REPORT

Hydrogeology Investigation
Buntine-Marchagee
Natural Diversity Recovery
Catchment

Prepared for

Department of Environment and Conservation

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Acknowledgements

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This project was funded by the Department of Environment and Conservations’ Natural Diversity Recovery Catchment program and the “Whiteout” project which was funded by the Northern Agricultural Catchments Council (NACC).
Executive Summary

The Buntine-Marchagee Natural Diversity Recovery Catchment (BMNDRC) covers 181,000 hectares in the northern wheatbelt of Western Australia. It has saline, braided channels traversing the catchment and a high diversity of wetlands and ecosystems. Due to their setting in the regional landscape, the wetlands and ecosystems are at threat from rising water tables, salinity, and water-logging.

This study was undertaken to advance the conceptual hydrogeological understanding of the BMNDRC, at the catchment, sub-catchment and biodiversity asset scale. This conceptual hydrogeology is applied to generate sub-catchment-scale water balance and salt balance models. The accuracy of these models can be improved, however findings of this study are intended to assist the Department of Environment and Conservation (DEC) to develop options for on-ground management of secondary salinity at representative wetland areas in the BMNDRC.

Study Scope and Investigation Outcomes

URS Perth was engaged by the DEC to investigate and provide an understanding of the water balance and local-scale geological, hydrological and hydrogeological regimes within the BMNDRC with particular focus on five representative wetland areas. Aspects of the investigation included interpretation of salinity and water balances, estimation of relative contributions of groundwater, surface water and rainfall to the wetlands and a brief review of catchment management options.

As these investigations were undertaken within wetland environments on both private land and areas of natural vegetation it was essential that all field activities, including drilling of monitoring bores, were completed without significant ground disturbance or discharge of hypersaline and/or acidic groundwater. A comprehensive Health, Safety and Environmental Management Plan was developed to identify and manage risks associated with the project.

The BMNDRC is in the Northern Agricultural Region of Western Australia and contains nearly 23,000 hectares of native vegetation. The DEC, through the State Salinity Strategy (2001) is responsible for ensuring such significant natural areas threatened by salinity are protected.

The BMNDRC has a high diversity of wetlands including fresh and brackish wetlands, wetlands with unusual bentonite and gypsum sub-strata, primary saline playa lakes and fresh brackish sand-plain seeps. Other characteristics include:

- a wide diversity of terrestrial vegetation associations representing the ‘Avon Wheatbelt’ and ‘Geraldton Sandplain’ biogeographic regions;
- a high flora species richness, including many flora taxons of special interest, declared rare and priority flora;
- potential Threatened Ecological Communities (TEC);
- threatened and priority fauna; and
- indigenous, non-indigenous heritage and recreational values.

This hydrogeological study compliments other studies within the catchment and has the following objectives that include:

- Develop simple conceptual models, in terms of flow and quality, for the catchment and each wetland area. These conceptual models will define horizontal and vertical groundwater head gradients, flow directions and approximate groundwater travel times surrounding the various sites.
- Provide monitoring and evaluation recommendations for indicators of salinity threat and hydrological change.
- Provide recommendations for future investigations, with particular focus on potential management options for secondary salinity.
Executive Summary

This study was completed in a series of specific tasks including:

- Literature Review.
- Conducting landholder interviews.
- Contracting and supervising the installation of a groundwater monitoring network.
- Collation and interpretation of data.
- Developing hydrological/hydrogeological conceptual models including; geochemistry and sedimentological evolution of each wetland.
- A brief assessment of the current-potential threat from salinity and related issues such as water-logging.
- Recommending options for management intervention to assist DEC in identifying priority areas for on-ground works.
- A presentation of the findings of this report.

Study Outcomes

- Seasonal rainfall trends for Coorow BOM station show a significant decline in five-year moving average winter trend. This downward winter rainfall trend would result in lower groundwater levels and less surface water runoff. The summer season rainfall shows an upward trend (5 year-moving average).

- The Indian Ocean Panel on Climate Change indicate further declines in average rainfall of up to 20% over the next 25 years. Rainfall records over the past 100 years show a number of localised summer storm events are known to deliver substantial rainfall over a short time period (>50 mm in 1 hour). The frequency of these high intensity events is predicted to increase (IOCI, 2006) which is of some concern as similar events have created wide-scale expansions in areas of vegetation death.

- Recharge estimates using recent rainfall data (1966 to 2006) indicate groundwater levels in the Fresh/Brackish and Bentonite wetland catchments are declining as a result of lower rainfall and a generally drying climate. The Gypsum and Primary Saline wetland catchments show a declining trend in groundwater levels however current levels are rising at a rate of about 0.001m/yr. The fresh/Brackish to valley Floor wetland catchment shows little change in groundwater levels between the dry and wet periods. However, at all wetland catchments, the increased occurrence of high magnitude rainfall events may drive groundwater tables to rise. This is possibly most important in respect to the Fresh/Brackish Valley Floor Wetland that is reporting a current rise groundwater level.

- Although limited in long-term data, these conclusions are consistent with measured groundwater tables throughout each wetland catchment. Groundwater tables show significant response to extreme rainfall events with long delays in recovery to pre-event groundwater levels.

- Changes in recharge and groundwater levels impact on gain or loss of salt, as evaporation changes based on the depth to water relationship. As evapotranspiration accounts for a significant proportion of annual rainfall, water balance simulations in all wetland catchments show a gain in salt. However compared with past wetter annual averages (1953 to 1993), salt accumulation is also in decline due to lower rainfall recharge and declining groundwater levels.

- The knowledge of the geology and stratigraphy of BMNDRC was linked with the findings of drilling investigations to frame a conceptual hydrogeological model. This model provides an overall catchment-wide appraisal of the hydrogeology of the BMNDRC. It may also be applied on a local and sub-catchment scale, understanding that small-scale geological and structural...
controls might strongly influence the local groundwater environment. Key elements of the conceptual hydrogeological model include:

- The Landscape-Soil Systems are important aspects of the sub-catchment hydrogeology and hydrology.

- Recharge domains occur on hill-crest and mid-slope landscapes, and infiltrates the sandy superficial formations until laterally deflected upon encountering the clayey and cemented successions of the transported colluvium, silcrete or saprolite profiles.

- Groundwater discharge domains occur in valley-floor and foot-slope settings. Groundwater discharge rates may be comparatively high along reaches of the Buntine Palaeodrainage system and associated watercourses that are juxtaposed by the Upsan Downs, Balgerbine and Ballidu Soil Systems. The prevalence of larger lakes adjacent to the Upsan Downs Soil System may be due to comparatively high local groundwater discharge rates or runoff dynamics. The absence of large lakes on downstream reaches of the Buntine Palaeodrainage system and near the confluence with the Moore-Coonderoo River System may support reductions in local discharge from the Inering Hills Soil System.

- Groundwater flow and water table settings are closely aligned with the topography. Depths to the water table are typically in the range of 2 to 5 m. As such, BMNDRC is predominantly characterised by shallow water table settings. Several of the playa lakes are perennial and closely represent the local water table. Geological-basement structures may control the locations of the perennial lakes.

- Groundwater flow predominantly occurs in three aquifer systems. These systems, which are formed by sandplain dunal deposits that characterise the superficial formations of the Upsan Downs, Balgerbine and Ballidu Soil Systems; sand successions of the Buntine Palaeodrainage; and structured or sandy profiles in saprolitic and fresh bedrock.

- Groundwater flow, at least on a local scale, can be in-part controlled by structures in the bedrock fabric, be they faults or intrusives (dykes). Structural controls are evident and known to influence depths of weathering, alignment of the Buntine Palaeodrainage (including tributaries) and topography.

- The hydraulic characteristics of the local shallow groundwater flow systems are predominantly influenced by lithology, with sandy successions forming preferred flow paths.

- Catchment-scale groundwater flow is probably dominated by the Buntine Palaeodrainage and transported sandplain regolith. Fractures in the bedrock profile may promote and facilitate flow on a local scale.

- Observed horizontal hydraulic gradients are lowest beneath valley-floor settings in association with the Buntine Palaeodrainage, however strong salinity stratification in these areas promotes high vertical hydraulic gradients. The transmissivity of the valley-filling palaeochannel and transported sediments is comparatively high, even beneath upper catchment reaches.

- Selected reaches of the Buntine Palaeodrainage, particularly in proximity to the large lakes, may have reverse hydraulic gradients and be characterised by internal drainage, except during flooding events.

- Where drilling has occurred, the palaeochannel successions have increasing cross-section areas from upper-catchment to lower-catchment settings.

- Groundwater is a sodium-chloride type throughout the catchment areas sampled.
Executive Summary

- Groundwater quality varies substantially within the catchment, being fresh beneath recharge domains, but increasingly brackish along flow paths towards discharge zones. Groundwater in the Buntine Palaeodrainage is hypersaline, reflecting long residence time in sediments containing salts and a long flow path in shallow water table valley-floor settings where losses from storage due to evaporation are a significant aspect of the water balance.
- The aquifer systems and successions associated with the Buntine Palaeodrainage are full, with limited available storage for additional groundwater resources.
- The groundwater environment is changing slowly under stressors applied by land-clearing, significant storm recharge events, increasing salinisation over time and modifications to drainage imposed by prior and current land managers.

Fresh/Brackish Wetlands

The conceptual hydrogeological model of the Fresh/Brackish Wetlands are dominated by groundwater flow in aquifer systems formed by dunal and sheet superficial formation sands of the Balgerbine Soil System; and palaeochannel deposits in a tributary of the Buntine Palaeodrainage. In broad terms, rainfall recharge enters the sandy superficial formations and is transmitted vertically until it enters the water table and lateral flow paths. That portion being transmitted laterally discharges into the wetlands where the clayey colluvial deposits outcrop and truncate the flow paths in the superficial formations. On a local scale, groundwater discharge also occurs from the clayey colluvial deposits and palaeochannel. It is recognised, however, that clayey colluvial, cemented layers and palaeochannel successions have potential through-flow beneath the wetlands, with more regional valley-floor flow paths to discharge zones located further downstream.

Bentonite Wetlands

The Bentonite Wetlands occur in a very similar setting to the Fresh/Brackish Wetlands being a mid-slope setting in dunal sands of the Balgerbine Soil System; and at the headwater of a palaeotributary of the Buntine Palaeodrainage. These wetlands occur in settings in the valley-floor landscape at comparatively high elevations in the catchment, where expressions of the water table outcrop. Each wetland represents a small-scale depression in the landscape where the superficial formations are absent and the topography forms a sink for surface water and groundwater flow. Most of the higher elevation catchment is characterised by the sedimentary successions that overlie bedrock. Rainfall recharge that enters the superficial formations is deflected laterally on the contact of underlying clayey colluvial deposits. This contact is commonly characterised by silcrete in thin horizons. The wetlands occur where the clayey colluvial deposits, including bentonite, outcrop and truncate the flow paths in the superficial formations. Individual wetlands also represent local discharge zones for groundwater flow in the colluvial successions and bedrock profiles.

Gypsum Wetlands

The Gypsum Wetlands occur low on the landscape in a setting where groundwater flow may be controlled at both local subcatchment and catchment scale. The wetlands occur in close association with palaeochannel deposits interpreted to form major reaches of the Buntine Palaeodrainage and hence may be dominated by regional rather than local water balances.

Landscapes in the immediate hinterland of the Gypsum Wetlands are formed of loam and rocky superficial formations of the Inering Hills Soil System and thin successions of clayey colluvium overlying shallow bedrocks. Interpretations of limited drill logs indicate that comparatively large-scale palaeochannels occur beneath the foot slopes of the local catchment.

Primary Saline Wetlands

The Primary Saline Wetland groundwater flow and water table settings are closely aligned with the topography and conditions imposed by the Buntine Palaeodrainage. Those that do not are anticipated to...
Executive Summary

be similar to those of the Fresh/Brackish or Bentonite Wetlands where the water table outcrops in small-scale depressions recharged by seasonal flows on dunal sands of the Ballidu Soil System.

Water balances of the larger lakes may be controlled, in part at least, by groundwater flow in transmissive structures in the bedrock profile. It is also interpreted that recharge to the deep sandpans of the Upsan Downs Soil System and subsequent discharge to the Buntine Palaeodrainage is a significant aspect of the catchment water balance.

**Fresh Brackish Valley Floor Wetlands**

These wetlands (damplands, seepages and ephemeral lakes) occur in valley-floor settings, where expressions of the water table outcrop in localised depressions in the landscape, or at breaks of slope. Local groundwater is typically hypersaline. There is, however, evidence of salinity stratification with the shallow flow systems, with less saline water discharging into the higher elevation lakes. This is likely related to localised flow regimes and not the regional palaeochannel system. Marginally further downslope, the palaeochannel successions are expected to dominate the wetland water balances. In this aspect the depth to the water table is likely to be a significant factor together with the local low hydraulic gradients imposed by the palaeochannel aquifer system. The conceptual hydrogeological model for the Fresh Brackish Valley Floor Wetlands is compatible with that of the Fresh Brackish Wetlands. Locally, the concepts are supported by the occurrence high in the catchment of discrete and isolated wetlands and fresh water seeps where the water table outcrops in small depressions.

**Study Conclusion and Recommendations**

The development of strategies by which to mitigate risks potentially imposed by rising water tables is complex. Limited long-term groundwater levels data presents an uncertainty regarding wetland water balances and the range over which local water tables might be managed to conserve the existing environment and ecosystems. Likely water table and aquifer system responses to potential stressors are also uncertain, as are distances or areas over which responses might prevail. A continuous longer term record and detailed analysis will be required to understand this.

There is potential for changes in past and/or current water balances in individual catchments (compared to those in this report which only represent a snapshot) and, transient changes in salinity of the local groundwater. The interpretations based on available data indicate that significant rainfall events have a strong influence on recharge and hence water table elevations. A change in the recurrence interval of the significant rainfall events (from the 1:13 years recorded to date) would potentially lead to changes in water table elevations. Irrespective of water table trends, wetland and shallow water table domains from discharge zones wherein increasing salinisation is expected due to groundwater losses through evaporation.

On a scale relevant to the representative wetlands, particularly the Fresh/Brackish, Gypsum, Primary Saline and Fresh/Brackish Valley Floor catchments, this uncertainty is manifested by questions regarding causes and effects of changing water tables. For instance “are water table levels in the individual wetlands predominantly linked to catchment-wide influences on the palaeochannel or changes in water balance on a local scale?” The former could cause the backing-up of groundwater along individual palaeotributaries and watercourses. On the other hand, the latter would reflect increasing excesses of groundwater shedding from local catchment areas. Mitigation measures would need to be developed cognisant of the predominant water balance influence, presumably preferentially targeting either downstream or upstream influences depending on which is dominant. Additional groundwater, climate and surface water monitoring (minimum 5-10 years) will be required to understand the water balances under a range of rainfall events, to an extent to facilitate a detailed threat analysis.
1.1 Natural Diversity Recovery Catchments

The Department of Environment and Conservation (DEC) is committed, in partnership with the community, to protecting and conserving our state's natural wonders. As part of its corporate vision, the DEC aspirational goal for biodiversity is:

“To protect, conserve and, where necessary and possible, restore Western Australia’s natural biodiversity” (CALM, 2002).

The DEC also has the responsibility to ensure that regionally significant natural areas, such as wetlands, are protected in perpetuity (State Salinity Council, 2000). This responsibility is supported through a regionally coordinated Natural Diversity Recovery Catchments (NDRC) Programme. High priority catchments are selected using a range of biodiversity criteria and the programme aims to conserve the significant biodiversity values of the individual catchments.

In the Western Australian Salinity Action Plan (1996), the objective for managing natural diversity recovery catchments is:

“The Government will develop and implement a coordinated Wetlands and Natural Diversity Recovery Programme targeting at least six key catchments over the next 10 years to ensure that critical and regionally significant natural areas, particularly wetlands, are protected in perpetuity”.

While not a specific objective of the programme, the importance of using work in recovery catchments to devise and test methods for combating salinity has long been recognised. In the Toolibin Lake Recovery Plan (Toolibin Lake Recovery Team and Toolibin Lake Technical Advisory Group, 1994), three of the principal goals specifically recognise this point, namely to:

- Demonstrate, within a large catchment that it is possible to stabilise hydrological trends that if unchecked threaten land, water and biodiversity resources.
- Demonstrate methods of protecting biodiversity, land, and water resources to other land managers.
- Develop mechanisms which lead to community ownership of the natural resources, including recognition of the problems and identifying potential solutions.

There are currently six Natural Diversity Recovery Catchments; Lake Toolibin, Lake Bryde, Lake Warden, Lake Muir-Unicup, Buntine-Marchagee and Drummond.
The Buntine-Marchagee Natural Diversity Recovery Catchment (BMNDRC) is located in the northern wheatbelt of Western Australia, approximately 280 km northeast of Perth and 130 km from the coast (Figure 1). It covers 181,000 hectares, extending 60 km east to west and 40 km north to south between the town sites of Dalwallinu, Buntine, Coorow and Watheroo. The BMNDRC is a sub-catchment of the Moore River Catchment.

The selection of the Buntine-Marchagee as a NDRC is linked to a number of reasons; in particular the naturally saline braided channels which traverse the catchment are known to support a significant proportion of the regional invertebrate fauna, especially salt-adapted species. Due to its setting in the regional landscape, this system is at threat from rising water tables, salinity, and water-logging. The BMNDRC also has a high diversity of wetlands types including saline playa lakes, meandering flow lines, fresh and brackish wetlands, naturally acidic wetlands, wetlands with unusual gypsum and bentonite substrata, granitic rock pools, and sand-plain seeps. Other key values of the BMNDRC include terrestrial vegetation associations, special flora taxa, declared rare and priority flora, potential Threatened Ecological Communities (TEC), threatened and priority fauna, indigenous and non-indigenous cultural heritage, and recreation values. Lastly, there is demonstrated local support for landcare associated projects in the area, such as that provided by the Marchagee Catchment Group and the Waddy Forest Land Conservation District Committee (LCDC). These biological and social values contributed towards BMNDRC being regarded as a priority catchment worthy of biodiversity protection.

Numerous investigations have been undertaken in the past to gain a broad understanding of the catchment. The more relevant studies that deal specifically with the BMNDRC included SKM (2003), Griffin and Goulding (2004), Speed and Strelein (2004), URS (2004) and Short et al (2006). These reports have been used to provide a catchment summary below.

2.1 Physiography

The BMNDRC is located east of the Moore-Coonderoo River System, within the Northern Zone of Ancient Drainage (258) (WA Agricultural Department, 2004). It predominantly consists of gently undulating plains with broad saline watercourses that deliver water into the northern Moore-Coonderoo River System. Most watercourses are characterised by alluvial and lacustrine sand and clay deposits that provide bed-forms for a chain of more than 1,000 discrete salt lakes, playas and clay pans. Catchment-scale surface water flow occurs infrequently, the last flow occurred following tropical cyclones Elaine and Vance in 1999.

The landscape of BMNDRC is generally of low relief with topography closely related to the underlying geology. The elevation ranges from about 380 m Australian Height Datum (AHD) near the north-eastern boundary of the catchment to 248 m AHD at the north-western margin near the confluence with the Latham Lake chain before heading towards the Moore-Coonderoo River System.

Previous work by Griffin and Goulding (2004) divided BMNDRC into five soil-landscape systems termed the Inering Hills, Upsan Downs, Ballidu, Balgerbine and Wallambin (Figure 2). The Inering Hills System is an area of low hills and intervening valleys with moderate to gently inclined slopes, many rock outcrops and dolerite dykes particularly along ridge crests. Its soils are typically brown and yellow sandy and loamy duplexes, clay and rock. The Upsan Downs System is dominated by sandplain, with small areas of soils derived from weathered bedrock. The Ballidu System is similar to the Upsan Downs System, with gently undulating sandplain areas. It is, however, generally of lower relief. It also has small areas of soils derived from weathered bedrock and more common bedrock outcrops. Valleys are also more prominent with narrow alluvial plains dominated by red and brown duplex soils. The Balgerbine System is a gently undulating plain overlain by dunes and sand sheets that in places fill or cross the major alluvial plain of the catchment. Finally, the Wallambin System is an alluvial plain characterised by numerous playa lakes and associated saturated subsoils.

2.2 Climate

Climate in the BMNDRC is a Mediterranean-type, with mild wet winters and warm to hot summers. Rainfall extremes recorded at Coorow and Dalwallinu are provided in Table 2-1. Average annual rainfall
Section 2  

BMNDRC Description

decreases from west to east across the BMNDRC, being 379 mm at Coorow (Bureau of Meteorology (BOM), 2006) and decreasing to 314 mm in Dalwallinu (from 1912 to 2006 and 1913 to 2006, respectively). Median annual summer and winter rainfall across BMNDRC were interpolated (Figure 3a) using rainfall records from BOM stations Koobabbie, Ytinichie, Hakea, Manavi, Buntine, Wubin, Sunnydale and Dalwallinu (Appendix J) and tipping bucket rain gauges Hunt, Doley (BoM location Koobabbie) and Barnes. For comparison, the annual wet season summer and winter rainfall for the catchment were also interpolated using the same stations and are presented on Figure 3b. On average, about 80% of the rainfall occurs from April to October inclusive. Extreme rainfall events are influenced by cyclonic activity and are more likely in the summer months. For example, in Dalwallinu the highest monthly rainfall of 200.5 mm was recorded in March 1999, with 140 mm falling over three days subsequent to Cyclone Elaine. Daily rainfall has been known to exceed 100 mm (112.3 mm in Dalwallinu on 28th March 1971).

Table 2-1  Rainfall Extremes Recorded at Coorow and Dalwallinu (1912/1913 to 2006)

<table>
<thead>
<tr>
<th>Month</th>
<th>Highest Daily Rainfall (mm)</th>
<th>Highest Monthly Rainfall (mm)</th>
<th>Lowest Monthly Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coorow</td>
<td>Dalwallinu</td>
<td>Coorow</td>
</tr>
<tr>
<td>January</td>
<td>99.2</td>
<td>90.6</td>
<td>138.0</td>
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<tr>
<td>February</td>
<td>58.0</td>
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<tr>
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<td>44.8</td>
<td>52.3</td>
<td>61.8</td>
</tr>
<tr>
<td>December</td>
<td>51.1</td>
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</table>

Source:  Bureau of Meteorology (2006), Coorow Station No. 008037, Dalwallinu Station No. 008039

2.2.1 Evaporation

Evaporation is measured from an open pan called a Class A Evaporation Pan. The rate of evaporation depends on factors such as cloudiness, air temperature, shade, humidity and wind speed. The Bureau of Meteorology has collected evaporation data from 1975 to 2005 for Moora to the south of the BMNDRC and Three Springs to the north of the catchment.

There are no pan evaporation data available at BMNDRC and the average of pan evaporation recorded at Moora and Three Springs (Table 2-2) will be used interpretations within the BMNDRC. Average annual pan evaporation is six times the mean annual rainfall (Luke et al., 2003).
Section 2

BMNDRC Description

Table 2-2 Monthly and Annual Average Class A Pan Evaporation Rates (mm) for Moora and Three Springs With Estimated BMNDRC Evaporation Rates

<table>
<thead>
<tr>
<th>Stations</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
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<td>333</td>
<td>291</td>
<td>173</td>
<td>113</td>
<td>73</td>
<td>70</td>
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<td>124</td>
<td>193</td>
<td>269</td>
<td>360</td>
<td>2456</td>
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<tr>
<td>Three Springs</td>
<td>404</td>
<td>370</td>
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<td>143</td>
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<td>BMNDRC</td>
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</table>

2.2.2 Seasonal Rainfall Trends

Winter rainfall records from 1912 to 2005 for Coorow plotted in Figure 4a, indicate great variability. On average Coorow receives 258 mm of rainfall from May to October. During 1917 and 1963, winter rainfall was 277 mm more than the mean winter rainfall of 258 mm. Coorow received below average winter rainfall in each of the last nineteen years except 1996. During 2004, winter rainfall was the lowest on record, 244 mm below the mean.

The five-year moving average trend line shows a downward trend in the winter rainfall received by Coorow over the last 94 years (Figure 4a). This downward trend of winter rainfall would reflect lower recharge to groundwater and surface runoff.

The summer season rainfall has been calculated by adding rainfall during November and December of the first year and rainfall from January to April in the succeeding year. Coorow receives an average summer rainfall of 132 mm. The five–year moving average trend line shows an upward trend in summer rainfall for Coorow over the past 94 years (Figure 4b). This increase in summer rainfall may be linked to an increase in the frequency of summer storm events (Figure 5).

2.3 Surface Water Hydrology

BMNDRC forms a series of internally draining sub-catchments with surface water flows typically occurring at localised scales. Catchment-scale surface water flow (connected flow within the main braided watercourse) occurs less frequently than localised flows (Short et al, 2006) and typically only during high magnitude rainfall events.

The major watercourses of BMNDRC are broad saline braided systems, up to 1.5 km in width, made up of many hundreds of wetlands ranging in diameter from less than 50 m up to 2.7 km. Slope gradients are generally between <0.5% and 3%. Steeper grades between 3 and 5% are less common and are mostly restricted to ridges (such as dolerite dyke outcrops) and drainage divides. The lowest gradients are found on the valley floor, where slopes of less than 0.5% commonly occur.

Many watercourses appear to be developed along orientations that emphasise the structural fabric and dykes of the Yilgarn Craton (Figure 2). The main structural orientations are approximately northeast-southwest and southeast-northwest. These watercourses flow towards the salt lake chains on the valley floor.

The likelihood of stream flow is dependent on numerous factors such as intensity and duration of rainfall, soil type, soil properties (water repellence, infiltration rates and hydraulic conductivity), topography, vegetation type and vegetation density. Stream flow events are more numerous in the east than the west of the catchment, due to the increased occurrence of intense storms and the characteristics of the soil systems. Based up recent data collected by the DEC, low flow events at a local scale are known to occur following comparatively small rainfall events (15 mm rainfall events over 24 hours) which are more typically associated with winter frontal systems. In addition, localised summer storm events are also...
known to deliver substantial rainfall (>50 mm in 1 hour) over short time periods and often result in higher rates of runoff.

Rainfall records over the past 100 years indicate a number of significantly high rainfall events have occurred (Figure 5). The most recent were due to severe Tropical Cyclones Elaine and Vance in March 1999. Measured rainfall was about 50% more than the long-term annual average in the catchment (Bureau of Meteorology, 2006). Such storm events provide enough surface water flow to link the braided and intermittent drainage of the BMNDRC (Figure 1).

A number of deep drains have been constructed with the intent to lower shallow water tables and reduce water-logging. Deep drains are prevalent in the eastern third of the catchment, in the heavy clay soils of the valley floor where groundwater flow gradients are low. Many of these drains are poorly maintained and appear at present to have little influence on groundwater levels.

Surface water structures have been constructed throughout the catchment. These consist of contour and grade banks which reduce surface water flow velocity, inundation, and associated erosion impacts. In addition there are numerous other structures such as roaded catchments used to replenish dam water supplies. These are found particularly on shedding landscapes such as the gravely soils of the Inering Hills System.

### 2.4 Geology

BMNDRC is underlain by Archaean (3,800 to 2,500 Million Years Ago (mya)) crystalline granitic bedrocks of the Yilgarn Craton. Numerous generations of Proterozoic (2,500 to 543 mya) dolerite dykes intrude the granitic basement (Figure 2), with increasing abundance toward the west (Carter and Lipple, 1982, Baxter and Lipple, 1985). The weathering and erosion of the granites in the catchment, over a long period of relative geological stability, has resulted in several characteristic deep weathering and sedimentary profiles. In-situ weathering has formed a typical mottled zone, pallid zone and transition zone profile above fresh crystalline basement. The crystalline bedrock is typically overlain by colluvium in the lower parts of catchment and a surficial yellow sandplain blanket in the western, south-western and north-eastern areas.

Speed and Strelein (2004) compiled information from monitoring bore drilling to develop a conceptual understanding of the local geology. This understanding has been further developed from the results of recent drilling. The following stratigraphic units, in order of increasing depth, are defined based on the drill-logs:

- **Superficial formations:**
  - aeolian sands of the Balgerbine, Upsan Downs and Ballidu Soil Systems.
  - colluvium as lithic sand, silts and clays, though predominantly clayey throughout the catchment.
  - alluvium as clay, silt and sand, though again predominantly clayey.

- **Lacustrine clays.**

- **Transported sediments;** variable sandy, silty and clayey colluvial and valley-fill profiles derived from deeply weathered granite bedrocks.

- **Palaeochannel silts, sands, and gravels in a succession of valley fill deposits (Buntine Palaeodrainage).**

- **Weathered granitic bedrock, saprolite and saprock derived from granite and dolerite, variable clay, silt, sand and rock fragments in the make-up.**

- **Fractured and fresh granitic bedrock.**

Schematic representations of the stratigraphy of the BMNDRC are shown on Figure 6.
Section 2

BMNDRC Description

The local superficial formations typically form 2 to 10 m thick successions, extending beneath ancient and current watercourses and lakes and thickening beneath mid-slopes and crests. These successions are variable, comprising deep aeolian sands of the Balgerbine Soil System, shallow stony and loamy duplex soils of the Inering Soil System, and lenses of vuggy laterite and silcrete that reflect palaeo-water tables and physicochemical processes. Silcrete generally comprises indurated rock of strongly cemented silica. Shallow silcrete has been reported at depths ranging between 1 and 6 m, often in association with yellow sandplain soils of the Balgerbine Soil System (Speed and Strelein, 2004).

The superficial formations are typically underlain by transported sediments that are predominantly clayey, though irregularly interbedded with thin sand, silcrete and ironstone gravel deposits. Silcrete is also interspersed at the unconformity between the transported sediments and saprolite.

Lacustrine clays and palaeochannel successions are prevalent beneath the valley floor. Due to scarcity of data, however, the location and extent of palaeochannels throughout the BMNDRC remains largely subject to interpretation. Sand and gravel deposits form the major successions in basal portions of the palaeochannels, being overlaid by low energy silt and clay deposits. The palaeochannel deposits are possibly up to 500 m in width and typically 10 to 20 m thick (maximum intersected thickness 38 m in the east). The upper part of the palaeochannel is characterised by silty sands that fine upwards into predominantly silty and clayey beds. The margins of the palaeochannel are typically clayey and silty. Basal elevations of the palaeochannel locally occur from 252 mAHD in the east to 220 mAHD in the west.

The bedrock profile is formed of Archaean granitic rocks of the Yilgarn Craton. Weathered and fractured bedrock forms a regolith zone, typically 10 to 30 m thick, with localised increases in thickness associated with deep weathering as a result of faults and associated fractures that promote oxidation and groundwater flow.

2.5 Regional Conceptual Hydrogeology

The conceptual regional hydrogeology of BMNDRC was first developed by Speed and Strelein (2004). This report delivered a broad understanding of the BMNDRC hydrogeology based on the results of a drilling investigation programme conducted in 2002. The programme comprised reconnaissance drilling at 52 sites in the BMNDRC and construction of 89 monitoring bores with varying depths of investigation. Details of this programme are outlined in Table 2-3, inclusive of monitoring bore construction data, groundwater levels (2002 and 2006) and groundwater quality (Electrical Conductivity (EC), May 2003). Locations of the investigation sites are shown on Figure 7. Transects that enable presentation of the available local data and interpretations of the hydrostratigraphy together with groundwater levels and salinity are provided on Figure 8 (a to g) and Figure 9 (a to g).

The interpretations of the hydrostratigraphy are based on the local lithological profiles and presence of valley-fill palaeochannel successions beneath the major drainage lines.

Catchment-wide interpretations have subsequently been developed by interpolation of the data from the individual transects. These interpolations are broad-based, as reflected by the spatial distribution of relevant data. It is intended that they provide a generic overview of the catchment hydrogeology and hydrological processes, understanding that settings on a local scale will provide differences from the regional model. Key elements of the interpolations are intuitive, based on the assumption that occurrences of the many playa lakes is linked to shallow water table settings, occurrence of palaeochannel deposits, distributions of sandy soil profiles of the Upsan Downs and Ballidu Soil Systems and potential occurrence of transmissive structures in bedrocks.

Outcomes of the completed catchment interpretations are shown on Figures 10 to 13, inclusive, providing an outline of potential palaeochannel sediment distributions, water table contours, zones of groundwater discharge where the water table is less than 2 m below the ground surface and salinity of the water table beneath valley-floor areas.
## Table 2-3 Groundwater level data for September 2006, and water quality data from bores installed in 2002

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<td>19.39 - 17.39</td>
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</tr>
</tbody>
</table>

Note: D- Deep Bore  ob – Observation Bore  I – Intermediate Bore
Section 2

BMNDRC Description

The interpreted findings show:

- Valley-floor areas of BMNDRC often being underlain by the Buntine Palaeodrainage, comprising a main palaeochannel and numerous tributary palaeochannels, which traverse significant areas of the catchment.

- Alignment of the Buntine Palaeodrainage with the mapped soil system boundaries and structures in the fabric of Archaean bedrocks.

- Prevalence of larger and more numerous lakes on valley-floor transects bounded by the Balgerbine, Ballidu and Upsan Downs Soil Systems that are dominated by dunes, sand-sheet and sandplain superficial covers.

- Potential occurrence of internal drainage beneath selected mid-catchment reaches of the Buntine Palaeodrainage. These reaches are typically characterised by proximity to larger lakes and playas wherein evaporation effects may cause groundwater sinks.

- Broad distributions of shallow water table zones throughout the catchment, traversing valley floor areas of the Wallambin Soil System (alluvial plain and playa lakes) and extending further upslope in association with tributary palaeochannels. Most wetlands are aligned with shallow water table zones.

- The Buntine Palaeodrainage and tributaries are characterised by hypersaline groundwater. It is anticipated that salinity concentrations in excess of 50,000 mg/L are closely aligned with the palaeochannel deposits.

2.6 Land-use

The principle commercial activity in the district is broad acre agriculture, consisting of cereal cropping and sheep farming. Approximately 87% of the catchment has been cleared. The numbers of livestock in BMNDRC indicates that they are an important aspect of most farming systems (CALM and Colmar Brunton, 2005).

2.7 Regional Vegetation

At a broad level, the BMNDRC lies within the South West Botanical Province. At the bio-regional scale the catchment falls within the Ancient Drainage sub-region of the Avon Wheatbelt Region (Avon Wheatbelt 1) and the Lesueur sub-region of the Geraldton Sandplain Region (Geraldton Sandplain 3). The vegetation associated with a number of wetlands has been described by Richardson, Keighery and Manson (2005).

The vegetation of the Avon Wheatbelt component within BMNDRC is characterised by Melaleuca spp. shrublands in the main drainage line, woodlands of Eucalypts on the lower slopes, mallee Eucalypts on the mid–slopes and shrublands on the upper slopes. Vegetation associated with the Geraldton Sandplain Region component is also characterised by shrublands dominated by Melaleuca spp., Eucalyptus spp and Banksia spp. There is a marked difference in species between these two vegetation components.

Remnant vegetation of the valley floor is a major component of the biodiversity in BMNDRC. Almost 30% of the remnant vegetation lies within 500 m of the valley floor. The drainage lines are often occupied by thick woodlands with salt-tolerant halophytes, such as samphire and saltbush, surrounding the playa lakes.

Beard’s (1980) broad scale mapping is the most commonly used flora mapping covering the WA agriculture belt. Using ‘Beards’ vegetation types, the percentage reduction of original vegetation extent ranges from 83 to 95%, with just one shrubland vegetation type with 64% remaining. Overall, 88 to 89% of the pre-European vegetation has been removed for agriculture. Four of the eleven vegetation types covering BMNDRC are currently ‘limited in extent’ in the Northern Agricultural Region and/or the State.
Section 2

BMNDRC Description

There are a number of Declared Rare and Priority Flora in the BMNDRC. A number of taxa are threatened by salinity, by virtue of their distribution in the lower landscape.

2.8 Aquatic Invertebrate Surveys

The richness and diversity of aquatic invertebrates within BMNDRC is probably not yet appreciated. Past work by Storey et al., (2004a, 2004b) and Lynas et al., (2006), has indicated water chemistry/quality to be a strong determinant of the invertebrate fauna of the wetlands. Within the wetlands of BMNDRC, greater invertebrate species richness, species diversity, levels of endemism and conservation values are associated with fresh and brackish wetlands rather than saline or hypersaline wetlands.

Importantly, saline wetlands support assemblages of aquatic invertebrates that are different and less diverse than those of primary saline wetlands. This highlights the importance of conserving both fresh/brackish and primary saline wetlands in BMNDRC to ensure the maintenance of a diversity of fauna.

2.9 Representative Wetlands

The BMNDRC includes more than 1,000 individual wetlands occurring in an extensively cleared agricultural landscape. The majority of the wetlands occur along the valley floor within the Wallambin System. The Balgerbine System supports around 20% of the wetlands and small numbers occur in the Upsan Downs and Ballidu Systems. There are currently six wetland types recognised within the BMNDRC. These are fresh/brackish wetlands, bentonite wetlands, freshwater claypans, gypsum lakes, granite rock pools, and saline wetlands and channels.

To focus management effort and resources, five wetland areas were selected. The selection of these wetlands was based upon a number of factors such as the biodiversity values, current condition, perceived salinity threat and willingness of landholders to participate. The wetland areas selected for this report comprise four of the representative wetland types, including:

- Bentonite Wetlands – Wetlands W056 to W059.
- Gypsum Wetlands – Wetlands W001 and W002.
- Primary Saline Wetlands and channels – Wetland W448.
- Fresh/Brackish to Valley Floor Wetlands (characterised by numerous sandplain seeps, graduating to a valley floor wetland) – Wetlands W015, W016, W017 and W051

The granite pools are located higher in the landscape, typically collect fresh rainfall and are subsequently not threatened by salinity. In addition, one freshwater claypan has been identified within the BMNDRC. Being situated in the upper part of the landscape the threat of altered hydrology is considered moderate to low. The focus of this study is upon wetlands threatened by altered hydrology, particularly salinity. Consequently these two wetland types have been excluded from this study.

The following table (Table 2-4) provides a brief overview of the catchment areas and proportion of remnant vegetation remaining at each of the representative wetlands.
### Table 2-4  Wetland Catchment Area

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<th>Wetland</th>
<th>Catchment Area (ha)</th>
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<tr>
<td>Fresh/Brackish (W011 and W012)</td>
<td>1,783</td>
<td>135</td>
<td>1,648</td>
<td></td>
</tr>
<tr>
<td>Bentonite (W056 to W059)</td>
<td>987</td>
<td>385</td>
<td>602</td>
<td></td>
</tr>
<tr>
<td>Gypsum (W001 and W002)</td>
<td>3,991</td>
<td>578</td>
<td>3,413</td>
<td></td>
</tr>
<tr>
<td>Primary Saline (W448)</td>
<td>80,000</td>
<td>9,000</td>
<td>71,000</td>
<td></td>
</tr>
<tr>
<td>Fresh/Brackish to Valley Floor</td>
<td>924</td>
<td>81</td>
<td>843</td>
<td></td>
</tr>
</tbody>
</table>
Section 3

Scope of Investigation

URS was engaged by the DEC to investigate and provide an understanding of the water balance and local-scale hydrological and hydrogeological function of five representative wetland areas within the BMNDRC. Aspects of this investigation include assessment of salinity and water management for each of the wetland areas, estimation of relative contributions of groundwater, surface water and rainfall to the wetlands, and review options for future management.

The key focus of this investigation is to provide the DEC an improved understanding of the sedimentological and hydrological/hydrogeological function of the five representative wetland areas. To ensure synergy of data and facilitate criteria development, the investigations was focussed on:

- Investigate catchment-scale seasonal rainfall variation.
- Investigating the hydraulic connectivity with the groundwater flow systems and measure the depth to groundwater in the area surrounding the wetland to provide a depth to water table map of the areas where the fringing vegetation is potentially groundwater dependant.
- Determining the horizontal and vertical groundwater head gradients, flow directions and approximate groundwater travel times in the sub–catchments associated with the selected wetlands.
- Investigating water content in the unsaturated zone, depth to water and the likely seasonal variations in both. This will indicate the potential for future water-logging.
- Investigating the sediments surrounding and where possible in the actual wetland systems, in terms of both hydraulic parameters and Potential Acid Sulphate Soils (PASS).
- Gathering detailed lithological data from monitoring bores drilled within the five representative wetland areas and preparing cross-sections to ground-truth and calibrate future geophysical investigations.
- Develop simple conceptual models (salt and water balances) for each representative wetland area.
- Where possible, investigating wetland nutrient loading, pH/acidity, and sedimentological evolution.
- Providing monitoring and evaluation recommendations for indicators of salinity threat and hydrological change.
- Providing recommendations for future investigations, with particular focus on potential management options for secondary salinity.

Specific tasks completed for this study included:

- An on-site review of the DEC proposed groundwater monitoring bore locations at the five wetland areas.
- Conducting Landholder interviews.
- Contracting and supervising the installation of a groundwater monitoring network.
- Collation and interpretation of data.
- Developing conceptual models of the hydrological/hydrogeological function, geochemistry and sedimentological evolution of each wetland.
- A brief assessment of the current-potential threat from salinity and related issues such as water-logging.
Section 3  Scope of Investigation

- Recommend options for management intervention to assist DEC in identifying priority areas for on-ground works.
- A presentation of the findings of this report.
Section 4

Methodology

4.1 Field Investigations

4.1.1 Landholder Interviews

All of the representative wetland areas in this study occur on private land. Therefore, the landholders were consulted and advised of all aspects of the project. In addition, many of the landholders in BMNDRC have long associations with their properties and anecdotal knowledge of the changes linked to rising of the water table over time.

In many cases multiple landholders occupy the catchment of the selected wetlands. In addition to general consultation each of these landholders (and their family) was interviewed by URS. A series of questions (Appendix A) was asked, such as land use history etc.

4.1.2 Air Photograph Interpretation

Historical aerial photographs at 1: 25,000 scale for each wetland area were obtained from the Department of Land Information covering years 1959, 1969, 1970, 1980, 1994, 1996, 2000 and 2004 (Appendix B). The photographs were used to interpret major lineaments, dolerite dykes and expressions of soil salinity over time.

4.1.3 HSE Plan

A HSE and Environmental Management Plan was developed to address potential human and environmental health issues associated with installation of the groundwater monitoring infrastructure. Based on the previous drilling experience in the catchment (Speed and Strelein, 2004) the DEC anticipated that hypersaline and/or acidic groundwater would be encountered at a number of sites. It was inevitable that some of this groundwater would be lifted to the surface during bore development and sampling activities. The Environmental Management Plan particularly addressed the handling and disposal of groundwater and other issues such as weed and fire management.

Prior to the development of the Environmental Management Plan, the DEC reviewed the potential impact of drilling activities upon each of the wetland areas. This review included surveys of Declared Rare Flora and Priority Flora in the catchment and on site access routes. Consequently the Environmental Management Plan formed an induction tool with the contractors and applied on-site prior to commencement of drilling.

The HSE Plan developed for this project is provided in Appendix C.

4.1.4 Drilling

A total of 45 monitoring bores were constructed as part of the investigation. Plate 1 shows photographs of the drilling equipment and selected activities.

Three types of monitoring bores were installed at the five representative wetland areas. These were:

- Shallow bores, which were drilled to a depth of up to 6 m using a Geophone rig fitted with either pneumatic push-probe or hollow-stem auger, or using hand-auguring techniques (where site access was limited).
- Intermediate bores, installed at depths ranging between 13.5 to 27 m to target specific aquifers.
- Deeper bores, typically drilled using the E-Core, air-core method to bedrock.

Each method drilled a 150 mm diameter hole.
Section 4 Methodology

To limit potential environmental impacts imposed by the drilling, small inflatable wading pools were positioned beneath the drill cyclone to collect hypersaline and/or acidic groundwater. A threshold of 4,000 mg/L TDS (field salinity) and/or pH 4 was defined to indicate whether containment was required. Groundwater of salinity <4,000 mg/L was disposed directly onto the ground surface, in areas away from any natural vegetation or crops. Groundwater exceeding these thresholds was disposed in a rubbish tip located in the valley floor on a landholder’s property.

All bores were cased with 50 mm, Class 9 uPVC casing; slotted casings had a 1mm aperture. Slotted sections ranged from 1 to 5 m in length. Bottom caps of the shallow bores were slotted to provide vertical drainage.

Graded gravel of size 3.2 to 6.4 mm was packed in the annulus around and extending at least 1.5 m above the slotted section. The shallow bores were sealed with cement slurry to about 0.5 m below ground surface. In the deeper bores, a minimum of about 6 m of cement was installed, with annular zones then backfilled to surface with either gravel pack or drill cuttings. Where possible the monitoring bores were developed using air-lift techniques until abstracted groundwater was clear and silt free. Low-yielding bores were developed using a small 12 volt pump. All bores were completed with a concrete block around the surface collar and a protector cap. An Odyssey (64kb) data logger with a capacitance probe was fitted to each of the monitoring bores by the DEC. These log groundwater levels at 6 hourly intervals.

All existing and new monitoring bores were surveyed for X and Y coordinates and Z elevations (with accuracy of 0.05 m) using Thales Z Max GPS receivers in Real Time Kinematic (RTK) mode by the Department of Land Information (Landgate).

