (8.5 W/m²) are shown in Table 7.5 to show the full range of possible future runoff changes in percentage terms. Inland provinces are projected to produce very little runoff which may impact adversely on GDEs, especially river pools. The dry projections range from about a 40% reduction in the Granite Greenstone Terrain, Chichester Range and Oakover provinces to more than 50% reductions in inland provinces (East Upper Fortescue, Ashburton, Sylvania Dome, Upper Fortescue Valley and Hamersley Range). These provinces have lower median runoff so a high percentage change can reflect the low denominator. However such reductions could adversely affect GDEs in these provinces. The Lower Fortescue Valley is the most resilient to both wet and dry scenarios because of its buffering with its aquifer system.
Figure 7.7 Percentage change in runoff across Assessment area under six future climate scenarios relative to the baseline (Historical climate)
Table 7.5 Changes in median annual runoff and median annual recharge under a future wet (C50wet8.5) and future dry (C50dry8.5) climate for nine hydrogeological provinces

<table>
<thead>
<tr>
<th>HYDROLOGICAL PROVINCE</th>
<th>CHANGE IN MEDIAN RUNOFF UNDER A WET FUTURE CLIMATE (%)</th>
<th>CHANGE IN MEDIAN RUNOFF UNDER A DRY FUTURE CLIMATE (%)</th>
<th>CHANGE IN RECHARGE UNDER A WET FUTURE CLIMATE (%)</th>
<th>CHANGE IN RECHARGE UNDER A DRY FUTURE CLIMATE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ashburton</td>
<td>11.4</td>
<td>-56.1</td>
<td>0.95</td>
<td>-5.6</td>
</tr>
<tr>
<td>Granite Greenstone Terrane</td>
<td>20.2</td>
<td>-39.2</td>
<td>1.0</td>
<td>-6.6</td>
</tr>
<tr>
<td>Hamersley Range</td>
<td>13.8</td>
<td>-52.9</td>
<td>7.0</td>
<td>-22.9</td>
</tr>
<tr>
<td>Oakover†</td>
<td>21.9</td>
<td>-40.7</td>
<td>2.9</td>
<td>-23.6</td>
</tr>
<tr>
<td>Chichester Range</td>
<td>16.5</td>
<td>-38.6</td>
<td>2.0</td>
<td>-9.7</td>
</tr>
<tr>
<td>Upper Fortescue Valley†</td>
<td>15.0</td>
<td>-53.6</td>
<td>10.3</td>
<td>-43.2</td>
</tr>
<tr>
<td>Lower Fortescue Valley</td>
<td>9.4</td>
<td>-32.8</td>
<td>4.8</td>
<td>-21.3</td>
</tr>
<tr>
<td>Sylvania Dome</td>
<td>14.9</td>
<td>-55.8</td>
<td>0.3</td>
<td>-16.5</td>
</tr>
<tr>
<td>East Upper Fortescue†</td>
<td>17.3</td>
<td>-57.2</td>
<td>0.6</td>
<td>-17.9</td>
</tr>
</tbody>
</table>

† Less reliable data

Estimates of recharge from streambeds and diffuse recharge in inter-stream areas under future climate scenarios are important given this is the main mechanism whereby aquifers are recharged in the Pilbara and groundwater is the main water resource (Figure 7.8). The estimates come from the SIMHYDGW model and have not been checked against recharge, which is not available over regional areas, and, therefore, may not be accurate. However, they are the best that we have over nine of the thirteen provinces and their relative values may be more accurate than their absolute values given they are based on data recorded at 26 gauging stations over a long period. While not perfect, the SIMHYDGW model was the best of six that were evaluated for reproducing runoff in the Pilbara.

Over 3 mm of recharge (averaged of over the entire province) occurs in the Granite Greenstone Terrane and Chichester Range provinces and over 2mm in the Hamersley Range and Oakover provinces (Figure 7.8). The inland, low rainfall provinces of Ashburton, Sylvania Dome and East Upper Fortescue have very low leakages.