4.2 Field Data Measurements

4.2.1 Lithological Descriptions

An understanding of the local hydrostratigraphy was gained by detailed lithological descriptions being completed at 1 m intervals during the drilling of each monitoring bore. Typically, lithologies were described in terms of colour, grain size, angularity, grain sorting, percentage composition, identifiable minerals present and texture. A Maunsell colour chart was used to establish a consistent set of logs. A number of continuous cores were also obtained using the push-probe Geoprobe drill rig. These samples enabled greater detail in lithological descriptions.

A representative soil sample at 1 m increments was bagged by DEC staff and is kept in storage in Geraldton, should there be a need for additional analysis.

4.2.2 Soil EC and pH Profiles

Drilling samples were analysed to investigate the relative distribution of salt and acidity in the weathered profile. Samples at 1 m intervals were collected from both above and below the water table and mixed at 1:5 ratio with deionised water and shaken by hand for two minutes. Sample EC and pH was measured using hand-held TDScan and pHScan models, made by Eutech Cybermetrics of Singapore.

Differences in the soil EC and pH provide guides to variable characteristics in drainage, water-logging and recharge – each of which is linked to water and salt balances. Moore (2001) and Mc Arthur (2001) developed ratings for soil EC and Ph that enable relevant data to be assigned to domains, compared on a uniform basis and used to interpret the broad water balance functions of individual settings.

Salt stored in the soil is a major factor contributing to potentials for the development of secondary salinity. The amount of salt stored in the profile may also indicate the mechanism of recharge. Profiles with high salt store indicate recharge probably occurs through preferred pathway flow, while areas of low salt store indicate recharge by matrix flow (Moore, 2001).

Moore (2001) identified a series of soil groups that can be used to explain the effects on recharge and subsequent salt storage. Uniform Coarse Textured Soils are typically well to rapidly drained and the amount and timing of rainfall are probably the critical factors affecting recharge and salt store.
Conversely, Permeability Contrast Soils, such as those that contain higher proportions of clay, are imperfectly to poorly drained. Recharge to these soils is predominantly by saturated flow along preferred pathways typically including large pores, cracks and old root channels. Recharge in these soils is often closely linked with water-logging, so measures to reduce water-logging will reduce recharge.


<table>
<thead>
<tr>
<th>Rating</th>
<th>EC</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;50 mS/m</td>
<td>Minimal effects on plant growth</td>
</tr>
<tr>
<td>Medium</td>
<td>50 to 200 mS/m</td>
<td>Plant growth is inhibited</td>
</tr>
<tr>
<td>High</td>
<td>&gt;200 mS/m</td>
<td>Plant growth is severely restricted</td>
</tr>
</tbody>
</table>

These ratings provide a guide to potential risks rather than specific evaluation. The effects on plant growth vary with species and salts present in the soil.

Results of soil profile EC analyses were used to identify potential discharge zones where evaporation from the shallow water table has caused increased salt concentrations in the vertical profile. In addition, the profiles assisted to identify zones associated with horizontal groundwater flow.

Soil pH is a measure of the acidity or alkalinity. Soil acidity is a natural process, however it is generally accelerated by agriculture. In Western Australia, soils which are often acidic include yellow earthy sands in the eastern and north-eastern wheatbelt and the dark grey peaty sands in the southwest (Moore, 2001). Acidic sub-soils may be found underlying neutral to alkaline clays. Soil acidity may impose a number of effects on plant growth including direct toxicities and nutrient deficiencies.

Alkalinity of soils is typically caused by carbonates of calcium and/or sodium. When evaporation exceeds rainfall, various minerals precipitate in soils. If bicarbonate is concentrated in the soil, the pH has a tendency to rise. A soil with alkaline to strongly alkaline characteristics can have a number of nutrient and trace metal deficiencies including phosphorus, nitrogen, copper, zinc manganese and iron. Alkaline soils lead invariably to sodium rich sodic soils.

Ratings adapted by Moore, (2001) for soil pH are:

<table>
<thead>
<tr>
<th>Rating</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;5.5</td>
</tr>
<tr>
<td>Medium</td>
<td>5.5 to 8.0</td>
</tr>
<tr>
<td>High</td>
<td>&gt;8.0</td>
</tr>
</tbody>
</table>
Section 4  Methodology

In addition Mc Arthur (1991), reported surface soils of the Moora, Coorow and Dalwallinu region of Western Australia as having the following typical EC and pH readings.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Profile No.</th>
<th>EC (1:5) mS/m</th>
<th>pH (1:5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siliceous Sand</td>
<td>(GNT10)</td>
<td>1</td>
<td>5.7 to 6.9</td>
</tr>
<tr>
<td>Siliceous Sand</td>
<td>(MRA5)</td>
<td>1 to 2</td>
<td>5.6 to 6.1</td>
</tr>
<tr>
<td>Siliceous Sand</td>
<td>(MRA6)</td>
<td>1</td>
<td>5.9 to 6.2</td>
</tr>
<tr>
<td>Siliceous Sand</td>
<td>(MRA9)</td>
<td>1 to 2</td>
<td>6 to 7.1</td>
</tr>
<tr>
<td>Siliceous Sand</td>
<td>(MRA3)</td>
<td>2 to 4</td>
<td>4.7 to 4.8</td>
</tr>
<tr>
<td>Siliceous Sand</td>
<td>(WH3)</td>
<td>1 to 3</td>
<td>6.1 to 6.7</td>
</tr>
<tr>
<td>Yellow Duplex Soil</td>
<td>(MRA1)</td>
<td>7 to 100</td>
<td>6.5 to 8.8</td>
</tr>
<tr>
<td>Yellow Duplex Soil</td>
<td>(MRA7)</td>
<td>2 to 3</td>
<td>5.7 to 5.9</td>
</tr>
<tr>
<td>Yellow Duplex Soil</td>
<td>(MRA8)</td>
<td>1 to 2</td>
<td>5.3 to 6.3</td>
</tr>
<tr>
<td>Yellow Duplex Soil</td>
<td>(WH1)</td>
<td>3 to 44</td>
<td>5.6 to 6.1</td>
</tr>
<tr>
<td>Red Duplex Soil</td>
<td>(MRA2)</td>
<td>1 to 22</td>
<td>5.3 to 6.1</td>
</tr>
<tr>
<td>Red Duplex Soil</td>
<td>(WH2)</td>
<td>28 to 210</td>
<td>5.9 to 9.2</td>
</tr>
<tr>
<td>Red Earth</td>
<td>(MRA10)</td>
<td>2 to 3</td>
<td>5.7 to 7.0</td>
</tr>
<tr>
<td>Red Clay</td>
<td>(MRA4)</td>
<td>12 to 170</td>
<td>8.6 to 9</td>
</tr>
</tbody>
</table>

4.2.3 Potential Acidifying Soils Survey

Acidifying soils typically result from sulphate in the groundwater reacting with sediments containing iron oxides and organic matter. The chemical reaction produces iron sulphides in the sediments. These sediments can be clay or sand, usually dark grey and soft. Below the water table, the lack of air prevents oxygen reacting with the iron sulphides. Such sediments are commonly known as potential acid sulphate soils (PASS) because they have potential to oxidise and produce sulphuric acid leachates. When exposed to air, these sulphides oxidise to generate acids. The acid lowers the groundwater pH, makes soil nutrients less available to plants and therefore reduces farm productivity.

Field pH tests at 1 m intervals were mixed at 1:5 ratio with deionised water, shaken by hand for two minutes, and the pH measured using hand-held pHScan models, made by Eutech Cybermetrics. A measurement of pH<4 for the soil paste indicated oxidation of sulphides had probably occurred in the past. This indicates that an actual acid sulphate soil is present.

Field pH tests do not account for any sulphide present that has not yet been oxidised. To test for potential acid sulphate soils (PASS), soil samples were treated with 30% hydrogen peroxide (H₂O₂, pH adjusted 4.5 to 5.5 with a few drops of 0.1 M NaOH). The test was done with a few mL of peroxide and a small sample of soil in clear test tubes. When effervescence (sometimes violent) had ceased, further peroxide was added until the reaction appeared complete. The pH of the resultant mixture was measured as pH_{fox}. A combination of three factors is considered in arriving at a positive field sulphide identification:
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- The strength of the reaction with peroxide is a useful indicator but cannot be used alone. Organic matter and other soil constituents such as manganese oxides can also cause a reaction. This reaction should be rated.

- A $\text{pH}_{(\text{fox})}$ value at least one unit below field $\text{pH}_{(f)}$ may indicate a PASS. The greater the difference between the two measurements the more indicative the value is of a PASS.

- The lower the final $\text{pH}_{(\text{fox})}$ value, the better the indication of a positive result. If the $\text{pH}_{(\text{fox})} < 3$, and the other conditions apply, then it strongly indicates a PASS. As $\text{pH}_{(\text{fox})}$ drops below 3, the more positive the presence of sulphides.

The DEC (formerly Department of Environment) (2006) has reported possible problems can arise from this method as peroxide oxidation of pyrite is less efficient in alkaline samples.

“It is important to note that whilst a useful exploratory tool, soil field $\text{pH}_{(f)}$ and $\text{pH}_{(\text{FOX})}$ tests are indicative only and cannot be used as a substitute for laboratory analysis to determine the presence or absence of ASS. Recent review of field $\text{pH}_{(f)}$ and $\text{pH}_{(\text{FOX})}$ tests in Western Australian soils indicates that these tests provide an accurate identification of ASS in only 60% to 80% of cases and are capable of providing both false positives and false negatives (i.e. may underestimate or overestimate acid-generating potential). Underestimation of acid-generating potential appears to be most common in clays and may be due to poor mixing during the field test" Department of Environment (2006).

In addition, there needs to be caution with such measurements as sulphides may be present in small quantities, and poorly reactive under quick test field conditions. Also samples may contain carbonate, which neutralises some or all acid produced by oxidation. The analytical method Peroxide Oxidation-Combined Acidity and Sulphate (POCAS), would provide more reliable estimate in this situation.

4.2.4 Soil Nutrient Sampling

In the vicinity of representative wetland areas, nitrogenous and phosphorous fertilisers have been applied to promote fodder and cereal crops. Over time the application of these fertilisers may result in nutrient loading of the soil profiles.

Moore (2001) and Bruce and Rayment (1982) developed ratings for soil nutrients Total Nitrogen and Total Phosphorus that enable relevant data to be compared to baseline and assessed in terms of loadings. Mc Arthur (2001), reported surface soils of the Moora, Coorow and Dalwallinu region of Western Australia as having the following typical Total Nitrogen and Total Phosphorus contents:

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Total N</th>
<th>Total P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mg/kg)</td>
<td>(mg/kg)</td>
</tr>
<tr>
<td>Siliceous Sand</td>
<td>&lt;100 to 300</td>
<td>23 to 50</td>
</tr>
<tr>
<td>Yellow Duplex Soil</td>
<td>100 to 400</td>
<td>29 to 89</td>
</tr>
<tr>
<td>Red Duplex Soil</td>
<td>100 to 200</td>
<td>32 to 100</td>
</tr>
<tr>
<td>Red Clay</td>
<td>&lt;100</td>
<td>15 to 110</td>
</tr>
</tbody>
</table>

The purpose of determining phosphorus sorption is to predict the capacity of the soil to bind and reduce the potential for phosphorus leachates entering the surface water and groundwater resources. The Phosphorus Sorption Index (PSI) is defined as the ratio of Phosphorus adsorbed from solution to the concentration of Phosphorus remaining in solution when it reaches equilibrium. A soil with a high PSI is considered desirable because they are less likely to lose Phosphorus by leaching and therefore less likely to pollute waterways.

Ratings for Total Phosphorus concentrations are taken from Moore, (2001):
Sorption of water soluble phosphorus from groundwater and surface water is largely controlled by chemical reactions with aluminium and iron, to form less soluble, more stable compounds (Bolland et al., 2003). These reactions mostly take place on the surface of soil constituents (clays, oxides of iron and aluminium, organic matter and aluminium and iron compounds coating the surface of sands). After the initial surface reaction, the adsorbed phosphorus diffuses slowly towards the interior of the particle and becomes less available to plants. This diffusion can occur in dry conditions.

P sorption is closely related to soil P buffer capacity. With increasing buffer capacity, the proportion of available P (whether native or from fertiliser), which is absorbed by plants, tends to decrease.

In this study only nine surface soil samples were collected throughout the representative wetland areas to provide analyses for Total Nitrogen, Total Phosphorus and Phosphorus Sorption Index (PSI). Samples were collected from areas in the middle slopes and valley floor. All of these samples were within the recommended holding times for analysis of the nutrient analytes. A more comprehensive sampling programme may be warranted in the future.

### 4.2.5 Water Sampling

In September 2006, groundwater quality samples were taken from all of the 45 recently completed groundwater monitoring bores. Prior to sample collection, bores were purged (three bore volumes) to gain a representative groundwater sample. Samples were collected using a Teflon bailer. The samples were analysed in the field to determine E.C. and pH.

A total of 14 groundwater samples taken from different depths (BMC56d, BMC54d, BMC58i, BMC87ob, BMC59d, BMC64i, BMC59ob, BMC72d, BMC76ob, BMC74i, BMC66d, BMC83ob, BMC70d, and BMC70ob) were sent for analysis of E.C., TDS, and major ions by ALS Environmental Laboratory. Four surface-water samples (2 x at Fresh/Brackish Wetlands, 2 x at Fresh/Brackish to Valley Floor Wetlands) were also collected for laboratory testing. A single rainfall sample was collected from Koobabbie and analysed for chloride concentration. In addition, a duplicate sample (duplicate of BMC66d) was submitted with a sample batch. A blank sample containing distilled water was also included as part of the QA/QC procedures.

All samples were stored at 4°C during transport and dispatch to the laboratory. Due to the scale of field sampling, the groundwater samples exceeded the laboratory recommended holding times for analysis of pH.

In addition to the soil assessments, a series of down-hole EC profiles were conducted in selected monitoring bores in order to identify vertical salinity stratification. All shallow bores having a slotted section through the upper water table (BMC56ob, BMC59ob, BMC60ob, BMC63ob, BMC64ob, BMC69ob, BMC70ob, BMC75ob, BMC76ob, BMC77ob, BMC78ob, BMC83ob, and BMC85ob) were selected for EC profiling. The EC profiles were carried out using a TPS Model 90C salinity meter (made by TPS Pty. Ltd. of Brisbane, Australia). EC readings were recorded in the slotted interval at 0.2 m increments. Plots of EC verses depth were used to identify salinity stratification.
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Classifications of salinity are taken from Tille et al (2001):

<table>
<thead>
<tr>
<th>Class</th>
<th>EC (mS/m)</th>
<th>Total Dissolved Solids (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>&lt;90</td>
<td>&lt;500</td>
</tr>
<tr>
<td>Marginal</td>
<td>90 to 195</td>
<td>500 to 1,070</td>
</tr>
<tr>
<td>Brackish</td>
<td>195 to 900</td>
<td>1,707 to 5,000</td>
</tr>
<tr>
<td>Saline</td>
<td>&gt;900</td>
<td>&gt;5,000</td>
</tr>
</tbody>
</table>

4.2.6 Groundwater Levels

Interpretations of groundwater level trends and possible threats of increased salinisation and waterlogging were made using the water and salt balance results and the HARTT-XLS model (Hydrograph Analysis: Rainfall and Time Trends; Lote-Tree Software, 2004). The HARTT-XLS model is a statistical analysis tool that differentiates the effects of rainfall fluctuations and the underlying trend of groundwater levels over time. Due to the influences of evaporation on groundwater levels, only monitoring bores with groundwater levels greater than 4 m below ground were used in the analyses.

Density differences occur as groundwater salinity in the valley floor areas is typically higher than that beneath the mid to upper slopes. Groundwater beneath the wetland areas typically has densities in the range of 1.08 to 1.16 g/cm³, compared to more regional groundwater densities of 1.002 g/cm³. Any future groundwater flow modelling, or hydrogeological cross section analysis will need to include density stratification effects due to the variable densities.

Macumber (1991) indicated that hypersaline systems may become self-perpetuating. Incident rainfall, surface water flows, vertical downward outflow of hypersaline brines and evaporation control the water and salt balance of the individual wetlands. The observed low groundwater gradients may not generate hydraulic gradients and heads immediately up-basin of the wetlands sufficient to flush the brines present beneath the valley floor via groundwater throughflow.

To observe the impacts of local density variations within each representative wetland, fresh water equivalent environmental heads were interpreted. The EC measured in each monitoring bore was converted to a water density. These density values were applied to the measured groundwater levels to interpret fresh water equivalent heads. Diagram 1 presents the rationale and method for converting these equivalent heads. Future work will also need to account for these density variations.
4.2.7 Aquifer Testing

To gain an understanding of local groundwater flow system hydraulics, a series of field-testing and laboratory testing was carried out on continuous core samples taken from the Geoprobe drilling and in-situ measurements in the monitoring bores. Results of laboratory testing were compared to hydraulic parameters interpreted from slug tests, in which the response to a slug of water introduced into the monitoring bore is measured.

Slug tests were conducted in 44 groundwater monitoring bores. Slug tests measurements were interpreted using the method described by Bouwer and Rice (1976) and Cooper, Bredehoeft and Papadopolus (1995) in Kruseman, (1994). An average 2 m head of water was either displaced with a bailer or a known volume of water added to individual monitoring bores. Recovery of the groundwater level was measured using an Odyssey data logger fitted with a capacitance probe, set to log at 5 second intervals. Graphical analysis of the measured responses was carried out on the early-time (1 to 5 minute) data.

Typically, the Bouwer method represents shallow unconfined aquifers and the Cooper, Bredehoeft and Papadopolus method the deeper confined aquifers. For comparison, however, both methods were used to analyse data from the shallow and deeper bores. The interpretations of hydraulic conductivity are usually semi-quantitative, with accuracy of the results constrained by numerous factors linked to monitoring bore construction, point-source stressors and the small-scale of the tests.
For comparison, suggested average values (McArthur, 1991) for horizontal saturated hydraulic conductivity for a variety of aquifers from South-western Australia are presented below:

<table>
<thead>
<tr>
<th>Type of Aquifer</th>
<th>Estimated Typical Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary sand</td>
<td>4</td>
</tr>
<tr>
<td>Saprock over major faults</td>
<td>3</td>
</tr>
<tr>
<td>Saprock over minor faults</td>
<td>1</td>
</tr>
<tr>
<td>Saprock over mafic/intermediate dykes</td>
<td>0.7</td>
</tr>
<tr>
<td>Saprock over granite</td>
<td>0.7</td>
</tr>
<tr>
<td>Mixed Tertiary sands and clays</td>
<td>0.5</td>
</tr>
<tr>
<td>Pallid zone over major faults</td>
<td>0.5</td>
</tr>
<tr>
<td>Pallid zone over minor faults</td>
<td>0.5</td>
</tr>
<tr>
<td>Pallid zone over mafic/intermediate dykes</td>
<td>0.2</td>
</tr>
<tr>
<td>Pallid zone of granite</td>
<td>0.08</td>
</tr>
<tr>
<td>Tertiary clays</td>
<td>0.01</td>
</tr>
</tbody>
</table>

A total of 16 drill core samples were laboratory tested (Western Geotechnics, Perth) to interpret hydraulic conductivity. These samples were taken from both clay and sandy cores.

### 4.3 Conceptual Modelling

In order to refine the current hydrogeological understanding of the catchment and functionality of the nominated representative wetland areas, several sub-tasks were completed. These included:

- A review of groundwater hydrographs from the monitoring bores installed by DEC in 2002, corrected to surveyed elevations, and identifying trends and possible causes of such trends.
- Review of groundwater hydrographs from a limited number of monitoring bores installed by the Marchagee Catchment Group and the Waddy Forest LCDC.
- Development of local catchment water table maps (elevation and depth to water) for each representative wetland.
- Interpretation of local and regional groundwater flow directions using measured groundwater levels and surveyed wetlands.
- Interpretation of vertical groundwater flow within each representative wetland area.
- Interpretation horizontal groundwater flow within each representative wetland area.
- Interpretation of salinity stratification.
- Calculation and interpretation of aquitard characteristics.

To develop an understanding of the relationship between surface water and groundwater, a series of groundwater flow nets were developed in vertical sections beneath the representative wetland areas.
These were used to identify the relationship between the wetlands, the water table and aquifers within the weathered bedrock profile.

Surface runoff and rainfall infiltration rates were applied to evaluate the surface water entering the groundwater system, allowing estimates of rainfall, surface water and throughflow contributing to the water and salt balances of the wetland areas.

Further analysis and interpretation of water and soil quality was made with the aim of:

- Producing and interpreting groundwater/surface water salinity maps measured from monitoring bores and wetlands.
- Comparing field soil and water quality measurements (EC and pH) and laboratory results within each representative wetland area.
- Interpreting nutrient data to form an understanding of the threat of nutrient loading within each representative wetland.
- Preparing tri-linear and stiff diagrams for comparison of results of chemical analyses between and within each representative wetland area.

### 4.4 Water and Salt Balances

An understanding of water movement on the surface and in the subsurface profiles is required to understand the physical processes responsible for biodiversity asset degradation, particularly the altered hydrology and salt mobilisation. This understanding includes the processes that govern the volumes of water infiltrating the soil zone, the amount of deep drainage leaving the root zone to recharge the groundwater systems, and the subsurface processes controlling groundwater throughflow and discharge. These processes are part of a connected hydrological system that is described as a catchment water balance. Simple one and two dimensional water balance models are useful for estimating the relative water balance and impacts under various combinations of climate, soil type, slope, land-use and management practices. One dimensional models are typically used to define inputs such as salt concentration. Two dimensional models define horizontal and vertical spatial changes, such as flow nets.

#### 4.4.1 Daily Soil Water Balance Model

A simple mathematical representation of sub-surface soil drainage and recharge is a bucket model. Bucket models are generally conceptualised as the water capacity of the root zone across the catchment. The bucket fills with infiltration and empties through evapotranspiration. Actual evaporation and soil moisture are calculated on the basis of a simple daily soil water balance. Potential evapotranspiration is estimated as a proportion of the pan evaporation. For simplicity, it is assumed that the soil and unsaturated zone act in a manner similar to a ‘leaking bucket’, with recharge to groundwater occurring only when the soil moisture content is above field capacity.

The AgET model was initially used to calculate daily water balance of the BMNDRC using 1954 to 1993 Coorow and/or Dalwallinu daily rainfall data. A daily soil water balance was developed to estimate periods of wetness and drought whereby deep drainage can be simulated.

A simple daily water balance (W) of the soil can be calculated by taking a soil water storage capacity (S) of 200 mm per meter area and zero respectively as upper and lower limits, rainfall (R) as input and crop evapotranspiration (ETc) as output:

\[ W_n = W_{n-1} + R - ETc \]

So on day n, the daily water balance for the soil, \( W_n \) is evaluated by taking its value on the previous day, adding the rainfall on day n and subtracting the ETc. If the result is less than zero, it is set to zero, while if it is greater than S it is set to S (corresponding to a soil profile at field capacity).
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4.4.2 Predicated Peak Discharge Rates

The Rational Method has been used to determine the peak flows for the BMNDRC. The Rational Method is a universally accepted simplistic method to calculate the peak flood flows of selected Average Recurrence Intervals (ARI) from an average rainfall intensity of the same ARI. The Rational Method incorporates the intensity of the rainfall, the area of the catchment and a coefficient of runoff. In this study, where possible, individual wetland catchments were divided into sub-catchments based on the surface elevation model.

The coefficient of runoff for a catchment depends on the inter-related factors, such as soil type and hydraulic conductivity, land vegetation type, density and slope and intensity of rainfall.

The Rational Formula used for the estimation of the peak discharge is:

\[ Q = 0.278 \frac{C_{10}}{C_{10}} \frac{I_{10}}{I_{tc,Y}} A \]

Where

- \( Q \) = Peak discharge (in m³/s⁻¹).
- \( C \) = A dimensionless run-off coefficient.
- \( I \) = Mean rainfall intensity (mm hr⁻¹) of a storm of the design ARI and duration equal to the time of concentration, \( tc \).
- \( A \) = Catchment area (km²).
- \( CL \) = Amount of vegetation clearing (0-100% of the catchment).

4.4.3 Surface Runoff for Wetlands

The following Rational Formula was used for the estimation of the surface runoff into wetlands:

\[ Q = 0.00278 C I_{tc,Y} A \]

Where

- \( Q \) = Peak discharge (in m³/s).
- \( C \) = A dimensionless run-off coefficient.
- \( I \) = Mean rainfall intensity (mm hr⁻¹) of a storm of the design ARI and duration equal to the time of concentration, \( tc \).
- \( A \) = Catchment area (ha).

In order to estimate the Rational Runoff coefficient ‘\( C \)’ for different soil types, multiple land uses and variable slopes, the wetlands were subdivided into sub-catchments. An average coefficient ‘\( C \)’ for composite areas was calculated on an area-weighted basis using:

\[ C = \frac{\sum Ci \times Ai}{\sum Ai} \]

where \( Ci \) is the coefficient applicable to the area \( Ai \).

The following Rational Runoff Coefficient ‘\( C \)’ was used in the simulations:
Rainfall intensities for different durations and ARI were calculated for the BMNDRC using Coorow rainfall data and the Australian Rainfall and Runoff (AR&R) method (Institute of Engineers, 1987). In large areas, corrections are required to adjust the point rainfall data and account for uneven distribution of the storm over the catchment (Fangmeier et al., 2006). The rainfall intensities with correction factors for use in catchments of 40 km² and 400 km² are presented in Table 4-1.

### Table 4-1 Rainfall Intensities (mm hr⁻¹) and Correction Factors for Representative Wetland Catchments

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Average Recurrence Interval (Years)</th>
<th>Correction Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0.5</td>
<td>19.3</td>
<td>25.4</td>
</tr>
<tr>
<td>1</td>
<td>12.6</td>
<td>16.5</td>
</tr>
<tr>
<td>6</td>
<td>3.6</td>
<td>4.7</td>
</tr>
<tr>
<td>12</td>
<td>2.2</td>
<td>2.9</td>
</tr>
<tr>
<td>24</td>
<td>1.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

### 4.4.4 Predicted Runoff and Deep Flows Using AgET

There are a limited number of stream flow gauging stations in the BMNDRC. Consequently it was necessary to conduct a simulation study to estimate the rates of surface run-off and groundwater recharge under different cropping systems in a season.

AgET is a simple Water Balance Calculating program developed by the Natural Resource Management Unit, Agriculture WA and the University of Melbourne (Argent and George, 1997). The model compares water use and recharge under different land-use rotations on different soil types. It is a bucket model and does not take into account any throughflow from neighbouring areas, only direct rainfall. This model uses average climatic data and representative soil and plant information obtained within the agricultural areas of Western Australia. Estimations of evapotranspiration (ET) are based on the Pan Evaporation Method (FAO, 1977). A pan coefficient of 0.8 is used to calculate potential evaporation from pan evaporation. AgET is not designed to cope with excessive water-logging and lateral flow and therefore has not been used to assess the valley floor flow systems. Crop coefficients for bare soil, cereal crops and native vegetation are presented on Figure 14. The rooting depths for bare soil, cereal crops and native vegetation are summarised in Table 4-2.
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In AgET, water simply moves straight through the soil profile ignoring influences other than plant water use, evaporation and runoff. AgET also does not consider recharge associated with water-logging and preferred pathway flow. As a result, recharge on some soil types may be higher than the model suggests.

The AgET model was initially used to calculate daily water balance of the BMNDRC using Coorow and Dalwallinu daily rainfall data for the period 1954 to 1993. As the seasonal rainfall trend has changed in recent years, rainfall data sets for both Coorow and Dalwallinu were subsequently updated to capture trends from 1966 to 2006. This provided an opportunity to test the sensitivity of the model to changes in daily rainfall.

### Table 4-2 Rooting Depths for Different Vegetation Types

<table>
<thead>
<tr>
<th>Crops/Soil</th>
<th>Rooting Depth (m)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Effective</td>
<td>Maximum</td>
</tr>
<tr>
<td>Bare</td>
<td>0.1</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Cereals</td>
<td>0.2</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Native Vegetation</td>
<td>2</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>

Water use is based on leaf area index of the different crops and this closely ties to rooting depth. The daily water balance for any soil is based upon the soil moisture available over the lesser of the soil layer thickness and the effective rooting depth of the crop. Thus, if the crop or plant has roots in the A-horizon, the balance is performed on the A-horizon: any drainage from the A-horizon goes to the deep flow component. AgET takes no account of the water table and all calculations are carried out as if the water table is too deep to impact on the plants.

The basic steps in the operation of AgET each day are:

1. Determine the rainfall for the day, with allowance made for runoff from intense storms.
2. Determine ET for the day. This is dependent upon the climate (evaporation), monthly crop factor (ability of the plant to grow) and the moisture available in the soil.
3. Perform the water balance for the day by adding rainfall and subtracting ET. This also determines if there is any surface runoff, how much moisture drains into different soil levels and how much water goes to deep flow.
4. Alter the current soil moisture levels to reflect the results of the daily balance.

The water balance components of rainfall, runoff, evapotranspiration, soil storage and deep flow are summed to provide monthly and annual data. Several simulations for each soil type were investigated. Each simulation reported results for probability of exceedence representing a predicted drying climate, mean or current climate and a wet climate. Outputs from these AgET simulations are semi-quantitative.

Estimates of evapotranspiration, runoff and recharge from the Coorow and Dalwallinu water balance outputs were then applied using average annual rainfall from Koobabbie, Buntine and Hakea rainfall stations more suited to the individual representative wetlands. As the seasonal rainfall trend has changed in the recent past, the most representative values for the period from 1966 to 2006 were applied to final water and salt balance estimates.

### 4.4.5 Water and Salt Mass Balance

In the period immediately prior to clearing, the water balance was near equilibrium with recharge seen as small (<1 to 2 mm/annum) and the changes in soil water storage negligible from year to year, although water stored in the soil profile fluctuates with seasonal conditions (Moore, 2001). A change in land use...
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has now resulted in a reduced ability of the soil to store moisture subsequent to high winter rainfall or rainfall from heavy unseasonal storms.

However, in past 20 years it appears that south-western Australia has experienced a decline in annual rainfall, a shift in rainfall season patterns and increased occurrence of high intensity storms. This drying period is typically leading to lowering of water tables. This does not mean there is a significant decrease in the area affected by salinity. It may take many years (if at all) for the water table to decline to a setting from which evaporation does not occur and during this period salt will continue to be mobilised from shallow newly saturated soils. Further, it may take many years to leach mobilised salts from the saturated profile and reach a new equilibrium (Moore, 2001), depending on soil type.

To understand the physical process responsible for dryland salinity and salt mobilisation, an understanding of water movement in the surface and subsurface is required. To develop simple conceptual salt and water balance models all information gained during this study was collated for each representative wetland area into catchment inputs and outputs. Diagram 2 presents a schematic diagram of the conceptual water and salt balance model. Rates of recharge following clearing vary with rainfall, catchment factors and vegetation. Recharge is not uniform through the landscape and is variable between years because it is highly dependent on rainfall.

Each representative wetland catchment was divided into areas covered by cereal crops and native vegetation. Percentages of evapotranspiration, runoff and recharge estimated from the AgET model were applied to the average annual rainfall from the closest BOM station to each wetland area. Horizontal groundwater inflows and outflows were determined for each individual wetland catchment using Darcy’s law. Horizontal groundwater flows were estimated using transmissivity values, cross-sectional areas at the top and bottom of each catchment and hydraulic gradients. In addition, the vertical flow component was inferred to account for the impact of deeper upward groundwater flow from palaeochannel sediments and bedrock on water and salt balances.

Diagram 2: Conceptual Water and Salt Balance Model
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In general terms, groundwater recharge is defined as that part of the rainfall which reaches the watertable via soil and the unsaturated zone. Results from the AgET model provide estimates for evapotranspiration, recharge and runoff. The results were applied to estimate annual groundwater volume inputs and outputs for each representative wetland. Salt volumes were calculated using measured salinity concentrations of rainfall and groundwater measured during the investigation.

4.5 Management and Recommendations

Following interpretation of all relevant information, recommendations are provided for cost-effective future work where information gaps occur and further data are required to evaluate management strategies. Where possible, recommendations for groundwater modelling and various monitoring strategies for groundwater, surface water, and terrestrial vegetation have been provided. Given the current limited availability of time-series data, however, this study is only able to provide a limited review of management actions. Future investigations and feasibility studies will be able to draw upon knowledge gained from this study. In addition, definitive management solutions (and robust asset specific risk assessments) will require ongoing monitoring at the assets and throughout the catchment for a number of years.
Section 5  Fresh/Brackish Wetland Findings

5.1 Wetlands Area W011 and W012

Fresh/Brackish Wetlands W011 and W012 form part of a suite of wetlands located on the Balgerbine Soil System in the west of the catchment. The topographic catchment area is 1,783 ha, which contains 135 ha (8%) of remnant vegetation. These two wetlands are separated by a sand spit with surface water seasonally flowing from W011 eastward to W012.

Limited assessments of water quality in 2004 to 2005 by the DEC revealed that W011 is fresh to brackish (40 to 230 mS/m), with W012 being saline (70 to >300 mS/m). Acidity ranged from pH 7.3 to 8.9 at W011 and pH 4.2 to 9.4 at W012. The highest acidity readings occurred during the summer months, accompanied by annual drying of the lakes, with water depths ranging between nil to ~0.40 m in W011 and nil to ~1.0m in W012.

Historically, these wetlands were described as having a clay rich substrate, which could persist at depth. Recent drilling nearby W012, however, showed this clay substratum is overlaying a hard silcrete horizon. The fringing vegetation of the wetlands consists of Melaleuca sp., Baumea rubiginosa, and Juncus acutus. More information can be found in Davies and Ladd (2000) and Richardson et al (2005).

The location of the Fresh/Brackish Wetlands is shown in a regional context on Figure 1. Photographs of the wetland are shown on Plate 2. Interpretations of the Fresh/Brackish Wetlands hydrogeology are provided on Figure 15 (a to j), inclusive of hydrostratigraphy, groundwater levels and groundwater salinity. Data collected in the Fresh/Brackish Wetlands during the recent hydrogeological investigations are presented in Appendix D, inclusive of lithological and bore logs, salinity profiles and results of hydraulic tests.

5.2 Results of Landholder Interviews

Discussions with the landholder indicated that clearing of native vegetation surrounding these wetlands commenced in the early 1960’s and continued through to the 1980’s. Minimum tillage and no burning practices occur today. Many of the wetlands were fenced in 1999 to control the movement of stock. Large numbers of kangaroos, however, still frequent the remnant native vegetation surrounding the wetlands.

It was reported that most rainfall infiltrates into the sand with surface flows only recorded following significant high rainfall events. These high rainfall events have caused significant erosion in the past.

The clayey substrate limits vertical infiltration such that both groundwater and wetland water levels rise during years of high rainfall. For example, in 1963 and 1964 higher rainfall periods, the water level rose by up to 0.5 m in some wetlands in the local area. Groundwater levels have continued to rise in some wetlands. This is seen at an old wind-less well that was constructed adjacent to a wetland in the early years and is now submerged under water by about 2 m.

The wetland water quality has been reported as comparatively saline. This is probably due to the effects of evaporation on shallow water tables increasing near-surface salt concentrations. Neighbouring wetlands are fresher and are used to water stock and house gardens.

Surrounding soils were reported to be acidic and water repellent, as typically found in “Banksia, pear country, and native pine” environments.

5.3 Monitoring Bore Construction Details

A total of seven groundwater monitoring bores were completed between June and August 2006. This complements the existing seven groundwater bores constructed along the Buntine-Marchagee Road and the Midlands Road. Details of monitoring bore construction are presented in Table 5-1. Locations of monitoring bores, including those previously drilled, are shown on Figure 15(a).

Bores ranged in depth between 3.5 and 51 m. All bores were constructed with 50 mm uPVC casing, with a slotted section between 2 to 4 m in length through the relevant aquifer zones. Three deeper
piezometers (BMC72d, BMC73d and BMC74d) were drilled to basement. A single intermediate monitoring bore was completed at site BMC74i to test a deep transported colluvium succession. To complement these bores, three shallow monitoring bores (BMC75ob, BMC76ob and BMC77ob) were installed on the shoreline of the wetland.

5.4 Wetland Geology

Dunal aeolian deposits of the Balgerbine Soil System form a sandy blanket of superficial formations over the local catchment. This sandy cover is typically limited to a thickness of several metres, being greatest on crests and mid-slopes and least on the valley floor. In addition, gravel over sand is also often seen on some crest areas, likely resulting from fluvial or alluvial winnowing.

Results from drilling in the lower catchment suggest that a deep weathered profile has been incised and subsequently infilled by a succession of transported colluvium and palaeochannel sediments. BMC74d, located on mid-slope dunes to the west of the wetland area, intersected a 25 m thick succession of transported clayey colluvium below thin superficial sands. The transported sediments were interbedded with sub-angular to moderately-rounded quartz pebbles up to 30 mm in diameter. This sequence overlies palaeochannel sediments consisting of sub-rounded sands and silty clays. This sequence was also about 25 m thick. Interpreted catchment stratigraphy is presented on cross-sections shown on Figures 15 (b and c). A detailed snapshot of the interpreted wetland stratigraphy is presented on Figure 15 (j)
### Table 5-1  Fresh/Brackish Wetlands W011 and W012 – Summary of Monitoring Bore Completions

<table>
<thead>
<tr>
<th>Bore</th>
<th>RL</th>
<th>Status</th>
<th>Date Completed</th>
<th>Collar (m AHD)</th>
<th>Ground Level (m AHD)</th>
<th>Casing</th>
<th>Top of Gravel</th>
<th>Top of Bentonite</th>
<th>Top of Cement/Gravel</th>
<th>Airlift Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Collar Height</td>
<td>Depth Drilled</td>
<td>Casing</td>
<td>Top</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(m)</td>
<td>(m agl)</td>
<td>Casing</td>
<td>Depth</td>
<td>Slotted Interval</td>
<td>Slotted Length</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td>(m)</td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMC72d</td>
<td>286.49</td>
<td>Shallow</td>
<td>31/07/2006</td>
<td>6</td>
<td>0.57</td>
<td>5.7</td>
<td>2.6 - 5.7</td>
<td>3.1</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>BMC73d</td>
<td>285.07</td>
<td>Shallow</td>
<td>31/07/2006</td>
<td>6</td>
<td>0.2</td>
<td>5.87</td>
<td>1.87 - 5.87</td>
<td>4</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>BMC74d</td>
<td>295.86</td>
<td>Deep</td>
<td>14/07/2006</td>
<td>51</td>
<td>0.2</td>
<td>51</td>
<td>47.0 - 51.0</td>
<td>4</td>
<td>46</td>
<td>12</td>
</tr>
<tr>
<td>BMC74i</td>
<td>295.87</td>
<td>Intermediate</td>
<td>14/07/2006</td>
<td>27</td>
<td>0.2</td>
<td>27</td>
<td>23.0 - 27.0</td>
<td>4</td>
<td>22</td>
<td>6</td>
</tr>
<tr>
<td>BMC75ob</td>
<td>283.72</td>
<td>Shallow</td>
<td>26/07/2006</td>
<td>3.5</td>
<td>0.2</td>
<td>3.31</td>
<td>1.31 - 3.31</td>
<td>2</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>BMC76ob</td>
<td>284.38</td>
<td>Shallow</td>
<td>26/07/2006</td>
<td>3.5</td>
<td>0.2</td>
<td>3.31</td>
<td>1.31 - 3.31</td>
<td>2</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>BMC77ob</td>
<td>285.87</td>
<td>Shallow</td>
<td>26/07/2006</td>
<td>3.5</td>
<td>0.2</td>
<td>3.31</td>
<td>1.31 - 3.31</td>
<td>2</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Section 5

Fresh/Brackish Wetland Findings

5.4.1 Generalised Soil Description

The Fresh/Brackish Wetlands area is located within the Balgerbine Soil System. The soils and geomorphology of the superficial formation are typically:

- Undulating shallow aeolian dunes, with potential for intradunal lakes.
- Deep aeolian yellow sands in the higher dunes.
- Sandy duplexes.
- Sandy colluvium from deeply weathered granite on hill slopes.

A thin band of cemented sand and/or silcrete was intersected up to 3 m below ground level in areas closely adjacent to wetland areas. This intensely indurated rock comprised well cemented, sub-rounded quartz sand and was generally less than 1m in thickness. Spatially, this band appears to be discontinuous. This stratigraphic layer was generally overlaying a sandy zone comprised of organic rich lake sediments.

5.4.2 Soil EC and pH Profiles

Soil EC was measured at 1 m intervals on drill cuttings from each bore within the wetland area. Diagrams are presented in Appendix D and as raw data in Appendix J.

Results show generally low (9 to 27 mS/m) EC values in the top 2 m at the three sites. These are similar to those reported by Mc Arthur (1991). BMC074d, located high on dunal sands, reported EC values generally between 2 and 11 mS/m, typical of sandy soils. In contrast, two deeper zones at 252 and 265 mAHId reported medium (39 and 43 mS/m) EC values. These values are linked to saline groundwater in gravely aquifer zones within the transported and palaeochannel sediments.

EC in BMC72d and BMC73d was generally uniform throughout the profiles. BMC72d is located low in the wetland landscape and represents a typical discharge zone where evaporation from the shallow water table causes increased (24 mS/m EC) salt concentrations. Below 2 m depth, EC ranged between 9 and 16 mS/m, with a few spikes (up to 32 mS/m) of medium EC values associated with hypersaline groundwater.

BMC73d located down gradient of the wetland area reported lower EC values of between 3 and 12 mS/m. Again a few spikes up to 15 mS/m in EC were measured as a result of the intersection of hypersaline groundwater.

Results of EC in the upper 2 m of the soil profile typically indicate links to soil type and recharge. The dunal sands on the higher slopes appear to have a low salt store, indicating recharge by surface infiltration and matrix flow. The zones of high EC at depth may indicate release of salt from storage due to rising water tables and recharge through preferred flow paths.

Soil pH measured on the drill samples showed a typical neutral pH associated with fresher waters, becoming more alkaline as the salinity increased. A medium pH of 7.3 to pH 7.7 was measured in the upper 2 m of superficial sands, similar to that reported by Mc Arthur (2001). A high soil pH of 8.2 to 8.3 is associated with the transported and palaeochannel successions.

The silty sands of the superficial formation tended to have low EC readings and a neutral pH. There was no indication of acidic type soils in this wetland area. When comparing soil pH and EC with soil types, there appears to be a correlation with transported clayey soils having low EC and slightly alkaline pH. Palaeochannel sandy sediments correspond to a medium EC and high pH.
Section 5

Fresh/Brackish Wetland Findings

5.4.3 Potential Acidifying Soils Analysis

A number of landscape features indicate the possible presence of acid sulphate soil conditions beneath this wetland area. These features include the low-lying topography and shallow water table around the wetlands, abundant Melaleuca sp. and iron-stained waterlogged soils. In addition, an offensive odour due to hydrogen sulphide gas was identified during drilling dark grey muds in BMC75ob.

Results from field testing using the peroxide oxidation method showed little chemical reaction indicating a low potential for acidic soils. Results from field testing are presented in Table 5-2. Soil pH throughout the profile was typically neutral to slightly alkaline. Only two samples from BMC75ob recorded a moderate oxidation reaction. All other samples recorded either no reaction or a low reaction.

It has been reported that peroxide oxidation of pyrite becomes less efficient at alkaline pH. (EPA, 1999). Buffering effects may also promote self-neutralisation due to the presence of organic material and carbonates identified in this wetland area.

![Table 5-2](image)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>BMC75</th>
<th>BMC76</th>
<th>BMC77</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH&lt;sub&gt;w&lt;/sub&gt;</td>
<td>pH&lt;sub&gt;f&lt;/sub&gt;</td>
<td>Reaction</td>
</tr>
<tr>
<td>1.0</td>
<td>7.5</td>
<td>7.1</td>
<td>L</td>
</tr>
<tr>
<td>2.0</td>
<td>7.5</td>
<td>7.0</td>
<td>M</td>
</tr>
<tr>
<td>3.0</td>
<td>7.3</td>
<td>6.7</td>
<td>M</td>
</tr>
<tr>
<td>4.0</td>
<td>8.2</td>
<td>7.3</td>
<td>L</td>
</tr>
<tr>
<td>5.0</td>
<td>8.4</td>
<td>7.3</td>
<td>L</td>
</tr>
</tbody>
</table>

Note: pH<sub>w</sub> - pH of 1:5 soil: water
pH<sub>f</sub> - pH of 1:5 soil: water following oxidation with Hydrogen Peroxide
Reaction – N= no reaction, L= low reaction, M= moderate reaction, H= high reaction

5.4.4 Soil Laboratory Analysis

Results are summarised in Table 5-3, with laboratory certificates presented in Appendix I. The wetland area reported low concentrations for most parameters measured when compared to suggested baseline values, however BMC77ob reported high Total Nitrogen. A Nitrate concentration below 0.1 mg/kg and Total Nitrogen of less than 20 mg/kg were reported for the lake bed.

Results indicate Total Nitrogen has the highest concentration in the mid-slopes, probably associated with the application of fertilisers. Further down slope on the wetland shoreline Total Nitrogen was reduced by 70%. Within the lake sediments Total Nitrogen reduced further to less than 20 mg/L. If the Total Nitrogen (as ammonium nitrogen) is not taken up quickly by plants it is converted to nitrate by the process of nitrification.

Low soil nitrate concentrations on the middle slopes possibly indicates significant amounts of Total Nitrogen are being absorbed readily by plants. Within the lake sediments nitrate concentrations were lowest (<0.100 mg/kg). This may be due to denitrification, where by nitrate is lost due to anaerobic conditions associated with the waterlogged lake sediments.

The phosphorus concentrations recorded in this wetland area show a similar trend to Total Nitrogen concentrations. The higher concentrations reported in middle slope soils are possibly linked to fertiliser application. The decline in Total Phosphorus concentrations from 17 mg/kg beneath mid-slopes to about...
Section 5

Fresh/Brackish Wetland Findings

7 mg/kg down gradient to the lake sediments may indicate sorption of fertilisers beneath the middle slope soils, as would be expected by the greater absorptive capacity of phosphate than nitrate to sediments.

The measured PSI ranged between 2 and 4 mg/kg/log_{10}. Based on other sites within the BMNDRC this value appears to be very low and therefore indicates the local soils may be more likely to lose Phosphorus by leaching, with potential for contamination in waterways lower in the landscape.

<table>
<thead>
<tr>
<th>Site</th>
<th>Locality</th>
<th>Nitrate as N (mg/kg)</th>
<th>Total Nitrogen (mg/kg)</th>
<th>Total Phosphorus (mg/kg)</th>
<th>Phosphate Sorption Index (mg/kg/log_{10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark1</td>
<td>Deep Sandy Loam Soil Type</td>
<td>-</td>
<td>100 to 200</td>
<td>32 to 100</td>
<td>-</td>
</tr>
<tr>
<td>BMC77</td>
<td>Middle slope</td>
<td>1.01</td>
<td>470</td>
<td>17</td>
<td>3</td>
</tr>
<tr>
<td>BMC76</td>
<td>Lake shore</td>
<td>16.8</td>
<td>140</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Wetland W012</td>
<td>Lake bed</td>
<td>&lt;0.100</td>
<td>&lt;20</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

1 Suggested values for common soils in the South-West Hydrogeological Region (Mc Arthur, 1991)

5.5 Wetland Hydrogeology

5.5.1 Surface Water Runoff

The Fresh/Brackish Wetlands area was divided into four sub-catchments based on discrete ridge lines identified on the Digital Elevation Model (Figure 15a). One sub-catchment has sand sheets and low dunes over granite and comprises about 1,069 ha or 60% of the total catchment area. The second sub-catchment is characterised by shallow gravel and loamy duplexes over granite and accounts for an estimated 15% (268 ha) of the catchment area. The third sub-catchment is characterised by deep yellow sands and sandy duplexes and represents about 268 ha or 15% of the catchment area. The final sub-catchment of about 178 ha or 10% is represented by deep yellow sands associated with wetlands W011 and W012. The catchment peak flows are calculated for 0.5, 1, 6, 12 and 24-hour rainfall events, for 1, 2, 5, 10, 20, 50 and 100-year ARIs in Table 5-4.

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Peak Flows (m^3/sec) at Average Recurrence Interval in Years</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td></td>
<td>28.6</td>
<td>37.7</td>
<td>49.5</td>
<td>57.8</td>
<td>69.0</td>
<td>85.4</td>
<td>99.1</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>20.5</td>
<td>26.8</td>
<td>34.7</td>
<td>40.1</td>
<td>47.5</td>
<td>58.2</td>
<td>67.1</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>6.3</td>
<td>8.2</td>
<td>10.6</td>
<td>12.3</td>
<td>14.5</td>
<td>17.8</td>
<td>20.5</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>3.9</td>
<td>5.1</td>
<td>6.7</td>
<td>7.7</td>
<td>9.1</td>
<td>11.2</td>
<td>12.9</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>2.4</td>
<td>3.1</td>
<td>4.1</td>
<td>4.8</td>
<td>5.7</td>
<td>7.1</td>
<td>8.2</td>
</tr>
</tbody>
</table>
Section 5

Fresh/Brackish Wetland Findings

Similarly, expected runoff volumes calculated for this wetland catchment are given in the Table 5-5. As an example, the catchment will have a peak flow of 14.5 m³/sec for a 6-hour duration 20-year ARI rainfall event. For this event the peak runoff volume would be 313, 947 m³.

Table 5-5  Fresh/Brackish Wetlands W011and W012 – Runoff Volumes

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Peak Volumes (m³) at Average Recurrence Interval in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>858</td>
</tr>
<tr>
<td>1</td>
<td>73,729</td>
</tr>
<tr>
<td>6</td>
<td>135,340</td>
</tr>
<tr>
<td>12</td>
<td>170,012</td>
</tr>
<tr>
<td>24</td>
<td>205,701</td>
</tr>
</tbody>
</table>

5.5.2 Groundwater Level Data

The initial measurements of depth to groundwater in the seven monitoring bores were taken in September 2006 and are presented in Table 5-6. Interpreted lateral and vertical flow line cross-sections are presented on Figures 15 (b and c). Interpreted water table contours for September 2006 are shown on Figure 15 (d and h) and depths to the water table on Figure 15(e). A more detailed interpretation of wetland groundwater elevations is presented on Figure 15j.

Groundwater levels range between about 1.0 m below ground surface in the east, beneath the low-lying areas of the catchment, to 6.3 m below middle slopes to the west. The hydraulic gradient of the water table is locally about 10 m/km (0.01). The direction of groundwater flow is generally towards the northeast. Environmental water heads due to the water quality (TDS) based density variations show little change from the observed heads.

The hydraulic gradients in the deeper aquifer appear to be similar to the shallow aquifer (Table 5-6). BMC 74i/d, located high on the dune to the west of the wetlands, shows a downward head, typical of a local recharge area.

Table 5-6  Fresh/Brackish Wetlands W011 and W012 – Measured Groundwater Levels

<table>
<thead>
<tr>
<th>Bore No.</th>
<th>Profile</th>
<th>Collar RL (m AHD)</th>
<th>Observed Groundwater Levels</th>
<th>Fresh Water Equivalent Environmental Heads</th>
<th>Difference In Head</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC072d</td>
<td>Deep</td>
<td>286.49</td>
<td>1.15</td>
<td>285.34</td>
<td>1.12</td>
</tr>
<tr>
<td>BMC073d</td>
<td>Deep</td>
<td>285.07</td>
<td>2.04</td>
<td>283.03</td>
<td>2.01</td>
</tr>
<tr>
<td>BMC074d</td>
<td>Deep</td>
<td>295.86</td>
<td>6.53</td>
<td>289.33</td>
<td>6.34</td>
</tr>
<tr>
<td>BMC074i</td>
<td>Intermediate</td>
<td>295.87</td>
<td>6.12</td>
<td>289.75</td>
<td>6.10</td>
</tr>
<tr>
<td>BMC075ob</td>
<td>Shallow</td>
<td>283.72</td>
<td>0.66</td>
<td>283.06</td>
<td>0.65</td>
</tr>
<tr>
<td>BMC076ob</td>
<td>Shallow</td>
<td>284.38</td>
<td>1.46</td>
<td>282.92</td>
<td>1.41</td>
</tr>
<tr>
<td>BMC077ob</td>
<td>Shallow</td>
<td>285.87</td>
<td>1.13</td>
<td>284.74</td>
<td>1.12</td>
</tr>
</tbody>
</table>
Section 5

Fresh/Brackish Wetland Findings

BMC 17D, representing groundwater trends in the deep weathered profile in this subcatchment, was selected for groundwater level trend analysis. Groundwater level data covers four years from 2002 to 2006. Average monthly rainfall data (1911 to 2006) from the Koobabbie BOM station was used in the model. Table 5-7 presents a summary of results. Results suggest that BMC 17D located on the upper slopes, has a 147 mm/year rate of groundwater level decline.

Data collected over the last year since installation (Figure 15m) indicates that the groundwater levels are relatively stable, with little response to rainfall over the 2007 winter. Since installation, the groundwater levels in the low-lying areas are typically about 0.5 m below ground surface and in steady state, with recharge balancing the effects of evapotranspiration.

<table>
<thead>
<tr>
<th>Bore</th>
<th>Landscape Position</th>
<th>Predicted Lag (months)</th>
<th>Predicted Long-Term Groundwater Level Change</th>
<th>Predicted Average Rate of Change (mm/year)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC 17D</td>
<td>Upper Slope</td>
<td>0</td>
<td>Decline</td>
<td>-147</td>
<td>0.81</td>
</tr>
</tbody>
</table>

5.5.3 Groundwater Recharge

Long-term seasonal groundwater level fluctuations in BMC15ob range from 0.83 m in 2003, through to 0.64 m in 2004 and 0.55 m in 2005, reflecting differences in rainfall recharge (Figure 15n). Assuming an average effective specific yield of 0.1 for the strata in the zone of water table fluctuations, these seasonal variations indicate recharge of 55 mm in a dry year, to 83 mm in a particularly wet one. An annual recharge of 69 mm is estimated in an average rainfall year. The recharge will vary according to the hydraulic conductivity of the surface soil and other factors.

The Fresh/Brackish Wetlands area occurs in an area of deep sandy loam soil. Soil depths used in the water balance simulations were developed from existing AgET model parameters and bore logs. Soil depths included 1.5 m deep horizon A and 1.5 m deep horizon B for bare soil, cereals and perennial grasses. An available water of 135 mm m⁻¹ with Ksat of 8 mm day⁻¹ was used for horizon A and 195 mm m⁻¹ with Ksat of 20 mm day⁻¹ used for horizon B. These values were derived from AgET standards for such soil types. Predicted surface run-off and groundwater recharge generated under bare soils, cereal crops and native vegetation are presented in Table 5-8. All results are reported as proportions of annual rainfall, with estimates for both modelled periods (1953 to 1993 and 1966 to 2006) presented in Table 5-8.
## Section 5

### Fresh/Brackish Wetland Findings

Table 5-8  Fresh/Brackish Wetlands W011 and W012 – Regional Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>Annual Rainfall (mm)</th>
<th>DEEP SANDY LOAM SOIL TYPE</th>
<th>ET (mm/annum)</th>
<th>Runoff (mm/annum)</th>
<th>Recharge (mm/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
<td>Native Vegetation</td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>317 (280)</td>
<td>194 (224)</td>
<td>277 (285)</td>
<td>283 (286)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>50%</td>
<td>389 (379)</td>
<td>214 (250)</td>
<td>306 (333)</td>
<td>320 (365)</td>
<td>2 (0)</td>
</tr>
<tr>
<td>25%</td>
<td>446 (437)</td>
<td>246 (279)</td>
<td>346 (371)</td>
<td>394 (395)</td>
<td>15 (10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coorow Rainfall Station</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>288 (270)</td>
<td>190 (187)</td>
<td>275 (265)</td>
<td>271 (261)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>50%</td>
<td>361 (324)</td>
<td>224 (224)</td>
<td>306 (304)</td>
<td>315 (305)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>25%</td>
<td>423 (391)</td>
<td>241 (241)</td>
<td>338 (320)</td>
<td>363 (343)</td>
<td>10 (10)</td>
</tr>
<tr>
<td>Dalwallinu Rainfall Station</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>288 (270)</td>
<td>190 (187)</td>
<td>275 (265)</td>
<td>271 (261)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>50%</td>
<td>361 (324)</td>
<td>224 (224)</td>
<td>306 (304)</td>
<td>315 (305)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>25%</td>
<td>423 (391)</td>
<td>241 (241)</td>
<td>338 (320)</td>
<td>363 (343)</td>
<td>10 (10)</td>
</tr>
</tbody>
</table>

Note: 317 Daily water balance AgET 1953 to 1993 daily rainfall data  
(280) Daily water balance AgET 1967 to 2006 daily rainfall data

Using these regional estimates and applying them to the annual rainfall average of 324 mm for Koobabbie BOM station, more representative estimates for predicted runoff and recharge were calculated. For ease of interpretation results are presented in Table 5-9 as percentages of annual rainfall.
Section 5

Fresh/Brackish Wetland Findings

Table 5-9  Fresh/Brackish Wetlands W011 and W012 – Local Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>ET (% of Annual Rainfall)</th>
<th>Runoff (% of Annual Rainfall)</th>
<th>Recharge (% of Annual Rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
<td>Native Vegetation</td>
</tr>
<tr>
<td>Annual Rainfall (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>261</td>
<td>75%</td>
<td>83%</td>
</tr>
<tr>
<td>50%</td>
<td>324</td>
<td>67%</td>
<td>91%</td>
</tr>
<tr>
<td>25%</td>
<td>374</td>
<td>87%</td>
<td>83%</td>
</tr>
</tbody>
</table>

Note: 324 Daily water balance AgET 1967 to 2006 daily rainfall data

Results indicate that under current rainfall trends, up to 95% of annual rainfall is lost through ET and there is no surface runoff. Recharge estimates range from 29% of annual rainfall for bare soil to 15% for cropped areas and 2% for native vegetation. The Indian Ocean Climate Initiative Report (2006) predicts rainfall trends will continue declining over the next 25 years. This report predicts declines in winter rainfall up to 20%. Under a continued drying climate trend, recharge may decline by 1.5% to 8%, potentially leading to lowering of groundwater levels. An increased occurrence of high intensity storms may, however, influence both recharge rates and potentials for groundwater level decline.

5.5.4 Water Quality Data

Table 5-10 presents a summary of result of field EC and pH measurements. Figure 15 (f and g) show interpretations of the groundwater salinity distributions on cross-sections. A more detailed plan of groundwater and surface water salinity is presented on Figure 15 (i). Table 5-11 presents results of laboratory analyses of both surface water and groundwater, with formal correspondence from the laboratory shown in Appendix I.

The groundwater EC in this wetland area ranges from 266 to 8,010 mS/m, being brackish to saline. On the western sand sheets and low dunes (BMC74d/i) groundwater in the shallow zone represents a local recharge area as identified by a groundwater EC close to marginal quality (200 mS/m). The alkaline pH is possibly linked to bicarbonate in the dunal sands. Groundwater in the deeper gravels within the transported and palaeochannel sediments is saline (972 mS/m).

Down-slope of the dunal sand, BMC77ob reported a brackish EC of 297 mS/m, similar to BMC74i. This area is characterised by a groundwater seep (Figure 15i) with a marginal laboratory EC of 136 mS/m (Table 5-11). BMC72d on the southern edge of wetland W012 reported a brackish EC of 305 mS/m in the deep transported and palaeochannel sediments. A brackish EC of 431 mS/m was also measured in the saprolite formation in BMC73d. The groundwater measured in BMC76ob, located adjacent to W012 reported saline (8,010 mS/m) EC possibly directly linked to the existing saline surface water body.

The groundwater in all areas is typically neutral to slightly alkaline, ranging in pH from 7.2 to 8.0. There appears to be no correlation between shallow and deep groundwater acidity. Increased concentrations of bicarbonate measured in the shallow groundwater may, however, be providing buffering of the pH.
Section 5

Fresh/Brackish Wetland Findings

Table 5-10  Fresh/Brackish Wetlands W011 and W012 – Groundwater EC and pH Field Measurements

<table>
<thead>
<tr>
<th>Bore No.</th>
<th>Profile</th>
<th>Depth (m)</th>
<th>Electrical Conductivity (mS/m)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC072d</td>
<td>Deep</td>
<td>22</td>
<td>305</td>
<td>7.22</td>
</tr>
<tr>
<td>BMC073d</td>
<td>Deep</td>
<td>20</td>
<td>431</td>
<td>7.72</td>
</tr>
<tr>
<td>BMC074d</td>
<td>Deep</td>
<td>51</td>
<td>972</td>
<td>7.31</td>
</tr>
<tr>
<td>BMC074i</td>
<td>Intermediate</td>
<td>27</td>
<td>266</td>
<td>7.99</td>
</tr>
<tr>
<td>BMC075ob</td>
<td>Shallow</td>
<td>6</td>
<td>510</td>
<td>8</td>
</tr>
<tr>
<td>BMC076ob</td>
<td>Shallow</td>
<td>3.5</td>
<td>8,010</td>
<td>7.2</td>
</tr>
<tr>
<td>BMC077ob</td>
<td>Shallow</td>
<td>6</td>
<td>297</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Historical differences in pH in W011 and W012 may be linked to the large difference in the surface water EC (Table 5-11) as a result of the influence of groundwater seepage from W011, evapo-concentration, and the throughflow to W012.

Two methods of presenting results of chemical analyses are Piper (trilinear) and Stiff diagrams. This classification system shows anions and cations to indicate the water type. A plot of each diagram is presented on Figure 15(k and l). Results indicate the groundwater and surface water samples are of type sodium-chloride.

Table 5-11  Fresh/Brackish Wetlands W011 and W012 – Laboratory Water Analyses

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>EC (mS/m)</th>
<th>TDS mg/L</th>
<th>OH</th>
<th>CO₂ mg/L</th>
<th>HCO₃ mg/L</th>
<th>Total Alkalinity mg/L</th>
<th>SO₄ mg/L</th>
<th>S mg/L</th>
<th>Cl mg/L</th>
<th>Ca mg/L</th>
<th>Mg mg/L</th>
<th>Na mg/L</th>
<th>K mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMC72d</td>
<td>311</td>
<td>1,700</td>
<td>&lt;1</td>
<td></td>
<td></td>
<td>57</td>
<td>57</td>
<td>91</td>
<td>30</td>
<td>896</td>
<td>30</td>
<td>85</td>
<td>478</td>
</tr>
<tr>
<td>BMC74i</td>
<td>315</td>
<td>1,610</td>
<td>&lt;1</td>
<td></td>
<td></td>
<td>104</td>
<td>104</td>
<td>84</td>
<td>28</td>
<td>698</td>
<td>24</td>
<td>24</td>
<td>516</td>
</tr>
<tr>
<td>BMC76ob</td>
<td>7,370</td>
<td>48,400</td>
<td>&lt;1</td>
<td></td>
<td></td>
<td>174</td>
<td>174</td>
<td>1,860</td>
<td>619</td>
<td>29,900</td>
<td>228</td>
<td>2,280</td>
<td>16,300</td>
</tr>
</tbody>
</table>

| Surface Water|       |          |    |          |           |                       |          |        |         |         |         |         |        |
| W011        | 136     | 994      | <1 |          |           | 88                    | 88       | 60     | 20      | 495     | 5       | 20      | 353    |
| W012        | 9,170   | 67,600   | <1 |          |           | 274                   | 456      | 730    | 1,890   | 629     | 33,200  | 63      | 623    |

Note:
W011 6678054mN 415123mE
W012 6679456mN 415973mE
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5.4.5 Hydraulic Parameters

To understand the groundwater flow systems, a series of hydraulic tests were carried out on a selection of monitoring bores within each wetland area. A total of seven slug tests were completed in the newly completed monitoring bore. Results of analyses are presented in Table 5-12.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Transmissivity (m²/day)</td>
<td>Average Hydraulic Conductivity (m/day)</td>
</tr>
<tr>
<td>Superficial Formations, Clayey</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Superficial Formations, Sandy</td>
<td>1.3</td>
<td>2.2, 1.9, 1.5</td>
</tr>
<tr>
<td>Transported Sediments, Clayey</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Transported Sediments, Sandy</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Lacustrine Deposits, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Clayey</td>
<td>0.15, 0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>Palaeodrainage, Sandy</td>
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<td>2.3, 1.9, 1.5</td>
</tr>
<tr>
<td>Saprolite</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Saprock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathered Dolerite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The superficial sandy profile has an interpreted hydraulic conductivity of about 2 m/day. Results from laboratory measurements ranged between 0.02 to 2.2 m/day for the superficial sediments and sandy palaeochannel (Table 5-13). Applying an average aquifer thickness of 1 m, a transmissivity of 2 m²/day was calculated. This compares to a measured transmissivity of 1.3 m²/day in BMC75ob.

The deeper transported sediments have interpreted transmissivity of 0.15 m²/day for the clay zone and 1.8 m²/day for the sandy horizons. Sandy zones of hydraulic conductivity about 2 m/day, over an estimated aquifer thickness of about 40 m, have a transmissivity of 80 m²/day. The clayey saprolite in BMC73d has an estimated transmissivity of 0.2 m²/day.

The groundwater system in this wetland area is also characterised by an estimated hydraulic gradient of 0.0025 (dimensionless). Using the Darcy formula:

\[ V = i \frac{k}{p} \]

Where \( V \) is the groundwater flow velocity, \( i \) is the hydraulic gradient, \( k \) is the hydraulic conductivity and \( p \) is the effective porosity. Using an effective porosity of 0.1 (dimensionless) a groundwater velocity of 0.05 m/day was estimated.
## Section 5

### Fresh/Brackish Wetland Findings

#### Table 5-13  Fresh/Brackish Wetlands W011 and W012 – Laboratory Hydraulic Parameters

<table>
<thead>
<tr>
<th>Bore</th>
<th>Sample (m bgl)</th>
<th>Lithology</th>
<th>Formation</th>
<th>Dry Density (t/m³)</th>
<th>Initial Moisture Content (%)</th>
<th>Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC75ob</td>
<td>3.2–3.3</td>
<td>CLAYEY SAND – pale yellow grey, fine to medium grained, sub-rounded to angular.</td>
<td>Palaeochannel</td>
<td>1.77</td>
<td>14.7</td>
<td>0.02</td>
</tr>
<tr>
<td>BMC76ob</td>
<td>0.6–0.7</td>
<td>SAND – yellow brown, fine to medium, sub angular, well sorted.</td>
<td>Superficial Formation</td>
<td>1.66</td>
<td>6.1</td>
<td>2.2</td>
</tr>
<tr>
<td>BMC77ob</td>
<td>3.6–3.7</td>
<td>SAND –, minor pink / red grains.</td>
<td>Palaeochannel</td>
<td>1.9</td>
<td>14.6</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Section 6  Bentonite Wetland Findings

6.1 Wetland Area W056 to W059

There are a small number of wetlands in the region which have a bentonite (montmorillonite-rich) substrate. Most of these occur in the Marchagee and Watheroo areas (Abeyesinghe, 2002). Bentonite found in the region is thought to originate from the weathering of doleritic rocks and is known to occur in Quaternary (1.8mya to present) lacustrine deposits overlying the Moora Group (Abeyesinghe, 2002). Three wetlands with this substrate have been identified within the BMNDRC. These appear to be mostly located in the south-western area of the catchment in association with the Balgerbine Soil System (Griffin & Goulding, 2004). These wetlands have a catchment of approximately 987 ha of which nearly 385 ha (39%) is remnant vegetation.

Wetlands W057 to W059 have a bentonite-rich substrate. Previous work by the DEC indicates that these wetlands represent the only examples in the BMNDRC. Anecdotal evidence from neighbouring landholders suggests that the bentonite wetlands fill with surface water following significant rainfall events or in wetter years. To date, the DEC has not been able to take surface water samples.

Wetland W056 is called Jocks Well, which is a gazetted Nature Reserve. Due to its proximity to wetlands W057 to W059 it has been included in this suite of wetlands. Wetland W056 is an ephemeral wetland with a clay-rich substrate. Limited assessment by the DEC between 2004 and 2005, reveals that water quality is likely to range from fresh to brackish, whilst pH is likely to be neutral to alkaline.

The location of the Bentonite Wetlands is shown in a regional context on Figure 1. Photographs are shown on Plate 3. Interpretations of the Bentonite Wetlands hydrogeology are provided on Figure 16 (a to k). Data on the Bentonite Wetlands from the recent hydrogeological investigations are presented in Appendix E, inclusive of lithological and bore logs, salinity profiles and results of hydraulic tests.

6.2 Results of Landholder Interviews

Past discussions by the DEC with the landholder have revealed that bentonite has been removed from wetlands W057 and W058. Bentonite was removed between 1996 and 1998 to condition the soils of sandy paddocks to assist with water retention and reduce wind erosion. Approximately 90 tonnes was removed from W057 and 18 tonnes from W058. The bentonite is not believed to be of significant economic value.

At W057, a drain was constructed by the landholders to release saline surface water to the saline watercourse which tends in a north-easterly direction towards the valley floor. This drain is believed to be aligned with an underlying dolerite dyke. Previous DEC discussions with landholders revealed that this drain was constructed to improve the health of the fringing vegetation, which appeared to be declining as a consequence of secondary salinity. The date of construction is not known, however, there is anecdotal support for improved health of the fringing vegetation since the drain was constructed. It is unclear to the DEC whether there is a clear relationship between improved vegetation health and the construction of the drain. There is, however, clear evidence of a recruitment event (melaleuca and eucalyptus seedlings) which may be related to such a change, or other significant events such as the removal of stock or the 1999 floods.

A fire occurred in remnant vegetation at W056 following a thunder storm in late – December 2006. The fire was apparently quite small and was allowed to burn itself out. A review of historical aerial photographs showed numerous fire scars from fires which may have occurred in the mid to late – 1950s.

No anecdotal information on past water level change or farming practices was available at the time of this study.

6.3 Monitoring Bore Details

A total of nine groundwater monitoring bores were completed between June and August 2006. These bores complement the earlier monitoring bores constructed along Mason Road. Bore completion details are presented in Table 6-1 and bore locations are plotted on Figure 16(a).
Section 6  Bentonite Wetland Findings

Four deeper monitoring bores (BMC68d, BMC69d, BMC70d and BMC71d) were drilled to basement. Five shallow bores (BMC69ob, BMC70ob, BMC80ob, BMC81ob and BMC82ob) were installed in the immediate vicinity of the wetlands.

Bores ranged in total depth from 1.5 to 30.5 m.

6.4  Wetland Geology

Results from drilling in the vicinity of the Bentonite Wetlands indicate the local catchment is characterised by a thin superficial formation succession, consisting of wind-blown sands and silts of the Balgerbine Soil System. Beneath the sand cover is a succession of predominantly clayey transported colluvium that unconformably rests on weathered bedrock. A west-east section (Figure 16(b)) shows a shallow weathered profile bounded by shallow crystalline bedrock. BMC69d intersected a comparatively deep weathered profile and fresh dolerite bedrock at a depth of 30 m. Such local deep weathering is probably due to the structural setting and chemical processes associated with the dolerite intrusion. As evident in the north-south section (Figure 16 (c)), local preferential weathering has formed a narrow deep valley that has been eroded and subsequently filled by a sequence of transported sediments overlying saprolite and saprock. The interpreted stratigraphy in the north-south cross-section shows a valley-fill profile. The transported sediments are predominantly clayey colluvial successions up to about 13 m thick. Below these more recent sediments lies granite bedrock with various degrees of weathering. A zone of saprock sits on fresh crystalline granite.

The Bentonite Wetlands occur in a mid slope setting that is characterised by thin superficial sands (absent in the lake bed), 1.5 m of interbeds of bentonite and silt and a 0.2 m underlay of silcrete and clayey colluvial successions. The recently inspected bentonite profile was dry and desiccated over the upper 0.5 m, then damp. As anecdotal information suggests, wetting of the full bentonite profile possibly occurs seasonally following significant rainfall.

Three bentonite samples were obtained with the Geoprobe rig at wetland W057. Samples were obtained at depth intervals from 0 - 0.1, 0.3 – 0.4, and 0.5 – 0.6 m. All samples were sent to Western Geotechnics Pty Ltd for X-Ray Differential (XRD) analysis. Results are discussed in section 6.4.4, and laboratory results are in Appendix I.
# Bentonite Wetland Findings

## Table 6-1  Bentonite Wetlands W056 to W059 – Summary of Monitoring Bore Completion

<table>
<thead>
<tr>
<th>Bore</th>
<th>RL</th>
<th>Profile</th>
<th>Date Completed</th>
<th>Depth Drilled (m)</th>
<th>Collar Height (m agl)</th>
<th>Depth Cased (m)</th>
<th>Slotted Interval (m)</th>
<th>Slotted Length (m)</th>
<th>Top of Gravel (m)</th>
<th>Top of Bentonite (m)</th>
<th>Top of Cement/Gravel (m)</th>
<th>Airlift Yield (L/ minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC069d</td>
<td>Collar: 300.58, Ground Level: 300.39</td>
<td>Deep</td>
<td>12/07/2006</td>
<td>30.5</td>
<td>0.18</td>
<td>30.12</td>
<td>28.12 - 30.12</td>
<td>2</td>
<td>26</td>
<td>12</td>
<td>6.25</td>
<td></td>
</tr>
<tr>
<td>BMC069ob</td>
<td>Collar: 300.64, Ground Level: 300.41</td>
<td>Shallow</td>
<td>2/08/2006</td>
<td>3.6</td>
<td>0.22</td>
<td>3.11</td>
<td>1.11 - 3.11</td>
<td>2</td>
<td>0.5</td>
<td>0</td>
<td>6.25</td>
<td></td>
</tr>
<tr>
<td>BMC070d</td>
<td>Collar: 301.90, Ground Level: 301.25</td>
<td>Deep</td>
<td>12/07/2006</td>
<td>16.5</td>
<td>0.58</td>
<td>15.52</td>
<td>13.52 - 15.52</td>
<td>2</td>
<td>11</td>
<td>4</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>BMC070ob</td>
<td>Collar: 301.92, Ground Level: 301.26</td>
<td>Shallow</td>
<td>3/08/2006</td>
<td>3.6</td>
<td>0.5</td>
<td>3.49</td>
<td>1.49 - 3.49</td>
<td>2</td>
<td>0.5</td>
<td>0</td>
<td>trace</td>
<td></td>
</tr>
<tr>
<td>BMC71d</td>
<td>Collar: 313.15, Ground Level: 312.74</td>
<td>Deep</td>
<td>12/07/2006</td>
<td>6</td>
<td>0.4</td>
<td>6.0</td>
<td>4.5 – 6.0</td>
<td>1.5</td>
<td>2</td>
<td>1.5</td>
<td>0</td>
<td>dry</td>
</tr>
<tr>
<td>BMC080ob</td>
<td>Collar: 301.61, Ground Level: 301.42</td>
<td>Shallow</td>
<td>3/07/2006</td>
<td>2</td>
<td>0.18</td>
<td>1.98</td>
<td>0.48 - 1.98</td>
<td>1.5</td>
<td>0.4</td>
<td>0</td>
<td>trace</td>
<td></td>
</tr>
<tr>
<td>BMC081ob</td>
<td>Collar: 302.08, Ground Level: 301.90</td>
<td>Shallow</td>
<td>3/07/2006</td>
<td>1.5</td>
<td>0.17</td>
<td>1.34</td>
<td>0.34 - 1.34</td>
<td>1</td>
<td>0.2</td>
<td>0</td>
<td>dry</td>
<td></td>
</tr>
<tr>
<td>BMC082ob</td>
<td>Collar: 300.81, Ground Level: 300.61</td>
<td>Shallow</td>
<td>3/07/2006</td>
<td>2</td>
<td>0.18</td>
<td>1.87</td>
<td>0.87 - 1.87</td>
<td>1</td>
<td>0.4</td>
<td>0</td>
<td>dry</td>
<td></td>
</tr>
</tbody>
</table>
Section 6  Bentonite Wetland Findings

6.4.1 Soil Descriptions

The Bentonite Wetlands are located within the Balgerbine Soil System. Local soils are typically:

- Linked to undulating dunes with the potential for intradunal lakes.
- Deep aeolian deposited yellow sands in the higher dunes.
- Sandy duplexes.
- Sandy colluvium from deeply weathered granite on hill slopes.
- Isolated claypans with saprolitic bentonite substrate.

6.4.2 Soil EC and pH Profiles

Soil EC was measured at 1 m intervals on drill cuttings from monitoring bores BMC68d, BMC69d, BMC70d and BMC71d. Diagrams are presented in Appendix E and as raw data in Appendix J. Soil samples were not analysed at those bores (BMC80ob, BMC81ob, and BMC82ob) which were hand augered in locations adjacent to wetlands W058 and W059.

Results of EC in the upper 2 m indicate a strong link to soil type, location within the wetland and recharge characteristics. Results at BMC71d show low soil EC values (23 mS/m) in the top 2 m in areas of natural vegetation located away from saline lakebeds. Surface soil salinity at BMC69d was slightly higher (70 mS/m), which is possibly due to the close proximity to a shallow surface water drain. These are similar to those values noted by Mc Arthur (1991) of between 7 to 100 mS/m for yellow duplex soils. BMC68d, located on deep sands adjacent to cropped paddocks reported a medium EC of surface soil of 139 mS/m. Located adjacent to W056, BMC70d also reported a EC in the medium range for the upper 2 m up to 141 mS/m. This is linked to sallow saline groundwater associated with W056 (Jocks Well).

EC within the saprolite/ saprock aquifer in BMC68d and BMC69d reported generally uniform low values throughout the profiles. BMC68d is located low in the wetland landscape and reported values between 6 and 20 mS/m. BMC69d reported similar values with a few minor increases up to 124 mS/m in deeper clayey zones.

At BMC70d the soil salinity decreased at 3 m, perhaps due to a lesser influence of evaporation. Below this depth soil salinity gradually increased to a depth of about 7 m, where salinity increased to 263 mS/m. This is possibly linked to saline groundwater associated with medium to coarse sands within the lower transported sediments. An increase in the high EC range (527 mS/m) was reported at about 13 m bgl (289 m AHD). This zone is also linked to more saline groundwater from a partially weathered saprolite aquifer.

Soil pH measured on the drill samples showed a typical neutral pH (medium range) associated with fresher waters, becoming more alkaline (high range) as the salinity increased. In the lower landscape a medium pH of 6.9 to pH 7.6 was measured in the upper 2 m of superficial sands. BMC70d reported a shallow alkaline pH of 8.4. BMC68d and BMC70d both reported uniform EC values throughout the profile. A high soil pH of 8.2 to 8.3 is associated with the transported and saprolite successions. These values are consistent with field measurements under taken by Mc Arthur (1991) in yellow duplex soils.

The silty sands of the superficial formation tended to have low to medium EC readings and a corresponding neutral pH. There was no acidic pH (low range) measured in this wetland area. When comparing soil pH and EC with soil types, there appears to be a correlation with transported clayey soils having low EC and slightly alkaline pH. Sandy sediments within the transported and saprolite zones correspond to a medium EC and pH.
6.4.3 Potential Acidifying Soils Analysis

The low-lying topography and shallow water table indicates the possible presence of acid sulphate soil conditions. Results from field testing using the peroxide oxidation method show very little chemical reaction indicating a low potential for acidic soils. Results from field testing are presented in Table 6-2. The soil pH throughout the profile was typically neutral to slightly alkaline. Only two samples, from BMC68 and from BMC69, recorded a low oxidation reaction. All other samples shared no reaction.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>BMC68</th>
<th>BMC69</th>
<th>BMC70</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH&lt;sub&gt;w&lt;/sub&gt;</td>
<td>pH&lt;sub&gt;f&lt;/sub&gt;</td>
<td>Reaction</td>
</tr>
<tr>
<td>1.0</td>
<td>7.1</td>
<td>6.9</td>
<td>N</td>
</tr>
<tr>
<td>2.0</td>
<td>7.5</td>
<td>7.0</td>
<td>L</td>
</tr>
<tr>
<td>3.0</td>
<td>7.6</td>
<td>6.8</td>
<td>N</td>
</tr>
<tr>
<td>4.0</td>
<td>7.6</td>
<td>7.3</td>
<td>N</td>
</tr>
<tr>
<td>5.0</td>
<td>7.6</td>
<td>7.2</td>
<td>N</td>
</tr>
</tbody>
</table>

Note: pH<sub>w</sub> - pH of 1:5 soil: water
pH<sub>f</sub> - pH of 1:5 soil: water following oxidation with Hydrogen Peroxide
Reaction – N= no reaction, L= low reaction, M= moderate reaction, H= high reaction

6.4.4 Soil Laboratory Analysis

Results from XRD analysis at wetland W057 showed that the three samples (0 - 0.1, 0.3 – 0.4, and 0.5 – 0.6 m) are almost identical, being dominantly a smectite clay (Montmorillonite Group) and minor quartz (Appendix I). Smectites are widely found in soils resulting from the weathering of basic rocks such as basalt and dolerite, are typically of variable composition and commonly referred to as bentonite. The XRD trace gave rather poor patterns with broad peaks possibly suggesting a mixture. These gave values of 60 to 63% SiO<sub>2</sub>, 5 to 6% Al<sub>2</sub>O<sub>3</sub>, 24 to 28% MgO, 2 to 3% Na<sub>2</sub>O, 1 to 3% FeO and <0.5% K<sub>2</sub>O. It is likely that these values are diluted with free silica. The high magnesia and low aluminium/iron contents are compatible with saponite. High silica contents are compatible with illite.

Soil samples were taken from a single drill core in August 2006 (BMC70ob) were submitted for analysis of Nitrate, Total Nitrogen, Total Phosphorus and Phosphorus Sorption Index (PSI). For comparison, common values have been reported for Total Nitrogen and Total Phosphorus (Mc Arthur, 1991). Results are summarised in Table 6-3 with laboratory certificates presented in Appendix I.

<table>
<thead>
<tr>
<th>Bore No.</th>
<th>Location</th>
<th>Nitrate as N (mg/kg)</th>
<th>Total Nitrogen (mg/kg)</th>
<th>Total Phosphorus (mg/kg)</th>
<th>Phosphorus Sorption Index (mg/kg/log&lt;sub&gt;10&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Yellow Duplex Soil</td>
<td>-</td>
<td>100 to 400</td>
<td>29 to 89</td>
<td>-</td>
</tr>
<tr>
<td>BMC70ob</td>
<td>Middle slope</td>
<td>36.3</td>
<td>40</td>
<td>&lt;2</td>
<td>45</td>
</tr>
</tbody>
</table>

<sup>1</sup> Suggested values for common soils in the South-West Hydrogeological Region (Mc Arthur, 1991)
The wetland area reported low concentrations for all parameters measured when compared to reported benchmark values. This is likely to be a consequence of the native vegetation upslope of the sample site.

BMC70ob, located at Jocks Well on the mid-slope region within localised natural vegetation reported a moderately low (40 mg/kg) Total Nitrogen concentration. This concentration lies outside the lower limit of the typical range presented by Mc Arthur (1991) for a similar soil type and therefore should be viewed in understanding that there can be considerable seasonal variation due to biological activity and human intervention.

If the Total Nitrogen (as ammonium nitrogen) is not taken up quickly by plants it is converted to nitrate by the process of nitrification. With this in mind, the similar Nitrate concentration (36.3 mg/kg) measured at this site possibly indicates significant amounts are not being absorbed readily by plants and/or little is lost from the root zone by leaching.

Very low concentrations of Total Phosphorus were recorded in this wetland area, with BMC70ob reporting less than 2 mg/kg. The very low clay contents of the sandy soils typically have very low capacities to absorb phosphorus.

The PSI measured at BMC70ob was 45 mg/kg/log\(_{10}\). Based on other sites investigated in this study, this value appears to be high. A soil with a high PSI is considered desirable because they are less likely to lose Phosphorus by leaching and therefore less likely to pollute waterways.

### 6.5 Wetland Hydrogeology

#### 6.5.1 Surface Water Runoff

The catchment representing the Bentonite Wetlands was divided into two sub-catchments (Figure 16a). Soils of the first sub-catchment were identified as deep sands and earths over granite and comprised about 463 ha or 47% of the total catchment area. Wetlands W056, W057 and W058 are located in this sub-catchment. The second sub-catchment was characterised by sandy duplexes and equated to about 524 ha or 53% of the catchment. Surface water from this latter sub-catchment drains towards wetland W059.

The catchment peak flows are calculated for 0.5, 1, 6, 12 and 24-hour rainfall events, associated with 1, 2, 5, 10, 20, 50 and 100-year ARIs and are presented in Table 6-4.

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Peak Flows (m(^3)/sec) at Average Recurrence Interval in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>34.8</td>
</tr>
<tr>
<td>1</td>
<td>24.9</td>
</tr>
<tr>
<td>6</td>
<td>7.6</td>
</tr>
<tr>
<td>12</td>
<td>4.8</td>
</tr>
<tr>
<td>24</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Expected runoff volumes calculated for the Bentonite Wetlands catchment are given in Table 6-5. The Bentonite Wetlands catchment will have a peak flow of 11.1 m\(^3\)/sec for a 12-hour duration 20-year ARI rainfall event. For this event, the peak runoff volume would be 480,012 m\(^3\).
Section 6

Bentonite Wetland Findings

Table 6-5  Bentonite Wetlands W056 to W059 – Runoff Volumes

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Peak Volumes (m³) at Average Recurrence Interval in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>1,045</td>
</tr>
<tr>
<td>1</td>
<td>89,740</td>
</tr>
<tr>
<td>6</td>
<td>164,728</td>
</tr>
<tr>
<td>12</td>
<td>206,929</td>
</tr>
<tr>
<td>24</td>
<td>250,369</td>
</tr>
</tbody>
</table>

6.5.2 Groundwater Level Data

The initial measurements of depth to groundwater in the nine monitoring bores were taken in September 2006 and are presented in Table 6-6. Flow lines are presented on vertical cross-sections on Figures 16 (b and c). Water Table elevation contours for September 2006 are shown on Figure 16(d) and as depth to water on Figure 16(e). A more detailed interpretation of water table elevations covering the wetlands within the catchment is presented on Figure 16 (h).

Groundwater levels range between about 0.36 m below ground surface beneath the central low-lying areas of the catchment (Wetland W057) to 4.6 m below ground surface to the east beneath the middle slopes. The hydraulic gradient of the shallow aquifer is locally about 0.002 (dimensionless). The direction of groundwater flow is generally towards the northeast, corresponding with the alignment of the local watercourses. Environmental water heads show differences up to 2.1 m in the deeper monitor bores as a result of salinity and density stratification. Little difference is noted in the shallow bores.

There is a pronounced upward head in the vertical successions beneath BMC 69 and nearby wetland W057. The observed differential between the shallow and the deepest screened profiles is about 1 m however using corrected environmental water heads a differential of about 0.6 m is calculated. This compares with an observed downward head differential beneath BMC 70 of about 0.65 m.
Section 6

Bentonite Wetland Findings

<table>
<thead>
<tr>
<th>Bore</th>
<th>Profile</th>
<th>Collar RL (m AHD)</th>
<th>Observed Groundwater Levels (m btc)</th>
<th>Fresh Water Equivalent Heads (m AHD)</th>
<th>Difference In Head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC68d</td>
<td>Deep</td>
<td>306.10</td>
<td>4.6</td>
<td>301.50</td>
<td>4.58</td>
</tr>
<tr>
<td>BMC69ob</td>
<td>Shallow</td>
<td>300.64</td>
<td>1.4</td>
<td>299.24</td>
<td>0.67</td>
</tr>
<tr>
<td>BMC69d</td>
<td>Deep</td>
<td>300.58</td>
<td>0.36</td>
<td>300.22</td>
<td>+0.02</td>
</tr>
<tr>
<td>BMC70ob</td>
<td>Shallow</td>
<td>301.92</td>
<td>1.53</td>
<td>300.39</td>
<td>1.52</td>
</tr>
<tr>
<td>BMC70d</td>
<td>Deep</td>
<td>301.90</td>
<td>2.16</td>
<td>299.74</td>
<td>1.00</td>
</tr>
<tr>
<td>BMC71ob</td>
<td>Deep</td>
<td>313.15 dry</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BMC80ob</td>
<td>Shallow</td>
<td>301.61</td>
<td>1.51</td>
<td>300.10</td>
<td>1.51</td>
</tr>
<tr>
<td>BMC81ob</td>
<td>Shallow</td>
<td>302.08 dry</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BMC82ob</td>
<td>Shallow</td>
<td>300.81 dry</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Piezometer records for BMC34d, BMC35d and BMC37d were selected for trend analysis. Groundwater level data cover four years from 2002 to 2006. The Hakea BOM rainfall station that provides average monthly rainfall data for 96 years period from 1909 to 2005 was used in the model. Table 6-7 presents a summary of results.

All bores indicate a groundwater level decline up to 280 mm/yr, irrespective of the location in the landscape. There may also be a trend for increasing recharge lag (increased infiltration travel time to the water table) for locations higher in the catchment.

Similar changes are seen in short-term groundwater level monitoring in the newly installed bores. Typically, both the shallow and deep bores show stable to declining trends (Figure 16n). There is, however, a marked difference in response to rainfall in shallow bores compared to deeper bores. This is indicative of the recharge characteristics of deep yellow sands.

<table>
<thead>
<tr>
<th>Bore</th>
<th>Aquifer</th>
<th>Predicted Lag (months)</th>
<th>Predicted Long-Term Groundwater Level Change</th>
<th>Predicted Average Rate of Change (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC 34D</td>
<td>Middle</td>
<td>9</td>
<td>Decline</td>
<td>-280</td>
</tr>
<tr>
<td>BMC 35D</td>
<td>Middle</td>
<td>3</td>
<td>Decline</td>
<td>-158</td>
</tr>
<tr>
<td>BMC 37D</td>
<td>Lower</td>
<td>1</td>
<td>Decline</td>
<td>-16</td>
</tr>
</tbody>
</table>

6.5.3 Groundwater Recharge

Long-term groundwater hydrographs from BMC 33ob were used to estimate recharge rates for this setting (Figure 16o). Long-term seasonal water level fluctuations range from 0.67 m in 2003, through to 0.73 m in 2004 and 0.82 m in 2005, assuming these differences reflect differences in rainfall recharge.
Assuming an average specific yield of 0.1 for the strata in the zone of water table fluctuations, these seasonal variations indicate recharge ranging from about 67 mm in a dry year, to 82 mm in a particularly wet one. This implies an annual recharge of about 74 mm in an average rainfall year, however the amount of recharge at any particular location will vary according to the infiltration capacity of the surface soil and as a consequence of geology and vegetation cover.