Under a high emission scenario (RCP 8.5) the Upper Fortescue valley has both the greatest percentage increase of recharge under a future wet climate (+10%) and decrease under a dry climate (-45%) by 2050. Care must be taken because the median leakages in some provinces are low (especially the East Upper Fortescue and Sylvania Dome - Table 7.4). Recharge in the Lower Fortescue Valley is low and is insensitive to wet future climate, perhaps due to the buffering effect of the Millstream Calcrete as mentioned previously. Recharge in the Ashburton, East Upper Fortescue and Sylvania Dome provinces also appear relatively insensitive to changes in wet future climate. This may reflect the small capacity of their alluvial aquifers and their ability to be filled even if rainfall falls. Remote sensing shows a relative low sensitivity of GDEs to rainfall changes in all of these four provinces. The Hamersley Range province has the second highest responses to recharge in both the wet and dry scenarios. This correlates with the large variability in GDE areas (up to six fold) as recorded using the Normalised Difference Vegetation Index for satellite remote sensing images since 1988 in this province.
Figure 7.8 Percentage change in mean annual recharge across the Assessment area under six future climate scenarios relative to the baseline (Historical climate)
7.3 Hydrogeological province synthesis

The previous section examined the hydrogeological provinces in relation to others in the Assessment area; this section looks at them individually. A synthesis of findings for each province is related to a schematic cross-section that shows typical, but by no means all, possible relations between topography and underlying geological formations. In many cases these are across or along valleys given the importance of streamflow to recharge and groundwater being the most important water resource in the Assessment area. Most GDEs are also associated with modern valleys. The type of aquifer and aquitards in the cross-sections is shown to make them hydrogeological rather than geological in nature. The analyses are part-conceptual model and part-water balance under both the Historical (1961 to 2012) and under projected climates for 2030 and 2050.

7.3.1 Ashburton Hydrogeological Province

The Ashburton province occupies a fifth of the Assessment area but has disproportionately limited groundwater and surface water resources. The Ashburton River has a low runoff (9.2 mm/year) and a high rainfall threshold required to initiate runoff (26 mm/event). Its large size ensures a moderate streamflow of 534 GL/year which takes place over 70 days per annum on average.

The only known high-yielding aquifers in the province are associated with thin alluvial aquifers around current streambeds (Figure 7.9). Most rocks are clayey sediments and volcanics which weather to form clays. Recharge estimated by the SIMHYDGW model is therefore correspondingly low (83 GL/year). GDEs are associated with the thin modern alluvium around creek beds. They don’t require much rain to fill and therefore change little between years.

Groundwater may also be found associated with the Duck Creek and Wooly Dolomite formations, and the Beazley River Quartzite. These have been little investigated so their yields are poorly known.

The low runoff can be attributed to the relatively low rainfall and flat nature of much of the province. However, the province lies down slope from the Hamersley Range which has a high rainfall and elevation which is expected to generate substantial runoff entering the Ashburton River and its tributaries. Water from the Hamersley Range may be slowly seeping out through paleovalleys and dolomite aquifers resulting in 70 flow days per annum but relatively low volumes associated with groundwater discharge. Texture contrast sand-over-clay (or duplex) soils support mulga vegetation and stock grazing.

Under a future dry climate scenario (C50dry8.5) runoff is expected to reduce by about 56% but recharge may reduce by only 6%. A future dry climate, therefore, may have much less effect on recharge than on streamflow, and hence groundwater discharge to support GDEs may not be as affected. Under a wet future climate (C50wet8.5) runoff may increase by about 11% but recharge may increase by only 1%. Limited analyses of satellite images from about 1988 has shown GDEs to seem to be relatively insensitive to changes in historical rainfall so this relationship may have a long precedent. The images also show areas of high greenness (Normalised Difference Vegetation Index) on the southern flanks of the Hamersley Range which may indicate seepage from aquifers and fractured rocks adding water to the Ashburton province.
This province occupies about a sixth of the Assessment area and is characterised by flat granite batholiths associated with sandy soils interspersed with ridges of older greenstone containing mineralisation (gold, copper, etc.). The province is crossed by cyclones and has a higher rainfall zone between about 80 and 120 km from the coast associated with summer evening thunderstorms.

The province is crossed by moderate length streams (Hedland Coast basin) that originate in the Chichester Range and discharge to the Coastal Plain province. It has the highest runoff (23.5 mm/year) and runoff ratio (0.068) and a moderate rainfall threshold before runoff is initiated (24 mm/event). Recharge (173 GL/year) is the highest of all provinces, partly because it is the second largest province and it is located in a higher rainfall zone.