The Bentonite Wetlands area is comprised of a sandy clay/shallow sandy duplex soil type. Soil depths used in the water balance simulations were developed from existing AgET model parameters and bore logs. Soil depths used in the water balance simulations included 0.2 m deep horizon A and 0.8 m deep horizon B for bare soil, cereals and perennial grasses. An available water of 100 mm m⁻¹ with $K_{sat}$ of 2 mm day⁻¹ was used for horizon A and an available water of 80 mm m⁻¹ with $K_{sat}$ of 10 mm day⁻¹ used for horizon B. These values were derived from AgET standards for such soil types. Predicted surface run-off and groundwater recharge generated under bare soils, cereal crops and native vegetation are presented in Table 6-8.

### Table 6-8 Bentonite Wetlands W056 to W059 – Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>Annual Rainfall (mm)</th>
<th>ET (mm/annum)</th>
<th>Runoff (mm/annum)</th>
<th>Recharge (mm/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
<td>Native Vegetation</td>
<td>Bare Soil</td>
</tr>
<tr>
<td>75%</td>
<td>317 (280)</td>
<td>206 (244)</td>
<td>275 (276)</td>
<td>283 (17)</td>
</tr>
<tr>
<td>50%</td>
<td>389 (379)</td>
<td>239 (277)</td>
<td>318 (344)</td>
<td>335 (343)</td>
</tr>
<tr>
<td>25%</td>
<td>446 (337)</td>
<td>280 (305)</td>
<td>361 (387)</td>
<td>392 (393)</td>
</tr>
<tr>
<td>Coorow Rainfall Station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>288 (270)</td>
<td>214 (211)</td>
<td>272 (364)</td>
<td>267 (264)</td>
</tr>
<tr>
<td>50%</td>
<td>361 (324)</td>
<td>243 (252)</td>
<td>318 (299)</td>
<td>310 (299)</td>
</tr>
<tr>
<td>25%</td>
<td>423 (391)</td>
<td>278 (267)</td>
<td>254 (259)</td>
<td>378 (359)</td>
</tr>
<tr>
<td>Dalwallinu Rainfall Station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: 317 (280) Daily water balance AgET 1953 to 1993 daily rainfall data
(280) Daily water balance AgET 1967 to 2006 daily rainfall data

Under medium rainfall scenario, results show that more than 300 mm/annum representing about 77% annual rainfall is lost by evapotranspiration. As a proportion of annual rainfall, this rate increases up to about 90% with a projected drying climate. The model reported particularly little surface runoff (3 to 9%). Recharge estimations indicate significantly greater recharge under bare soils than under cereal crops. The simulation reported no recharge occurs under native vegetation.
Bentonite Wetland Findings

In a medium year, recharge rates for the western areas (Coorow) range between 70 mm (18%) for bare soils compared to 34 mm (9%) for cereal crops. The dryer eastern areas (Dalwallinu) reported a lower rate of 56 mm under bare soils and 28 mm under cereal crops.

When comparing rainfall periods 1953 to 1993 and 1966 to 2006 there has been an estimated 2 to 8% decline in annual rainfall in recent times. For example, this has lead to nil recharge in bare soil areas in the western catchment area (Coorow) from 40 mm estimated in the 1953 to 1993 period. Due to the drying rainfall pattern, recharge rates in cropped areas have declined by 100%.

Using the regional estimates and applying them to the annual rainfall average of 345 mm for Hakea BOM station, more representative estimates for predicted runoff and recharge were calculated. Table 6-9 presents results of this simulation as proportions of annual rainfall.

### Table 6-9  Bentonite Wetland W056 to W059 – Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>Annual Rainfall (mm)</th>
<th>ET (%) of Annual Rainfall</th>
<th>Runoff (%) of Annual Rainfall</th>
<th>Recharge (%) of Annual Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hakea Rainfall Station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>276</td>
<td>82%</td>
<td>116%</td>
<td>52%</td>
</tr>
<tr>
<td>50%</td>
<td>345</td>
<td>75%</td>
<td>92%</td>
<td>91%</td>
</tr>
<tr>
<td>25%</td>
<td>396</td>
<td>69%</td>
<td>77%</td>
<td>91%</td>
</tr>
</tbody>
</table>

Note: 280 Daily water balance AgET 1967 to 2006 daily rainfall data

Under current rainfall trends, up to 92% of annual rainfall is lost through plant uptake (ET). The shallow sandy duplex type soil associated with this wetland indicates only 10% surface runoff under bare soils. Areas under vegetation cover reported nil recharge. Wetland recharge estimates under bare soil range from 5% for drying climate to 15% for wet years. As predicted by the Indian Ocean Climate Initiative Report (2006), rainfall trends are predicted to continue declining over the next 25 years. They report as much as a 20% decline in rainfall. With this in mind, under a continued drying climate trend recharge may reduce to near zero, leading to lowering of groundwater levels. However, an increase in high rainfall events may however, influence recharge and groundwater levels.

### 6.5.4 Water Quality Data

Table 6-10 presents a summary of field EC and pH measurements. Figures 16 (f and g) show interpretations of the groundwater salinity distributions on cross-sections. A more detailed snapshot of the interpreted wetland salinity is presented as a plan on Figure 16 (i). Samples were also taken from a number of monitoring bores in September 2006, and submitted to the laboratory for analysis for pH, EC, TDS and major anions and cations. Table 6-11 presents results of laboratory analyses both surface water and groundwater and Certificates of Analyses are provided in Appendix I.

The groundwater EC in this wetland area ranges from 400 to 14,440 mS/m, being brackish to saline. Within the areas under dense vegetation cover, shallow groundwater in BMC80ob has a low EC of about...
Section 6

Bentonite Wetland Findings

400 mS/m. On the eastern sand sheets, BMC68d reported a similar EC of 410 mS/m. Both these sites represented areas of neutral or medium pH (6.7) and conform to possible local recharge areas.

Towards the bentonite wetlands themselves, groundwater EC increases in the shallow aquifers. A maximum groundwater EC of 1,200 mS/m EC was measured in these areas. This is consistent with results from downhole EC profiles (Appendix E). A uniform EC of 1,200 to 1,300 mS/m was recorded in BMC69ob and BMC70ob. BMC69ob reported an alkaline pH of 9.4 and may be linked to the proximity of shallow groundwater to alkaline bentonite clays.

Table 6-10  Bentonite Wetlands W056 to W059 –Groundwater EC and pH Field Measurements

<table>
<thead>
<tr>
<th>Bore No.</th>
<th>Profile</th>
<th>Depth (m)</th>
<th>Electrical Conductivity (mS/m)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC68d</td>
<td>Deep</td>
<td>18</td>
<td>410</td>
<td>6.74</td>
</tr>
<tr>
<td>BMC69ob</td>
<td>Shallow</td>
<td>3.6</td>
<td>1,227</td>
<td>9.44</td>
</tr>
<tr>
<td>BMC69d</td>
<td>Deep</td>
<td>30.5</td>
<td>1,130</td>
<td>8.02</td>
</tr>
<tr>
<td>BMC70ob</td>
<td>Shallow</td>
<td>16.5</td>
<td>1,261</td>
<td>6.2</td>
</tr>
<tr>
<td>BMC70d</td>
<td>Deep</td>
<td>3.6</td>
<td>14,440</td>
<td>6.32</td>
</tr>
<tr>
<td>BMC71d</td>
<td>Deep</td>
<td>6</td>
<td>dry</td>
<td>-</td>
</tr>
<tr>
<td>BMC80ob</td>
<td>Shallow</td>
<td>2</td>
<td>400</td>
<td>6.4</td>
</tr>
<tr>
<td>BMC81ob</td>
<td>Shallow</td>
<td>1.5</td>
<td>dry</td>
<td>-</td>
</tr>
<tr>
<td>BMC82ob</td>
<td>Shallow</td>
<td>2</td>
<td>dry</td>
<td>-</td>
</tr>
</tbody>
</table>

The salinity of the shallow groundwater decreases upslope of the wetlands, such as in BMC68d (410 mS/m). This is characteristic of recharge domains where increased groundwater depths reduce the influence of evaporation. The hypersaline groundwater found in the deeper aquifer associated with the topographic low near Jocks Well is associated with the saprock.

The groundwater in all areas is typically neutral to alkaline, ranging in pH from 6.2 to 9.4. There appears to be no correlation between shallow and deep groundwater acidity. The increased concentrations of bicarbonate measured in the shallow groundwater may, however, be providing buffering of the acidic deeper groundwater.
Piper trilinear and Stiff diagrams have been prepared to enable comparisons of chemical analyses of groundwater. Both methods use anions and cations to indicate the water type. A plot of each method is presented on Figure 16(l and m). Results indicate the groundwater is of a type sodium-chloride.

### 6.5.5 Hydraulic Parameters

A series of hydraulic tests were carried out on a selection of monitoring bores within the wetland area. A total of 5 slug tests were completed in each newly completed monitoring bore. Results of analyses are presented in Table 6-12.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Transmissivity</td>
<td>Average Hydraulic Conductivity</td>
</tr>
<tr>
<td></td>
<td>(m²/day)</td>
<td>(m/day)</td>
</tr>
<tr>
<td>Superficial Formations, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superficial Formations, Sandy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transported Sediments, Clayey</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Transported Sediments, Sandy</td>
<td>6.3, 14</td>
<td></td>
</tr>
<tr>
<td>Lacustrine Deposits, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Sandy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saprolite</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Sprock</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Weathered Dolerite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clay sediments within the transported sediments have interpreted hydraulic conductivity of about 0.2 m/day. This compares to the more sandy horizons of 6 to 14 m/day. Results from a single laboratory sample (BMC70ob) reported 0.002 m/day for silty sandstone within the transported sediments (Table 6-13). A range between 0.01 and 4 m/day for mean hydraulic conductivity values for similar sediments has been reported by Tille, et al (2001). Saprolite in BMC70d has an interpreted transmissivity of 2.2 m²/day. A similar interpretation of 2.1 m²/day in BMC69d was reported for saprock.
## Section 6

### Bentonite Wetland Findings

#### Table 6-13  Bentonite Wetlands W056 to W059 – Laboratory Hydraulic Parameters

<table>
<thead>
<tr>
<th>Bore</th>
<th>Sample (m bgl)</th>
<th>Lithology</th>
<th>Formation</th>
<th>Dry Density (t/m³)</th>
<th>Initial Moisture Content (%)</th>
<th>Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC 70ob</td>
<td>2.2 – 2.3</td>
<td>SILTY SANDSTONE - medium to coarse, sub-angular, cemented, poorly sorted.</td>
<td>Transported Sediments</td>
<td>1.93</td>
<td>9.7</td>
<td>0.002</td>
</tr>
</tbody>
</table>
Section 7

Gypsum Wetland Findings

7.1 Wetland Area W001 and W002

Gypsum lakes or playas have a distinctive chemistry that causes the formation of calcium sulphate (gypsum CaSO₄ 2H₂O) crystals. A few examples have been identified in the northwest of the BMNDR, on Koobabbie, and in the east, just north of Bailey Road adjacent to the main drainage line. All examples found thus far are located in a similar proximity to the main braided drainage line and appear to be largely isolated from surface water flows by sand-dominated aeolian lunettes.

The Gypsum Wetlands investigated in this study comprise two wetlands identified as W001 and W002. Previous work by the DEC indicates that these wetlands represent the best examples of this geomorphic-sedimentologic wetland in BMNDR. W001 has abundant gypsum crystal formations (crystals are often 20 to 30mm long). The precipitation of gypsum crystals is linked to the presence of elevated concentrations of calcium and sulphate under the influence of evaporation of groundwater from the lakebed. W002, which is located about 200 m to the west of W001, has a halite-rich clayey lakebed substrate, with small gypsum crystals throughout the surrounding lunette. Limited assessment of water quality during 2004 to 2005 by the DEC has revealed that W001 is fresh to marginal (32 to 216 mS/m), with W002 being slightly less variable (41 to 162 mS/m). pH ranges from 2.0 to 4.2 at W001 and 4.1-5.9 at W002.

Surface water flows into W001 appear to be localised and likely to be sourced only from the immediate vicinity of the lunettes. In contrast, W002 has a surface water inlet/outlet on the southern edge. The presence of a delta consisting of red clays at the inlet/outlet of this wetland indicates that sediments deposited in this wetland are likely sourced from surrounding watershed formed by neighbouring paddocks. The differing contributions of surface water/groundwater at each of these wetlands may explain the different gypsum crystal characteristics and water quality.

In the context of possible groundwater sources, wetlands W001 and W002 lay immediately east of the main braided drainage line of the BMNDR, and southeast of South Waddy Road, at the confluence of the Latham Lakes Chain and the BMNDR catchment. The catchment of the Latham Lakes Chain is about the same size as the BMNDR.

The topographic catchment area is 3,991 ha, which contains 578 ha (14%) of remnant vegetation. Significant areas of vegetation within the vicinity of W001 and W002 have been set aside for conservation by the landholder. Several taxa of note can be found within or near to these wetlands including Caladenia drakeoides ms (Critically endangered), and Halosarcia koobabbiensis ms (Priority 1).

The location of the Gypsum Wetlands is shown in a regional context on Figure 1. Plate 4 shows photographs of the wetlands. Interpretations of the Gypsum Wetlands hydrogeology are provided on Figure 17 (a to l). Data on the Gypsum Wetlands from the recent hydrogeological investigations is presented in Appendix F, inclusive of lithological and bore logs, salinity profiles and results of hydraulic tests.

7.2 Results of Landholder Interviews

Discussions with the landholder indicated the land adjacent to the wetland area was cleared around 1919. Most paddocks adjacent to the valley floor were cleared around the same period. An article was written by the landholders’ father in 1949 (Rudduck, 1949), which indicated that paddocks adjacent to W001 and W002, were reported becoming saline from as early as 1932. This article also indicated that the development of salinity in this area “appeared gradually over the years, receiving an impetus when the country became saturated …..some 9 years before” (circa 1940).

Minimum tillage and no burning practices have occurred since 1995. Today there is little cropping undertaken adjacent to the wetlands.

The property was reported to have numerous bores and wells. Long-term farm records, which extend prior to the 1950’s, indicate that over time some of these have become saline. In general, however, groundwater levels in these bores and wells have changed little. In 1996, four shallow groundwater
Section 7

Gypsum Wetland Findings

Monitoring bores were installed by the Waddy Forest LCDC within or near the wetland sub-catchment area. In 1998 an additional four monitoring bores were installed by the LCDC in the same catchment. Groundwater monitoring records for these bores commence in June 1996, and April 1998 respectively. These records cover the 1999 flood events, capturing the rising of the water table in response to these events and the subsequent lowering of the water table as a consequence of recent dry years. It was reported during the 1999 floods that stream flow was significant both on the property and in the main braided drainage line.

7.3 Monitoring Bore Construction Details

A total of 13 groundwater monitoring bores were completed between June and August 2006. These complement four monitoring groundwater bores installed by the Waddy Forest LCDC in 1996 and the four in 1998, and those installed by the DEC in 2002. Details of monitoring bores are presented in Table 7-1, with bore locations shown on Figure 17(a).

The new bores range in total depth from 4.9 to 52 m. In contrast to other deep bores, BMC60d was completed with a 6 m slotted section. Five deep monitoring bores (BMC59d, BMC60d, BMC61d, BMC62d and BMC64d) were drilled to basement in the lower parts of the wetland area. A single intermediate monitoring bore (BMC64i) was drilled on the valley floor to investigate a deep transported colluvium succession overlying palaeochannel sediments. Seven shallow monitoring bores (BMC59ob, BMC60ob, BMC61ob, BMC63ob, BMC64ob, BMC64ob and BMC79ob) were installed in the wetland area.

The rationale for the selection of sites for BMC60, BMC61 and BMC62 was not only for the assessment of the groundwater characteristics of the Gypsum wetlands, but also based upon the potential for future studies on the Ecological Water Requirements of Salmon Gum woodlands. A number of these woodlands on Koobabbie Farm have significant biodiversity value for the conservation of birds such as Carnaby's Cockatoo (*Calyptorhynchus latirostris*). In addition, BMC64d, BMC64i and BMC64ob were installed on an old gazetted road, called Hogbin Road, which crosses the main drainage line. These monitoring bores were installed to characterise the groundwater beneath the valley floor. These bores are likely to represent the groundwater conditions of the Buntine Palaeodrainage rather than specifically those present at wetlands W001 and W002.

7.4 Wetland Geology

The catchment of the Gypsum Wetlands is formed of shallow stony and loam soils of the Inering Soil System; the wetlands actually occur in the Wallambin Soil System at the confluence of the BMNDRC and Latham Lakes Chain. The Inering Soil System overlies a thin succession of transported colluvium and weathered bedrock. Interpreted stratigraphy is presented on Figure 17 (b, c, f, and i). Beneath the high and middle slopes a succession of superficial sands and silts, up to 10 m thick, overlays transported clayey sediments of interbedded quartz sand, clay and gravel. Beneath the middle slopes BMC62d intersected transported sediments to 19 m below ground. A basal quartz vein was also intersected at this site.

Towards the valley floor, palaeochannel sediments were intersected in BMC61d. The succession comprised sub-rounded sands and silty clays, between 27 and 44 m below ground. Further to the west, beneath the valley floor, BMC59d intersected a thick 15 m profile of bleached pallid clays.

7.4.1 Soil Descriptions

The Gypsum Wetlands are located within the Inering Hills and Wallambin Soil Systems. Local soils are typically:

- Red/yellow sandy and loamy duplex soils and loams.
- Hillcrest and slopes derived from weathered granite with shallow red stony soils and rock outcrops.
- Considerable areas of shallow and deep laterite/gravel to the east of the wetlands.
Section 7

Gypsum Wetland Findings

- Dolerite dykes along ridge crests and traversing many of the paddocks.

Soils beneath the lower valley are typically linked with salt and playa lake chains of the Wallambin Soil System and interpreted Buntine Palaeodrainage. Lacustrine soils and calcareous loamy playa soils are typically found.
### Gypsum Wetland Findings

#### Table 7-1 Gypsum Wetlands W001 and W002 – Summary of Monitoring Bore Completions

<table>
<thead>
<tr>
<th>Bore</th>
<th>RL Collar (m AHD)</th>
<th>Ground Level (m AHD)</th>
<th>Profile</th>
<th>Date Completed</th>
<th>Depth Drilled (m)</th>
<th>Collar Height (m agl)</th>
<th>Depth Cased (m)</th>
<th>Slotted Interval (m)</th>
<th>Slotted Length (m)</th>
<th>Top of Gravel (m)</th>
<th>Top of Bentonite Gravel (m)</th>
<th>Top of Cement/Gravel (m)</th>
<th>Airlift Yield (l/minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC059d</td>
<td>257.93</td>
<td>257.80</td>
<td>Deep</td>
<td>1/07/2006</td>
<td>37</td>
<td>0.13</td>
<td>37.5</td>
<td>35.1-37.1</td>
<td>2</td>
<td>32</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>BMC059ob</td>
<td>257.82</td>
<td>257.62</td>
<td>Shallow</td>
<td>1/08/2006</td>
<td>6</td>
<td>0.2</td>
<td>6</td>
<td>2.0-6.0</td>
<td>4</td>
<td>1.5</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>BMC060d</td>
<td>262.54</td>
<td>262.34</td>
<td>Deep</td>
<td>4/07/2006</td>
<td>45</td>
<td>0.19</td>
<td>44.31</td>
<td>38.31 - 44.31</td>
<td>6</td>
<td>35</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>BMC060ob</td>
<td>262.46</td>
<td>262.25</td>
<td>Shallow</td>
<td>2/08/2006</td>
<td>5.7</td>
<td>0.2</td>
<td>5.68</td>
<td>3.68 - 5.68</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>BMC061d</td>
<td>263.44</td>
<td>263.25</td>
<td>Deep</td>
<td>5/07/2006</td>
<td>52</td>
<td>0.2</td>
<td>51.74</td>
<td>49.74 - 51.74</td>
<td>2</td>
<td>45</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>BMC061ob</td>
<td>263.35</td>
<td>263.14</td>
<td>Shallow</td>
<td>2/08/2006</td>
<td>5</td>
<td>0.2</td>
<td>4.95</td>
<td>2.95 - 4.95</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>BMC062d</td>
<td>271.65</td>
<td>271.45</td>
<td>Deep</td>
<td>6/07/2006</td>
<td>29</td>
<td>0.2</td>
<td>27.82</td>
<td>25.82 - 27.82</td>
<td>2</td>
<td>24</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>BMC063ob</td>
<td>257.25</td>
<td>257.04</td>
<td>Shallow</td>
<td>3/07/2006</td>
<td>4.75</td>
<td>0.2</td>
<td>4.09</td>
<td>1.09 - 4.09</td>
<td>3</td>
<td>0.75</td>
<td>0.5</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>BMC064d</td>
<td>262.40</td>
<td>261.70</td>
<td>Deep</td>
<td>7/07/2006</td>
<td>44.7</td>
<td>0.2</td>
<td>43.03</td>
<td>39.03 - 43.03</td>
<td>4</td>
<td>37</td>
<td></td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>BMC064i</td>
<td>262.36</td>
<td>261.64</td>
<td>Intermediate</td>
<td>7/07/2006</td>
<td>26</td>
<td>0.2</td>
<td>24.75</td>
<td>20.75 - 24.75</td>
<td>4</td>
<td>19</td>
<td></td>
<td>8</td>
<td>6.6</td>
</tr>
<tr>
<td>BMC064ob</td>
<td>262.38</td>
<td>261.67</td>
<td>Shallow</td>
<td>1/08/2006</td>
<td>6</td>
<td>0.2</td>
<td>5.92</td>
<td>1.92 - 5.92</td>
<td>4</td>
<td>0.5</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>BMC078ob</td>
<td>256.94</td>
<td>256.71</td>
<td>Shallow</td>
<td>2/08/2006</td>
<td>6</td>
<td>0.21</td>
<td>5.95</td>
<td>1.95 - 5.95</td>
<td>4</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
<td>2.3</td>
</tr>
<tr>
<td>BMC079ob</td>
<td>259.47</td>
<td>259.27</td>
<td>Shallow</td>
<td>2/08/2006</td>
<td>6</td>
<td>0.65</td>
<td>5.93</td>
<td>1.93 - 5.93</td>
<td>4</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
<td>trace</td>
</tr>
</tbody>
</table>
7.4.2 Soil EC and pH Profiles

Soil EC was measured at 1 m intervals on drill cuttings from each bore within the wetland area. The entire soil profile in monitoring bores BMC59d, BMC60d, BMC61d, BMC62d and BMC64d were tested. Diagrams are presented in Appendix F and as raw data in Appendix J.

Results show that soil EC in the top 2 m at the sites within the valley floor range between 14 mS/m to 247 mS/m. BMC61d reported low surface EC of 14 mS/m, while further east away from the valley floor, BMC62d reported up to 100 mS/m. Located within the valley floor, BMC64d, reported high EC values up to 247 mS/m. These are similar to those reported by Mc Arthur (1991).

Soil EC within the transported sediments ranged between 30 mS/m up to 800 mS/m. In the deeper palaeochannel sands EC up to 1,500 mS/m was measured (BMC60d and BMC64d). In the deeper profile, salinity levels tend to increase with depth. Zones where EC increases are often associated with gravelly aquifer zones within the transported and palaeochannel sediments. However EC values in BMC62d become less saline, 100 mS/m to 9 mS/m, with depth. This site intersects a basal quartz vein over granite bedrock.

Sediments within the weathered saprolite profile reported EC values between 100 mS/m and 2,170 mS/m. A high EC of about 600 mS/m was measured in the pallid clay zone intersected in BMC 59d. This increased salt concentration at depth is possibly associated with salt accumulation from basement weathering and slow horizontal groundwater flow.

Soil pH measured on the drill samples indicate a typical medium or neutral pH associated with low to medium surface soil EC. A more alkaline pH was measured as salinity increased. The pH in all sites close to the valley floor reported declining pH with depth. For example, BMC61d reported a high surface pH of 8.8, declining to 7.5 at depth. This may be due to sulphidic layers within the regolith or sulphide-rich bedrocks. The pH was generally stable at pH 6.3 in BMC62d until the intersection of granite and associated quartz vein. At this depth the pH increased to 8.2. Palaeochannel sediments in BMC64d reported a medium pH of about pH 6.5.

7.4.3 Potential Acidifying Soils Analysis

Results from field testing using the peroxide oxidation method showed very little chemical reaction, indicating a low potential for acidic soils. In addition, increased buffering effects may promote self-neutralisation due to the presence of organic material and carbonates identified in this wetland area.

Results from field testing are presented in Table 7-2. Soil pH throughout the profile was typically neutral to slightly acidic. Only two samples from BMC78 and BMC79 recorded a low oxidation reaction. All other samples recorded no visible reaction.
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Table 7-2  Gypsum Wetlands W001 and W002 – Summary of Acid Sulphate Soils Analyses

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>BMC60</th>
<th>BMC78</th>
<th>BMC79</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pHw</td>
<td>pHf</td>
<td>Reaction</td>
</tr>
<tr>
<td>1.0</td>
<td>7.5</td>
<td>7.1</td>
<td>N</td>
</tr>
<tr>
<td>2.0</td>
<td>7.6</td>
<td>7.0</td>
<td>N</td>
</tr>
<tr>
<td>3.0</td>
<td>7.8</td>
<td>6.9</td>
<td>N</td>
</tr>
<tr>
<td>4.0</td>
<td>8.0</td>
<td>7.1</td>
<td>N</td>
</tr>
<tr>
<td>5.0</td>
<td>8.0</td>
<td>7.2</td>
<td>N</td>
</tr>
</tbody>
</table>

Note:  
- pHw - pH of 1:5 soil: water  
- pHf - pH of 1:5 soil: water following oxidation with Hydrogen Peroxide  
- Reaction – N= no reaction, L= low reaction, M=moderate reaction, H=high reaction

7.4.4 Soil Laboratory Analysis

Soil samples were taken from two drill cores, in August 2006, and submitted for analysis for Nitrate, Total Nitrogen, Total Phosphorus and Phosphorus sorption capacity. For comparison, common values have been reported for Total Nitrogen and Total Phosphorus (Mc Arthur, 1991). Results are summarised in Table 7-3 with laboratory certificates presented in Appendix I.

Table 7-3  Gypsum Wetlands W001 and W002 – Soil Analysis

<table>
<thead>
<tr>
<th>Bore No.</th>
<th>Locality</th>
<th>Nitrate as N (mg/kg)</th>
<th>Total Nitrogen (mg/kg)</th>
<th>Total Phosphorus (mg/kg)</th>
<th>Phosphate Sorption Index (mg/kg/log_{10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark</td>
<td>Yellow Duplex Soils</td>
<td>-</td>
<td>100 to 400</td>
<td>29 to 89</td>
<td>-</td>
</tr>
<tr>
<td>BMC60 ob</td>
<td>Middle slope</td>
<td>26.9</td>
<td>70</td>
<td>22</td>
<td>44</td>
</tr>
<tr>
<td>BMC78 ob</td>
<td>Valley floor</td>
<td>0.466</td>
<td>&lt;20</td>
<td>4</td>
<td>20</td>
</tr>
</tbody>
</table>

1 Suggested values for common soils in the South-West Hydrogeological Region (Mc Arthur, 1991)

The wetland area reported low concentrations for all parameters measured when compared to suggested benchmark values.

Results indicate Total Nitrogen of high concentration (70 mg/kg) beneath the mid-slopes, probably associated with the application of nitrogenous fertilisers. Further down slope on the valley floor Total Nitrogen has reduced by more than 30%. Within the lake sediments associated with BMC78ob the Total Nitrogen concentration was less than 20 mg/kg.

High soil Nitrate concentrations beneath the middle slopes possibly indicate significant amounts of Total Nitrogen are not being absorbed readily by plants. These high concentrations may also indicate there is little loss of Total Nitrogen through leaching. Beneath the valley floor nitrate concentrations were lowest.
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(0.466 mg/kg). This may be due to denitrification, where by nitrate is lost due to anaerobic conditions associated with the waterlogged lake sediments.

The Total Phosphorus concentrations recorded in this wetland area show a similar trend to Total Nitrogen concentrations. The higher concentrations reported in middle slope soils are possibly linked to fertiliser application. The sands with very low clay contents associated with the middle slopes typically have very low capacities to absorb phosphorus. This can be seen with a decline in concentrations from 22 mg/kg to about 4 mg/kg down gradient to the lake sediments associated with the valley floor.

The PSI measured at BMC60ob located in the middle slopes was 44 mg/kg/log10. BMC78ob measured 20 mg/kg/log10. The site is located in the valley floor. Based on other sites within the BMNDRC this value appears to be high. Although results report low concentrations they also indicate relatively poor sorption capacity at tested site and therefore the potential for contamination in waterways lower in the landscape.

7.5  Wetland Hydrogeology

7.5.1 Surface Water Runoff

No sub-catchments were identified within the Gypsum wetland catchment. (Figure 17a). Therefore the entire catchment is represented by loamy earths, duplexes and sandy duplex soil types and shallow red stony soils.

The catchment peak flows are calculated for 0.5, 1, 6, 12 and 24-hour rainfall events, for 1, 2, 5, 10, 20, 50 and 100-year ARIs is presented in Table 7-4.

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Peak Flows (m³/sec) at Average Recurrence Interval in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>43.4</td>
</tr>
<tr>
<td>1</td>
<td>31.0</td>
</tr>
<tr>
<td>6</td>
<td>9.5</td>
</tr>
<tr>
<td>12</td>
<td>6.0</td>
</tr>
<tr>
<td>24</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Expected runoff volumes calculated for the Gypsum Wetlands catchment are given in Table 7-5. As an example, the Gypsum Wetlands will have a peak flow of 18.6 m³/sec for a 6-hour duration 10-year ARI rainfall event. For this event, the peak runoff volume would be 401,424 m³.
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Table 7-5 Gypsum Wetlands W001 and W002 – Runoff Volumes

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Peak Volumes (m³) at Average Recurrence Interval in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>1,301</td>
</tr>
<tr>
<td>1</td>
<td>111,742</td>
</tr>
<tr>
<td>6</td>
<td>205,116</td>
</tr>
<tr>
<td>12</td>
<td>257,663</td>
</tr>
<tr>
<td>24</td>
<td>311,753</td>
</tr>
</tbody>
</table>

7.5.2 Groundwater Level Data

The initial measurements of depth to groundwater in the thirteen monitoring bores are presented in Table 7-6. Flow lines are presented on vertical cross-sections on Figure 17 (b and c). BMC61ob was dry. Water table contours for September 2006 are shown on Figure 17(d) as elevation and on Figure 17(e) as depth to water. In addition, a more detailed plan showing water table elevation in the wetland area is presented on Figure 17(g). With limited long-term groundwater level data, this plot represents the seasonal low water table during the period of record.

Groundwater levels in the monitoring bores range from about 4.2 m below ground surface beneath the middle slope areas of the catchment to 1.7 m below ground beneath the valley floor. Interpreted groundwater levels are up to 6 m below ground level in the upper reaches of the catchment.

The hydraulic gradient of the shallow aquifer is locally about 0.0007 (dimensionless). The direction of groundwater flow is generally westerly, towards the valley floor.

Environmental water heads indicate significant upward head differential between the shallow and deeper aquifers in the valley floor. Located adjacent to W001, BMC59d shows a differential of about 3.5 m. This theory is supported by the gypsum formation found on the surface of this wetland. Similarly, BMC64d, located in the valley floor, which intersected deep palaeochannel sediments shows an upward head differential of 3.6 m. Linked via preferential flow paths, these differential heads are possibly associated with discharge areas within the saline playas. Conditions in BMC64d are inferred to represent the regional groundwater trends beneath the valley floor of the BMNDRC, supporting the interpretation that the aquifer systems underlying the valley floor are full. Consequently, additional water input to the valley floor may further increase groundwater salinity (as even rainfall infiltration would bring additional chloride). Detail analysis with a numerical model incorporating density coupled flow would promote improved understanding of the local groundwater hydrodynamics, including vertical dead distributions and density stratification.
Groundwater records from two shallow (BMC02ob, and BMC04ob) and ten deep monitoring bores (BMC01d, BMC02d, BMC04d, BMC05d, BMC12d, BMC13d, BMC16d, BMC17d, BMC21d, and BMC22d) located near the wetland area were selected for trend analysis. These groundwater level data cover four years, from 2002 to 2006. In addition, data collected from Waddy Forest LCDC monitoring bores D1 to D3 provided groundwater trends in the middle slope superficial formations, adjacent to the wetland area. These results provide estimates only as groundwater levels are typically less than 4m below ground surface in D1 to D3 and may be impacted on by evaporation. Groundwater level data for these bores cover the period from 1996 to 2006. The Koobabbie BOM rainfall station, average monthly rainfall data for 95 years for the period from 1911 to 2006 was used in the model. Table 7-7 presents a summary of results.

Generally, deep bores located in the middle slopes indicate a 28 to 107 mm/year rate of groundwater decline. Bores located in the upper slopes indicated a decline in groundwater level of between 8 to 149 mm/year. These assessments indicate there is a range of lag times of 0 to 9 months between rainfall and impact on the shallow water table (0 to 9 months).

Declines in groundwater levels are also evident in data from the newly installed bores. There is a marked difference in this short-term rate of decline with the shallow bores having a slightly steeper gradient and response to change (Figure 17I). Groundwater levels beneath the low-lying areas are typically about 0.5 m below surface (0.5m) and stable as a result of the effects of evaporation.
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Results from the analyses of the Waddy Forest LCDC monitoring bores incorporate rainfall data covering the 1999 Cyclone rainfall events. Rates of groundwater level decline range between 8 to 64 mm/year for D1 and D2 respectively located in the upper slopes to about 72 mm/year for D3 middle slope.

Table 7-7  Gypsum Wetlands W001 and W002 – Groundwater Trends

Summary of Results from the HARTT Analysis

<table>
<thead>
<tr>
<th>Bore</th>
<th>Aquifer</th>
<th>Predicted Lag (months)</th>
<th>Predicted Long-Term Groundwater Level Change</th>
<th>Predicted Average Rate of Change (mm/year)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC 1D</td>
<td>Upper Slope</td>
<td>9</td>
<td>Decline</td>
<td>-8</td>
<td>0.95</td>
</tr>
<tr>
<td>BMC 2ob</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-51</td>
<td>0.90</td>
</tr>
<tr>
<td>BMC 2D</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-61</td>
<td>0.79</td>
</tr>
<tr>
<td>BMC 4ob</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-58</td>
<td>0.65</td>
</tr>
<tr>
<td>BMC 4D</td>
<td>Middle Slope</td>
<td>8</td>
<td>Decline</td>
<td>-57</td>
<td>0.91</td>
</tr>
<tr>
<td>BMC 5D</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-28</td>
<td>0.69</td>
</tr>
<tr>
<td>BMC 12D</td>
<td>Upper Slope</td>
<td>3</td>
<td>Decline</td>
<td>-28</td>
<td>0.66</td>
</tr>
<tr>
<td>BMC 13D</td>
<td>Middle Slope</td>
<td>6</td>
<td>Decline</td>
<td>-107</td>
<td>0.92</td>
</tr>
<tr>
<td>BMC16D</td>
<td>Middle Slope</td>
<td>3</td>
<td>Decline</td>
<td>-59</td>
<td>0.76</td>
</tr>
<tr>
<td>BMC 17D</td>
<td>Upper Slope</td>
<td>1</td>
<td>Decline</td>
<td>-148</td>
<td>0.81</td>
</tr>
<tr>
<td>BMC 21D</td>
<td>Upper Slope</td>
<td>6</td>
<td>Decline</td>
<td>-149</td>
<td>0.97</td>
</tr>
<tr>
<td>BMC 22D</td>
<td>Upper Slope</td>
<td>2</td>
<td>Decline</td>
<td>-138</td>
<td>0.97</td>
</tr>
</tbody>
</table>

WADDY FOREST LCDC MONITORING BORES

<table>
<thead>
<tr>
<th></th>
<th>Aquifer</th>
<th>Predicted Lag (months)</th>
<th>Predicted Long-Term Groundwater Level Change</th>
<th>Predicted Average Rate of Change (mm/year)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Upper Slope</td>
<td>0</td>
<td>Decline</td>
<td>-8</td>
<td>0.77</td>
</tr>
<tr>
<td>D2</td>
<td>Upper Slope</td>
<td>0</td>
<td>Decline</td>
<td>-64</td>
<td>0.61</td>
</tr>
<tr>
<td>D3†</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-72</td>
<td>0.63</td>
</tr>
</tbody>
</table>

† Note – Results from Hartt Analysis for Waddy Forest LCDC monitoring bores are estimates only as groundwater levels are typically less than 4m below ground surface and may be impacted on by evaporation.

7.5.3 Groundwater Recharge

Water loss though plant uptake or evapotranspiration is simulated as a significant proportion of annual rainfall. About 85% of annual rainfall is lost by evapotranspiration (average probability of exceeding rainfall). The deep sandy loam soil shows particularly little surface runoff. Recharge is estimated to be greater under bare soils than under native vegetation. A smaller variation occurs between bare soils and cropped paddocks. Recharge rates for the western areas (Coorow) range between 42 and 87 mm for bare soils compared to 0 and 71 mm for cereal crops. Nil recharge was simulated in areas of native vegetation. The dryer eastern areas (Dalwallinu) reported lower total estimates of recharge.

When comparing rainfall periods 1953 to 1993 and 1966 to 2006 it is apparent there has been an estimated 20% decline in annual rainfall in recent times. The reduction in rainfall has lead to a recharge...
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Reduction. For example, in bare soil areas in the western catchment area (Coorow) the AgEt simulated recharge has declined by about 55%, from 70 to 40 mm. Simulated recharge rates in cropped areas have declined by 100%.

Using these regional estimates and applying them to the annual rainfall average of 324 mm for Koobabbie BOM station, more representative estimates for predicted runoff and recharge were calculated. For ease of interpretation results are presented in Table 7-9 as percentages.

Results indicate that under current rainfall, up to 92% of annual rainfall is lost through ET. The dominant soil type in the Gypsum Wetland catchment is sandy loam. According to the modelled AgEt output and given the soil type and the range of rainfall events recorded for the catchment, there is no capacity for surface runoff; with all rainfall infiltrating. This is in contrast with observations by the DEC, where surface water inputs to W002 wetland appear to be a significant component of the water balance during the winter months. Recharge estimates range from 12% of annual rainfall for bare soil with nil recharge from areas cropped or under native vegetation. The Indian Ocean Climate Initiative Report (2006) predicts rainfall trends will continue declining over the next 25 years. This report predicts as much as a 20% decline in rainfall. Under a continued drying climate trend, recharge may decline by about 5% leading to lowering of groundwater levels. An increased occurrence of high intensity storms may, however, influence recharge and groundwater levels. A very high intensity rainfall event may also generate runoff for this catchment.

### Table 7-8  Gypsum Wetlands W001 and W002 – Regional Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>Annual Rainfall (mm)</th>
<th>ET (mm/annum)</th>
<th>Runoff (mm/annum)</th>
<th>Recharge (mm/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
<td>Natural Vegetation</td>
<td>Bare Soil</td>
</tr>
<tr>
<td>75% Coorow Rainfall Station</td>
<td>317 (280)</td>
<td>206 (244)</td>
<td>275 (276)</td>
<td>283 (17)</td>
</tr>
<tr>
<td>50% Coorow Rainfall Station</td>
<td>389 (379)</td>
<td>239 (277)</td>
<td>318 (344)</td>
<td>335 (343)</td>
</tr>
<tr>
<td>25% Coorow Rainfall Station</td>
<td>446 (337)</td>
<td>280 (305)</td>
<td>361 (387)</td>
<td>392 (393)</td>
</tr>
<tr>
<td>75% Dalwallinu Rainfall Station</td>
<td>288 (270)</td>
<td>214 (211)</td>
<td>272 (364)</td>
<td>267 (264)</td>
</tr>
<tr>
<td>50% Dalwallinu Rainfall Station</td>
<td>361 (324)</td>
<td>243 (252)</td>
<td>318 (299)</td>
<td>310 (299)</td>
</tr>
<tr>
<td>25% Dalwallinu Rainfall Station</td>
<td>423 (391)</td>
<td>278 (267)</td>
<td>254 (259)</td>
<td>378 (359)</td>
</tr>
</tbody>
</table>

Note: 317 Daily water balance AgET 1953 to 1993 daily rainfall data  
(280) Daily water balance AgET 1967 to 2006 daily rainfall data
Table 7-9  Gypsum Wetlands W001 and W002 – Local Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>Annual Rainfall (mm)</th>
<th>ET (% of Annual Rainfall)</th>
<th>Runoff (% of Annual Rainfall)</th>
<th>Recharge (% of Annual Rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
<td>Native Vegetation</td>
<td>Bare Soil</td>
</tr>
<tr>
<td>75%</td>
<td>261</td>
<td>83%</td>
<td>98%</td>
<td>99%</td>
</tr>
<tr>
<td>50%</td>
<td>324</td>
<td>75%</td>
<td>92%</td>
<td>91%</td>
</tr>
<tr>
<td>25%</td>
<td>374</td>
<td>79%</td>
<td>103%</td>
<td>104%</td>
</tr>
</tbody>
</table>

Note: 280  Daily water balance AgET 1967 to 2006 daily rainfall data

7.5.4 Water Quality Data

Table 7-10 presents a summary of field EC and pH measurements. Figure 17(f) shows interpretations of groundwater salinity distributions on cross-section. Figure 17(h) shows interpreted salinity in plan view. Samples were also taken from a selection of bores and from surface water sites, in September 2006, and submitted for analysis for pH, EC, TDS and major anions and cations. Table 7-11 presents results of laboratory groundwater analyses and Certificates of Analyses are provided in Appendix I.
### Gypsum Wetland Findings

#### Table 7-10  Gypsum Wetlands W001 and W002 – Groundwater EC and pH Field Measurements

<table>
<thead>
<tr>
<th>Bore</th>
<th>Profile</th>
<th>Location</th>
<th>Depth (m)</th>
<th>Electrical Conductivity (mS/m)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC059ob</td>
<td>Shallow</td>
<td>Low Slopes</td>
<td>6</td>
<td>7,600</td>
<td>6.8</td>
</tr>
<tr>
<td>BMC059d</td>
<td>Deep</td>
<td>Low Slopes</td>
<td>37</td>
<td>15,600</td>
<td>6.3</td>
</tr>
<tr>
<td>BMC060ob</td>
<td>Shallow</td>
<td>Middle Slopes</td>
<td>5.7</td>
<td>2,840</td>
<td>7.5</td>
</tr>
<tr>
<td>BMC060d</td>
<td>Deep</td>
<td>Middle Slopes</td>
<td>45</td>
<td>14,470</td>
<td>5.0</td>
</tr>
<tr>
<td>BMC061ob</td>
<td>Shallow</td>
<td>Middle Slopes</td>
<td>4.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BMC061d</td>
<td>Deep</td>
<td>Middle Slopes</td>
<td>52</td>
<td>15,640</td>
<td>5.8</td>
</tr>
<tr>
<td>BMC062d</td>
<td>Deep</td>
<td>Middle Slopes</td>
<td>29</td>
<td>473</td>
<td>6.7</td>
</tr>
<tr>
<td>BMC063ob</td>
<td>Shallow</td>
<td>Valley Floor</td>
<td>5</td>
<td>11,940</td>
<td>5.9</td>
</tr>
<tr>
<td>BMC64ob</td>
<td>Shallow</td>
<td>Valley Floor</td>
<td>6</td>
<td>10,740</td>
<td>5.7</td>
</tr>
<tr>
<td>BMC064i</td>
<td>Intermediate</td>
<td>Valley Floor</td>
<td>26</td>
<td>11,730</td>
<td>5.74</td>
</tr>
<tr>
<td>BMC064d</td>
<td>Deep</td>
<td>Valley Floor</td>
<td>45</td>
<td>14,350</td>
<td>5.57</td>
</tr>
<tr>
<td>BMC078ob</td>
<td>Shallow</td>
<td>Valley Floor</td>
<td>5.7</td>
<td>15,930</td>
<td>6.8</td>
</tr>
<tr>
<td>BMC079ob</td>
<td>Shallow</td>
<td>Valley Floor</td>
<td>6</td>
<td>10,280</td>
<td>5.2</td>
</tr>
</tbody>
</table>

The groundwater, whether shallow or deep parts of the profile, is generally brackish to hypersaline, with EC ranging from 473 mS/m to 15,640 mS/m in the middle slopes, 498 mS/m to 15,600 mS/m in the lower slopes and 10,280 mS/m to 14,350 mS/m in the valley floor.

Within the middle slope areas the salinity in the shallow aquifer was generally less saline than in the deeper aquifer. However, although a very low groundwater yield, the salinity in BMC62d was measured at less than 500 mS/m and may be due to fresh water inflows from a basal quartz vein. This compares to groundwater in the lower slopes where a density stratification from fresh nearer the surface. The highest groundwater salinity concentrations were measured in BMC60d, BMC61d and BMC64d palaeochannel sands. Groundwater salinity linked to the palaeochannel sediments in the valley floor was typically saline in all aquifers to basement (BMC64d, BMC64i, and BMC64ob).

The groundwater in all areas is almost exclusively slightly acidic, ranging from 5.0 to 7.5. There appears to be no correlation between shallow and deep groundwater acidity.

Piper and Stiff diagrams that characterise the local groundwater type are provided on Figure 17(j) and Figure 17(k). Results indicate the groundwater is of a type is sodium-chloride with the shallow aquifer characterised by greater proportions of both these ions.
Section 7

Gypsum Wetland Findings

Table 7-11  Gypsum Wetlands W001 and W002 – Summary of Groundwater Analyses

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>EC (mS/m)</th>
<th>TDS mg/L</th>
<th>OH &lt;1</th>
<th>CO&lt;sub&gt;3&lt;/sub&gt; &lt;1</th>
<th>HCO&lt;sub&gt;3&lt;/sub&gt; 62</th>
<th>Total Alkalinity 62</th>
<th>SO&lt;sub&gt;4&lt;/sub&gt; 2,130</th>
<th>S 73,400</th>
<th>Cl 2,370</th>
<th>Ca 5070</th>
<th>Mg 37,900</th>
<th>Na 767</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC59d</td>
<td>15,600</td>
<td>140,000</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>62</td>
<td>6,380</td>
<td>2,130</td>
<td>73,400</td>
<td>2,370</td>
<td>5070</td>
<td>37,900</td>
<td>767</td>
</tr>
<tr>
<td>BMC59ob</td>
<td>7,710</td>
<td>55,800</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>3,380</td>
<td>1,120</td>
<td>27,000</td>
<td>532</td>
<td>1,720</td>
<td>16,200</td>
<td>481</td>
</tr>
<tr>
<td>BMC64i</td>
<td>12,000</td>
<td>106,000</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>59</td>
<td>7,490</td>
<td>2,500</td>
<td>52,900</td>
<td>924</td>
<td>4,150</td>
<td>30,000</td>
<td>590</td>
</tr>
</tbody>
</table>

7.5.5  Hydraulic Parameters

A total of 7 slug tests were completed in the newly completed monitoring bores. Results of analyses are presented in Table 7-12.

The shallow aquifer is moderately transmissive, with hydraulic conductivity of about 6 m/day. Results from laboratory measurements measured a hydraulic conductivity of 1.5 m/day for the shallow sandy aquifer and ranged between 9.5 x 10<sup>-5</sup> m/day and 1.1 x 10<sup>-4</sup> m/day for less transmissive clayey zones (Table 7-13).

The aquifer associated with the deeper transported sediments is much less transmissive than the shallow superficial sandy aquifer, being two orders of magnitude lower at 0.02 m/day. This corresponds to a transmissivity of about 0.24 m<sup>2</sup>/day. The hydraulic conductivity of the palaeochannel sandy sediments was measured at 5.2 m/day, with clayey zones reporting about 0.08 m/day (BMC64i). The saprolite reported a hydraulic conductivity of about 2 m/day. Using an effective porosity of 0.1 a groundwater velocity of 0.02 m/day was estimated for the weathered profile. This low groundwater velocity effectively prevents groundwater from being moved downstream to the valley floor.
## Section 7

### Gypsum Wetland Findings

#### Table 7-12  Gypsum Wetlands W001 and W002 – Field Hydraulic Parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Transmissivity (m²/day)</td>
<td>Average Hydraulic Conductivity (m/day)</td>
</tr>
<tr>
<td>Superficial Formations, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superficial Formations, Sandy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transported Sediments, Clayey</td>
<td>0.24</td>
<td>0.027, 0.15, 0.95</td>
</tr>
<tr>
<td>Transported Sediments, Sandy</td>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td>Lacustrine Deposits, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Clayey</td>
<td>1.2</td>
<td>0.08</td>
</tr>
<tr>
<td>Palaeodrainage, Sandy</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>Saprrolite</td>
<td>0.07, 0.32, 0.003</td>
<td>2</td>
</tr>
<tr>
<td>Saprrock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathered Dolerite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 7-13  Gypsum Wetlands W001 and W002 – Laboratory Hydraulic Parameters

<table>
<thead>
<tr>
<th>Bore</th>
<th>Sample</th>
<th>Lithology</th>
<th>Formation</th>
<th>Dry Density (t/m³)</th>
<th>Initial Moisture Content (%)</th>
<th>Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC 59ob</td>
<td>1–1.1</td>
<td>SANDY CLAY – light brown (5YR 6/4) fine to coarse quartz, sub-angular.</td>
<td>Superficial Formation</td>
<td>1.89</td>
<td>15.2</td>
<td>5.62E-06</td>
</tr>
<tr>
<td>BMC 60ob</td>
<td>5.1–5.2</td>
<td>SANDY GRAVELLY CLAY – light red (SR 6/6) to greyish pink (SR 8/2) to light brown (5YR 5/6), fine to very coarse grained, minor gravel 5mm, sub-angular, silty clay.</td>
<td>Superficial Formation</td>
<td>1.91</td>
<td>14.5</td>
<td>1.5</td>
</tr>
<tr>
<td>BMC 61ob</td>
<td>3.4–3.5</td>
<td>SANDY CLAY – light brown (5YR 5/6) to very pale orange (10YR 8/2), fine to medium grained, silty clay, nodules of calcite, minor siliceous/ironstone bands.</td>
<td>Transported Sediments</td>
<td>1.56</td>
<td>15.3</td>
<td>0.00003</td>
</tr>
<tr>
<td>BMC 64ob</td>
<td>5–5.1</td>
<td>CLAYEY SAND – (10YR 6/6), predominantly medium grained, very poorly sorted, sub-angular with fine stained fragments.</td>
<td>Transported Sediments</td>
<td>2</td>
<td>11.1</td>
<td>0.0001</td>
</tr>
<tr>
<td>BMC 78ob</td>
<td>5.3–5.4</td>
<td>SANDY CLAY – moderate yellowish brown, fine to medium grained, minor hard ferruginous lateritic bands.</td>
<td>Transported Sediments</td>
<td>1.68</td>
<td>18.2</td>
<td>0.00001</td>
</tr>
<tr>
<td>BMC 79ob</td>
<td>2.1–2.2</td>
<td>CLAY - Greenish orange pink (5YR 7/2), minor coarse quartz/feldspar, plastic clays.</td>
<td>Transported Sediments</td>
<td>1.73</td>
<td>17.6</td>
<td>0.000005</td>
</tr>
</tbody>
</table>
8.1 Wetland Area W448

Wetland W448 is one of the larger primary saline wetlands in the catchment, covering an area of about 200 ha. The topographic catchment area is difficult to ascertain, however it is likely to be greater than 80,000 ha, or more than 40% of the BMNDRC. The area of remnant vegetation is over 9,000 ha or 11% of this catchment area.

There were no surface water quality records available at the time of report compilation. Given the location of this wetland within the drainage line and the size of the catchment area, however, it is likely that fresh surface water and shallow groundwater inputs may be sourced at both local and sub-catchment scales. These would quickly become saline to hypersaline following mixing with the salt crust on the lake bed and hypersaline shallow groundwater; and the subsequent concentration of salts from evaporation. Anecdotal information provided by landholders and recent evidence collected by the DEC indicates that surface water from W448 exits via the culverts on Gunyidi-Wubin Road. Due to the braided and flat nature of this landscape it is difficult to ascertain volumes of water discharge from any given rainfall event.

The location of W448 is shown in a regional context in Figure 1. Plate 5 shows photographs of the wetland. Interpretations of the hydrogeology are provided on Figure 18 (a to i), inclusive of location in a local context, hydrostratigraphy, groundwater levels and groundwater quality. Data collected are presented in Appendix G, inclusive of lithological and bore logs, salinity profiles and results of hydraulic tests.

8.2 Results of Landholder Interviews

There are numerous landholders within the W448 catchment area. Only two of the landholders located adjacent to the wetland were interviewed. Discussions with one of the landholders, who has an extensive knowledge of the farm history, indicated that clearing of the wetland subcatchment area began in the early 1900s. The majority of the remaining vegetation is located in areas where shallow bedrock occurs. From 1993, minimum tillage and no burning practices were implemented. Although less cultivation over the past 20 to 30 years was reported, there has however been deep tillage in the past 20 years in areas of the catchment. This has occurred in association with a general four-year paddock rotation cycle.

Typical farming practices include sheep, cattle grazing and wheat and chickpea alternate crops.

It was reported and subsequently confirmed by URS that remnants of an old river channel exist high in the catchment. At a location east of one of the homesteads, coarse well-rounded quartz river gravel was observed.

Another landholder acknowledged that most clearing occurred in the mid 1950’s. They also reported that wetland W448 became inundated between 1963 and 1966 following a period of high rainfall. During this period water skiing on the wetland was popular.

It was also reported that during the 1999 floods, the drainage associated with the valley floor braided lakes flooded and began to flow. At the time, landholders estimated the flow rate at the Gunyidi-Wubin Road was about 242 ML/day. Interestingly they only measured a flow rate of 91 ML/day at the crossing on the Miling Road, only a few kilometres downstream.

During past storm events, it was indicated that at least 180 to 200 mm of rain was required over 24 to 48 hours to get the main braided drainage channel to flow. This has been a rare event and occurs subsequent to low pressure cyclonic systems. Flow last occurred in 1999 following Tropical Cyclones Elaine and Vance.

8.3 Monitoring Bore Construction Details

A total of six groundwater monitoring bores were completed between June and August 2006. These complement the existing 10 groundwater bores constructed in a transect line across the main drainage between Gunyidi-Wubin and Bailey Roads. Details of monitoring bore construction are presented in Table 8-1, with bore locations shown on Figure 18(a).
Three shallow monitoring bores (BMC83ob, BMC84ob and BMC85ob) were installed on the valley floor drainage line. These bores were drilled to 6 m and cased with a 3 to 5 m basal slotted section. Three deeper monitoring bores (BMC65d, BMC66d and BMC67d) were drilled to basement wetland area. These bores ranged in total depth between 9.5 and 43 m. At BMC65d a zone of high-yielding medium to coarse grained silty sand was encountered between 19 to 22 m depth.

### 8.4 Wetland Geology

The catchment area for Wetland W448 is characterised by alluvial plains and playas of the Wallambin Soil System that overlie the Buntine Palaeodrainage successions in valley-floor settings. Local catchment areas are dominated by the sandplain superficial formations of the Ballidu and Upsan Downs Soil Systems. Results from recent and past drilling indicate the depth of weathering and location of palaeochannel sediments is strongly influenced by the depth to fresh basement. Interpreted stratigraphy is presented on Figure 18 (b and c).

BMC66d, located on the south side of Gunyidi-Wubin Road, intersected a thick sequence of transported sediments over palaeochannel sands. The depth to fresh bedrock was 41 m. Located about 700 m north-west of BMC66d, BMC67d intersected shallow bedrock at 9 m.

Beneath the braided drainage, thin (2 m) superficial sands typically overlayed transported sediments to about 15 m below ground. These transported sediments are interbedded with sub-angular to moderately-rounded quartz sands and gravels. Below this sequence, palaeochannel sediments consisting of sub-rounded sands and silty clays are intersected over a 20 to 30 m interval. The palaeochannel sediments sit directly on fresh bedrock in the deeper channels or over weathered bedrock (saprolite) away from the main channel.

### 8.4.1 Soil Descriptions

W448 is located within the Wallambin Soil System. Local soils are typically:

- Linked to salt lakes and braided drainage channels.
- Waterlogged, seasonally or after significant rainfall events.
- Saline drainage channels, often from secondary salinity.
- Alluvial flats with occasional playa lakes.
## Primary Saline Wetland Findings

### Table 8-1 Primary Saline Wetland W448 – Summary of Monitoring Bore Completions

<table>
<thead>
<tr>
<th>Bore</th>
<th>RL (m AHD)</th>
<th>Ground Level (m AHD)</th>
<th>Profile</th>
<th>Date Completed</th>
<th>Depth Drilled</th>
<th>Casing Collar Height (m agl)</th>
<th>Depth Cased (m)</th>
<th>Slotted Interval (m)</th>
<th>Slotted Length (m)</th>
<th>Top of Gravel (m)</th>
<th>Top of Bentonite (m)</th>
<th>Top of Cement/Gravel (m)</th>
<th>Airlift Yield (L/minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC065d</td>
<td>288.13</td>
<td>287.94</td>
<td>Deep</td>
<td>7/07/2006</td>
<td>36</td>
<td>0.19</td>
<td>35.31</td>
<td>33.31 - 35.31</td>
<td>2</td>
<td>31</td>
<td>12</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>BMC066d</td>
<td>286.89</td>
<td>286.69</td>
<td>Deep</td>
<td>10/07/2006</td>
<td>43</td>
<td>0.2</td>
<td>41.33</td>
<td>39.33 - 41.33</td>
<td>2</td>
<td>37</td>
<td>15</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>BMC067d</td>
<td>286.29</td>
<td>286.08</td>
<td>Deep</td>
<td>11/07/2006</td>
<td>9.5</td>
<td>0.21</td>
<td>9</td>
<td>7.0 - 9.0</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>BMC083ob</td>
<td>285.93</td>
<td>285.73</td>
<td>Shallow</td>
<td>4/08/2006</td>
<td>5.3</td>
<td>0.2</td>
<td>5.27</td>
<td>2.27 - 5.27</td>
<td>3</td>
<td>1.5</td>
<td>1</td>
<td>0</td>
<td>trace</td>
</tr>
<tr>
<td>BMC084ob</td>
<td>287.26</td>
<td>287.05</td>
<td>Shallow</td>
<td>4/08/2006</td>
<td>6</td>
<td>0.2</td>
<td>5.98</td>
<td>0.98 - 5.98</td>
<td>5</td>
<td>0.5</td>
<td>0.2</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>BMC085ob</td>
<td>287.84</td>
<td>287.64</td>
<td>Shallow</td>
<td>5/08/2006</td>
<td>6.1</td>
<td>0.2</td>
<td>6.05</td>
<td>1.05 - 6.05</td>
<td>5</td>
<td>0.5</td>
<td>0.2</td>
<td>2.3</td>
<td></td>
</tr>
</tbody>
</table>
8.4.1 Soil EC and pH Profiles

Soil EC was measured at 1 m intervals on drill cuttings at each bore location within the wetland area (Appendix G). Results indicated soil salinity within the top 1 m, ranging from 120 to 1,256 mS/m, being highest in BMC66d. The soil salinity in BMC66d decreased significantly at 2 m from 1,256 mS/m to 100 mS/m. This trend represents a typical discharge zone where evaporation of the shallow groundwater causes increased salt concentrations in the vertical profile near the surface.

Increases in soil salinity were also found associated with distinct beds of transported sediments. Soil EC of these beds ranged from 80 to 1,000 mS/m. In the palaeochannel profile (BMC65d and BMC66d), EC tended to increase up to 8,000 mS/m in association with gravely aquifer zones, however these measurements may be due to the influence of groundwater salinity rather than a direct measurement of soil salinity.

Soil pH at the surface was slightly alkaline, becoming neutral and slightly acidic with depth. A pH of 7.4 to 7.8 was measured in the upper 2 m of superficial sands. The soil associated with the aquifer zones within the transported sediments measured pH 6.8 to 7.5 and within the palaeochannel sediments, pH 6.1 to 6.8.

8.4.2 Potential Acidifying Soils Analysis

The peroxide oxidation method results shared very little chemical reaction, indicating a low potential for acidic soils.

Results from field testing are presented in Table 8-2. Soil pH on the valley floor was typically neutral to slightly acidic. BMC83 located between two large playa lakes reported a slightly alkaline pH. At this site a high oxidation reaction was observed indicating possible acid sulphate conditions. Low rates of reaction were observed at the other two sites on the valley floor.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>BMC83</th>
<th>BMC84</th>
<th>BMC85</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH_w</td>
<td>pH_f</td>
<td>Reaction</td>
</tr>
<tr>
<td>1.0</td>
<td>8.0</td>
<td>6.6</td>
<td>N</td>
</tr>
<tr>
<td>2.0</td>
<td>7.8</td>
<td>7.0</td>
<td>H</td>
</tr>
<tr>
<td>3.0</td>
<td></td>
<td>6.7</td>
<td>5.5</td>
</tr>
<tr>
<td>4.0</td>
<td></td>
<td>6.1</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Note: pH_w - pH of 1:5 soil: water
pH_f - pH of 1:5 soil: water following oxidation with Hydrogen Peroxide
Reaction – N= no reaction, L= low reaction, M=moderate reaction, H=high reaction

8.4.3 Soil Laboratory Analyses

Soil samples were taken from a single drill core at BMC85ob, in August 2006, and submitted to ALS Environmental Laboratories for analysis for Nitrate, Total Nitrogen, Total Phosphorus and Phosphorus sorption capacity. For comparison common values have been reported from Total Nitrogen and Total Phosphorus (Mc Arthur, 1991). Results are summarised in Table 8-3 with laboratory certificates presented in Appendix I.
The wetland area reported low concentrations for all measured parameters when compared to suggested baseline values. Results indicate Total Nitrogen concentration is low beneath the valley floor.

Soil nitrate also reported low concentrations (3 mg/kg). The Total Phosphorus concentration recorded at BMC85ob was 13 mg/kg. All results report low concentrations of nutrients.

8.5 Wetland Hydrogeology

8.5.1 Surface Water Runoff

Wetland W448 has a catchment area of about 80,000 ha. This catchment was divided into a northern and southern sub-catchment for calculations of peak flows and peak volumes (Figure 18a). Both sub-catchments are characterised by deep yellow sands, shallow sandy duplexes and shallow to deep yellow sands. The northern sub-catchment peak flows are calculated for 0.5, 1, 6, 12 and 24-hour rainfall events, for 1, 2, 5, 10, 20, 50 and 100-year ARIs and are presented in Table 8-4.

Expected runoff volumes calculated for the northern sub-catchment are given in Table 8-5. As an example, northern sub-catchment will have a peak flow of 10.2 m³/sec for a 6-hour duration 10-year ARI rainfall event. For this event, the peak flow volume would be 220,842 m³.
8.5.2 Groundwater Level Data

The initial measurements of depth to groundwater from the six monitoring bores are presented in Table 8-8. Groundwater contours for September 2006 are shown on Figure 18(d) as water table elevation and Figure 18(e) as depth to the water table. Groundwater flow lines are presented on vertical cross-sections on Figures 18 (b and c). A more detailed plan of Wetland W448 water table elevations is presented on Figure 18(g).

Although the dataset is limited, groundwater levels appear to range between about 1.4 m below ground surface to the east in the low-lying areas of the catchment to 4.0 m below ground surface to the west.
Section 8

Primary Saline Wetland Findings

beneath the middle slopes. Environmental water heads show a difference up to about 6.0 m in deeper bores as a result of salinity and density stratification. Little difference was noted in shallow bores. The hydraulic gradient of the shallow aquifer is locally about 0.0003 (dimensionless). The direction of groundwater flow is generally towards the southwest.

The hydraulic gradient in the deeper successions appear to be similar in both slope and direction to the shallow aquifer. Based on water levels measured in BMC66d and BMC83ob, there appears to be a moderate downward head between the aquifers, the differential between the shallow aquifer and the deepest screened aquifer, being about 0.8 m.

<table>
<thead>
<tr>
<th>Bore No.</th>
<th>Profile</th>
<th>Collar RL (m AHD)</th>
<th>Observed Groundwater Levels (m btc)</th>
<th>Fresh Water Equivalent Environmental Heads (m AHD)</th>
<th>Difference In Head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC065d</td>
<td>Deep</td>
<td>288.13</td>
<td>3.94</td>
<td>284.19</td>
<td>+0.38 +4.32</td>
</tr>
<tr>
<td>BMC066d</td>
<td>Deep</td>
<td>286.89</td>
<td>3.35</td>
<td>283.54</td>
<td>+2.72 +6.07</td>
</tr>
<tr>
<td>BMC067d</td>
<td>Deep</td>
<td>286.29</td>
<td>2.02</td>
<td>284.27</td>
<td>1.25 285.04 +0.77</td>
</tr>
<tr>
<td>BMC083ob</td>
<td>Shallow</td>
<td>285.93</td>
<td>1.4</td>
<td>284.53</td>
<td>1.29 284.64 +0.11</td>
</tr>
<tr>
<td>BMC084ob</td>
<td>Shallow</td>
<td>287.26</td>
<td>5.4</td>
<td>281.86</td>
<td>5.22 282.04 +0.18</td>
</tr>
<tr>
<td>BMC085ob</td>
<td>Shallow</td>
<td>287.84</td>
<td>1.6</td>
<td>286.24</td>
<td>1.42 286.42 +0.18</td>
</tr>
</tbody>
</table>

Groundwater level records for BMC 42D and BMC43I, representing groundwater trends in the deep weathered profile, were selected for trend analysis. Groundwater level data cover from four years from 2002 to 2006. Average monthly rainfall data from the East Buntine BOM rainfall station was used in the model. Table 8-9 presents a summary of results.

<table>
<thead>
<tr>
<th>Bore</th>
<th>Aquifer</th>
<th>Predicted Lag (months)</th>
<th>Predicted Long-Term Groundwater Level Change</th>
<th>Predicted Average Rate of Change (mm/year)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC 42D</td>
<td>Middle Slope</td>
<td>29</td>
<td>Decline</td>
<td>-3</td>
<td>0.22</td>
</tr>
<tr>
<td>BMC 43I</td>
<td>Lower Slope</td>
<td>1</td>
<td>Decline</td>
<td>-34</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Section 8  Primary Saline Wetland Findings

Results show there is little correlation between rainfall and groundwater trends in this catchment with significance values ($r^2$) less than 22%. Significant differences in time between rainfall and impacts on groundwater levels derived for BMC42 (29 months) may be a consequence of the correlation rather than an actual time lag. BMC43i, located lower on the valley floor, which had a lower correlation between rainfall and groundwater trends ($r^2$ of 0.11), reported a lag of only 1 month. Rates of change in groundwater level reported in both bores were comparatively low at between 3 to 7 mm/year.

Similar declines are seen in short-term groundwater level monitoring of newly installed bores. Typically both shallow and deep bores show a stable to declining trends over the past 15 months (Figure 18I). There is a marked difference in response to rainfall in shallow bores compared to deeper bores with shallow bores responding more rapidly to seasonal changes. These responses are a consequence of the shallower water table setting and possible effects of evaporation on the water table zone.

Using BMC44ob (Figure 18m), long-term seasonal water level fluctuations range from 1.5 m in 2003, through to 0.78 m in 2004 and 0.54 m in 2005. For recharge estimation, it is assumed these changes reflect differences in rainfall recharge rather than land use. Assuming an average effective specific yield of 0.1 for the strata in the zone of water table fluctuations which are generally somewhat silty or clayey, these seasonal variations indicate recharge of 54 mm in a dry year, to 150 mm in a particularly wet one. This implies an annual recharge up to 102 mm in an average rainfall year.

The Wetland W448 area is comprised of shallow sandy duplex soil type. Soil depths used in the water balance simulations were developed from existing AgET model parameters and bore logs. Soil depths used in the water balance simulations included 0.2 m deep horizon A and 0.8 m deep horizon B for bare soil, cereals and perennial grasses. An available water of 80 mm m$^{-1}$ with $K_{sat}$ of 10 mm day$^{-1}$ was used for horizon A and an available water of 80 mm m$^{-1}$ with $K_{sat}$ of 10 mm day$^{-1}$ used for horizon B. These values were derived from AgET standards for such soil types. Predicted surface run-off and groundwater recharge generated under bare soils, cereal crops and native vegetation are presented in Table 8-10.
### Table 8-10 Primary Saline Wetland W448 – Predicted Regional Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>Annual Rainfall (mm)</th>
<th>ET (mm/annum)</th>
<th>Runoff (mm/annum)</th>
<th>Recharge (mm/annum)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
<td>Perennial Grasses</td>
<td>Bare Soil</td>
</tr>
<tr>
<td>75%</td>
<td>317 (280)</td>
<td>206 (244)</td>
<td>275 (276)</td>
<td>283 (17)</td>
</tr>
<tr>
<td>50%</td>
<td>389 (379)</td>
<td>239 (277)</td>
<td>318 (344)</td>
<td>335 (334)</td>
</tr>
<tr>
<td>25%</td>
<td>446 (337)</td>
<td>280 (305)</td>
<td>361 (387)</td>
<td>392 (393)</td>
</tr>
<tr>
<td>Coorow Rainfall Station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>288 (270)</td>
<td>214 (211)</td>
<td>272 (364)</td>
<td>267 (264)</td>
</tr>
<tr>
<td>50%</td>
<td>361 (324)</td>
<td>243 (252)</td>
<td>318 (299)</td>
<td>310 (299)</td>
</tr>
<tr>
<td>25%</td>
<td>423 (391)</td>
<td>278 (267)</td>
<td>254 (259)</td>
<td>378 (359)</td>
</tr>
<tr>
<td>Dalwallinu Rainfall Station</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>288 (270)</td>
<td>214 (211)</td>
<td>272 (364)</td>
<td>267 (264)</td>
</tr>
<tr>
<td>50%</td>
<td>361 (324)</td>
<td>243 (252)</td>
<td>318 (299)</td>
<td>310 (299)</td>
</tr>
<tr>
<td>25%</td>
<td>423 (391)</td>
<td>278 (267)</td>
<td>254 (259)</td>
<td>378 (359)</td>
</tr>
</tbody>
</table>

**Note:**
317 Daily water balance AgET 1953 to 1993 daily rainfall data
(280) Daily water balance AgET 1967 to 2006 daily rainfall data

Under a medium rainfall scenario, results show that more than 300 mm/annum representing about 82% annual rainfall is lost by evapotranspiration. As a proportion of annual rainfall, this rate increases up to about 86% with a projected drying climate. The model reported particularly little surface runoff (20%). Recharge estimations indicate significantly greater recharge under bare soils than under cereal crops. The simulation reported no recharge occurs under native vegetation.

Using these regional estimates and applying them to the annual rainfall average of 302 mm for Buntine East BOM station, more representative estimates for predicted runoff and recharge were calculated. Table 8-11 presents results of this simulation as proportions of annual rainfall.

Results indicate that under current rainfall trends, up to 91% of annual rainfall is lost through ET. The dominant soil type indicates about 5 to 10% surface runoff. Recharge estimates range from 12% of annual rainfall for bare soil with nil recharge from areas cropped or under native vegetation. The Indian Ocean Climate Initiative Report (2006) predicts rainfall trends will continue declining over the next 25 years. (IOCI, 2006) predicts as much as a 20% decline in rainfall. Under a continued drying climate trend, recharge may decline by about 5% leading to lowering of groundwater levels. An increased occurrence of high intensity storms may, however, influence recharge and groundwater levels.
Table 8-11 Primary Saline Wetland W448 – Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>Annual Rainfall (mm)</th>
<th>ET (% of Annual Rainfall)</th>
<th>Runoff (% of Annual Rainfall)</th>
<th>Recharge (% of Annual Rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
<td>Native Vegetation</td>
<td>Bare Soil</td>
</tr>
<tr>
<td>Buntine Rainfall Station</td>
<td>75%</td>
<td>241</td>
<td>83%</td>
<td>98%</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>302</td>
<td>75%</td>
<td>91%</td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td>347</td>
<td>79%</td>
<td>103%</td>
</tr>
</tbody>
</table>

Note: 280 Daily water balance AgET 1967 to 2006 daily rainfall data

8.6 Water Quality Data

Monitoring of groundwater EC and pH from all recently completed groundwater monitoring bores was undertaken in September 2006. Table 8-12 presents a summary of result of EC and pH measurements. Figure 18(f) shows interpretations of the groundwater salinity distributions on cross-sections. Wetland W448 salinity in plan view is presented on Figure 18(h). Samples were also taken from BMC83ob and BMC66d, and submitted to the laboratory for analysis of pH, EC, TDS and major anions and cations. Table 8-13 presents results of laboratory analyses; Certificates of Analyses are provided in Appendix I.

Table 8-12 Primary Saline Wetland W448 – Groundwater EC and pH Field Measurements

<table>
<thead>
<tr>
<th>Bore No.</th>
<th>Profile</th>
<th>Location</th>
<th>Depth (m)</th>
<th>Electrical Conductivity (mS/m)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC65d</td>
<td>Deep</td>
<td>Valley Floor</td>
<td>36</td>
<td>21,300</td>
<td>5.93</td>
</tr>
<tr>
<td>BMC66d</td>
<td>Deep</td>
<td>Valley Floor</td>
<td>43</td>
<td>20,310</td>
<td>5.26</td>
</tr>
<tr>
<td>BMC67d</td>
<td>Deep</td>
<td>Valley Floor</td>
<td>9.5</td>
<td>16,150</td>
<td>5.59</td>
</tr>
<tr>
<td>BMC83ob</td>
<td>Shallow</td>
<td>Valley Floor</td>
<td>5.3</td>
<td>9,100</td>
<td>6.9</td>
</tr>
<tr>
<td>BMC84ob</td>
<td>Shallow</td>
<td>Valley Floor</td>
<td>6</td>
<td>13,600</td>
<td>5.7</td>
</tr>
<tr>
<td>BMC85ob</td>
<td>Shallow</td>
<td>Valley Floor</td>
<td>6.1</td>
<td>12,510</td>
<td>6.8</td>
</tr>
</tbody>
</table>
Section 8

Primary Saline Wetland Findings

The groundwater, whether shallow or deep parts of the profile, ranged from brackish to hypersaline, with EC of 9,100 mS/m in shallow sediments in BMC83ob up to 21,300 mS/m in BMC65d palaeochannel sediments.

No surface water quality data has been reported.

The groundwater ranged from slightly acidic to neutral, ranging in pH from 5.3 to 6.8.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>EC (mS/m)</th>
<th>TDS mg/L</th>
<th>OH &lt;1</th>
<th>CO₂ 122</th>
<th>HCO₃ 122</th>
<th>Total Alkalinity 18,400</th>
<th>S 6,150</th>
<th>Cl 134,000</th>
<th>Ca 732</th>
<th>Mg 11,500</th>
<th>Na 74,700</th>
<th>K 2,550</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater BMC 66d</td>
<td>23,100</td>
<td>272,000</td>
<td>&lt;1</td>
<td>122</td>
<td>122</td>
<td>18,400</td>
<td>6,150</td>
<td>134,000</td>
<td>732</td>
<td>11,500</td>
<td>74,700</td>
<td>2,550</td>
</tr>
<tr>
<td>BMC 83ob</td>
<td>12,400</td>
<td>112,000</td>
<td>&lt;1</td>
<td>104</td>
<td>104</td>
<td>3,180</td>
<td>1,060</td>
<td>27,200</td>
<td>632</td>
<td>1,950</td>
<td>15,700</td>
<td>415</td>
</tr>
</tbody>
</table>

Two methods of presenting results of chemical analyses are Piper (trilinear) and Stiff diagrams. This classification system shows anions and cations to indicate the water type. A plot of each diagram is presented on Figure 18 (j and k). Results indicate the groundwater and surface water samples are of type sodium-chloride.

8.6.1 Hydraulic Parameters

To understand the groundwater flow systems, a total of five slug tests were completed on the newly completed monitoring bore. Results of analyses are presented in Table 8-14.

Clayey transported sediments reported a hydraulic conductivity of between 0.002 m/day (BMC83ob) and 0.5 m/day (BMC84ob). Results from laboratory measurements of similar zones were highly variable and ranged between $1.0 \times 10^{-5}$ and 0.4 m/day (Table 8-13). Applying an average aquifer thickness of about 10 m, a transmissivity up to 4 m²/day was calculated. This compares to a measured transmissivity of 1.5 m²/day in BMC67d.

The palaeochannel sediments reported a transmissivity of 0.09 m²/day for the clay zone (BMC65d) and 3.1 m²/day for the more sandy horizons (BMC65d).
### Table 8-14  Primary Saline Wetland W448 – Field Hydraulic Parameters

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Transmissivity</td>
<td>Average Hydraulic Conductivity</td>
</tr>
<tr>
<td></td>
<td>(m²/day)</td>
<td>(m/day)</td>
</tr>
<tr>
<td>Superficial Formations, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superficial Formations, Sandy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transported Sediments, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transported Sediments, Sandy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lacustrine Deposits, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Clayey</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Sandy</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Saprolite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saprock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathered Dolerite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 8-15  Primary Saline Wetland W448 – Laboratory Hydraulic Parameters

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology</th>
<th>Formation</th>
<th>Dry Density (t/m³)</th>
<th>Initial Moisture Content (%)</th>
<th>Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC84ob</td>
<td>SIlTYY SANDSTONE - medium to coarse, sub-angular, cemented, poorly sorted.</td>
<td>Transported Sediments</td>
<td>1.41</td>
<td>32.4</td>
<td>0.00001</td>
</tr>
<tr>
<td>BMC85ob</td>
<td>WEATHERED SILCRETE - Moderately well cemented, hard.</td>
<td>Transported Sediments</td>
<td>2.03</td>
<td>12.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>
9.1 Wetland Areas W015 to W017 and W051

These wetlands lie directly adjacent to or within the valley floor and are mostly saline seeps or located at the break of slope and experience seasonal or periodic inundation. They are found in the Wallambin Soil System as remnants of the regional ancient drainage system.

The Fresh/Brackish to Valley Floor Wetlands includes specifically identified wetlands W015, W016, W017 and W051. The wetlands consist of a series of small groundwater seeps often fringed and/or covered with *Juncus acutus* and *Typha domingensis* (Richardson et al, 2005). One smaller seep (donslope to the east) is devoid of vegetation. The culturally significant Nabappie Spring is located within this wetland area with Jun Jun Spring located about 1.5 km northwest. These seeps occur along a gentle spur that runs down to W016. On either side of this spur are samphire and the occasional dead/dying River Red Gum (*Eucalyptus camaldulensis*). The largest of the seeps, W015, is situated at the top of this spur. The spur appears to start at a geological feature, possibly silcrete/calcrete outcropping. Upslope, to the west vegetation becomes *Casuarina obesa* dominant woodland. Groundwater from these seeps typically flows down slope to wetlands W017 and W078 to W080 located adjacent to the braided drainage line.

Limited water quality data have been collected by the DEC from 2004 to 2005 at the numerous seeps and wetlands through this area. In summary, the salinity at wetland W015 ranged from 47 to 127 mS/m, W016 was marginal to saline ranging from 209 to 1,168 mS/m, W017 was saline and ranged from 922 to 2,170 mS/m. Upslope of these wetlands, W051 was fresh with salinity of 56 to 84 mS/m. Wetlands located in the valley floor were saline; salinity typically ranged from 2,740 to over 8,000 mS/m (only one measurement made at these wetlands in August 2004). Corresponding acidity ranged between pH 7.5 to 7.8 for W015; between pH 7.8 to 8.6 for W016; between pH 7.1 and 8.6 for W017 and between pH 7.4 and 8.0 for W051. All wetlands are reported to have an annual drying cycle except for W051 which is a permanent damp land.

The catchment area is 924 ha, which contains 81 ha (9%) of remnant vegetation. There is a significant area (about 23 hectares) of Tagasaste (*Chamaecytisus palmensis*) which was planted up slope from the sandplain seeps. This area was planted by the previous landowner, presumably for use as a source of feed for livestock. Based upon recent observations, this area is no longer being used for grazing and is considerably overgrown.

The location of the catchment for the Fresh/Brackish to Valley Floor Wetlands is shown in a regional context on Figure 1. Photographs are provided on Plate 6 and interpretations of hydrogeology are shown on Figure 19 (a to j). Data on the Fresh/Brackish to Valley Floor Wetlands that were collected during the recent hydrogeological investigations are provided in Appendix H, inclusive of lithological and bore logs, salinity profiles and results of hydraulic tests.

9.2 Results of Landholder Interviews

The landholder was unavailable for discussions at the time of this study. Discussions with a neighbouring landholder indicated the wetland area has significant cultural history. In the past both Nabappie and Jun-Jun Springs, located about 1.5 km northwest of the wetland area, have been used by Benedictine Monks. No anecdotal information was available on historic groundwater level changes or groundwater quality.

9.3 Monitoring Bore Construction Details

A total of 10 groundwater monitoring bores were completed between June and August 2006. These complement the existing 12 monitoring bores constructed to the north. Details of recently installed monitoring bores are presented in Table 9-1, with bore locations shown on Figure 19(a).

Five deeper monitoring bores (BMC54d, BMC55d, BMC56d, BMC57d and BMC58d) were drilled to basement. A single intermediate monitoring bore BMC58i investigates a deep transported sediment bed. Three additional shallow monitoring bores (BMC86ob, BMC87ob and BMC88ob) were installed around
Section 9

Fresh/Brackish to Valley Floor Wetland

Findings

the shoreline of W017 and BMC56ob was completed to characterise the water table near wetland W016 and to compliment BMC56d. Bores ranged in depth between 3.9 and 40m.
### Section 9

#### Fresh/Brackish to Valley Floor Wetland Findings

#### Table 9-1  Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051 – Summary of Monitoring Bore Completion

<table>
<thead>
<tr>
<th>Bore</th>
<th>RL</th>
<th>Profile</th>
<th>Date Completed</th>
<th>Depth Drilled</th>
<th>Collar Height</th>
<th>Depth Cased</th>
<th>Slotted Interval</th>
<th>Slotted Length</th>
<th>Top of Gravel</th>
<th>Top of Bentonite</th>
<th>Top of Cement/Gravel</th>
<th>Airlift Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC054d</td>
<td>259.00</td>
<td>Deep</td>
<td>27/06/2006</td>
<td>23</td>
<td>0.19</td>
<td>21.59</td>
<td>19.59 - 21.59</td>
<td>2</td>
<td>17</td>
<td>6</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>BMC055d</td>
<td>260.33</td>
<td>Deep</td>
<td>28/06/2006</td>
<td>40</td>
<td>0.2</td>
<td>38.62</td>
<td>36.62 - 38.62</td>
<td>2</td>
<td>34</td>
<td>4</td>
<td>10.9</td>
<td></td>
</tr>
<tr>
<td>BMC056d</td>
<td>260.20</td>
<td>Deep</td>
<td>28/06/2006</td>
<td>25</td>
<td>0.2</td>
<td>24.79</td>
<td>22.79 - 24.79</td>
<td>2</td>
<td>19</td>
<td>5</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>BMC056ob</td>
<td>260.78</td>
<td>Shallow</td>
<td>6/08/2006</td>
<td>6</td>
<td>0.2</td>
<td>5.82</td>
<td>1.82-5.82</td>
<td>4</td>
<td>1.5</td>
<td>0</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>BMC057d</td>
<td>263.10</td>
<td>Deep</td>
<td>29/06/2006</td>
<td>27</td>
<td>0.48</td>
<td>25.42</td>
<td>23.41 - 25.41</td>
<td>2</td>
<td>20</td>
<td>4</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>BMC058d</td>
<td>269.95</td>
<td>Deep</td>
<td>30/06/2006</td>
<td>20.75</td>
<td>0.19</td>
<td>19.03</td>
<td>17.03 - 19.03</td>
<td>2</td>
<td>14</td>
<td>6</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>BMC058i</td>
<td>270.00</td>
<td>Intermediate</td>
<td>30/06/2006</td>
<td>13.5</td>
<td>0.2</td>
<td>13.31</td>
<td>11.31 - 13.31</td>
<td>2</td>
<td>8</td>
<td>3</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>BMC086ob</td>
<td>258.79</td>
<td>Shallow</td>
<td>5/08/2006</td>
<td>4.5</td>
<td>0.46</td>
<td>4.29</td>
<td>1.29 - 4.29</td>
<td>3</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
<td>trace</td>
</tr>
<tr>
<td>BMC087ob</td>
<td>258.71</td>
<td>Shallow</td>
<td>5/08/2007</td>
<td>3.9</td>
<td>0.4</td>
<td>3.45</td>
<td>0.45 - 3.45</td>
<td>3</td>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>trace</td>
</tr>
<tr>
<td>BMC088ob</td>
<td>258.37</td>
<td>Shallow</td>
<td>6/08/2006</td>
<td>5.5</td>
<td>0.2</td>
<td>5.38</td>
<td>1.38 - 5.38</td>
<td>4</td>
<td>1</td>
<td>0.5</td>
<td>trace</td>
<td></td>
</tr>
</tbody>
</table>

Prepared for Department of Environment and Conservation, 28 April 2008

Prepared by URS

9-3
9.4 Wetland Geology

Dunal sands of the Balgerbine Soil System form a superficial cover over the local catchment. The depth of cover is greatest beneath crests and mid-slopes, but is thin in the vicinity of the wetlands. A thick succession of clayey colluvium then overlies weathered and fresh bedrock.

Interpreted stratigraphy is presented on Figure 19 (b and c). Results show shallow depths to bedrock in parts of the wetland area control the thickness and depth of subsequent superficial, transported and palaeochannel layers. Beneath the middle slopes (BMC58) a thin (<5 m) section of superficial sands and silts overlays transported sediments of interbedded sand, clay and gravel. The transported sediments in this area were reported to a thickness of 11 m. Further down gradient the thickness increases to 20 m. This transported sequence is typically above a saprolite over bedrock profile. A deep weathered profile was intersected in BMC55 between two wetlands and is possibly associated with preferential weathering on a geological structure.

Beneath the lower valley, palaeochannel sediments were intersected. BMC56d intersected sub-rounded sands and silty clays between 11 and 23 m depth, with a clean sand lens between 22 and 23 m. The palaeochannel sediments were sitting on a thin (2 m) zone of weathered bedrock.

9.4.1 Soil Descriptions

The higher landscape areas of the Fresh/Brackish to Valley Floor Wetlands are located within the Balgerbine Soil System. Local soils are typically:

- Linked to undulating dunes and intradunal wetlands.
- Yellow deep aeolian deposited sands in the higher dunes and wet soils adjacent to the wetlands.
- Sandy duplexes.
- Sandy colluvium from deeply weathered granite on hill slopes.

The Wallambin Soil System represents the lower valley within this catchment. The soils of this system are typically linked with wet soils of the saline drainage and calcareous loamy earths.

9.4.2 Soil EC and pH Profiles

Appendix H presents results of soil salinity profiles. Soil EC, was measured at 1 m intervals on drill cuttings from each bore. The results indicate soil EC in the top 2 m ranging between 3.6 mS/m on the middle sandy slopes (BMC58d) to 2,700 mS/m in low lying areas adjacent to W017 (BMC54d). These comparatively high values in the low lying areas typically represent a discharge zone where evaporation of the shallow groundwater causes increased salt concentrations.

Soil salinity within the transported sediments ranged between 30 and 1,000 mS/m. This zone is typically below the influence of evaporation and is generally associated with fresher horizontal groundwater flow from the middle slopes.

In the deeper profile, EC tends to increase at depths associated with gravely aquifer zones within the transported and palaeochannel sediments. A range for the weathered bedrock of between 65 and 2,500 mS/m was measured. This is in contrast to the significantly more saline palaeochannel sediments in which EC up to 10,000 mS/m (BMC54d) was measured.

Soil pH measured on the same drill samples ranged from slightly acid, in bores located towards the valley floor, to slightly alkaline, in association with bores located in mid-slope positions (Appendix H). In BMC55d, soil pH was slightly acidic and ranged from about 5.3 in the top 3 m up to about 6.3 at 9 m depth. Alkaline soil pH (6.9 to 8.5) was found throughout most of the soil profile in BMC56d, BMC57d, and BMC 58d. Soil pH measurements were not taken in BMC54d, however based upon water quality results and soil pH measurements in neighbouring bores it is likely that soil pH would be slightly acidic.
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9.4.3 Potential Acid Sulphate Soils Analyses

A number of local landscape features indicate the possible presence of acid sulphate soil conditions, these include the low-lying topography, very shallow water table, abundant she-oaks (Casuarina spp.) upslope and iron staining waterlogged soils.

Field results using the peroxide oxidation method show very little chemical reaction indicating a low potential for acidic soils. Results are presented in Table 9-2. Soil pH throughout the profile is typically neutral to slightly alkaline. One sample from BMC56ob recorded a moderate oxidation reaction and a single sample from BMC88ob from 2 m below ground surface reported a low reaction. All other samples recorded no reaction. Groundwater samples taken from surface seeps in the wetland area reported neutral to slightly alkaline pH (Table 9-3).