There are no highly productive aquifers in this province although fractured rock aquifers are associated with the greenstones and occasional quartz veins (Figure 7.10). Modern sandy alluvium associated with the numerous streamlines and fractures and dykes support GDEs. Remote sensing analyses show that these GDEs have been stable to climate variability in the past.

Under a future dry climate (C50dry8.5) runoff may decrease by about 39% but recharge may reduce by only 7%. Under a future wet climate (C50wet8.5) runoff may increase by about 20% but recharge to groundwater may increase by only 1%. These results indicate that recharge to the shallow alluvial areas may decrease under a wet future as the aquifers may fill and reject further recharge.
This province contains the three highest peaks in Western Australia (Mounts Meharry, Bruce and Nameless) and occupies about a seventh of the Assessment area. The high ranges result in a relatively high rainfall, low potential evaporation and low rainfall deficit. The range is underlain by the Archean and Proterozoic Hamersley Basin including some of the richest iron deposits in the world. These deposits constitute important local aquifers in the form of mineralised zones in fractured rock and channel iron deposits in paleochannels (Figure 7.11 and Figure 7.12). Broad depositional valleys are often underlain by dolomite of the Wittenoom Formation which can be karstic and have the ability to store large volumes of runoff and mine dewater. The province has the highest number of days with streamflow (92 per annum).

Despite the higher rainfall and high peaks the province only produces about 12 mm of runoff per annum. Recharge has been modelled to be about 110 GL/year, the second highest province. It also has a high density of streamlines which may help account for the relatively high recharge rate. It is possible that the streams that have been gauged miss some of the runoff from this province, and water leaves as groundwater seepage and fracture (gorge) flow which may account for long streamflows in the Ashburton province to the south and the maintenance of groundwater levels in the Upper and Lower Fortescue Valley provinces to the north.

The Hamersley Range province has the most diverse range of GDEs in the Assessment area. They are also the most affected by climate variability. Under a future dry climate (C50dry8.5) runoff in the province may decrease by about 53% and recharge by about 23%. Under a future wet climate (C50wet8.5) runoff may increase by about 14% and recharge by about 7%. These elasticities result in recharge responding much more similarly to rainfall which often has a 1:3 relationship with runoff (i.e. runoff decreases or increase by 3% for every 1% change in rainfall).

In broad depositional valleys, groundwater is located in the modern sediments as well as channel iron deposits (pisolite) and cavernous parts of dolomite of the Wittenoom Formation (Figure 7.11). In erosional valleys the channel iron deposits in the paleochannel may be close to the valley surface (Figure 7.12). Once mined the hydrogeological nature of the depositional/erosional valleys will have changed.
Figure 7.11 Schematic cross-section across a depositional valley in the Hamersley Range Hydrogeological Province

Figure 7.12 Longitudinal section along an erosional valley in the Hamersley Range Hydrogeological Province
### 7.3.4 Canning Basin Hydrogeological Province

This province contains one of the most prospective groundwater resources in the Assessment area, fresh water contained in the Wallal Formation and brackish to saline water in the Broome Sandstone separated by the low permeability Jarlemai Siltstone (Figure 7.13). Recharge is believed to be via rain falling on inland areas where the aquifers outcrop rather than from streambeds as for most other aquifers in the Pilbara (apart from fractured rock aquifers which usually have a low productivity). The landform is flat and sandy with paleodrainages, and occasional brackish to saline lakes in the Great Sandy Desert.

This area was modelled under a continuation of the Historical climate as well as under future wet and dry climate scenarios. There is little impact on net recharge under a wet future climate (C50wet8.5) but a dry climate (C50dry8.5) could reduce net storage by about 17 GL/year. Given recharge is mainly as a result of intense cyclones crossing the Great Sandy Desert and CGMs are not accurate predictors of cyclones the estimates are necessarily approximate.

More northerly Canning Basin areas have a more complex hydrogeology with areas of fresh and saline groundwater associated with Cretaceous and Jurassic sediments (Figure 7.14). This area has been less investigated so groundwater resources have not been fully evaluated. Inland area includes watering points in the Canning Stock Route bordering the Assessment area.