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>BMC56</th>
<th>BMC86</th>
<th>BMC88</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pH&lt;sub&gt;w&lt;/sub&gt;</td>
<td>pH&lt;sub&gt;f&lt;/sub&gt;</td>
<td>Reaction</td>
</tr>
<tr>
<td>1.0</td>
<td>7.6</td>
<td>5.2</td>
<td>N</td>
</tr>
<tr>
<td>2.0</td>
<td>8.4</td>
<td>6.4</td>
<td>N</td>
</tr>
<tr>
<td>3.0</td>
<td>8.6</td>
<td>6.0</td>
<td>M</td>
</tr>
</tbody>
</table>

Note: pH<sub>w</sub> - pH of 1:5 soil: water
      pH<sub>f</sub> - pH of 1:5 soil: water following oxidation with Hydrogen Peroxide
      Reaction – N= no reaction, L= low reaction, M=moderate reaction, H=high reaction

9.4.4 Soil Laboratory Analyses

Two soil samples were taken from a selection of drill cuttings and core, in August 2006, and submitted to the laboratory for analysis for Nitrate, Total Nitrogen, Total Phosphorus and Phosphorus sorption capacity. For comparison, common values have been reported for Total Nitrogen and Total Phosphorus (Mc Arthur, 1991). Results are summarised in Table 9-4 with laboratory certificates presented in Appendix I.

<table>
<thead>
<tr>
<th>Wetland Area</th>
<th>Location</th>
<th>EC (mS/m)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seep</td>
<td>418202mE, 6683668mN</td>
<td>5,940</td>
<td>7.4</td>
</tr>
<tr>
<td>Seep</td>
<td>418250mE, 6683609mN</td>
<td>11,870</td>
<td>7.3</td>
</tr>
<tr>
<td>Seep</td>
<td>418336mE, 6683517mN</td>
<td>16,920</td>
<td>8.9</td>
</tr>
<tr>
<td>Seep</td>
<td>418112mE, 6683833mN</td>
<td>10,100</td>
<td>7.8</td>
</tr>
<tr>
<td>Seep</td>
<td>418040mE, 668360mN</td>
<td>12,680</td>
<td>8.8</td>
</tr>
</tbody>
</table>
Section 9

Fresh/Brackish to Valley Floor Wetland Findings

Table 9-4  Fresh/Brackish to Valley Floor Wetlands W015 to 017, and W051 - Soil Analysis

<table>
<thead>
<tr>
<th>Bore</th>
<th>Locality</th>
<th>Nitrate as N (mg/kg)</th>
<th>Total Nitrogen (mg/kg)</th>
<th>Total Phosphorus (mg/kg)</th>
<th>Phosphate Sorption Index (mg/kg/log_{10})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark</td>
<td>Deep Sandy Loam Type Soils</td>
<td>-</td>
<td>1,000</td>
<td>120</td>
<td>-</td>
</tr>
<tr>
<td>BMC56</td>
<td>Middle slope</td>
<td>&lt;0.100</td>
<td>250</td>
<td>31</td>
<td>18</td>
</tr>
<tr>
<td>BMC87</td>
<td>Lake shoreline</td>
<td>&lt;0.100</td>
<td>160</td>
<td>12</td>
<td>64</td>
</tr>
</tbody>
</table>

1 Suggested values for common soils in the South-West Hydrogeological Region (Mc Arthur, 1991)

The wetland area reported low concentrations for all measured parameters when compared to suggested baseline values.

Results indicate Total Nitrogen has the highest concentration in the mid-slopes probably associated with the soil properties, and proximity to farming activities. Further down slope within the lake sediments Total Nitrogen is reduced by 35%. Very low soil Nitrate concentrations beneath both the middle and lower slopes possibly indicates significant absorption by plants and/or loss from the root zone by leaching. Nitrate concentrations measured at <0.100 mg/kg. In the lower lying areas this may be due to denitrification.

The Total Phosphorus concentrations recorded at this wetland area show a similar trend to Total Nitrogen concentrations. The higher concentrations reported in middle slope soils are possibly linked to fertiliser application. The decline in Total Phosphorus concentrations from 31 to 12 mg/kg between middle slopes and the lake shoreline may indicate sorption of fertilisers beneath the middle slopes.

9.5 Wetland Hydrology

9.5.1 Surface Water Runoff

The Fresh/Brackish to Valley Floor Wetlands the catchment was divided into two sub-catchments. The first sub-catchment has shallow gravel over granite to deep yellow sands and sandy duplexes and comprises about 490 ha or 53% of catchment area. The second sub-catchment has a soil type typically represented by sand sheets and low dunes that occupy the remaining 434 ha or 47% of the catchment area. The catchment peak flows are calculated for 0.5, 1, 6, 12 and 24-hour rainfall events, for 1,2, 5, 10, 20, 50 and 100-year ARIs are presented in Table 9-5.
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Fresh/Brackish to Valley Floor Wetland Findings

Table 9-5 Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051 – Peak Flows

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Peak Flows (m³/sec) at Average Recurrence Interval in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>27.5</td>
</tr>
<tr>
<td>1</td>
<td>19.7</td>
</tr>
<tr>
<td>6</td>
<td>6.0</td>
</tr>
<tr>
<td>12</td>
<td>3.8</td>
</tr>
<tr>
<td>24</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Expected runoff volumes calculated for the Fresh/Brackish to Valley Floor Wetlands are given in Table 9-6. As an example, the catchment will have a peak flow of 11.8 m³/sec for a 6-hour duration 10-year ARI rainfall event. For this event, the peak flow volume would be 254,614 m³.

Table 9-6 Fresh Brackish Valley Floor Wetlands W015 to W017 and W051 – Runoff Volumes

<table>
<thead>
<tr>
<th>Duration (Hours)</th>
<th>Peak Volumes (m³) at Average Recurrence Interval in Years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0.5</td>
<td>825</td>
</tr>
<tr>
<td>1</td>
<td>70,875</td>
</tr>
<tr>
<td>6</td>
<td>130,100</td>
</tr>
<tr>
<td>24</td>
<td>197,737</td>
</tr>
</tbody>
</table>

9.5.2 Groundwater Level Data

The initial measurements of depth to groundwater from the ten monitoring bores are presented in Table 9-7. Groundwater contours for September 2006 are shown on Figure 19(d) and Figure 19(e) as water table elevation and depth to water table. A plan view of water table elevations for the discrete wetland area is presented on Figure 19(h). Flow lines are presented on vertical cross-sections on Figures 19(b and c).

The shallow water table ranges between about 0.93 m in BMC56ob to 1.7 m below ground to the west beneath the lower slopes. Environmental water heads show differences up to about 1.8 m in deeper bores as a result of density differences. Little difference was noted in shallow bores, however this may be

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A function of the approximate lake level datum used. This information needs to be analysed by a numerical model, due to the complexities involved, once a substantial dataset is obtained. The hydraulic gradient is about 0.00036 (dimensionless) for the shallow water table. The direction of groundwater flow is generally towards the east.

Beneath the lower valley floor there is little difference in observed head between the shallow and deep aquifers. In BMC56, however, the groundwater level was 1.63 m above ground level which indicates an upward head differential between the shallow aquifer and the deeper screened aquifer of about 2.4 m.

Table 9-7 Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051 - Groundwater Levels

<table>
<thead>
<tr>
<th>Bore</th>
<th>Profile</th>
<th>Collar RL (m AHD)</th>
<th>Observed Groundwater Levels (m btc)</th>
<th>Fresh Water Equivalent Environmental Heads (m AHD)</th>
<th>Difference In Head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC054d</td>
<td>Deep</td>
<td>259.00</td>
<td>1.82</td>
<td>257.18</td>
<td>0.02</td>
</tr>
<tr>
<td>BMC055d</td>
<td>Deep</td>
<td>260.33</td>
<td>1.08</td>
<td>259.25</td>
<td>+0.77</td>
</tr>
<tr>
<td>BMC056d</td>
<td>Deep</td>
<td>-</td>
<td>+1.63</td>
<td>262.25</td>
<td>+1.69</td>
</tr>
<tr>
<td>BMC056ob</td>
<td>Shallow</td>
<td>260.78</td>
<td>0.93</td>
<td>259.85</td>
<td>0.91</td>
</tr>
<tr>
<td>BMC057d</td>
<td>Deep</td>
<td>263.10</td>
<td>0.43</td>
<td>262.67</td>
<td>0.39</td>
</tr>
<tr>
<td>BMC058d</td>
<td>Deep</td>
<td>269.95</td>
<td>1.89</td>
<td>268.06</td>
<td>1.85</td>
</tr>
<tr>
<td>BMC058i</td>
<td>Intermediate</td>
<td>270.00</td>
<td>2.1</td>
<td>267.90</td>
<td>2.08</td>
</tr>
<tr>
<td>BMC086ob</td>
<td>Shallow</td>
<td>258.79</td>
<td>1.68</td>
<td>257.11</td>
<td>1.58</td>
</tr>
<tr>
<td>BMC087ob</td>
<td>Shallow</td>
<td>258.71</td>
<td>1.62</td>
<td>257.09</td>
<td>1.58</td>
</tr>
<tr>
<td>BMC088ob</td>
<td>Shallow</td>
<td>258.37</td>
<td>1.32</td>
<td>257.05</td>
<td>1.12</td>
</tr>
</tbody>
</table>

Groundwater level data from two shallow (BMC02ob, and BMC04ob) and four deep monitoring bores (BMC01d, BMC02d, BMC04d, and BMC05d) were used to gain an understanding of historic groundwater level change. Groundwater level data from 2002 to 2006 and average monthly rainfall data from the Koobabbie BOM rainfall station was used in the model. Table 9-8 presents a summary of results.

Generally, deep bores located in the middle slopes indicate a 28 to 61 mm/year rate of groundwater level decline. BMC01D, located on the upper slopes indicated an 8 mm/year decline in groundwater level. There is a range of lag times from nil to 9 months between rainfall and impacts on shallow water table levels. In most cases, there was a strong correlation ($r^2$ values ranged from 0.65 to 0.95) between rainfall and groundwater trends.
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Fresh/Brackish to Valley Floor Wetland Findings

Table 9-8 Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051 – Groundwater Trends

<table>
<thead>
<tr>
<th>Bore</th>
<th>Aquifer</th>
<th>Predicted Lag</th>
<th>Predicted Long-Term Groundwater Level Change</th>
<th>Predicted Average Rate of Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(months)</td>
<td></td>
<td>(mm/year)</td>
</tr>
<tr>
<td>BMC01D</td>
<td>Upper Slope</td>
<td>9</td>
<td>Decline</td>
<td>-8</td>
</tr>
<tr>
<td>BMC02ob</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-51</td>
</tr>
<tr>
<td>BMC02D</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-61</td>
</tr>
<tr>
<td>BMC04ob</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-58</td>
</tr>
<tr>
<td>BMC04D</td>
<td>Middle Slope</td>
<td>8</td>
<td>Decline</td>
<td>-57</td>
</tr>
<tr>
<td>BMC05D</td>
<td>Middle Slope</td>
<td>0</td>
<td>Decline</td>
<td>-28</td>
</tr>
</tbody>
</table>

9.5.3 Groundwater Recharge

Long-term seasonal water level fluctuations in BMC07ob range from 0.52 m in 2003, through to 0.73 m in 2004 and 0.57 m in 2005, reflecting differences in rainfall recharge (Figure 19n). Assuming an average specific yield of 0.1 for the strata in the zone of water table fluctuations, these seasonal variations indicate recharge ranging from 52 mm in a dry year and 73 mm in a particularly wet one. These data imply an annual recharge of about 62 mm in an average rainfall year.

The Fresh/Brackish Wetlands to Valley Floor area is predominantly comprised of a shallow sandy soil type. Soil depths used in the water balance simulations were developed from existing AgET model parameters and bore logs. Soil depths included 0.3 m deep horizon A and 1.2 m deep horizon B for bare soil, cereals and perennial grasses. An available water of 30 mm m\(^{-1}\) with K\(_{sat}\) of 5 mm day\(^{-1}\) was used for horizon A and 156 mm m\(^{-1}\) with K\(_{sat}\) of 30 mm day\(^{-1}\) used for horizon B. These values were derived from AgET standards for such soil types. Predicted surface run-off and groundwater recharge generated under bare soils, cereal crops and native vegetation are presented in Table 9-9. All results are reported as proportions of annual rainfall, with estimates for both modelled periods (1953 to 1993 and 1966 to 2006) presented.

In a regional sense, water loss through plant uptake or evapotranspiration is a significant proportion of annual rainfall. About 60% of annual rainfall is lost by evapotranspiration (ET). Very low runoff was simulated on bare soils (1.5%) and cereal cropped areas (1%). However under native vegetation a runoff of about 10% was simulated. This higher runoff rate possibly indicates moderate to high water repellent soils associated with areas covered by native vegetation. Recharge is estimated to be greater under bare soils than under cereal crops. No recharge was simulated under native vegetation. Recharge rates for the western areas (Coorow) range between 89 and 167 mm for bare soils compared to 52 and 128 mm for native vegetation. The dryer eastern areas (Dalwallinu) reported lower total estimates of recharge.

When comparing rainfall periods 1953 to 1993 and 1966 to 2006 it is apparent there has been an estimated 10% decline in annual rainfall in recent times. The reduction in rainfall has lead to a recharge reduction. For example, in bare soil areas in the western catchment area (Coorow) the AgET simulated recharge has declined by 34%, from 128 to 84 mm. Simulated recharge rates in cropped areas have declined by about 87%.
Using these regional estimates and applying them to the annual rainfall average of 324 mm for Koobabbie BOM station, more representative estimates for predicted runoff and recharge were calculated. For ease of interpretation results are presented in Table 9-10 as percentages of annual rainfall.

Results indicate that under current rainfall trends, up to 91% of annual rainfall is lost through ET and there is 5 to 10% surface runoff. Recharge estimates range from 12% of annual rainfall for bare soil with no simulated recharge under cropped areas and native vegetation. The Indian Ocean Climate Initiative Report (2006) predicts rainfall trends will continue declining over the next 25 years. This report predicts as much as a 20% decline in winter rainfall. Under a continued drying climate trend, recharge may decline by up to 5%, leading to lowering of groundwater levels. An increased occurrence of high intensity storms may, however, influence recharge and rates of groundwater level decline.

Table 9-9 Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051 - Regional Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>Annual Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>Coorow Rainfall Station</td>
</tr>
</tbody>
</table>
|                           | 317 (280)  
|                           | 215 (239)  
|                           | 238 (286)  
|                           | 283 (297)  
|                           | 0 (0)     
|                           | 0 (0)     
|                           | 17 (0)    
|                           | 89 (39)   
|                           | 52 (4)    
|                           | 0 (0)     

|                           | Dalwallinu Rainfall Station |
|                           | 361 (324)   
|                           | 243 (245)   
|                           | 337 (245)   
|                           | 337 (313)   
|                           | 1 (0)      
|                           | 0 (0)      
|                           | 98 (82)    
|                           | 0 (0)      

| 50%                       | Coorow Rainfall Station  |
|                           | 389 (379)   
|                           | 233 (373)   
|                           | 280 (333)   
|                           | 335 (371)   
|                           | 6 (0)      
|                           | 4 (0)      
|                           | 37 (0)     
|                           | 128 (84)   
|                           | 93 (12)    
|                           | 0 (0)      

|                           | Dalwallinu Rainfall Station |
|                           | 288 (270)   
|                           | 206 (203)   
|                           | 288 (203)   
|                           | 288 (270)   
|                           | 0 (0)      
|                           | 0 (0)      
|                           | 65 (43)    
|                           | 0 (0)      

| 25%                       | Coorow Rainfall Station  |
|                           | 446 (437)   
|                           | 267 (306)   
|                           | 304 (371)   
|                           | 392 (410)   
|                           | 22 (10)    
|                           | 22 (7)     
|                           | 167 (115)  
|                           | 128 (47)   
|                           | 0 (0)      

|                           | Dalwallinu Rainfall Station |
|                           | 423 (391)   
|                           | 258 (262)   
|                           | 383 (262)   
|                           | 383 (372)   
|                           | 15 (17)    
|                           | 10 (17)    
|                           | 139 (126)  
|                           | 5 (126)    
|                           | 5 (0)      

Note: 317 Daily water balance AgET 1953 to 1993 daily rainfall data
(280) Daily water balance AgET 1967 to 2006 daily rainfall data
Table 9-10  Fresh/Brackish to Valley Floor Wetland W015 to W017 and W051 - Predicted Runoff and Deep Flows

<table>
<thead>
<tr>
<th>Probability of Exceedence</th>
<th>ET (SHALLOW SANDY SOIL TYPE)</th>
<th>Runoff (SHALLOW SANDY SOIL TYPE)</th>
<th>Recharge (SHALLOW SANDY SOIL TYPE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare Soil</td>
<td>Cereal Crop</td>
<td>Native Vegetation</td>
</tr>
<tr>
<td>Annual Rainfall (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>261</td>
<td>80%</td>
<td>88%</td>
</tr>
<tr>
<td>50%</td>
<td>324</td>
<td>87%</td>
<td>82%</td>
</tr>
<tr>
<td>25%</td>
<td>374</td>
<td>79%</td>
<td>86%</td>
</tr>
</tbody>
</table>

Note: 280 Daily water balance AgET 1967 to 2006 daily rainfall data

9.5.4 Water Quality Data

Monitoring of groundwater EC and pH from all recently completed groundwater monitoring bores was undertaken in September 2006. Table 9-11 presents a summary of field EC and pH measurements. Figures 19 (f and g) show interpretations of groundwater salinity distributions on cross-sections. A more detailed plan view of wetland EC is presented on Figure 19(i). Samples were also taken from BMC56d, BMC54d, BMC58i, BMC87ob and from two surface water sites, in September 2006, and submitted to the laboratory for analysis for pH, EC, TDS and major anions and cations. Table 9-12 presents results of laboratory analyses both surface water and groundwater; Certificates of Analyses are provided in Appendix I.
### Table 9-11  Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051 - Groundwater EC and pH Field Measurements

<table>
<thead>
<tr>
<th>Bore</th>
<th>Profile</th>
<th>Depth (m)</th>
<th>Electrical Conductivity (mS/m)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC054d</td>
<td>Deep</td>
<td>23</td>
<td>15,200</td>
<td>6.2</td>
</tr>
<tr>
<td>BMC055d</td>
<td>Deep</td>
<td>40</td>
<td>9,350</td>
<td>6.9</td>
</tr>
<tr>
<td>BMC056d</td>
<td>Deep</td>
<td>25</td>
<td>450</td>
<td>7.8</td>
</tr>
<tr>
<td>BMC056ob</td>
<td>Shallow</td>
<td>6</td>
<td>1,104</td>
<td>7.2</td>
</tr>
<tr>
<td>BMC057d</td>
<td>Deep</td>
<td>27</td>
<td>373</td>
<td>7.9</td>
</tr>
<tr>
<td>BMC058d</td>
<td>Deep</td>
<td>20.75</td>
<td>455</td>
<td>7.8</td>
</tr>
<tr>
<td>BMC058i</td>
<td>Intermediate</td>
<td>13.5</td>
<td>426</td>
<td>6.8</td>
</tr>
<tr>
<td>BMC086ob</td>
<td>Shallow</td>
<td>4.5</td>
<td>10,570</td>
<td>5.8</td>
</tr>
<tr>
<td>BMC087ob</td>
<td>Shallow</td>
<td>3.9</td>
<td>9,600</td>
<td>6.1</td>
</tr>
<tr>
<td>BMC088ob</td>
<td>Shallow</td>
<td>5.5</td>
<td>13,340</td>
<td>7.1</td>
</tr>
</tbody>
</table>
Section 9

Fresh/Brackish to Valley Floor Wetland Findings

Table 9-12 Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051 - Summary of Laboratory Water Analyses

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>EC (mS/m)</th>
<th>TDS mg/L</th>
<th>OH</th>
<th>CO₂</th>
<th>HCO₃</th>
<th>Total Alkalinity</th>
<th>SO₄ mg/L</th>
<th>S mg/L</th>
<th>Cl mg/L</th>
<th>Ca mg/L</th>
<th>Mg mg/L</th>
<th>Na mg/L</th>
<th>K mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC54d</td>
<td>14,600</td>
<td>129,000</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>85</td>
<td>85</td>
<td>8,790</td>
<td>2,930</td>
<td>60,800</td>
<td>732</td>
<td>3,520</td>
<td>34,600</td>
<td>679</td>
</tr>
<tr>
<td>BMC56d</td>
<td>437</td>
<td>2,580</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>35</td>
<td>35</td>
<td>115</td>
<td>38</td>
<td>1,410</td>
<td>24</td>
<td>102</td>
<td>784</td>
<td>17</td>
</tr>
<tr>
<td>BMC58i</td>
<td>537</td>
<td>3,410</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>35</td>
<td>35</td>
<td>194</td>
<td>65</td>
<td>1,630</td>
<td>35</td>
<td>113</td>
<td>964</td>
<td>18</td>
</tr>
<tr>
<td>BMC87ob</td>
<td>10,800</td>
<td>86,400</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>221</td>
<td>221</td>
<td>5,730</td>
<td>1,910</td>
<td>42,600</td>
<td>1,060</td>
<td>3,250</td>
<td>24,600</td>
<td>442</td>
</tr>
</tbody>
</table>

Groundwater from the deeper aquifers within the weathered profile at sites beneath the valley floor were generally hypersaline, with field EC up to 15,200 mS/m in BMC54d. By contrast, field EC in the artesian BMC56d was measured at 450 mS/m. These two bores are located only 500 m from each other, which emphasises the heterogeneity of the underlying geology.

All deep bores located up-gradient from the valley floor reported relatively low field EC, ranging from 373 to 450 mS/m. BMC56ob on the upper slopes away reported a lower field EC than shallow bores around W016.

The groundwater pH in all areas ranged from slightly acidic to neutral (5.8 to 7.9). There appears to be no correlation between shallow and deep groundwater acidity. In contrast, the surface water collected from two groundwater seeps is generally neutral to alkaline. Summary results are presented in Table 9-3 and on Figure 19(i). Results indicate the field EC of surface seepage is variable ranging between 5,900 mS/m on the western side of the seepage to 16,920 mS/m on the eastern side. The pH is typically slightly alkaline (pH 7.5) in the central area of the seepage. On the eastern side of the seepage area, however, a pH of 8.8 was measured.

Piper and Stiff diagrams have been prepared to characterise the local groundwater as shown on Figure 19 (k and l). Results indicate the groundwater is of a type sodium-chloride. Laboratory groundwater analyses show a relative high (221 mg/L) concentration of Bicarbonate in BMC87ob and in surface water sample 2 of 130 mg/L (Table 9-12). These concentrations are indicative of the shallow calcrete layer observed beneath the upper valley flats.
9.5.5 Hydraulic Parameters

A total of ten slug tests were completed on each newly completed monitoring bore. Summary results of analyses are presented in Table 9-13.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Transmissivity</td>
<td>Average Hydraulic Conductivity</td>
</tr>
<tr>
<td></td>
<td>(m²/day)</td>
<td>(m/day)</td>
</tr>
<tr>
<td>Superficial Formations, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superficial Formations, Sandy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transported Sediments, Clayey</td>
<td>0.5</td>
<td>0.6, 0.02, 0.07</td>
</tr>
<tr>
<td>Transported Sediments, Sandy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lacustrine Deposits, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Clayey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Sandy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saprolite</td>
<td>2, 0.7, 0.05</td>
<td></td>
</tr>
<tr>
<td>Saprocks</td>
<td>3.5, 1.5</td>
<td></td>
</tr>
<tr>
<td>Weathered Dolerite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Local groundwater flow systems are characterised by a hydraulic gradient for the middle slopes at 0.002 (dimensionless) and 0.007 beneath the valley floor. Using an effective porosity of 0.1 a groundwater velocity of 0.05 m/day was estimated for the middle slopes and 0.2 m/day was estimated for the lower valley floor.

Laboratory measurements taken on a sample from the superficial sandy clays reported a hydraulic conductivity of 0.05 m/day. The shallow transported sandy profile has an interpreted hydraulic conductivity of between 0.02 and 2 m/day. Results from laboratory measurements of more discrete zones ranged between 0.0004 to 0.01 m/day (Table 5-13). Applying an average aquifer thickness of 5 m for this zone, a transmissivity of about 2 m²/day is estimated. This compares to a field measured transmissivity of 0.5 m²/day in BMC58i.

The deeper saprolite and saprock profiles reported similar hydraulic conductivities of 2.3 to 2.5 m/day.
## Fresh/Brackish to Valley Floor Wetland Findings

### Table 9-14  Fresh Brackish Valley Floor Wetland W015 to W017 and W051 - Laboratory Hydraulic Parameters

<table>
<thead>
<tr>
<th>Bore</th>
<th>Sample From (m bgl)</th>
<th>Sample To (m bgl)</th>
<th>Lithology</th>
<th>Formation</th>
<th>Dry Density (t/m³)</th>
<th>Initial Moisture Content (%)</th>
<th>Hydraulic Conductivity (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMC 56ob</td>
<td>2.9</td>
<td>3</td>
<td>FERRUGINOUS CLAY – light brown (5YR 5/5) to moderate brown (5YR 3/4), interbedded lateritic hard cemented bands, minor laterite gravel nodules, well rounded, minor pale yellowish brown (10YR 6/2).</td>
<td>Transported Sediments</td>
<td>1.77</td>
<td>9.9</td>
<td>0.0004</td>
</tr>
<tr>
<td>BMC86ob</td>
<td>3.2</td>
<td>3.3</td>
<td>CLAY – mid green grey, plastic lake clays.</td>
<td>Transported Sediments</td>
<td>1.03</td>
<td>49.1</td>
<td>0.0008</td>
</tr>
<tr>
<td>BMC87ob</td>
<td>3</td>
<td>3.1</td>
<td>CLAY – mid green grey, plastic lake clays.</td>
<td>Transported Sediments</td>
<td>0.67</td>
<td>108.4</td>
<td>0.01</td>
</tr>
<tr>
<td>BMC88ob</td>
<td>1.8</td>
<td>1.9</td>
<td>SANDY CLAY – mid to dark brown, interbedded cemented bands.</td>
<td>Superficial Formation</td>
<td>0.69</td>
<td>73.1</td>
<td>0.05</td>
</tr>
</tbody>
</table>
10.1 Water and Salt Balance Results

Analysis of daily soil water balance has been used to estimate the proportions of ET, runoff and groundwater recharge rates in the BMNDRC.

Daily rainfall data collected from both Coorow and Dalwallinu have been used to gain an understanding of the rainfall variation throughout the BMNDRC. These data have subsequently been applied to estimate the optimum timetables for the planting of winter crops at 25% probability (early planting), 50% probability (normal planting) and at 75% probability (late planting). These probabilities have been used to provide a suitable range for the water balance calculations.

The daily soil water balance ($W$) of BMNDRC from 1963 to 1969 (Coorow) is presented on Figure 20. In the years when $W$ is less than 100 mm there is a low likelihood of recharge, with $W$ of 100 to 150 mm there is a limited likelihood of groundwater recharge and when the $W$ is more than 150 mm there is a likelihood of groundwater recharge. The $W$ exceeded 150 mm for long periods during 1963, 1964 and 1968. Serious floods inundated the areas in 1963 and 1968, and two in 1999. The $W$ of less than 50 mm during 1969 indicates that this year was a dry year. There was a widespread drought in the Wheatbelt of WA during 1969.

For comparison, the $W$ during the 1999 floods and prevailing drought in the west of the BMNDRC from 1999 to 2005 have been plotted on Figure 21. There were two episodic daily rainfall events in March and May during 1999 that resulted in a $W$ of 150 mm or more for a long length of time. A $W$ of less than 75 mm occurred from 2000 to 2005 indicating low likelihood of recharge to groundwater, low water availability in lakes and farm dams and decrease in water available for crops. Groundwater level data from D1 located adjacent to the Gypsum Wetlands catchment has been plotted as a hydrograph along with the $W$ from 3 June 1996 to 31 December 2005 (Figure 22). These data support the relationship between rainfall and groundwater level rise and use of the daily water balance to predict the groundwater recharge.

The AgET model was used to calculate daily water balance of the BMNDRC, initially using 1954 to 1993 daily rainfall data. An additional run using 1967 to 2006 daily rainfall data was used to test the sensitivity of the model to recent changes in rainfall. These results provided an indicative assessment of possible changes in groundwater level. Table 10-1 presents a summary of indicative wetland water balance parameters.
Section 10

Water and Salt Balance Results

Table 10-1  Summary of Water Balance Parameters

<table>
<thead>
<tr>
<th>Water Balance Parameter</th>
<th>Fresh/Brackish Wetlands W011 and W002</th>
<th>Bentonite Wetlands W056 to W059</th>
<th>Gypsum Wetlands W001 and W002</th>
<th>Primary Saline Wetland W448</th>
<th>Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment Area (ha)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop</td>
<td>1,648</td>
<td>602</td>
<td>3,413</td>
<td>71,000</td>
<td>843</td>
</tr>
<tr>
<td>Vegetation</td>
<td>135</td>
<td>385</td>
<td>578</td>
<td>9,000</td>
<td>81</td>
</tr>
<tr>
<td>Total</td>
<td>1,783</td>
<td>987</td>
<td>3,991</td>
<td>80,000</td>
<td>924</td>
</tr>
<tr>
<td>Rainfall (mm/yr)</td>
<td>339 (324)</td>
<td>367 (345)</td>
<td>339 (324)</td>
<td>315 (302)</td>
<td>339 (324)</td>
</tr>
<tr>
<td>Evapotranspiration (mm/yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff (mm/yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop</td>
<td>0 (0)</td>
<td>64 (18)</td>
<td>59 (17)</td>
<td>55 (15)</td>
<td>2 (0)</td>
</tr>
<tr>
<td>Vegetation</td>
<td>0 (0)</td>
<td>36 (16)</td>
<td>33 (15)</td>
<td>31 (14)</td>
<td>17 (0)</td>
</tr>
<tr>
<td>Recharge (mm/yr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop</td>
<td>100 (48)</td>
<td>32 (0)</td>
<td>30 (0)</td>
<td>28 (0)</td>
<td>42 (46)</td>
</tr>
<tr>
<td>Vegetation</td>
<td>29 (8)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Rainfall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salinity (mg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow Groundwater</td>
<td>40,000</td>
<td>1,400</td>
<td>55,000</td>
<td>65,000</td>
<td>6,000</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff</td>
<td>5,000</td>
<td>1,000</td>
<td>20,000</td>
<td>50,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Recharge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: 64 Daily water balance AgET 1954 to 1993 daily rainfall data
      (18) Daily water balance AgET 1967 to 2006 daily rainfall data

The salinity of the recharge is equivalent to the salinity (10 mg/L) of the rainfall. It is interpreted that recharge predominantly occurs beneath ridges and mid-slopes, in areas where salinisation is not widespread and there is limited opportunity for infiltration to mobilise additional salts.

In order to present some indicative estimates to the water balance, and subsequent salt balance, for each representative wetland a few assumptions were made:

- Cereal crops have rooting depths of less than 0.5 m in shallow saline water table environments.
- Natural vegetation has rooting depths up to 8 m in shallow saline water table zones.
- Recharge estimates derived for each wetland area were based on the representative soil-landscape systems.

In addition each representative wetland was divided into cropped and natural vegetated land areas.

A summary of simulation results for each wetland is show in Table 10-2.
## Section 10

### Water and Salt Balance Results

**Table 10-2  Interpreted Water and Salt Balance for BMNDRC Representative Wetlands**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh/Brackish Wetlands W011 and W012</td>
<td>Rainfall</td>
<td>6,044,370</td>
<td>5,776,920</td>
<td>3,622,290</td>
<td>3,405,150</td>
<td>13,529,490</td>
<td>12,930,840</td>
<td>252,000,000</td>
<td>241,600,000</td>
<td>3,132,360</td>
<td>2,993,760</td>
</tr>
<tr>
<td>Bentonite Wetlands W056 to W059</td>
<td>Recharge</td>
<td>1,687,150</td>
<td>801,840</td>
<td>192,640</td>
<td>0</td>
<td>1,023,900</td>
<td>0</td>
<td>19,880,000</td>
<td>0</td>
<td>354,060</td>
<td>387,780</td>
</tr>
<tr>
<td>Gypsum Wetlands W001 and W002</td>
<td>Groundwater Inflows</td>
<td>203,305</td>
<td>203,305</td>
<td>50,209</td>
<td>50,209</td>
<td>137,240</td>
<td>137,240</td>
<td>300,760</td>
<td>300,760</td>
<td>206,225</td>
<td>206,225</td>
</tr>
<tr>
<td>Primary Saline Wetland W448</td>
<td>Surface Water Runoff</td>
<td>0</td>
<td>0</td>
<td>523,880</td>
<td>169,960</td>
<td>2,204,410</td>
<td>666,910</td>
<td>41,840,000</td>
<td>11,910,000</td>
<td>30,630</td>
<td>0</td>
</tr>
<tr>
<td>Wetland Groundwater Evaporation</td>
<td>Gain/Loss</td>
<td>1,200,000</td>
<td>1,200,000</td>
<td>300,000</td>
<td>300,000</td>
<td>300,000</td>
<td>300,000</td>
<td>4,800,000</td>
<td>4,800,000</td>
<td>300,000</td>
<td>300,000</td>
</tr>
</tbody>
</table>

**WATER BALANCE**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>kL/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge</td>
<td>1,687,150</td>
</tr>
<tr>
<td>Groundwater Inflows</td>
<td>203,305</td>
</tr>
<tr>
<td>Surface Water Runoff</td>
<td>0</td>
</tr>
</tbody>
</table>

**SALT BALANCE**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>tonnes/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recharge</td>
<td>17</td>
</tr>
<tr>
<td>Due to Groundwater Evaporation</td>
<td>25,830</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater Outflows</td>
</tr>
<tr>
<td>Estimated Accumulation of Salt (tonnes/yr)</td>
</tr>
</tbody>
</table>
11 Conceptual Hydrogeological Model

11.1 Geology
The conceptual geology of BMNDRC was developed during past studies (Speed and Strelein, 2004). The geological model has been updated, based on information derived from the installation and testing of an additional 45 monitoring bores. The combined results from these hydrogeological investigations across the catchment suggests that the stratigraphy in BMNDRC can be described according to four main horizons.

- Superficial formations: sediments consisting of both clay and sand dominated successions. These deposits formed from alluvial, colluvial and Aeolian processes and may have a higher hydraulic conductivity than the sediments in the weathered profile. The superficial sediments occur on the middle slopes of the catchment and cover the entire valley flats on the main drainage line on the middle and lower parts of the BMNDRC. Cementation with silica, carbonate and iron is common and produces indurated silcrete, calcrete and mottled, ferricrete layers.

- Transported sediments: below the superficial sediments lays a sequence of transported sediments. These sediments typically form a mottled colluvium of sand, silts and coarse, well rounded quartz river pebbles.

- Palaeochannel deposits: The predominant sedimentary system are palaeochannel successions, which occur at depth. Groundwater flow in this system occurs in comparatively high transmissivity palaeochannel sands interpreted to underlie the valley floor. The alluvial palaeochannel deposits comprise sand and clay and are 20 to 50 m thick. The sand particles are mainly sub-angular to sub-rounded quartz indicating a short travel distance and a rapid mode of deposition. The alluvial sediments are typically overlain by up to 10 m thick lacustrine fine clay.

- Basement: Primary minerals weather in-situ to clay promoting the development of sandy-clay saprolite. The clay content decreases with depth as unaltered mineral contents increase. The saprolite forms a typical low-transmissivity profile in the catchment. Faults, structures and tree roots can provide vertical and horizontal preferential groundwater flow paths. The horizon developed above fresh basement is characterised by saprock. This slightly weathered bedrock material is primarily composed of angular quartz and feldspar.

11.2 Sedimentology and Palaeochannel Evolution
Over hundreds of millions of years the crystalline rocks underlying the valley floor in the BMNDRC have been incised by ancient watercourses which have been subsequently infilled with successions of sediments, which have themselves been subjected to ongoing weathering and reworking (palaeochannels). Commander et al, (2001) described the valley sediments of this region into two broad types: the thick palaeochannel sediments, which occur in deeply incised palaeovalleys and thin Quaternary colluvial, alluvial and lacustrine sediments which cover the full width of the valleys.

It is believed that widespread palaeochannel formation began in inland Western Australia at the end of the Permo-Carboniferous glaciation period 286 mya (Geological Survey of Western Australia, 1990). The erosion of regolith has contributed to the palaeochannel sediments and overlying alluvial and colluvial superficial formations. Quaternary (1.8 mya to present) aridity contributed to the development of salt lakes and associated gypsum dunes and lunettes (Commander et al, 2001).

The BMNDRC lays within the Western Division of the palaeochannel system (George, Clarke and English, 2006). This division is poorly understood, however the few studies that have been conducted indicate that the palaeochannels may range up to 60 m depth, with infilled sediments either Eocene (54 to 36 mya) or Pliocene (5 mya) age (George, Clarke and English, 2006).

The BMNDRC forms a largely internally draining landscape dominated by a valley floor characterised by discontinuous chains of salt playas and lakes. The location of palaeochannels in BMNDRC currently is
largely interpreted. Palaeochannels however, have been intersected during drilling programmes undertaken in 2002 (Speed and Strelein, 2004) and as part of this investigation. Results from these investigations have enabled the location of palaeochannels throughout the BMNDRC to be broadly interpreted. Figure 10 presents these current interpretations.

It has been documented that salinity possibly manifested itself widely in the Australian landscape in response to aridity during the glacial periods (George, Clarke and English, 2006). Plant extinctions and contraction of habitats resulted in less demand for rainfall. During this drying period, palaeo-freshwater lakes and rivers contracted and became braided as surface water diminished. Further more, seawater level decline during this period made it even more difficult for rivers to reach the oceans thereby inhibiting the flushing of the landscape of dissolved salts. This resulted in the formation of internal drainage networks (George, Clarke and English, 2006).

Salts within the regolith were mobilised due to Aeolian drift and as water tables rose in response to increasing groundwater recharge. As these water tables became closer to the landscape surface, stored salts became concentrated under the influence of evaporation. These saline soils promoted less vegetation cover and therefore widespread erosion and deflation and Aeolian landform development. Aeolian activity deflated and scoured saline playa surfaces forming saline landscapes from transported salt lake sediments (lunettes) and lowering of lake bed levels which increased the areas exposed to elevated water levels. These processes enhanced groundwater discharge and salt lake evolution. Discontinuous lunette and sand dune formations also result in restriction of surface water processes within these catchments.

11.3 Conceptual Hydrogeological Model

The structural fabric of the BMNDRC predominantly consists of Archaean bedrock, including intrusive dolerite dykes, faults and shear zones. This fabric imposes controls on the distributions and thicknesses of weathering profiles and alignment of watercourses. The structural fabric may occur on small, local, sub-catchment and catchment scales.

The structural fabric that shapes the landscape also influence the hydrogeology. Within the BMNDRC the known hydrogeology is in-part controlled by topography, soil systems, characteristics of the regolith and structures in the bedrock fabric. Predominantly, the BMNDRC landscape is dominated by a sediment regolith-landform terrain, where aeolian, fluvial and/or lacustrine deposits overlie bedrocks. On a local scale, crests and hill-tops form a bedrock regolith-landform terrain where erosion has exposed weathered or fresh bedrocks. Bedrock outcrop, particularly dolerite dykes, is common in the Inering Hills Soil System and immediately south-east of Primary Saline wetland W448. The Ballidu Soil System to the east is also prone to bedrock outcrops, but to a lesser extent.

It is interpreted that palaeochannels (forming the Buntine Palaeodrainage) exist beneath the lower parts of the BMNDRC landscape, particularly in association with the naturally saline braided drainage line. Such palaeochannels may form dominant aspects of the regional hydrogeology. Sedimentary successions found within these palaeochannels are widely variable in lithology, source material, grain-size and sorting. These aspects reflect the contrasting geology, climate and deposition environments over time.

Throughout the BMNDRC, several types of duricrust have been imposed on the regolith by chemical and groundwater processes. Laterite, though minor, occurs on some crests and hill-tops of the Ballidu Soil System. Elsewhere, gypsum, silica, and calcium duricrusts are known. Processes of silicification (formation of silcrete and red-brown playa hardpans) and gypsification (formation of gypsum) are also known in the BMNDRC.

In work undertaken by the Western Australian Department of Agriculture (Bennett et al, 2005), it was concluded that the duricrust may act as a physical barrier for plant growth and form a low-transmissivity barrier for vertical groundwater flow. The duricrust may promote the occurrence of ephemeral perched water tables that host thin fresh to brackish groundwater lenses important for plant growth. It is also reported that the perched groundwater may commonly infiltrate the duricrust via macropores and lithic-
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facies to recharge the deeper permanent water table. These processes are likely to be active in the BMNDRC, particularly in lower settings of the landscape.

The knowledge of the geology and stratigraphy of the BMNDRC is linked with the findings of drilling investigations that frame a conceptual hydrogeological model. This conceptual hydrogeological model provides a broad and catchment-wide appraisal of the BMNDRC hydrogeology. It may be also applied on a local and sub-catchment scale, understanding that small-scale structural fabrics may influence the local groundwater environment. Development of the conceptual hydrogeological model has been supported by Figure 2 (Soil-Landscape Systems), Figure 8 (a to g), and Figure 23 and 24(a and b, hydrogeology cross-sections).

Key elements of the conceptual hydrogeological model for the BMNDRC include:

- The Landscape-Soil Systems are important aspects of the sub-catchment hydrogeology. Significant characteristics of the individual representative wetland areas based on the mapped soils are outlined in Table 11-1.
- Recharge domains typically occur on crests and hill-tops.
- Recharge domains within the Upsan Downs Soil System are comparatively large and transmissive, due to the occurrence of shallow drainage lines and deep sands. Both the Balgerbine and Ballidu Soil Systems also provide superficial formations of sand that would promote recharge. Conversely, the Inering Soil System would promote comparatively low recharge due to the occurrence of numerous outcrops of bedrock and prevalence of rocky and loamy soils.
- Recharge would predominantly vertically infiltrate the sandy superficial formations until being laterally deflected by silcrete and/or clayey succession of the transported sediment profiles. The clayey superficial profiles will tend to limit infiltration.
- Recharge that infiltrates above duricrusts is often diverted through macropores to the deeper permanent water table.
- Dunal superficial sandy sediments in the valley floor setting act as localised recharge domains on the perimeter of local ephemeral wetlands.
- Discharge domains typically occur in valley-floor and footslope settings at breaks of slope. Discharge zones are also often controlled by geological structures and/or depth to bedrock.
- Groundwater throughput into the Buntine Palaeodrainage and associated watercourses that are juxtaposed by the Upsan Downs, Balgerbine and Ballidu Soil Systems may be comparatively high. The prevalence of larger lakes adjacent to the Upsan Downs Soil System may be manifested due to comparatively high local groundwater throughput brought about by the occurrence of comparatively large catchments and recharge.
- Both topography and the Inering Hills Soil System have lead to an absence of large lakes on downstream reaches of the palaeochannel and near the confluence with the Latham Lakes Chain.
- Groundwater flow and water table settings are closely aligned with the topography. Flow occurs from upland-recharge to valley-floor-discharge areas. Depths to the water table in the lower parts of the landscape are typically shallow in the range from <0.5 to 2 m. Several of the playa lakes are perennial and closely represent the local water table. Structural features may control the locations of lakes within the BMNDRC.
- Groundwater flow predominantly occurs in three aquifer systems formed by:
  - Sandplain dunal deposits that characterise the superficial formations of the Upsan Downs, Balgerbine and Ballidu Soil Systems.
  - Sand successions of the Buntine Palaeodrainage.
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- Structured or sandy profiles in saprolitic and fresh bedrock.

- Groundwater flow, at least on a local scale, is in-part controlled by transmissive structures in the bedrock fabric. Structural fabrics are evident and known to influence depths of weathering, alignment of the Buntine Palaeodrainage, tributaries and topography.

- Numerous wetlands occur comparatively high in the landscape, on drainage lines, within the Balgerbine Soil System. These wetlands reflect the occurrence of:
  - Recharge through sandy superficial formations profiles.
  - Infiltration to confining beds formed by clayey successions of colluvium and saprolitic bedrock.
  - Lateral flow to drainage lines, beneath which the thickness of sandy superficial formations is limited or there is a break of slope.
  - Ephemeral outcropping of the water table in the drainage lines, with excess groundwater being dissipated by throughflow and evaporation.

- It is anticipated that the catchments for individual wetlands in this higher landscape setting are small, flow paths to the lakes are short and shallow bedrock profiles limit the available storage for rainfall infiltration.

- The hydraulic characteristics of the local shallow groundwater flow systems are predominantly influenced by lithology, with sandy successions forming preferred flow paths. Interpreted hydraulic conductivity values for both sedimentary and bedrock profiles are summarised in Table 11-2. These interpreted values show the predominance of sandy profiles with comparatively high hydraulic conductivities.

- Hydraulic conductivity derived from laboratory tests is interpreted to indicate the vertical flow potentials through selected samples. Clay samples provided estimates of vertical hydraulic conductivity in the range from 0.000005 to 1.5 m/day, though results are predominantly <0.001 m/day. These analyses indicate the strong potentials for clayey beds to constrain vertical groundwater flow and form confining or perching strata.

- Groundwater flow is probably dominated by the Buntine Palaeodrainage and transported sandplain successions. Fractures in the bedrock profile may promote and facilitate flow on a local scale. Based on potential transmissivity and groundwater yields, the aquifer systems are interpreted to include in order of importance:
  - Palaeochannel sand deposits of the Buntine Palaeodrainage.
  - Transmitted superficial formation sands.
  - Transmissive fracture zones in the bedrocks.