![Figure 7.13 Schematic cross-section in the Canning Basin Hydrogeological Province](image-url)
7.3.5 Paterson Hydrogeological Province

This inland province (9% of the Assessment area) is characterised by a low rainfall and high potential evaporation, sand and rocky areas with limited groundwater resources associated with calcrete and Permian paleochannels (Figure 7.15). Most investigations have been carried out associated with the Telfer (gold) and Nifty (copper) mines.

The province coincides with the Little Sandy Desert and is little utilised or explored. There are few defined drainages and no gauging stations so estimates of the impact of future dry and wet climates could not be assessed.

The Permian glacial deposits and paleovalleys constitute a groundwater resource in the Pilbara that could be assessed were there demand for water in this area. Excess water from Telfer and Nifty mines is disposed to the environment.

GDEs are associated with groundwater-fed lakes which are especially associated with Rudall River in the Karlamilyi National Park.
This province (9% of the Assessment area) contains the catchment for the Oakover River, the main tributary of the De Grey River. It has alluvial aquifers, little-explored paleochannels associated with Permian glacial sediments and groundwater associated with the Carawine Dolomite (Figure 7.16). Dewatering of fresh groundwater from the Woodie Woodie manganese mine has been targeted for agricultural development in recent years. This originates in the Carawine Dolomite but is recharged partly through overlying sediments.

Some stream gauging in the province lacks a rating curve so estimates of hydrology is imprecise. Median runoff (19 mm/year) may be the second highest (behind the Granite Greenstone Terrane) and the rainfall threshold to initiate runoff (30 mm/event) is the highest. Recharge is estimated to be 45 GL/year. Under a future dry climate (C50dry8.5) streamflow may reduce by about 41% and recharge by about 24%. Under a wet future climate (C50wet8.5) streamflow may increase by about 22% and recharge by 3%.

GDEs include permanent river pools (including Carawine Gorge) and vegetation accessing groundwater. Remote sensing indicates that these GDEs have been able to withstand dry periods since 1988.
7.3.7 Chichester Range Hydrogeological Province

The Chichester Range is not very high but it is the most important watershed in the Assessment area with all north flowing rivers being initiated from its northern slopes and its southern flanks contributing runoff and groundwater to the Upper and Lower Fortescue Valleys (right hand part of Figure 7.1). It is underlain mainly by the Fortescue Group of Precambrian sediments in the Hamersley Basin and the Marra Mamba Formation that is important in a number of iron ore mines in the province (especially Cloudbreak, Christmas Creek and Roy Hill).

The province only occupies 7% of the Assessment area. It has the third highest median annual runoff (18 mm/year) and a moderate rainfall threshold to initiate runoff (22 mm/event). Some runoff occurs over about 80 days per annum, very similar to the Hamersley Range (92 days). The province is underlain by fractured rock aquifers with most productive areas being associated with mineralised zones in the Marra Mamba Formation. Groundwater becomes increasingly more saline with proximity to the Fortescue Marsh and to the east along the range. GDEs are limited in this province and mainly associated with fracture zones in the basement rocks.

Recharge is estimated to be the fourth highest of all provinces (160 ML/km stream/year) but it is proportionally estimated from stream gauges which are outside the province so may not be reliable. Under a future dry climate (C50dry8.5) runoff may decrease by 39% but recharge may only reduce by 10%. Given the rocky and clayey nature of soils, and the moderate slope of streams in this province, recharge would not be expected to be high. Under a wet future climate (C50wet8.5) runoff is projected to increase by about 17% and recharge by about 2%. There is therefore an asymmetry between the wet and dry responses which results from the drier scenarios being more extreme than the wetter scenarios (further from the historical mean rainfall). Recharge is also much less sensitive to changes in both rainfall and runoff as is the case across the Assessment area.
7.3.8 Upper Fortescue Valley hydrogeological province

This province only occupies 3.5% of the Assessment area and lies between the Hamersley and Chichester Ranges (central part of Figure 7.17). It is characterised by a very low runoff (5 mm/year) despite having a low rainfall threshold to initiate runoff (16 mm/event). Rainfalls are low and the province is the flattest in the Pilbara which contributes to this paradox. The province contains the ecologically important Fortescue Marsh which has hypersaline groundwater in its centre and less saline groundwater in its fringes where it receives seepage from the Hamersley and Chichester Ranges, groundwater from at least one paleochannel to the south and fresh runoff after intense rainfall events.

The valley is underlain by relatively shallow alluvium, calcrite and pisolite with Wittenoom Formation at depth, which includes cavities in the karstic dolomite. Runoff and mine discharge from the Hamersley Range infiltrates alluvial fans at the break of slope with this province, possibly discharging groundwater to the Wittenoom Formation. It is unclear how much additional water this formation can absorb.

Median recharge (14 GL/year) is about a quarter of median streamflow (55 GL/year), the highest ratio of all provinces. This may reflect the very low gradient of the province and the loss of streamflow into alluvial sediments and underlying paleochannels.

GDEs are very varied in this province, ranging from those associated with fresh groundwater discharge in the south associated with paleochannels and basement highs, to vegetation able to withstand hypersaline groundwater in the Marsh. While the Marsh has a history of being inundated with fresh runoff, the overall extent of GDEs seems to be relatively unaffected by dry and wet periods in the Historical record.

Under a future dry climate (C50dry8.5) runoff may decrease by about 54% and recharge by about 43%. This may reflect the very low gradient in this province with runoff ponding for long periods. Under a wet future climate (C50wet8.5) runoff may increase by about 15% and recharge by about 10%. These elasticities are less than in most provinces where leakages to groundwater may change by only about a third of runoff.
7.3.9 Carnarvon Basin Hydrogeological Province

The Carnarvon Basin encroaches on the northwestern part of the Assessment area and is overlain by a flat coastal plain. This province only occupies about 2.5% of the Assessment area. Alluvial deposits associated with the Fortescue (Figure 7.18), Robe (Figure 7.19) and Cane Rivers (Figure 7.20) contain locally important water supplies for nearly towns (e.g., Onslow) or mines.

These relatively low storage thin aquifers are recharged directly during episodic streamflow. Stream losses occur in all events but decrease with length of flow as the alluvial aquifers are progressively recharged. Groundwater modelling of the Lower Fortescue aquifer showed that recharge increased or reduced by only 20 to 35% of a 100% change in either runoff or flow days. Similar elasticities for the Lower Yule were 40 to 70% and Lower Robe; 25 to 60%. In all cases the decreases in recharge under a future dry climate scenario was less than the increase under a future wet climate, and in general the changes were more sensitive to changes in runoff than in flow days. This indicates that these aquifers may be relatively resilient to future climate in that major changes in runoff or flow days would be required to appreciably affect groundwater storages. How this affects divertible yields depends on the risk to GDEs posed by extraction so these numbers indicate sensitivities more than potential future yields.

This part of the Assessment area used to receive relatively reliable autumn and early winter rainfall associated with cold fronts, resulting in a bimodal distribution of rainfall and resultant runoff. In recent decades these fronts have not penetrated as far north and the province has had a fall in rainfall while most others (especially those in the east) received an increase because of increased summer rainfall.

Confined saline groundwater in the Cretaceous Birdrong Sandstone is being targeted for desalination to augment water from the Cane alluvial aquifer to supply Onslow town and the Wheatstone industrial area immediately to the south.

There are no gauging stations in this province so its hydrological response to future wet and dry climate scenarios cannot be determined.

Important GDEs are associated with all coastal rivers. The reduction in autumn and early winter rainfall in recent decades may have impacted on seasonal conditions but the gradual increase in summer rainfall appears to have reached this area in recent decades (Chapter 3).

Figure 7.18 Schematic cross-section in the Carnarvon Basin Hydrogeological Province near the Fortescue River
Coastal Plain hydrogeological province

Like the Carnarvon Basin province, this flat coastal province lacks gauging stations from which hydrological responses to a future wet or dry climate scenario can be assessed. It contains very important groundwater resources for the East Pilbara Water Supply Scheme, notably the Yule (Figure 7.21) and De Grey (Figure 7.22) alluvial aquifers. The latter is mainly associated with a deep paleochannel that is offset from the modern river channel (Figure 7.22).

GDEs include river pools and vegetation dependent on shallow groundwater discharge. These areas did not change much during historical dry or wet periods indicating that they are relatively insensitive to changes in runoff through two years at least.