- Hydraulic gradients are lowest beneath valley-floor settings in association with the Buntine Palaeodrainage. Transmissivity of the transported and palaeochannel sediments is comparatively high, even beneath upper catchment reaches.

- Hydraulic gradients steepen in successions that juxtapose the Buntine Palaeodrainage.

- Selected reaches of the Buntine Palaeodrainage, particularly in proximity to the large playas, may act as seasonal recharge and discharge zones. This seasonal reversal of hydraulic gradients may characterise internal drainage, but also playas with wide-ranging TDS concentrations.
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- The Buntine Palaeodrainage successions typically have slightly increasing cross-section areas from upper-catchment to lower-catchment settings.
- Groundwater is a sodium-chloride type throughout the catchment areas sampled (see Figure 25 for Stiff Diagrams).
- Groundwater quality varies substantially within the catchment, being fresh beneath recharge domains, but increasingly brackish along flow paths towards discharge zones. Groundwater in the Buntine Palaeodrainage is hypersaline, reflecting a long flow path in shallow water table valley-floor settings where losses due to evaporation are a significant aspect of the water balance.
- The aquifer systems and successions associated with the Buntine Palaeodrainage are full, with limited available storage for additional groundwater inputs.
- The groundwater environment is seen to change slowly under stressors applied by land-clearing, significant storm recharge events and modifications to drainage imposed by prior and current land managers.
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#### Table 11-1 Broad-Scale Soil-System Catchment Characterisation

<table>
<thead>
<tr>
<th>Soil Systems</th>
<th>Wetlands</th>
<th>Fresh/Brackish Wetlands</th>
<th>Bentonite Wetlands</th>
<th>Gypsum Wetlands</th>
<th>Primary Saline Wetland</th>
<th>Fresh/Brackish to Valley Floor Wetlands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W011 and W012</td>
<td>W056 and W059</td>
<td>W001 and W002</td>
<td>W448</td>
<td>W015 to W17 and W051</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Balgerbine</td>
<td>Balgerbine</td>
<td>Inering Hills</td>
<td>Wallambil</td>
<td>Balgerbine</td>
</tr>
<tr>
<td>Undulating Dunes</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Intradunal Lakes</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Deep Aeolian Yellow Sands</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sandy Duplexes</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Sandy Colluvium for Weathered Granite</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Red &amp; Talcy Loams</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Stony Soils &amp; Outcrop</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Dolerite Dykes</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Salt Lakes &amp; Braided Drainage</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Alluvial Flats</td>
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<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
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<tr>
<td>Playa</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Prepared for Department of Environment and Conservation, 28 April 2008
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#### Table 11-2  Wetlands Areas – Summary of Average Hydraulic Conductivity

<table>
<thead>
<tr>
<th>Formation</th>
<th>Fresh/Brackish Wetlands</th>
<th>Bentonite Wetlands</th>
<th>Gypsum Wetlands</th>
<th>Primary Saline Wetland</th>
<th>Fresh/Brackish to Valley Floor Wetlands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W011 and W012</td>
<td>W056 to W059</td>
<td>W001 and W002</td>
<td>W448</td>
<td>W015 to W017 and W051</td>
</tr>
<tr>
<td><strong>Hydraulic Conductivity (m/day)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superficial Formations, Clayey</td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superficial Formations, Sandy</td>
<td></td>
<td>0.09, 6.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transported Sediments, Clayey</td>
<td>0.1</td>
<td>1.9</td>
<td>5.1</td>
<td>0.002, 0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Transported Sediments, Sandy</td>
<td>0.2, 2.1</td>
<td>6.7</td>
<td>0.1</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Lacustrine Deposits, Clayey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palaeodrainage, Clayey</td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Palaeodrainage, Sandy</td>
<td>1.6</td>
<td>3.6</td>
<td>5.5</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Saprolite</td>
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<td>3.4</td>
<td>0.005, 2</td>
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<td>0.08, 2.3</td>
</tr>
<tr>
<td>Saprock</td>
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<td></td>
<td>0.5</td>
<td>3.8</td>
</tr>
<tr>
<td>Weathered Dolerite</td>
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<td></td>
<td></td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Bedrock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 11.3.1  Fresh Brackish Wetlands

The conceptual hydrogeological model of the Fresh/Brackish Wetlands is dominated by groundwater flow in aquifer systems formed by dunal superficial formation sands of the Balgerbine Soil System. Groundwater discharge occurs at breaks of slope, into intradunal depressions and into palaeochannel successions in a tributary of the Buntine Palaeodrainage.

Water table settings closely conform to the topography and the expression of cemented silcrete and clayey colluvial profiles that occur beneath the dunal sands. Wetlands W011 and W012 occur in mid-slope settings and are characterised by local depressions in the topography wherein the superficial formations are very thin or absent and clayey colluvial deposits form the lake beds. They are also located in headwaters of the palaeochannel tributary and are foci for both surface water and groundwater flow. The wetlands form discharge zones of the local groundwater flow systems.

In broad terms, rainfall recharge enters the sandy superficial formations and is transmitted vertically until it enters the water table and lateral flow paths within transported sediments, saprolite and palaeochannel successions. Laterally transmitted flows discharge into the wetlands where clayey colluvium outcrops and
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truncates the flow paths. On a local scale, groundwater discharge also occurs from the deeper colluvial and palaeochannel successions. It is recognised that the palaeochannel successions have potential throughflow beneath the wetlands, with flow paths beneath valley-floor areas possibly moving towards discharge zones located further downstream. Therefore management at local scales may also provide potential benefits down gradient on a more regional scale.

11.3.2 Bentonite Wetlands

The Bentonite Wetlands occur in a mid-slope setting in dunal sands of the Balgerbine Soil System where expressions of the water table outcrop. Each wetland represents a small-scale depression in the landscape where the superficial formations and the topography form a sink for surface water and groundwater flow. At the top of the catchment divide the granitic basement is relatively shallow (6 m depth in BMC71d), whilst the remainder of the higher catchment is characterised by transported successions that overlie bedrock. Rainfall recharge that enters the superficial formations is deflected laterally by clayey colluvial deposits and thin beds of silcrete. Three of the wetlands (W057, W058 and W059) occur where the clayey colluvial deposits, including transported bentonite, outcrop and truncate the flow paths in the superficial formations. Groundwater flow from W056 to W057 may be locally controlled by a dolerite dyke, the occurrence and strike of which is largely inferred. Aerial photography interpretations indicate a possible north-south strike orientation, compatible with the saline watercourse from W057 to the main braided drainage line. Wetland W059 appears to be in a separate sub-catchment and is set higher in the landscape than Wetlands W056 to W058. Wetland W056 (adjacent to “Jock’s Well”) is located in a topographic low, which combined with shallow groundwater levels, have resulted in salt crystals forming on the lake surface.

Beneath the wetlands, upward flow from deeper successions is providing saline groundwater to the basal lake sediments. Groundwater level mounding in the superficial formations dunal sediments surrounding each wetland provides local brackish discharge to the lakes. Shallow fresh to brackish groundwater lenses in the water table zone beneath the dunal sediments may support the fringing vegetation. Individual wetlands typically represent local discharge zones for groundwater flow in the colluvial successions and bedrock profiles.

11.3.3 Gypsum Wetlands

The Gypsum Wetlands occur low in the landscape where groundwater flow is controlled by the immediate catchment and that of Buntine Palaeodrainage through the palaeochannel tributary beneath the valley floor. In BMC59d, located immediately east of wetland W001, deep successions of pallid zone white clays were intersected. The presence of the pallid zone white clays may indicate occurrence of a prior fresh, non-evaporitic lake system during a wetter climate (George, Clarke and English, 2006). The switch to the current gypsiferous playa reflects recent periods of aridity, where groundwater discharged is evaporated.

Landscapes in the immediate vicinity of the Gypsum Wetlands are formed of loam and rocky superficial formations of the Inering Hills Soil System and thin successions of clayey colluvium overlying shallow bedrocks. The intersection of palaeochannel sediments in BMC60d, BMC61d, and BMC64d indicates the local occurrence of a tributary of the Buntine Palaeodrainage beneath the footslopes of the local catchment.

Recharge predominantly vertically infiltrates the sandy superficial formations until being laterally deflected by silcrete and/or clayey succession of colluvium or saprolite.

The wetlands occur in valley-floor settings, where expressions of the water table outcrop in localised depressions in the landscape. Local groundwater is hypersaline, however there is evidence of salinity stratification, with the shallow local flow systems being less saline.

The Buntine Palaeodrainage tributary underlying the Gypsum Wetlands is expected to dominate the local water balances. There is however, uncertainty regarding the interaction of the palaeochannel successions with the water table and the scale of their influence on the local water balance. Additional site investigations, longer data records of seasonal fluctuations in groundwater levels and quality and groundwater flow modelling, are required to provide increased knowledge on this aspect. At present, it is
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acknowledged that seasonal recharge and runoff, the depth to the water table and the low hydraulic
gradients imposed by the Buntine Palaeodrainage may be significant factors. The influence of
significantly wet years, such as 1917, 1963 and 1999 may also be contributing factor.

There are contrasting gypsum crystal formations at W001 and W002. In part, this may be a feature of
different stratigraphy underlying these wetlands, proximity to the braided drainage line and the influence
of the Buntine Palaeodrainage. It is also likely that these contrasts are a consequence of the greater
contribution of surface water to W002. Wetland W001 does not have a surface water inlet, or outlet and
therefore surface water is a relatively small component of this wetland water and salt balance.

Local mounded water tables in dunal sediments fringing W001 and W002 potentially provide lenses of
fresh to brackish groundwater to support fringing vegetation. There is continual formation of salt
precipitates at the wetland/lunette margin.

11.3.4 Primary Saline Wetland

The Primary Saline Wetland W448 conceptual hydrogeological model conforms to a regional model.
Groundwater flow and water table settings are closely aligned with the topography and conditions
imposed by the underlying geology, including the Buntine Palaeodrainage. The interpreted occurrence of
deeply incised palaeochannel successions beneath Wetland W448 is supported by the variability in depth
to basement in BMC66d and BMC67 (41 m and 9 m, respectively) which are located in close proximity to
each other.

Water balances of Wetland W448 and surrounding playa lakes may also be controlled, in part, by
groundwater flow in transmissive structures in the bedrock. It is also interpreted that recharge to the deep
sands of the Upsan Downs Soil System and subsequent throughflow to the Buntine Palaeodrainage may
be a significant aspect of the wetland water balance. This interpretation is linked to the large catchment of
the Wetland W448.

11.3.5 Fresh/Brackish to Valley Floor Wetlands

The conceptual hydrogeological model for the Fresh/Brackish to Valley Floor Wetlands is dominated by
the valley-floor position in the landscape and proximity of the Buntine Palaeodrainage. These wetlands
are also located near the confluence of the Buntine Palaeodrainage and the Latham Lakes chain and this
aspect may manifest on the water balance.

There are significant changes to the local geology and groundwater characteristics over relatively short
distances in the vicinity of the wetlands. In the upper areas of the catchment, water and salt balances are
dominated by local-scale inputs where shallow, fresh groundwater is expressed as seeps on breaks of
slope. The seeps are often characterised by exposed areas of silcrete and/or calcrete. In contrast, in the
lower parts of the catchment, groundwater is typically hypersaline and acidic due to influences of the
Buntine Palaeodrainage and evapotranspiration. The lower catchment represents a groundwater
discharge zone which is likely to be influenced by both regional and local aspects.
12.1 Threat of Rising Groundwater to Biodiversity Assets

Since 2002, groundwater levels in the BMNDRC beneath the valley floor, mid-slopes and upper slopes, have generally shown declining trends (Figure 26). There are some exceptions to these trends, however in general the declining groundwater trends reflect a period of drying subsequent to the floods of 1999. Given the climate variability over recent years it is necessary that the monitoring of groundwater water levels, and climate, is continued to gain confidence in future groundwater level trend predictions.

Using the results of AgET (Table 10-2), it appears the local water balances are sensitive to shifts in climatic trends. Based on the gains or losses of groundwater for each range of climate data, an equivalent groundwater level change was retrospectively estimated. Results show that during the wetter period between 1954 and 1993, groundwater levels rose in all wetlands; Fresh/Brackish Wetlands (W011 and W012), Bentonite (W056 to W059), Gypsum Wetlands (W001 and W002), Primary Saline Wetlands (W448) and Fresh/Brackish to Valley Floor Wetlands (W015 to W017 and W051). The estimated annual rate of groundwater level rise ranged between 0.02 to 0.08 m.

Rainfall data between 1967 and 2006 show on average a significant drying period, although significant rainfall events occurred in 1999. Results of interpreted groundwater level change during this period show a general declining trend in the Fresh/Brackish Wetlands (W011 and W012), Bentonite Wetlands (W056 to W059), Gypsum Wetlands (W001 and W002) and Primary Saline Wetlands (W448) areas. The annual rate of decline in groundwater levels averaged about 0.012 m/yr (Fresh/Brackish and Bentonite Wetlands). Both the Gypsum and Primary Saline Wetlands showed a declining trend in groundwater levels between the two periods, however they indicate groundwater levels are continuing to rise (0.1 m/yr). A continued rise in groundwater level (0.02 m/year) in the Fresh/Brackish to Valley Floor Wetlands (W015 to W017) and W051 indicates little change in groundwater trend between the two periods. This trend may indicate cause for future concern because the threat from salinity may continue in spite of a predicted drying-climate trend.

In a report by the Indian Ocean Climate Initiative (IOCI), 2006, climate change projections for South-West Western Australia (SSWA) for 2030 indicated that:
- Winter rainfall may fall by as much as 20% relative to the 1960 to 1990 baseline.
- Total annual rainfall may fall as much as 19% relative to the 1960 to 1990 baseline.
- The number of winter rainfall days may reduce by up to 17%.
- Catchments across the South-West Australia may experience decreases in runoff ranging between 5% and 40% relative to 1990.

Notwithstanding, an increased frequency of high intensity storms associated with summer cyclones may become the predominant factor contributing to future groundwater level trends. Although groundwater levels would be expected to show declining trends between major cyclonic events, they do not reach a long-term benchmark. Instead they are compounded by each cyclone event. These cyclone events are occurring on average every 13 years. For example, the groundwater level in shallow observation bore D1 (Figure 25), located in the Gypsum Wetlands catchment, rose by about 3 m after the 1999 storms. In spite of below average rainfall in the six subsequent years, the groundwater level in D1 is only now returning to the pre-1999 elevations. Given the uncertainty of future climate predictions in the BMNDRC, it is difficult to make accurate predictions of when groundwater levels will return to benchmark elevations. Thus the assessments of future threat from rising water tables at representative wetland areas are uncertain using current data.

The replacement of native vegetation with annual crops in the BMNDRC has led to increased recharge and runoff. Consequently, if cyclonic events occur with increased frequency, remnant native vegetation and wetlands will be under increased threat from rising groundwater, extended inundation and related occurrences such as waterlogging. Key outcomes in relation to these threats in the BMNDRC include:
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- The significant change in winter and summer rainfall patterns. Since the early 1980s summer rainfall has increased from a long-term average of 120 mm/yr to greater than 200 mm/yr. Winter rainfall has declined from 270 mm (5-year average) prior to 1987, to less than 200 mm/yr. The occurrence of greater rainfall in the summer may contribute to increases in sedimentation, erosion and groundwater recharge.

- The time between rainfall events greater than 150 mm is on average reducing by about 50 days/year. This aspect may lead to the compound effects of greater recharge and potential rises of groundwater levels.

- Declining groundwater levels within the BMNDRC since 1999 may be masking a longer-term trend of rising groundwater levels.

- Areas characterised by recent rising groundwater level trends may be at risk from salinity threats, particularly given future climate predictions.

- Based upon available long-term data, lower lying areas are reflecting comparatively steady groundwater level trends. Areas higher in the landscape reflect declining groundwater level trends.

- Periods of catchment-scale groundwater level rise are interpreted to be associated with high infiltration following significant summer cyclone events.

12.1.1 Fresh/Brackish Wetlands W011 and W012

The Fresh/Brackish Wetlands are located high on a mid-slope and are associated with dunes and sand sheets of the Balgerbine Soil System. Wetlands W011 and W012 are essentially discharge zones for groundwater. The wetlands also have inflow contributions from local groundwater seeps. Nearby BMC77ob, groundwater discharges at a break in slope and flows easterly into W012. Groundwater adjacent to the wetland is hypersaline (up to 8,000 mS/m) as a result of fluxes of salt concentrating in the water table zone. The salinity of groundwater flowing from the seep is brackish (136 mS/m). The deeper palaeochannel succession in this area is saline (972 mS/m).

The high landscape position together with dunal sands promotes conditions for aeolian drift and continuous geomorphologic change. As a result of change, the location and extent of the lakes and groundwater seeps may change. Past changes are evident due to the occurrence of high-sulphate lacustrine lake sediments at depths up to 5 m beneath superficial sands and at distance from the current wetlands. Provided these sediments remain saturated, influences from potential acid sulphate soils may be reduced. This aspect has implications for management actions, particularly those which may reduce groundwater levels in these wetlands.

The thickness of sands decreases from west to east and corresponds to a hydraulic gradient from the dunes to the wetland shoreline. Local superficial sands promote infiltration, with groundwater subsequently flowing horizontally above clay and hardpan silcrete beds. Results from the water balance indicated the majority of groundwater is sourced from localised recharge of the superficial sediments. Significant groundwater quantities (1,200,000 kL/year) leave the system though evaporation. For the period from 1954 to 1993, it is estimated that about 26,000 tonnes/year of salt were accumulated at these wetlands, whilst in the period from 1967 to 2006 this estimate is significantly reduced to 9,814 tonnes/year. Interpreted long-term local groundwater level declines over the next 23 years, may be manifested by reduced rates of salt accumulation.

Conversely, a number of significant frequent rainfall events may promote groundwater level rises, potentially increasing the threat from salt accumulation. It is not the long-term rainfall trend which may drive secondary salinity at this wetland area, but rather the impacts of significant cyclonic rainfall.
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12.1.2 Bentonite Wetlands W056 to W059

The Bentonite Wetlands are located high on the mid-slope and are associated with sand sheets over bedrock of the Balgerbine Soil System. This representative wetland area has a relatively high proportion of native vegetation (~39%) in the upper catchment, which may limit potential recharge rates.

Wetland W056, or Jocks Well, is located in a topographic low that combined with shallow groundwater levels, has resulted in salt precipitates forming on the lake surface. Wetlands W057 to W059 are typical of the bentonite wetlands of the Marchagee-Watheroo area. Groundwater flow from W056 to W057 is possibly controlled by a dolerite dyke. Wetland W059 appears to be in a separate catchment and are set higher in the landscape than W056 to W058.

Local groundwater mounding beneath fringing dunes of wetlands W057, W058 and W059 is typically fresh to brackish (400 to 1,200 mS/m), with low soil salinity (700 mS/m) measured in the unsaturated soil zone. Within the top 1 to 2 m below ground surface, local infiltration from rainfall is deflected by clay and silcrete bands at the superficial-transported sediment contact.

Groundwater in the saprock near wetland W056 (BMC70d) is hypersaline (14,000 mS/m), whilst groundwater in BMC68d, upslope of wetland W059 and east of an interpreted dolerite dyke is fresh (410 mS/m). BMC69d, which was drilled into a dolerite dyke, encountered brackish (1,130 mS/m) groundwater.

At the water table the groundwater is fresh to brackish. The water table (1.5 m depth) in BMC70b, adjacent to wetland W056, was brackish (1,261 mS/m) and seasonally influenced by recharge and discharge from the wetland. At wetland W057, the water table was at 1.4 m depth, supported by upward heads from deeper successions. The upward heads may reflect the local presence of a dolerite dyke that influences the groundwater flow. The water table beneath wetland W059 was at about 1.3 m depth, with salinity of 410 mS/m. The comparatively low salinity may be linked to the local catchment of native vegetation. Groundwater levels in BMC82ob, near wetland W057 were greater than the drilled depth of 1.75 m.

In addition to topographic lows contributing the surface salinity in W056, a dolerite dyke in the vicinity of W057 may be influencing the local groundwater flow.

Results from the interpreted water balance indicate the majority of groundwater leaving the catchment is through evaporation (300,000 kL/yr). Estimates of recharge have declined significantly from the earlier wet period (1953 to 1993) to the recent drying period (1966 to 2006). The interpretations of groundwater salinity are also estimated to be declining as a result reduced recharge, lower groundwater levels and lower losses to evaporation. The rate of salinity decline is estimated to be 4,700 tonnes/yr. An interpreted long-term local groundwater level decline of 0.20 to 0.30 m/yr over the next 23 years, may constrain the accumulation of salt. Notwithstanding, if a number of significant rainfall events occur and promote rises of the water table, the stored salts may be mobilised, increasing the local salinity threat.

It is interpreted that wetland W056 (Jocks Well) and surrounding vegetation are at the highest risk from salinity. Wetland W057, may also be at a moderate threat from salinity due to estimated climate trends. The threat from rising groundwater at W057 remains, though the local salinity threat may be diminished by the surface water conveyance structure constructed by the landholder. The threat from rising water tables at wetlands W058 and W059 is considered low.

12.1.3 Gypsum Wetlands W001 and W002

The Gypsum Wetlands are located on the valley floor, associated with dunal lunettes and the braided drainage of the Wallambin Soil System. Wetlands W001 and W002 are groundwater discharge zones. Groundwater salinity beneath the wetlands is hypersaline (up to 7,500 mS/m), linked to upward discharge of groundwater from the palaeochannel succession and evaporation. Local groundwater mound beneath the dunal lunettes fringing the wetlands is also hypersaline (12,000 to 15,000 mS/m). Localised rainfall recharge to the lunettes may provide thin fresh groundwater lenses to support the fringing native vegetation. The lowering of the groundwater levels beneath the lunette dunes as a result of declining rainfall, may impact on the viability of the vegetation communities on the dunes.
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Results from the water balance indicated the majority of groundwater inflow to the wetlands is from recharge and throughflow, with 300,000 kL/year leaving the catchment through evaporation. The recent dry climate has lead to declining trends in groundwater level, however levels are still rising at about 0.01m/yr. Rates of salt accumulation during the dry climate period from 1966 to 2006 have also declined from 160,000 tonnes/year to about 19,000 tonnes/year.

The interpreted occurrence of broad, deep tributary palaeochannel successions of the Buntine Palaeodrainage beneath the valley floor may have implications on the wetland environment on a local and catchment scale.

12.1.4 Primary Saline Wetland W448

The Primary Saline Wetland typically comprises water-logged saline soils associated with the alluvial plain and playa lakes of the Wallambin Soil System. Wetland W448 is a large playa groundwater discharge zone located on the valley floor braided drainage. Salt forms on the playa surface.

Groundwater flow may be locally influenced by a geological structure on the western shoreline of W448 and deep valley filled sediments associated with the Buntine Palaeodrainage. The extent and orientation of both the structure and palaeodrainage is interpreted.

Groundwater in the palaeochannel succession is hypersaline (20,000 mS/m). Shallow groundwater is interpreted to be brackish to saline, depending on the position in the landscape above the valley floor discharge zones. Thick superficial formation sands beneath the middle to upper slopes promote rainfall infiltration and fresh to brackish groundwater on the margins of the valley floor.

Local groundwater mounded beneath dunal lunettes that fringe the wetlands is also typically hypersaline (7,000 mS/m). Dunal sands are characterised by high unsaturated zone soil salinity up to 12,000 mS/m. The lunettes may, however, host thin fresh to brackish groundwater lenses at the water table following significant rainfall events.

Due to the size of the catchment (~80,000 ha), water and salt balance volumes are substantial. Results from the water balance indicated the majority of water is from throughflow, with significant quantities (4,800,000 kL/year) leaving the system through evaporation. More recent runoff values equate to about 12,000,000 kL/yr. Groundwater levels under the dry climate are interpreted to be declining by about 0.009 m/year and the rate of salt accumulation is about 476,000 tonnes/year. As this catchment is large in area, there may be relatively little change in the whole of catchment rates of salt accumulation with time.

Consequently the threat from rising groundwater tables at this wetland and neighbouring wetlands is considered low. However, the threat of salinity to the vegetation on the surrounding lunettes is considered high, particularly given the increased likelihood of catchment-scale surface water flows in the braided drainage line which are likely to mobilise salts within the series of salt lakes located upstream of wetland W448.

12.1.5 Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051

The Fresh/Brackish to Valley Floor Wetlands are located low on a mid-slope, associated with sandy duplex soils in the middle to upper landscape and clayey soils in the valley. All the wetlands are discharge zones. The thickness of superficial sands decreases towards the east and corresponds to a high hydraulic gradient from the top of the dune to the wetland shoreline.

Moderately high vertical hydraulic conductivity results in comparatively high infiltration rates through the local superficial formation sands, with groundwater subsequently flowing above clay and/or silcrete cemented horizon. Groundwater salinity beneath the wetland area ranges from brackish (400 mS/m, up-gradient to the west) to saline (9,000 mS/m, down-gradient to the east). Adjacent to W017, the shallow groundwater salinity is about 10,000 mS/m which is a consequence of its proximity to the valley floor and other factors such as evaporation.
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The groundwater in the palaeochannel successions located next to wetland W016 contrasts significantly to conditions encountered elsewhere in the BMNDRC. Groundwater in this palaeochannel is typically saline (450mS/m) and is characterised by a vertical upward head of 2.4 m. Consequently groundwater is likely to be discharging from the palaeochannel successions to the wetlands. The local extent of the palaeochannel succession remains poorly understood.

Results from water balance calculations indicated that estimations of groundwater inflows are currently greater than groundwater outflows. This is manifested in rising groundwater levels. During both the wetter period tested (1954 to 1993) and the more recent dry period (1967 to 2006) groundwater levels show an interpreted rising trend.

Water balance assessments show 300,000 kL/year losses through evaporation. Salt accumulation in the dry climate appears to be declining at a rate of about 12,200 tonnes/year. With limited groundwater recharge during the dry climate period, rates of salt accumulation have apparently reduced. With an anticipated long-term drying period, local groundwater levels may begin to stabilise as a result of reduced regional recharge. However, if a number of significant rainfall events occur at an interval more frequent than previously then groundwater levels may continue to rise.
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### Wetland Management

**Table 12-1  Summary of Wetland Catchments**

<table>
<thead>
<tr>
<th>Wetland ID</th>
<th>Geological Setting</th>
<th>Groundwater Trends</th>
<th>Salinity Threats</th>
<th>Water Balance</th>
<th>Salt Balance</th>
<th>Management Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh/Brackish Wetlands W011 and W012</td>
<td>Dunal aeolian deposits of the Balgerbine Soil System form a sandy blanket of superficial formations over the local catchment.</td>
<td>Limited results suggest groundwater levels in the upper slope, has a relatively high rate of groundwater decline (147 mm/year).</td>
<td>Wetlands W011 and W012 are essentially discharge lakes that are feed by shallow slow moving groundwater (0.05m/day). EC beneath the wetlands is saline (up to 8,000 mS/m) as a result of increases in concentrations due to evaporation. The wetlands are also fed from westerly located fresher quality groundwater seeps.</td>
<td><strong>Wetter Period (1953 to 1993)</strong>&lt;br&gt;Rainfall –6,044,370 kL/yr&lt;br&gt;Evapotranspiration – 5,310,360 kL/yr&lt;br&gt;Inputs&lt;br&gt;Recharge –1,687,150 kL/yr&lt;br&gt;Groundwater inflow –203,305 kL/yr&lt;br&gt;Surface Water – 0 kL/yr&lt;br&gt;Wetland Evaporation – 1,200,000 kL/yr&lt;br&gt;Groundwater Gain/Loss: +645,743kL/yr&lt;br&gt;<strong>Drying Period (1966 to 2006)</strong>&lt;br&gt;Rainfall –5,776,920 kL/yr&lt;br&gt;Evapotranspiration –5,262,270 kL/yr&lt;br&gt;Inputs&lt;br&gt;Recharge –801,840 kL/yr&lt;br&gt;Groundwater inflow – 203,305 kL/yr&lt;br&gt;Surface Water – 0 kL/yr&lt;br&gt;Wetland Evaporation – 9,583 tons/yr&lt;br&gt;Estimated Salt Change: +9,814 tons/yr</td>
<td><strong>Wetter Period (1953 to 1993)</strong>&lt;br&gt;Recharge –17 tons/yr&lt;br&gt;Groundwater inflow – 472 tons/yr&lt;br&gt;Wetland Evaporation – 25,830 tons/yr&lt;br&gt;Outflows&lt;br&gt;Groundwater outflow – 249 tons/yr&lt;br&gt;Estimated Salt Change: +26,070 tons/yr</td>
<td>Reforestation of upslope recharge areas to reduce recharge. Use of upgradient lakes (on cleared land) to intercept groundwater throughflow, the lakes might be modified to increase evaporation (by enlargement, aeration and controlled additional planting) or to enable abstraction and diverting of groundwater. Abstraction from the palaeochannel immediately downstream of the wetlands, to locally lower the water table.</td>
</tr>
</tbody>
</table>
Section 12

Wetland Management

<table>
<thead>
<tr>
<th>Wetland ID</th>
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<th>Groundwater Trends</th>
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<th>Water Balance</th>
<th>Salt Balance</th>
<th>Management Options</th>
</tr>
</thead>
</table>
| Bentonite Wetlands W056 to W059 | The wetland occurs in a mid slope setting that is characterised by very thin superficial formation sands (absent in the lake bed), transported interbeds of bentonite and silt with a thickness up to 1.5 m underlain by 0.2 m of silcrete and clayey colluvial successions. | A single deep bore in the lower landscape indicated a moderate rate of decline of 16 mm/yr. Bores analysed in the middle slopes reported a significant decline up to 280 mm/yr. In addition, there does appear to be a clear trend for increasing lag with increasing elevation. The groundwater level beneath the bentonite wetlands W058 and W059 may also be controlled, to some extent, by the impermeable bentonite clay substrate. From AgET simulations it was predicted that between 1953 and 1993 a median average groundwater level rise of 43 mm/annum. This compares with a decline in average groundwater level of 12 mm/annum for the period 1966 to 2006. | Salinity in the deeper saprock aquifer is typically saline and is under upward hydraulic pressure in the region of wetland W056. Further down gradient towards the valley flats, groundwater is under a downward head. Shallow groundwater is brackish as a result of increases in concentrations from evaporation. In addition to topographic lows contributing too the surface salinity (W056), a Dolomite structure adjacent to W057 in the East is possibly limiting the groundwater flow down-gradient. This may have implications following significant rainfall events and the apparent change in rainfall trends during summer and winter. High losses through evaporation, combined with the downward head beneath lower lying wetlands, salt accumulation is predicted to decline (~4,500 tons/yr). With a continued predicted drying climate and an anticipated long-term local groundwater level decline of about 0.12 m over the next ten years, the accumulation within this wetland catchment of salt may continue to decrease. Increased occurrence of high rainfall events may impact on theses estimates. | Wetter Period (1953 to 1993)  
Rainfall = -3,622,290 kL/yr  
Evapotranspiration = -3,311,980 kL/yr  
Inputs  
Recharge = -192,640 kL/yr  
Groundwater inflow = -50,209 kL/yr  
Surface Water = -523,880 kL/yr  
Outflows  
Groundwater outflow = -39,318 kL/yr  
Wetland Evaporation = -300,000 kL/yr  
Groundwater Gain/Loss:  
+427,412 kL/yr  
Drying Period (1966 to 2006)  
Rainfall = -3,405,150 kL/yr  
Evapotranspiration = -3,115,070 kL/yr  
Inputs  
Recharge = -0 kL/yr  
Groundwater inflow = -50,209 kL/yr  
Surface Water = -169,960 kL/yr  
Outflows  
Groundwater outflow = -39,318 kL/yr  
Wetland Evaporation = -167,000 kL/yr  
Groundwater Gain/Loss:  
-119,148 kL/yr  | Wetter Period (1953 to 1993)  
Inputs  
Recharge = -96 tons/yr  
Groundwater inflow = 502 tons/yr  
Wetland Evaporation = 598 tons/yr  
Outflows  
Groundwater outflow = 5,416 tons/yr  
Estimated Salt Change:  
-4,264 tons/yr  
Drying Period (1966 to 2006)  
Inputs  
Recharge = -0 tons/yr  
Groundwater inflow = 502 tons/yr  
Wetland Evaporation = 167 tons/yr  
Outflows  
Groundwater outflow = 5,461 tons/yr  
Estimated Salt Change:  
-4,792 tons/yr  | Establishment of buried deep drains on the downstream perimeter of cleared properties. There may be opportunities for economic benefit from salt production collected in discrete down-gradient modified playa lakes and/or purpose built evaporation ponds.  
Reforestation of sandy upload areas in the northwest catchment.  
Modifying the downstream watercourse through the advent of deeper drains and an artificial lake. |
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Wetland Management

<table>
<thead>
<tr>
<th>Wetland ID</th>
<th>Geological Setting</th>
<th>Groundwater Trends</th>
<th>Salinity Threats</th>
<th>Water Balance</th>
<th>Salt Balance</th>
<th>Management Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum Wetland W001-002</td>
<td>The catchment is arguably formed of shallow stony and loam soils of the Inering Soil System; the wetlands actually occur in the Wallambin Soil System at the confluence of the BMNDRC and Latham Lakes Chain. Towards the valley floor, palaeochannel sediments consist of sub-rounded sands and silty clays. These sediments were sitting on a thin zone of weathered bedrock (saprolite). Further to the west beneath the main valley floor a thick section (15 m) of bleached pallid clays was intersected. Generally, deep bores located in the middle slopes show a relatively moderate rate of groundwater decline of between 28 and 107 mm/year. Bores located in the upper slopes showed a decline in groundwater level of between 8 and 149 mm/year. Results from bores incorporating the 1999 rainfall events show rates of groundwater level decline range between 8 to 64 mm/year for bores located in the upper slopes to about 72 mm/year for the middle slope bores. The shallow bores in this wetland area respond dramatically to significant rainfall events.</td>
<td>Generally, deep bores located in the middle slopes show a relatively moderate rate of groundwater decline of between 28 and 107 mm/year. Bores located in the upper slopes showed a decline in groundwater level of between 8 and 149 mm/year. Results from bores incorporating the 1999 rainfall events show rates of groundwater level decline range between 8 to 64 mm/year for bores located in the upper slopes to about 72 mm/year for the middle slope bores. The shallow bores in this wetland area respond dramatically to significant rainfall events.</td>
<td>From AgET simulations it was predicted that between 1953 and 1993 a median average groundwater level rise of 76 mm/annum. This compares with a rise in average groundwater level of 11 mm/annum for the 1966 to 2006.</td>
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</table>

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</thead>
<tbody>
<tr>
<td><strong>Rainfall</strong></td>
<td>13,529,490 kL/yr</td>
<td><strong>Evapotranspiration</strong></td>
<td>12,349,530 kL/yr</td>
<td><strong>Recharge</strong></td>
<td>10 tons/yr</td>
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<tr>
<td><strong>Evapotranspiration</strong></td>
<td>12,349,530 kL/yr</td>
<td><strong>Inputs</strong></td>
<td></td>
<td><strong>Groundwater inflow</strong></td>
<td>745 tons/yr</td>
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<tr>
<td><strong>Recharge</strong></td>
<td>1,023,900 kL/yr</td>
<td><strong>Groundwater outflow</strong></td>
<td>165,755 tons/yr</td>
<td><strong>Wetland Evaporation</strong></td>
<td>6,683 tons/yr</td>
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<tr>
<td><strong>Groundwater inflow</strong></td>
<td>137,240 kL/yr</td>
<td><strong>Outflows</strong></td>
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<tr>
<td><strong>Surface Water</strong></td>
<td>2,204,410 kL/yr</td>
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<tr>
<td><strong>Groundwater outflow</strong></td>
<td>51,830 kL/yr</td>
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<tr>
<td><strong>Groundwater inflow</strong></td>
<td>15,000 mS/m</td>
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<tr>
<td><strong>Wetland Evaporation</strong></td>
<td>300,000 kL/yr</td>
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<tr>
<td><strong>Groundwater Gain/Loss</strong></td>
<td>+3,013,720 kL/yr</td>
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<tr>
<td><strong>Rainfall</strong></td>
<td>12,930,840 kL/yr</td>
<td><strong>Evapotranspiration</strong></td>
<td>11,847,490 kL/yr</td>
<td><strong>Recharge</strong></td>
<td>0 tons/yr</td>
</tr>
<tr>
<td><strong>Evapotranspiration</strong></td>
<td>11,847,490 kL/yr</td>
<td><strong>Inputs</strong></td>
<td></td>
<td><strong>Groundwater inflow</strong></td>
<td>745 tons/yr</td>
</tr>
<tr>
<td><strong>Recharge</strong></td>
<td>0 kL/yr</td>
<td><strong>Groundwater outflow</strong></td>
<td>24,878 tons/yr</td>
<td><strong>Wetland Evaporation</strong></td>
<td>24,878 tons/yr</td>
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<tr>
<td><strong>Groundwater inflow</strong></td>
<td>745 tons/yr</td>
<td><strong>Outflows</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>Surface Water</strong></td>
<td>666,910 kL/yr</td>
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<tr>
<td><strong>Groundwater outflow</strong></td>
<td>6,683 tons/yr</td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Groundwater Gain/Loss</strong></td>
<td>+452,320 kL/yr</td>
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</tr>
</tbody>
</table>

**Abstraction from the palaeochannel, possibly both upslope and downslope of the wetlands.**

**Reforestation of the footslopes immediately upslope of the wetlands.**

**Diverting of local runoff from the lakes.**

**Reducing the number of high velocity surface water runoff events which deposit sediment, nutrients and salt to the wetlands.**
Wetland ID Geological Setting Groundwater Trends Salinity Threats Water Balance Salt Balance Management Options
Primary Saline Wetland W448

This wetland area is characterised by alluvial plains, braided drainage lines, and playas of the Wallambin Soil System that overlie the Buntine Palaeodrainage successions in valley-floor settings.

The depth of weathering and location of palaeochannel sediments is strongly influenced by the depth to fresh basement.

Groundwater flow is possibly controlled locally by geological structures on the western shoreline and deep valley filled sediments associated with the palaeochannel.

Rates of decline in groundwater level reported in the mid to lower slopes are between 3 to 34 mm/year; however, results showing poor correlation ($r^2=0.2$).

From AgET simulations it was predicted that between 1953 and 1996 a median average groundwater level rise of 71 mm/yr. This compares with a rise in average groundwater level of 9 mm/yr during more recent times (1966 to 2006).

Salinity in the deeper palaeochannel aquifer is typically saline (20,000 mS/m). Shallow groundwater is interpreted to be brackish to saline, depending in the distance to the valley floor. This increase in salinity is a result of increases in concentrations from evaporation.

Local groundwater mounding in the fringing wetland lunettes and dunes is also typically saline to saline (7,000 mS/m) as a result of the low valley floor landscape position. This is linked to a typically high unsaturated zone soil salinity up to 12,000 mS/m associated with low lying discharge areas and 1,000 mS/m in the middle to lower slopes.

However, lunettes may provide fresher quality groundwater for fringing vegetation following rainfall events.

These high losses through evaporation, combined with possible upward heads of deeper saline groundwater, salt accumulation is very high (0.5 Mtons/yr). Water levels are anticipated to continue to decline in the valley floor as a result of increased recharge and accumulation of groundwater in the valley floor. With an anticipated long-term local groundwater level rise of up to 0.1m over the next ten years, the accumulation of salt may increase slightly or possibly remain stable due to the size of the catchment.

<table>
<thead>
<tr>
<th>Wetter Period (1953 to 1993)</th>
<th>Inputs</th>
<th>Groundwater inflow = 12,191 tons/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water inflow = 229,870,000 kL/yr</td>
<td>Evapotranspiration = 229,870,000 kL/yr</td>
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</tr>
<tr>
<td>Groundwater inflow = -19,880,000 kL/yr</td>
<td>Groundwater outflow = -77,471 kL/yr</td>
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<tr>
<td>Surface Water = -41,840,000 kL/yr</td>
<td>Groundwater outflow = 3,714,314 tons/yr</td>
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<tr>
<td>Outflows</td>
<td>Estimated Salt Change: +3,713,878 tons/yr</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Drying Period (1966 to 2006)</th>
<th>Inputs</th>
<th>Groundwater inflow = 12,191 tons/yr</th>
</tr>
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<tbody>
<tr>
<td>Water inflow = 4,800,000 kL/yr</td>
<td>Evapotranspiration = 4,800,000 kL/yr</td>
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<tr>
<td>Groundwater inflow = 12,825 tons/yr</td>
<td>Groundwater outflow = 12,825 tons/yr</td>
<td></td>
</tr>
<tr>
<td>Surface Water = -476,664 tons/yr</td>
<td>Outflows</td>
<td></td>
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<tr>
<td>Groundwater outflow = -77,471 kL/yr</td>
<td>Estimated Salt Change: +476,000 tons/yr</td>
<td></td>
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<tr>
<td>Groundwater Gain/Loss:  +57,143,289 kL/yr</td>
<td>Estimated Salt Change: +476,000 tons/yr</td>
<td></td>
</tr>
</tbody>
</table>

Wetter Period (1953 to 1993) Use of down-gradient lakes to intercept and abstract groundwater. The lakes might be modified to increase evaporation (e.g. deepening to expose groundwater water, aeration) and/or enable abstraction of groundwater.

Abstraction from the palaeochannel immediately downstream of the Playa Lakes.

The formation of a groundwater and salt sink on downstream reaches of the palaeochannel, promoting internal drainage and flow over a dedicated area. Installed infrastructure might be applied to enable harvesting of salt.

Initiatives to promote lateral drainage down-gradient on the valley-floor and within the palaeochannel, through a network of shallow drains. These drains may be linked to deepened purpose built ponds to increase evaporation by exposing groundwater to the surface.

<table>
<thead>
<tr>
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<td>Groundwater outflow = 12,825 tons/yr</td>
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<td>Groundwater outflow = -77,471 kL/yr</td>
<td>Estimated Salt Change: +476,000 tons/yr</td>
<td></td>
</tr>
<tr>
<td>Groundwater Gain/Loss:  +7,333,289 kL/yr</td>
<td>Estimated Salt Change: +476,000 tons/yr</td>
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<td>Groundwater outflow = 12,825 tons/yr</td>
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<tr>
<td>Surface Water = -476,664 tons/yr</td>
<td>Outflows</td>
<td></td>
</tr>
<tr>
<td>Groundwater outflow = -77,471 kL/yr</td>
<td>Estimated Salt Change: +476,000 tons/yr</td>
<td></td>
</tr>
<tr>
<td>Groundwater Gain/Loss:  +7,333,289 kL/yr</td>
<td>Estimated Salt Change: +476,000 tons/yr</td>
<td></td>
</tr>
</tbody>
</table>

Drying Period (1966 to 2006) | Wetter Period (1953 to 1993) Use of down-gradient lakes to intercept and abstract groundwater. The lakes might be modified to increase evaporation (e.g. deepening to expose groundwater water, aeration) and/or enable abstraction of groundwater.

Abstraction from the palaeochannel immediately downstream of the Playa Lakes.

The formation of a groundwater and salt sink on downstream reaches of the palaeochannel, promoting internal drainage and flow over a dedicated area. Installed infrastructure might be applied to enable harvesting of salt.