Groundwater modelling of the Lower Yule shows similar low sensitivities (40 to 70%) of recharge to changes in runoff and flow days as in the Lower Fortescue, Robe and Cane rivers. For the Lower De Grey River sensitivity of recharge to runoff is less substantial compared to sensitivity to flow days. The number of flow days in the De Grey River is large compared to other three coastal alluvial aquifers which were modelled. The substantial proportional change in flow days under future climate scenarios results in this larger sensitivity, which is defined as the ratio of recharge change to flow days change.
Figure 7.21 Schematic cross-section across the Coastal Plain Hydrogeological Province near the Yule River

Figure 7.22 Schematic cross-section across the Coastal Plain Hydrogeological Province near the De Grey River
7.3.11 Lower Fortescue Valley Hydrogeological Province

This province has several unusual features; 1) a highly transmissive calcrete aquifer located between the Hamersley and Chichester Ranges, 2) no runoff enters from the Upper Fortescue Valley, and 3) a relatively small area located around a major river resulting in atypical hydrological values compared with larger provinces.

It has a low runoff (10 mm/year), high rainfall threshold before runoff is initiated (27 mm/event), the second highest number of flow days (85/year) and a very low recharge (8 GL/year). Recharge to the calcrete aquifer is from river runoff and seepage from channel iron deposits and alluvium in the Hamersley Range especially (Figure 7.23). Groundwater modelling shows that groundwater levels are remarkably constant despite historical variability in both rainfall and extraction. Recharge is low because the aquifer is often full, and this also results in constant but surprisingly low volumes of streamflow.

Under a future dry climate scenario (C50dry8.5) runoff may reduce by about 33% but recharge may reduce by only 21%. Under a wet future climate (C50wet.8.5) runoff may increase by about 9% and recharge by 5%. Groundwater modelling indicates that both high extraction rates and dry climate scenarios need to occur to have a substantial impact on groundwater levels over large parts of the highly transmissive aquifer. This is fortunate because the valley supports very important GDEs. Remote sensing of GDEs shows them to be very stable over the Historical period.

Figure 7.23 Schematic cross-section across the Lower Fortescue Valley Hydrogeological province

![Figure 7.23 Schematic cross-section across the Lower Fortescue Valley Hydrogeological province](image)
7.3.12 Sylvania Dome Hydrogeological Province

This province (only 1.6% of the Assessment area) is characterised by granitic intrusions and thin sandy soils, thin alluvial deposit associated with streams and occasional deep paleochannels which may not coincide with modern drainages (Figure 7.24). Being in a low rainfall inland location, runoff is low (8.5 mm/year) and rainfall thresholds to initiate runoff are low to moderate (20 mm/event). Median recharge is only 3 GL/year compared with a streamflow of 28 GL/year.

GDEs are associated mainly with the modern drainage lines and have been relatively stable over the Historical period despite them only being dependent on local aquifers. This may result from relatively little rainfall and runoff being required to substantially recharge these aquifers and for the vegetation to be adapted to these conditions.

Under a future dry climate (C50dry8.5) runoff may reduce by about 56% and recharge by 17%. Under a future wet climate (C50wet8.5) runoff may increase by 15% and recharge is estimated to remain substantially unchanged.

![Figure 7.24 Schematic cross-section across the Sylvania Dome Hydrogeological Province](image)

7.3.13 East Upper Fortescue Hydrogeological Province

The smallest province (only 1.2% of the Assessment area) is located in one of the driest and least investigated parts of the Pilbara. It is underlain by un-mineralised basement rocks which predominantly weather to form clayey soils and very thin aquifers. Some groundwater may be found in fractures in the Robertson Range (Figure 7.25). Low-yielding stock water is sourced in fractures in the basement rocks.

Stream gauging indicates that runoff in this province is the lowest of all provinces at about 8.3 mm/year and about 20 mm of rainfall is required to initiate runoff. Recharge in this poorly drained province is estimated to be only 3 GL/year compared with about 28 GL/year of streamflow, similar numbers as Sylvania Dome.

Under a future dry climate (C50dry8.5) runoff may decrease by about 57% (the most of all provinces) and recharge by about 18%. Under a wet future climate (C50wet8.5) streamflow may increase by 17% and recharge remain substantially unchanged.

GDEs are not very common in this province, but those associated with modern drainage lines have not change much in the Historical climate period as assessed using satellite remote sensing.
7.4 Discussion

The thirteen hydrogeological provinces introduced in Chapter 2 have been used as a basis to integrate the surface water modelling results (Chapter 4), groundwater assessment and modelling (Chapter 5) and the GDE remote sensing analyses (Chapter 6). In most cases the resulting conceptual models and water balance components under the Historical and future climate scenarios support inferences drawn from limited monitoring data over many parts of the Assessment area.

The Assessment area is characterised by extremes – the highest elevations in Western Australia; the highest temperatures in the state if not the country; intense cyclonic rainfalls, tropical lows and thunderstorms; and episodic runoff that is initiated by rainfall excess because soils have usually dried between events.

Groundwater constitutes the main water resources and in all except the sedimentary basins and fractured rock areas, recharge to aquifers is via streambed recharge through alluvial material to underlying paleochannels or regional aquifers, often karstic dolomite. The streamlines also contain most of the important GDEs associated with groundwater storage and discharge.

The region is one of the most important iron ore provinces in the world and most mineralised areas are also aquifers because the leaching of silica has formed very permeable and porous channel iron deposits and enriched zones in banded iron formations. There are two surface water resources – Harding Dam used to supply water to the West Pilbara Water Supply Scheme and Ophthalmia Dam which is used to recharge a paleochannel for local water supplies and maintenance of GDEs.

Runoff changes proportionally by a factor of about three compared with rainfall changes while recharge (especially from streambeds) usually changes proportionally less. The SIMHYDGW model used across the Assessment area estimates that recharge may reduce by only 0.2 to 0.4 of a unit change in rainfall which may be because leakage into coarse and usually dry alluvium is rapid in well-defined channels in upland catchments. Recharge in coastal alluvial aquifers is much more sensitive (only 0.4 of runoff or flow days), possibly because the alluvium in these downstream areas is finer and the aquifers may already be full, at least around the river bed. Some of the difference in sensitivities may result from the method used to assess them – SIMHYDGW for non-coastal catchments and coupled surface water and groundwater models on the coastal plain. Coastal alluvial aquifers are especially important as drinking water sources for towns and ports.

Future climates are likely to be hotter but rainfall estimates are not as clear, especially related to the future frequency and intensity of cyclones. Dry scenarios, were they to eventuate, project much less runoff and
recharge which would affect available water supplies and dependent GDEs. Remote sensing has shown that GDEs can contract two to six times in area during dry periods, but recover provided there are later wet periods. There were no clear examples of complete loss or the formation of new GDEs in those images that were examined during the 1990 to 2012 period. There may be new GDEs which have formed in the Great Sandy Desert as a result of the wetter period but these images were not as closely examined as those in the Central Pilbara.

The Hamersley Range has both the most varied types and inter-annual variable of all GDEs. Those groundwater discharges that are fed by large groundwater systems are the most stable to seasonal conditions but are can be the ones most affected by groundwater extraction to access iron ore deposits in channel iron deposits. Compared with other hydrogeological provinces the Hamersley Range also has a high elevation, high rainfall, low potential evaporation, high recharge and therefore a relatively low runoff.

The Granite Greenstone Terrane is another hydrologically interesting province in that it has the highest runoff–rainfall ratio, runoff, streamflow and recharge of all the provinces. It receives runoff from the hydrologically-important Chichester Range and is crossed by cyclones, tropical lows and thunderstorms that can bring intense rainfall. It lacks any significant aquifers for storing water but has sandy alluvial aquifers and greenstones able to store water and sustain GDEs.

The Ashburton province has some unique features, having the lowest median rainfall and a relatively low runoff but the second largest number of days of streamflow, indicating that most flow is low. The Lower Fortescue has the highest number of days of flow but low leakages to groundwater because the calcrete aquifer is usually full and releases water throughout the year.

Volumetrically streamflow is five times greater than recharge as estimated with the SIMHYDGW model in the nine provinces for which estimates could be made. However groundwater is, and will likely remain, the main water resources in the Pilbara because most of the streamflow occurs in cyclonic events which are hard to capture and store, either above ground or in aquifers using managed aquifer recharge. Storage and recharge is successfully used in inland areas at Ophthalmia Dam near Newman but most cyclonic rainfall occurs on the coast and there may not be large capacity dam sites and adjacent aquifers with sufficient storage capacity to store these large volumes. Investigations of any opportunities to capture and divert streamflows are recommended however. As evidenced at Harding Dam, evaporation rates are high and water quality problems may arise if not well managed when water is stored above ground in the Pilbara.

7.5 References

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