Initiatives to promote lateral drainage down-gradient on the valley-floor and within the palaeochannel, through a network of shallow drains. These drains may be linked to deepened purpose built ponds to increase evaporation by exposing groundwater to the surface.
## Wetland Management

<table>
<thead>
<tr>
<th>Wetland ID</th>
<th>Geological Setting</th>
<th>Groundwater Trends</th>
<th>Salinity Threats</th>
<th>Water Balance</th>
<th>Salt Balance</th>
<th>Management Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh/Brackish to Valley Floor Wetlands W015 to W017, W051</td>
<td>Dunal sands of the Balgerbine Soil System form a superficial cover over the local catchment. The depth of cover is greatest beneath crests and mid-slopes, but is thin in the vicinity of the wetlands. A thick succession of clayey colluvial successions then overlies weathered and fresh bedrock. Towards the lower valley flats, palaeochannel sediments were intersected at depth. These sediments consist of sub-rounded sands and slaty clays</td>
<td>Deep bores in the middle slopes have a moderate rate of groundwater decline (28 to 61 mm/yr). Limited data located in the upper slopes indicated a decline in groundwater level of up to 8 mm/year. From AgET simulations it was predicted that between 1953 and 1995 a median average groundwater level rise of 20 mm/yr was also predicted during more recent times (1966 to 2006). Salinity beneath the wetland area is fresh (400mS/m) up-gradient (west) to saline (9,000mS/m) down-gradient (east). Adjacent to wetland W017, the shallow groundwater salinity is about 10,000mS/m as a result of increases in concentrations from evaporation. The deeper aquifer associated with palaeochannel sediments is typically saline (1,100mS/m), however due to the strong upward vertical groundwater head (2.4m), there is indication that more saline groundwater is flowing to the surface. The nature and extent of this palaeochannel is currently unknown. As a result of lower groundwater losses (2.8x10^6 kL/yr) through evaporation, current salt accumulation is low (620 tons/yr). However, with an anticipated long term local groundwater level rise of 0.2m over the next ten years, the accumulation of salt may increase. In addition, the increased occurrence of high rainfall events may impact on these estimates.</td>
<td><strong>Wetter Period (1953 to 1993)</strong>&lt;br&gt;Rainfall −3,132,360 kL/yr&lt;br&gt;Evapotranspiration − 2,809,920 kL/yr&lt;br&gt;Inputs&lt;br&gt;Recharge −354,060 kL/yr&lt;br&gt;Groundwater inflow −206,225 kL/yr&lt;br&gt;Surface Water − 30,630 kL/yr&lt;br&gt;Outflows&lt;br&gt;Groundwater outflow −108,588 kL/yr&lt;br&gt;Wetland Evaporation − 300,000 kL/yr&lt;br&gt;Groundwater Gain/Loss: +182,328 kL/yr</td>
<td><strong>Wetter Period (1953 to 1993)</strong>&lt;br&gt;Inputs&lt;br&gt;Recharge −4 tons/yr&lt;br&gt;Groundwater inflow − 619 tons/yr&lt;br&gt;Wetland Evaporation − 1,094 tons/yr&lt;br&gt;Estimated Salt Change: -12,231 tons/yr</td>
<td><strong>Wetter Period (1953 to 1993)</strong>&lt;br&gt;Inputs&lt;br&gt;Recharge −4 tons/yr&lt;br&gt;Groundwater inflow − 619 tons/yr&lt;br&gt;Wetland Evaporation − 1,113 tons/yr&lt;br&gt;Estimated Salt Change: -12,213 tons/yr</td>
<td>The use of wetland W051 up-gradient to intercept and abstract groundwater, limiting throughflow. The lake might be modified to increase evaporation and enable groundwater abstraction. Increasing areas of reforestation up-gradient of wetland W051 to reduce recharge throughflow by increasing uptake by plants. Further defining the extent of the palaeochannel sediments located nearby wetland W016 and abstraction from these sediments. Groundwater is fresh to brackish and may be used for irrigation and/or for stock watering purposes. Further water quality testing would identify potential uses. Treatment of the sandy superficial formations to constrain infiltration capacities and improve moisture-retention properties.</td>
</tr>
<tr>
<td>Dunal to Valley Floor Wetlands W015 to W017, W051</td>
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Section 12

Wetland Management

12.2 Management Options

At present, there is uncertainty about the hydrological function of the groundwater and surface water systems at each of the representative wetland areas in the BMNDRC, however valuable information has been gained and the water/salt balance methodology tested. In addition, there are biological uncertainties such as the ecological water requirements of associated biota. Likely water table and aquifer system responses to potential stressors are also uncertain, as are distances or areas over which responses might prevail. Consequently, the development of strategies by which to mitigate risks potentially imposed by rising water tables is complex.

Further to these aspects are potentials for future changes to past and/or current water balances in individual catchments and transient changes in salinity of the local groundwater. The interpretations based on available data indicate that significant rainfall events have a strong influence on recharge and hence water table elevations. A change in the recurrence interval of the significant rainfall events (from the 1:13 years recorded to date) would lead to changes in water table elevations. In some cases, such as at the Fresh/Brackish to Valley Floor Wetlands, rises in groundwater levels appear to be occurring irrespective of the current drying climate patterns. This suggests a groundwater catchment with considerable inertia and a responsive flow system.

On a scale relevant to the representative wetlands, particularly the Fresh Brackish, Gypsum, Primary Saline and Fresh Brackish Valley Floor catchments, this uncertainty is manifested by questions regarding causes and effects of rising water tables. For instance “are rising water tables in the individual wetlands predominantly linked to catchment-wide influences on the Buntine Palaeodrainage or changes in water balance on a local scale?” The former would potentially cause the backing-up of groundwater along individual palaeotributaries and watercourses. On the other hand, the latter would reflect increasing excesses of groundwater shedding from local catchment areas. Mitigation measures would need to be developed cognisant of the predominant water balance influence, presumably preferentially targeting either downstream or upstream influences depending on which is dominant.

The adoption of management actions should be mindful of negative downstream impacts associated with options such as deep drainage and pumping of hypersaline/acidic groundwater. Therefore, the management options should be put in a regional context and where possible, be managed within each subcatchment. The transference of potential issues to other catchments would limit the overall benefits of any mitigation strategies. Conversely, in some cases, it may be achievable to divert or use groundwater resources from representative wetland areas to the landholder to provide some form of economic return. As such, the management options for BMNDRC might be best considered in context with water demands of the wider community, including options for treatment, harvesting of salt and industry and/or domestic uses.

It is beyond doubt that the clearing of land for agriculture has significantly impacted upon the water and salt balance and dynamics of the BMNDRC. In order to address the resultant increases in recharge to the underlying shallow water table, and deeper regional aquifers, it is necessary to significantly increase the amount of water being utilised or remove some of this excess water from the water balance. Options which are to be considered include interception and abstraction of water before entry into the wetland environment. Alternatively, water can be removed directly from wetlands or down-gradient and moved into disposal points, such as sacrificial wetlands. In either instance, potential impacts on groundwater dependent ecosystems (inside and outside the wetlands) must be considered.

The undertaking of a risk assessment to evaluate the potential negative and positive impacts (again inside and outside of the wetlands) is a particularly important component of any feasibility studies prior to undertaking management actions. For instance, the propagation of even small-scale drawdown impacts beneath the wetlands might have detrimental impacts on riparian vegetation. The fate of the abstracted groundwater would also need to be considered; presumably impacts of disposal would also need to be managed. Other considerations such as the expected costs associated with establishing and maintaining options for the life of operation; social costs; the likelihood of success of options; and other factors which are beyond control such as climate variability.
Given the above factors, the mitigation of rising groundwater and conservation of representative wetlands is a challenge. It is understood that each representative wetland area has its own unique characteristics and these are likely drivers for unique mitigation measures, albeit with some commonality between alternative mitigation themes.

### 12.3 Review of Management Options

Currently there are significant knowledge gaps pertaining to the hydrological function of the representative wetlands in the BMNDRC. Consequently it is essential that time-series hydrological and climate data is continued to be collected to fill these knowledge gaps. This information will be just one of the tools used in future feasibility studies to assess the cost and benefits of potential management options. However, in spite of the current uncertainty there are many management options available to address the threat of salinity imposed upon the five representative wetland areas in the BMNDRC. A few options that might be considered include:

- **Management to control surface water inputs into representative wetland areas using techniques such as revegetation and construction of conservation earthworks (i.e. grade banks, level banks, constructed waterways etc).** Where possible, designs should initially attempt to reduce surface water velocities to reduce erosion of top soil, which will in-turn reduce impacts associated with nutrient and sediment fluxes. It is important that this is also done in the runoff generating areas of the catchment. Secondly, designs should reduce the impacts associated with water-logging of neighbouring paddocks. This management option will have productivity benefits to the landholder through increased topsoil, water, and nutrient retention. In many cases water-logging at the footslopes of catchments can be significantly reduced. Negative aspects of this option include the loss of agricultural land due to the footprint of management structures, limitations associated with suitable areas for implementation, cultural changes to farming practices (such as working to the contour) and relatively high infrastructure costs.

- **Plant-based solutions to salinity which are agriculturally profitable.** There are likely to be increased numbers of options available in the future under circumstances where water-efficient perennial plants may utilise deeper groundwater resources, reduce recharge, and opportunistically intercept recharge from summer rainfall events. These options may potentially be integrated with existing cropping systems; for example intercropping of perennials such as Lucerne. The Future Farm Industries CRC is working on other options for profitable perennials. This may be one of the most favourable options for the management of salinity. It is likely, however, that only representative wetland areas located in higher rainfall areas with comparatively productive soils will accommodate this option. Consequently, this option may be unsuitable in the eastern parts of the BMNDRC.

- **Deep drainage networks, either as traditional open-levied deep drains, or buried perforated pipes,** are an option to intercept groundwater up-gradient from representative wetland areas. The valley floor in the BMNDRC is a poor conveyance of surface water, which contains a significant proportion of the biodiversity values of the region. Consequently, consideration is required of the potentially negative impacts to the down-stream receiving environments. Prior to implementing this management option, the Notice of Intent to Drain (NoID) process is required to be completed.

- **Farm water storages,** such as sand dams, may be constructed to intercept excess fresh surface water and groundwater up-gradient of representative wetland areas. Collected water may be used on-farm for livestock or new farming opportunities such as irrigation of pasture, perennial crops or new food crops.

- **In some cases,** where the threats to biodiversity assets are imminent and management to ameliorate salinity is unprofitable to the landholder (such as to revegetate 100% of the catchment), then there may be opportunity for land purchase by the DEC. All costs of future management would then be transferred to the DEC. Prior to implementing this option, a full cost-benefit analysis would need to be undertaken. This analysis would consider the...
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biodiversity values, purchase costs, management implementation costs and the long-term costs for managing new estates.

- Groundwater abstraction may be a viable management option at a number of representative wetland areas. A negative aspect of groundwater abstraction would be the potential for off-site drawdown impacts and linked to the disposal of saline groundwater. There may, however, be alternatives for disposal of saline groundwater, such as construction of evaporation basins or re-injection into deeper palaeochannel successions. The benefits of this option would be that there will be a reduced likelihood of down-stream impacts from disposal of saline groundwater. A detailed study would be required prior to implementation to improve the understanding of the local hydrogeology.

- New industries. There may be future opportunities for alternative farming systems, which are currently unviable or unrealised. Industries such as aquiculture and seaweed production are two examples which may, in certain circumstances, provide new opportunities to utilise a resource which is currently a waste product. Given the potential for new developments, it is important that hydrogeological investigations and monitoring programmes are promoted to continually improve the understanding of the representative wetlands in the BMNDRC.

- The use of sacrificial wetlands. This option may be an appropriate method to store the first flush of salt which enters wetlands following the initial winter rains. Lake Toolibin is one of the best known examples in Western Australia where this has been successfully implemented. Alternatively, a sacrificial wetland may be used to receive a once-off volume of saline surface water from a wetland. Sacrificial wetlands may also be modified and used as evaporation basins, which receive groundwater from deep drains or groundwater abstraction.

- Amendment of soils to limit (reduce) recharge rates (passive). Additives such as clay might be tilled into the superficial sands. Outcomes may provide additional soil moisture for plant use and/or increase runoff.

- In some cases the option of “no management” will be appropriate. Situations where this may be likely are where a number of situations may occur such as:
  - Time and monetary investment into management will be too high (cost-benefit analysis);
  - the biodiversity assets are regionally represented elsewhere in locations not threatened by salinity, therefore there is little benefit in implementing management;
  - the damage has already been done, therefore the opportunity has been lost to restore the biological values;
  - too little is known about the hydrogeological function to implement management, therefore significant investment is still needed to increase scientific understanding;
  - the landholders are not willing or able to implement changes;
  - there are no alternative profitable options to manage salinity; or
  - there is no threat from salinity therefore there is no need to implement management.

12.4 Discrete Options for Individual Representative Wetlands

Findings of the hydrogeology investigations and associated interpretations have been applied to the individual representative wetlands to scope potential preferred options to mitigate rising water tables. Each option is framed to limit disturbance of the representative wetland areas. All options require further evaluation through feasibility and engineering studies. Opportunities for passive systems are probably preferred as these are likely to be cost and energy efficient. Alternatives with energy sourced from
renewable energies such as solar panels, wind mills or wind turbines are likely to also be more practical than diesel power generation in terms of ongoing management costs, safety of personnel and livestock and environmental noise.

12.4.1 Fresh/Brackish Wetlands W011 and W012

Preferred mitigation approaches might include:

- Revegetation of upslope recharge areas with perennial plants (native and/or agriculturally productive options) in order to reduce recharge and throughflow.
- Abstraction of fresh groundwater to irrigate new species of perennial crops.
- Use of upgradient lakes (on cleared land) to intercept groundwater throughflow, the lakes might be modified to increase evaporation (by enlargement, aeration and controlled additional planting) or to enable abstraction and diversion of groundwater.
- Abstraction from the palaeochannel immediately downstream of the wetlands, to locally lower the water table.
- Abstract a once-off volume of water from wetland W011 and W012 to reduce the overall salt load of these wetlands. This option is limited by the availability of a suitable and safe water disposal point.

12.4.2 Bentonite Wetlands W056 to W059

Preferred mitigation approaches might include:

- Revegetation of sandy upload areas in the south east of the subcatchment.
- Establishment of buried deep drains on the downstream perimeter of cleared properties. There may be opportunities for economic benefit from salt production collected in discrete down-gradient modified playa lakes and/or purpose built evaporation ponds.
- Modifying the downstream watercourse through the advent of deeper drains to pump, or drain saline water from W056 and/or W057 to an evaporation basin.

12.4.3 Gypsum Wetlands W001 and W002

Preferred mitigation approaches might include:

- Abstraction from the palaeochannel, possibly both upslope and downslope of the wetlands.
- Revegetation of the footslopes immediately upslope of the wetlands to reduce the impact of waterlogging and surface water runoff.
- Construction of conservation earthworks to assist with the management of waterlogging immediately east of wetland W001, and to reduce the impact of sediment from neighbouring paddocks entering wetland W002.

12.4.4 Primary Saline Wetland W448

The playa lakes domain is extensive, traversing at least 40% of the BMNDRC. Providing controls on water table elevations across the domain would be difficult to achieve and might involve significant abstractions of groundwater.

Preferred mitigation approaches might include:

- Abstraction from the palaeochannel immediately downstream of the playa lakes.
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Wetland Management

– The formation of a groundwater and salt sink on downstream reaches of the Buntine Palaeodrainage, promoting internal drainage and flow over a dedicated area. Installed infrastructure might be applied to enable harvesting of salt.

– Initiatives to promote lateral drainage down-gradient on the valley-floor and within the Buntine Palaeodrainage, through a network of shallow drains. These drains may be linked to purpose built ponds to increase evaporation by exposing groundwater to the surface.

– Construction of conservation earthworks in areas conducive to management of surface water. Areas adjacent to granite outcrops, and/or greater topographic relief will be particularly suitable.

– In areas where deep sands predominate, there may be future opportunities to implement alternative cropping systems to reduce recharge of to the shallow water table. Unfortunately, given the relatively low rainfall in the east of the catchment it is unlikely that suitable species be available in the near future.

12.4.5 Fresh/Brackish to Valley Floor Wetlands W015 to W017 and W051

Preferred mitigation approaches might include:

– Revegetation of upslope recharge areas with perennial vegetation (native and/or agriculturally productive options) in order to reduce recharge and throughflow.

– Abstraction of fresh groundwater to irrigate new species of perennial crops.

– The use of W051 up-gradient to potentially intercept and abstract groundwater, limiting throughflow. The lake might be modified to increase evaporation and enable groundwater abstraction.

– Further defining the extent of the palaeochannel sediments located nearby W016 and abstraction from these sediments. Groundwater is fresh to brackish and may be used for irrigation and/or for stock watering purposes. Further groundwater quality testing would identify potential uses.

– Treatment of the sandy superficial formations to constrain infiltration capacities and improve moisture-retention properties.
13 Recommendations

13.1 Monitoring Recommendations

Monitoring recommendations include:

– Continued groundwater level monitoring of all monitoring bores. It is recommended groundwater levels be continued to be measured at six weekly intervals. The use of data loggers to record daily (or 6-hourly) groundwater levels at representative wetlands should also continue.

– Groundwater quality sampling of all monitoring bores on an annual basis. Samples to be laboratory tested for EC, TDS, pH and chloride.

– Aquifer tests should be conducted in all monitoring bores. Either slug or pumping tests should be conducted to gain a better understanding of the variability of hydraulic conductivity within the soil-landscape systems.

– Installation of an automated weather station within the catchment. Limited measurement of local pan evaporation is currently undertaken by the BOM, therefore a local weather station reporting temperature, rainfall and evaporation would provide benefit in water balance estimates. The location of the weather station is to be determined by DEC.

– Continued monitoring of the DEC rain gauges within and surrounding the catchment, to provide a greater understanding of rainfall distributions.

– Upgrade and continue to monitor existing surface water gauging stations throughout the BMNDR to measure depth, water quality, and where possible rate sites for a given stage height.

13.2 Future Investigations

– Lake bathymetry survey to 0.2 m accuracy is recommended to link surface water levels with groundwater levels. This can be achieved remotely using airborne Light Detection and Ranging (LIDAR) survey or on-ground using RTK survey.

– Obtain a more accurate catchment Digital Elevation Model (DEM). The accurate determination of groundwater and surface water interaction requires topographic elevation data at 0.2 m accuracy. Suitable options include (LIDAR) although Kevron Photogrammetry (~0.5 m accuracy) may suffice.

– Undertake an airborne TEMPEST electromagnetic or similar survey to identify the bedrock surface, geological structures and palaeochannel drainage. This method has been used successfully in identifying bedrock topography and the Carey Palaeodrainage in the North-eastern Goldfields. Current conceptual understanding of the hydrogeology of the BMNDR is based upon a relatively small number of drill samples. Further work to improve the understanding of the depth to basement across the catchment will be essential to extrapolate findings from representative wetlands to other wetlands across the catchment.

– Complete additional groundwater exploration drilling in the near vicinity of the selected wetlands. Irrespective of all other recommendations for future investigations, the need for additional intrusive investigations is fundamental to improving the knowledge and understanding of the wetland functions and groundwater behaviours in the local catchments. At present, all hydrogeological interpretations are hinged on the simple concept that the water table elevations closely conform to the ground topography. This interpretation may be broadly correct, but needs to be verified as local-scale influences and variability in the depths to bedrock may be significant controls on wetland locations and water balances.

– Complete larger scale aquifer testing to characterise the effective transmissivity of the saturated successions above fresh bedrock. The effective transmissivity of the saturated
profiles within the catchment are expected to be determined in part be the depths to fresh bedrock. This recommendation is essential to refining the water balances and salt balances of the wetlands and hence how the function.

- Undertake a down-hole EM39 and Gamma survey of all bores in the BMNDRC. Data collected from this survey can be used to enhance the understanding of the geology throughout the catchment. In addition, this data can be used to calibrate airborne geophysics data, such as TEMPEST.

- Conduct a groundwater isotope study (O\(^{18}\), and H) to gain a better understanding of the recharge components of the water balance and ages of the groundwater in storage.

- Undertake ecological water requirements research. It is essential that changes to water regimes (quality and quantity) as a consequence of management actions are cognisant of possible impacts on the associated aquatic, riparian and terrestrial biota. Analytes such as nutrients, metals etc should be considered.
Section 14

Conclusions

A hydrogeological assessment has been undertaken that advances the BMNDRC conceptual hydrogeology, and this hydrogeology framework can now be developed in future studies to generate a catchment-scale water balance model.

The knowledge of the geology and stratigraphy of BMNDRC was linked with the findings of drilling investigations to frame a conceptual hydrogeological model. This model provides an overall broad and catchment-wide appraisal of the hydrogeology of the BMNDRC. It has also been applied on a local and sub-catchment scale, understanding that small-scale geological and structural controls might strongly influence the local groundwater environment. Key elements of the hydrogeological investigation are presented in Table 11-2.

Seasonal rainfall trends for Coorow BOM station show a significant decline in five-year moving average winter trend. This downward winter rainfall trend would reflect lower surface runoff and recharge to the groundwater during winter. Conversely, the summer season rainfall shows an upward trend (5-year moving average). Importantly, the increased frequency of larger summer rainfall events, occurring on a landscape that is largely devoid of vegetation, during these months is likely to result in recharge increases to the water table.

The Indian Ocean Panel on Climate Change (IOCC, 2006) indicate further declines in average rainfall of up to 20% over the next 25 years. Rainfall records over the past 100 years also show a number of localised summer storm events are known to deliver substantial rainfall over a short time period (>50 mm in 1 hour).

Recharge estimates using recent rainfall data (1966 to 2006) indicate groundwater levels in the Fresh/Brackish, Bentonite, Gypsum, and Primary Saline wetland catchments are likely to be declining as a result of lower rainfall and a generally drying climate. In contrast, rising groundwater trends were estimated for the Fresh/Brackish Valley Floor Wetland. Future predictions of groundwater trends must consider that the recent decline in groundwater levels across most of the BMNDRC since 1999 may be masking a longer-term trend of rising groundwater levels. This is particularly important given the likely increased occurrence of significant rainfall events, such as those which occurred in 1917, 1963, and 1999, which may drive groundwater tables to rise.

Although limited in long-term data, these conclusions are likely to be consistent with groundwater tables throughout each wetland catchment. Historical records from monitoring bores installed in the BMNDRC in 1996 showed a significant groundwater response to extreme rainfall events with long delays in recovery to pre-event groundwater levels. For example, following the significant rainfall events subsequent to tropical Cyclones Elaine and Vance in 1999, there was an 8 year delay for the water table to reach previous levels. It is important to note that long-term groundwater (>10 years) data is required to make accurate predictions on any influence of these events have on groundwater levels in other wetland areas within the BMNDRC.

With these changes in groundwater levels come changes in salt accumulation or loss. As evapotranspiration accounts for a significant proportion of the water balance, simulations in the Fresh/Brackish, Gypsum and Primary Saline wetland catchments show a gain in salt. By contrast, the Fresh/Brackish to Valley Floor wetland catchment and the Bentonite wetland catchment both show a decline in salt accumulation. However compared with past wetter annual averages (1953 to 1993), salt accumulation is also in decline in all wetland catchments due to lower rainfall recharge and declining groundwater levels.

The development of strategies to mitigate risks potentially imposed by rising water tables is complex. At present, there is some uncertainty regarding wetland water balances and the range over which local water tables might be managed to conserve the existing environment and ecosystems. Likely water table and aquifer system responses to potential stressors are also uncertain, as are distances or areas over which responses might prevail. With a broad network of groundwater monitoring bores recording continuous groundwater levels, this uncertainty can be refined with time.

Further to these aspects are potentials for future changes to past and/or current water balances in individual catchments, and transient changes in salinity of the local groundwater. The interpretations...
Section 14

Conclusions

Based on available data indicate that significant rainfall events have a strong influence on recharge and hence water table elevations. A continual change in the summer and winter rainfall trends and patterns would potentially lead to changes in water table elevations. Irrespective of water table trends in the valley floor, wetland and shallow water table domains from discharge zones wherein increasing salinisation is expected due to groundwater losses through evaporation.

On a scale relevant to the representative wetlands, particularly the Fresh Brackish, Gypsum, Primary Saline Lakes and Fresh Brackish Valley Floor catchments, the uncertainty of the water balance is manifested by questions regarding causes and effects of rising water tables. For instance “are rising water tables in the individual wetlands predominantly linked to catchment-wide influences on the Buntine Palaeodrainage or changes in water balance on a local scale?” The former would potentially cause the backing-up of groundwater along individual palaeotributaries and watercourses. On the other hand, the latter would reflect increasing excesses of groundwater shedding from local catchment areas. Mitigation measures would need to be developed cognisant of the predominant water balance influence, presumably preferentially targeting either downstream or upstream influences depending on which is dominant.
Section 15

References


Alluvium: Unconsolidated material deposited by running water such as a river. Includes gravel, sand, silt, clay and various mixtures of these.

Anaerobic: Describes conditions that are free of molecular oxygen. In soils, anaerobic conditions are usually caused by excess water filling most of the coarse pores in the soil.

Annual pan evaporation: An estimate of the average total evaporation occurring at a particular site over the period of a year based on measurements of how much water is lost from a Class A pan fitted with bird guards. The bird guard reduces the evaporation by about 7%.

Annual plant: A plant that completes its life cycle within 12 months. In the South-west Hydrological Region, annual pastures usually begin growing in late autumn or early winter and complete their life cycles in late spring or early summer.

Aquifer: A geological formation comprising layers of rock, unconsolidated deposits or regolith, that are capable of receiving, storing and transmitting significant quantities of water. Aquifers may be permeable or fractured bedrock, unconsolidated sediments or highly weathered rock. The term is usually applied to saturated materials that currently contain water.

Aquitard: A geological formation of low permeability that can only transmit water at much lower rates than adjacent aquifers. Aquitards occur above confined aquifers or below perched aquifers.

Available nutrients: The elements and minerals in the soil solution that can readily be taken up by plant roots.

Basalt: A dark coloured, fine grained, basic igneous rock formed in association with volcanic activity.

Basin (geology): A low area in which sediments have accumulated. Also used to refer to geological strata formed from sediments deposited in a basin.

Bedrock: A general term for the solid rock that lies underneath the soil and other unconsolidated material. When exposed at the surface it is referred to as rock outcrop.

Bedrock high: An area in which the bedrock is closer to the ground surface than in the surrounding areas. On slopes with patches of shallow bedrock, groundwater discharge is often initiated at lateral flows are forced to the surface.

Bore: A hole drilled through soil, regolith or rock, typically for the purpose of observing or extracting groundwater.

Brackish (water): A term used to describe water that has moderate salinity levels (1,070 -5,000 mg/L) these levels limit its suitability for many uses.

Break of slope seep: Seepage occurring where groundwater is discharged near the foot of a slope after being forced to the surface by a decrease in the slope of the water table.

Broadacre: A term used to describe farming or cropping enterprises that cover large areas of land, as are typical of farms in the Wheatbelt. The term “broadacre cropping” is used to differentiate the growing of crops such as wheat, lupins and canola from the intensive cropping practiced in horticulture.

Calcareous (soil): A soil with a high content of calcium carbonate (commonly referred to as lime). Calcareous sands that are found in coastal areas typically contain numerous sea shell fragments.

Capillary fringe: The zone immediately above a water table in which most pores and voids are filled with water, but the water is at less than atmospheric pressure (i.e. soil or regolith is almost saturated) and will not flow into a hole or macropore.

Capillary rise: The unsaturated flow of water upwards from the water table. Capillary rise is driven by matric suction maintained by evapotranspiration from the soil surface. The water moves upwards through fine pore spaces and as films around the soil particles.
Section 16

Glossary of Terms

Catchment: The total area of land potentially contributing to water flowing through a particular point.

Catchment divide: The boundary between two catchments that divides the surface waters that flow naturally in one direction from those that flow in the opposite direction.

Cemented: Soil and rock particles bound together by another material such as calcium carbonate or iron. The degree of cementation can range from weakly cemented to indurated.

Clay: (a) Fine soil particles <0.002 mm in diameter; (b) Soil texture class with more than 30% clay-sized particles and less than 25% silt sized particles; (c) Soil profiles with clayey texture in the top 3 cm.

Colluvium: Unconsolidated, unsorted earth materials deposited on sideslopes and/or at the base of slopes by local runoff (unconcentrated) or mass movement (e.g. direct gravitational action).

Complex (geology): A geological term referring to an area comprised of mixed group of rocks of varying origin or nature.

Confined aquifer: An aquifer (geological formation containing water) overlain by an aquitard (layer of low permeability) that restricts the upward movement of water. In a confined aquifer there is no water table because the aquitard prevents the water from rising (i.e. the piezometric head is above the aquifer).

Contour: An imaginary line on the surface of the earth connecting points of the same elevation (i.e. the same height above sea level).

Cracking clay: A soil profile with a clay texture throughout, which swells and forms a solid mass when wet, but which cracks (at least 5 mm wide and 10 cm deep) when drying.

Crest: The commonly linear, narrow summit of a ridge, hill or mountain.

Crust (soil): A thin surface layer of a soil profile that is harder than the underlying horizons. The crust can often retard infiltration. Usually referred to as surface crust.

Crystalline rock: An igneous or metamorphic rock comprised of interlocking crystals. Examples include granite or gneiss.

Dam: A barrier, embankment or excavated earth structure constructed primarily to impound water for storage. Dams are generally built in or near drainage lines. Dam walls can range from large concrete structure such as Wellington Dam to the small earthen walls typical of many farm dams.

Deep drainage: The removal of groundwater using deep open drains or sub-surface drains.

Deep open drains: Drains designed to intercept and remove groundwater (typically from surficial aquifers). Deep open drains are constructed with a bulldozer or excavator and are left uncovered. They are more than 60 cm deep and typically 1.2–2.5 m deep or more.

Deeply weathered profile: A deep (up to 50 m deep) section of soil and regolith formed by the weathering (physical disintegration, chemical decomposition or biologically-induced changes) or rock on the Earth’s surface over a long period of time of geological stability. In the South-west Hydrological Region, deep weathering usually resulted in the formation of laterite and the deeply weathered profile is usually a lateritic profile.

Degradation: The decline in the quality of natural resources such as soils, water and plants.

Deposit: Earth material of any type, either consolidated or unconsolidated, that has transported and subsequently accumulated by natural processes.

Deposition: The laying down of any material by any agent such as wind, water, ice or by other natural processes.

Depression: Any relatively sunken part of the Earth’s surface; especially a low-lying area surrounded by higher ground.
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**Discharge:** The water which moves from a groundwater body to the ground surface (or into a surface water body such as a lake or the ocean). Discharge typically leaves aquifers directly through seepage (active discharge) or indirectly through capillary rise (passive discharge). The term discharge is also used to describe the process of water movement from a body of groundwater.

**Discharge area:** An area where significant amounts of groundwater come to the surface, either directly or indirectly.

**Dispersion (soil):** The process whereby the soil aggregates break down in water into their constituent particles (sand, silt and clay) due to deflocculation. The clay particles go into suspension. Dispersion affects the structure and coherence of a soil and its pores get clogged by the loose clay particles, reducing its permeability and often resulting in waterlogging.

**Dissection:** The process by which valleys are cut into a land surface by eroding rivers and streams.

**Dissolved (salts or nutrients):** Describes the situation when salts or nutrients go into solution, becoming bonded to water molecules.

**Dolerite:** A medium grained, basic, igneous rock that has crystallised near the surface, typically occurring as a dyke, sill or plug.

**Drain:** A channel or tunnel constructed to intercept and remove water.

**Drainage:** The removal of water from a site or soil profile. **Site drainage** relates to the rate at which water is removed from a particular site. **Soil or profile drainage** relates to the rate at which water is removed from a particular soil profile. The term drainage is also used to describe systems that are artificially constructed to improve site or soil drainage (e.g. deep drains, seepage interceptors or pumping systems).

**Drainage line:** A channel down which surface water naturally concentrates and flows regularly, either permanently or for short periods. Examples include streams and the floors of drainage depressions.

**Drainage system:** A network of drainage lines and waterways (either natural or artificial) through which water occurring over an area is transported to an end point. Natural drainage systems typically consist of all the rivers and streams in a catchment. Artificial drainage systems usually comprise a series of connected drains and waterways designed and constructed to remove excess surface or groundwater from an area.

**Drawdown:** The lowering of a water table resulting from the removal of water from an aquifer or reduction in hydraulic pressure.

**Dryland salinity:** The salinisation of land which is not irrigated. The term dryland salinity does not imply that the land is dry, as areas affected by dryland salinity are typically also waterlogged.

**Dune:** A ridge, bank, hill or low mound of loose, wind-blown, granular material (generally sand), either bare or covered with vegetation; capable of movement from place to place but always retaining its characteristic shape.

**Duplex (soil):** A soil with a sudden increase in texture between the topsoil and subsoil, e.g. a sand over a clay.

**Duricrust:** A hard layer which looks like rock and is formed at, or near, the ground surface by the concentration of materials. In the South-west Hydrological Region, duricrust usually occurs as a layer of cemented ironstone gravels that are rich in iron-oxide. Duricrust is sometimes referred to as sheet laterite, ferricrete, ironstone or caprock.

**Dyke:** A sheet-like body of igneous rock cutting across the bedding or structural planes of the host rock. Dykes typically appear on the surface as relatively narrow, linear features.

**Dyke swarm:** Describes the situation where numerous dykes, usually of similar age, are found in the same area.
Earth (soil): A soil profile with a gradual increase in texture between the topsoil and subsoil, e.g. a sand grading into a loam with depth or a loam grading to clay with depth. Soils with a loam texture throughout the profile are also referred to as earths.

Earthwork: A structure made out of earth (soil or regolith) and designed or constructed to intercept, divert, retain, detain or dispose of runoff or throughflow.

EC: An abbreviation of electrical conductivity, a measure of the ability of a medium to conduct electricity. EC is used often as a surrogate measure of salinity levels in water or soil as the conductivity of a solution generally increases in proportion with its salt content. There are three types of electrical conductivity measurements made on soils:

ECe measurements are made on saturation extract paste from soil samples.
EC1:5 measurements are made on a solution obtained by mixing one part soil with five parts distilled water.
ECa measurements are taken in the field using an electromagnetic induction meter.

Eocene sediments: Sediments deposited during the Eocene Epoch (38-65 million years before the present). In the South-west Hydrological Region they consist mostly of cemented and unconsolidated layers of sand and clay.

Ephemeral stream: A stream; or part of a stream, that flows only in direct response to precipitation. Its channel is always above the water table.

Equilibrium: Describes the state of a flow system in which recharge equals discharge and the water table level therefore remains constant or rises and falls around a long-term average level.

Erosion: The wearing away of the land surface by running water, waves, wind or by other processes like mass wasting and corrosion (solution and other chemical processes). The term “geological erosion” refers to natural erosion processes occurring over long (geological) time spans. “Accelerated erosion” generically refers to erosion in excess of what is presumed or estimated to be naturally occurring levels, and which is a direct result of human activities such as cultivation.

Eutrophication: The enrichment of a water body with organic and inorganic plant nutrients. Eutrophication can cause the water body to become highly active biologically, with increased growth of algae.

Evaporation: The conversion of a liquid into vapour. In the hydrological cycle, evaporation involves heat from the sun transforming water (held in surface storages in soil) from a liquid state into a gaseous state. This allows the water to move from water bodies or the soil and enter the atmosphere as water vapour.

Evapotranspiration: The transfer of soil water to the atmosphere from vegetated land through the combined processes of evaporation from soils and transpiration from plants.

Farming system: A combination of the crops, pastures, livestock and agricultural practices (e.g. cultivation technique and fertiliser regime) that are used on a farm.

Fault: A fracture or fracture zone of the Earth’s crust with displacement along one side in respect to the other.

Fertiliser: A material that is added to the soil to supply one or more plant nutrients.

Flood plain: A plain built up by periodic flooding and alluvial deposition.

Floodling: The situation where large volumes of water flow across the ground surface. It usually occurs along drainage lines and on valley floors. Differs from inundation where water on surface is stationary.

Flow rate: The amount of surface water or groundwater flowing past a given point or line over a defined time period. Measured as volume, depth or area of water per minute, hour, day or year.
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Flow systems: The portions of the hydrological cycle which involve the movement of water across the land surface or through the ground. Includes surface flows (runoff and stream flow), temporary subsurface flows and permanent groundwater flows.

Flow velocity: The speed at which surface water or groundwater flows. Measured as a distance per time period (e.g. mm/hr or m/day).

Footslope: The lower part of a hillslope, commonly concave in profile.

Formation (geology): A geological term for a distinct layer of sedimentary deposits.

Fracture (geology): Cracks, joints, faults and other breaks in a rock as a result of that rock being subjected to pressure or movement.

Fractured rock aquifers: Rocks that capable of receiving, storing and transmitting significant quantities of water due to the presence of numerous cracks, fissures or fractures in what would otherwise be an impermeable material.

Fresh (rock): A colloquial term for bedrock that has been exposed on or near the surface relatively recently (in geological terms). The term can be misleading as the rocks involved are usually more than a billion years old. The term “fresh” refers to the fact that the rock has been stored underground in an undisturbed state in contrast to deeply weathered profiles in which the rock has been subjected to extensive alteration. Soils formed from fresh rock are typically fertile and often have a rich red or brown colour.

Fresh (water): A term used to describe water that has very low levels of salinity (less than 500 mg/L) these present no limitation to its suitability for most uses.

Geological structure: A feature produced by the displacement or deformation of rocks. Examples include faults, folds, shear zones and dykes.

Geology: The study of the Earth and the rocks of which it is composed.

Gneiss: Banded metamorphic rocks which are generally coarse-grained.

Gradient: The degree of inclination of a slope, usually expressed as a ratio of the change in height over a particular distance. For example, a gradient of 1:500 means the slope drops by a metre over every 500 m. Gradients of steeper slopes are expressed as a percentage, with a 100% slope being the equivalent of 1:1 gradient, a 25% slope being the equivalent of 1:4 gradients and a 10% slope being the equivalent of 1:10 gradient. Gradients can be measured on hillslopes, valley floors, water tables and earthworks.

Granite: A light coloured, coarse grained igneous rock formed by the slow cooling of a large intrusion of magma. Granite consists essentially of quartz (20-40%), feldspar and very commonly a mica as well.

Gravel: In the South-west Hydrological Region, the term gravel is most commonly used to describe the rounded ironstone gravel associated with laterite and commonly used as a road base. The correct technical definition relates to coarse mineral particles (rock fragments) in the size range of 2-75 mm in diameter.

Gravels (soil): The term applied to soil with a significant ironstone gravel content (>20%) in the top 15 cm of the profile. Includes shallow gravels, duplex sandy gravels, deep sandy gravels and loamy gravels.

Ground cover: Any matter that protects the soil surface from erosion. Ground cover is usually the same as vegetative cover (i.e. living plants) but can include dead plant matter, stones or gravel.

Groundwater drainage: Artificial drains (deep open and/or sub-surface drains) that are designed to intercept and remove excess groundwater and thereby lower water tables.

Groundwater management: A management system designed to lower water tables, usually with the aim of preventing the additional accumulation of salts while allowing rainfall to leach salt from the upper soil profile. Groundwater management systems can involve drains, bores with pumps or relief wells to extract the water.
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Groundwater pumping: The extraction of water from aquifers with the aid of electric, wind powered or compressed air pumps. Groundwater pumping involves drilling bores down into aquifers. Usually a number of bores and pumps are required to have any effect on water tables in a particular area.

Groundwater: Water that is held below the ground surface that is a pressure greater than atmospheric pressure and will therefore flow freely into a bore or a well. This term is most commonly applied to permanent bodies of water found under the ground.

Groundwater flow: The movement of groundwater in soil, regolith and rocks that are fully saturated.

Growing season: The length of the period each year when plants are growing actively. In the South-west Hydrological Region the term usually refers to the growing season of annual plants, which extends from late autumn into spring. There is little growth over the summer when evaporation exceeds rainfall.

Gully: A small channel with steep sides cut by running water and through which water ordinarily runs only after rain. Gullies are more than 30 cm deep and can incise several metres into the soil. They often have branches and usually cannot be crossed by farm machinery.

Hardpan: A hard soil layer cemented with organic matter, silica, sesquioxides, gypsum or calcium carbonate or formed by physical compaction of the soil.

Heavy clay: A heavy clay has a higher proportion of the fine particles (>50% clay) than a light or medium clay. Heavy clays typically have low permeability, can be difficult to cultivate and set very hard when dry.

Heavy-textured soil: A soil profile with a high clay content (>30% clay) throughout or a clay horizon close to the surface. Examples include cracking clays, non-cracking clays, shallow loamy duplexes and shallow sandy duplexes.

High rainfall district: A loose term used to describe areas close to the coast that receive more rainfall than inland areas. Typically applied to the districts receiving more than 600 or 800 mm per year on average.

Hillside seep: The discharge of groundwater on a hill slope. This discharge is usually associated with local flow systems and often occurs where the groundwater flow is forced to the surface by a barrier.

Horizon: A term used to describe individual layers in a soil profile. Each horizon has morphological properties different from those above and below it.

Hydraulic conductivity: A measure of the potential rate of flow of a fluid through soil or rock. As such it takes into account the nature of the fluid, the degree of saturation and the permeability of the material the fluid passes through. The hydraulic conductivity of a material can be measured in either the saturated or unsaturated states. He unsaturated hydraulic conductivity will change as a material becomes wetter, but the saturated hydraulic conductivity of a material remains constant. Hydraulic conductivity is expressed in units of length per unit of time, typically millimetres per hour (mm/hour) or metres per day (m/day).

Hydraulic gradient: The slope of a water table or piezometric head. The hydraulic gradient provides a measure of the force of gravity driving the movement of water within aquifers and can be measured by comparing the water level in two or more piezometers that have been drilled into a groundwater system.

Hydraulic pressure: The pressure exerted on water in an aquifer due to the weight of water present in it or in a connected aquifer upslope. Hydraulic pressure determines the hydraulic gradient and drives groundwater flow systems. Hydraulic pressure is also referred to as “piezometric pressure”.

Hydrological cycle: The continuous circulation of water between the land, sea (or other water surface) and the atmosphere.

Hydrological zone: An area of land where the geology, landform, soil, climate and land use combine to form a unique set of hydrological characteristics.

Hydrology: The study of water and water movement in relation to the land. Deals with properties, laws, geographical distribution and movement of water on the land or under the Earth’s surface.
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**Igneous rock**: Rock formed as magma from the core of the Earth cools and becomes solid on or near the surface. Igneous rocks include volcanic rocks (e.g. basalt) which form when magma erupts on the surface, and plutonic rocks (e.g. dolerite and granite) which form under the ground.

**Impermeable**: Describes the nature of a solid material that will not allow fluids to pass freely. A material described as being impermeable will have a saturated hydraulic conductivity of less than 0.02 m/day.

**Infiltration**: The process whereby water enters the soil through its surface. The downward movement of water into the soil profile.

**Infiltration capacity**: The maximum rate at which water can soak into, or be absorbed by, a soil. It assumes that the rate of water application is not limiting infiltration, and it varies with the degree of saturation of the soil.

**Infiltration rate**: The speed at which water soaks into, or is absorbed by, a soil. Expressed in units of depth and time (e.g. mm/hour).

**In situ**: In its original place or in the same place.

**Interception**: The process whereby rain adheres to the surfaces of leaves or branches of plants as water droplets or as a thin film and evaporates before it reaches the soil.

**Interceptor drains**: See seepage interceptor drains.

**Intermediate flow system**: A flow system transporting groundwater for distances of 5-10 km. Intermediate flow systems are typically found in areas of low relief with long slopes and broad valley floors, and may cross surface catchment boundaries.

**Inundation**: Describes the situation where water lies stationary above the soil surface. Sometimes referred to as surface ponding. Inundation is commonly confused with waterlogging because both processes often occur at the same time. In certain situations, soils can become inundated without being waterlogged, with the soil surface sealing and water lying on the ground but no infiltrating.

**Ironstone**: A material indurated with iron-oxides so that it appears like a rock. It can occur as sheets of duricrust or ferruginous nodules or concretions (ironstone gravel). Ironstone typically has a reddish or orange colour and is typically associated with the lateritic profile.

**Irrigation**: The process of supplying land with water by artificial means in order to promote plant growth.

**Landform**: Any physical, recognisable form or feature on the Earth’s surface, having a characteristic shape and range in composition, and produced by natural causes. Landforms provide an empirical description of similar portions of the Earth’s surface and can range in size from several metres across up to 100 km long.

**Landscape**: A collection of related, natural landforms; usually the land surface which the eye can comprehend in a single view.

**Lateral groundwater flow**: Movement of groundwater in a non-vertical direction (i.e. sideways instead of straight up or down). Lateral groundwater flows are usually more or less parallel to the ground surface, though this is not always the case.

**Laterite**: Deeply weathered material, thought to be formed in past tropical environments under climatic extremes of wet and dry seasons throughout the year. Leaching of the profile removes sodium, potassium, calcium and magnesium ions. Iron oxides remain to form a hardened and cemented layer.

**Lateritic profile**: A deeply weathered profile of soil and regolith that typically consists of sand or gravel on top of a ferruginous duricrust where the iron oxides have accumulated. This overlies the mottled zone (pale clay with mottles) and then a pallid zone (white clay) from which the leaching has occurred.

**Leach**: To wash material from the soil, both in solution and suspension. The process by which nutrients, chemicals or contaminants are dissolved and carried away by water, or are moved into a lower layer of soil.
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Lineament (geology): A geological term for a linear feature, such as a fault or fold, which expresses itself on the Earth’s surface. For example, the Darling Scarp is a topographical expression of the Darling Fault, which is a very large lineament.

Loam: A medium textured soil material containing a mix of clay, silt and sand particles (approximately 10-25% clay, 25-50% silt and <50% sand).

Local flow system: A flow system transporting groundwater in which discharge and recharge occur within a couple of kilometres of each other. Flows may be permanent or temporary and the water is typically transported down a hill slope through unconfined aquifers that are relatively thin (<20 m) and close to the surface.

Low rainfall district: A loose term used to describe inland areas that receive less rainfall than areas closer to the coast. Typically applied to districts receiving less than 400-500 mm/year on average.

Macropore: A large pore (such as an old root channel or animal burrow) which provides a pathway for water movement through a soil profile or regolith.

Marginal (water): A term used to describe water that has low salinity levels (500-1,070 mg/L) – these levels may limit its suitability for some uses.

Metamorphic rock: Rock of any origin altered in mineralogical composition, chemical composition or structure by heat, pressure, or movement at depth in the Earth’s crust. Examples of metamorphic rocks include schist, gneiss, quartzite, slate and marble. Most have parallel bands of minerals evident.

Miocene: The epoch of the Tertiary Period of geological time occurring approximately 5-23 million years ago.

Mottle (soil): Patches or spots of different colours in a soil material. Mottles develop due to oxidation-reduction reactions associated with waterlogging.

Mottled zone: A horizon of the lateritic profile consisting of a pale coloured clay with prominent red and orange mottles.

Mounding: The construction of a low pile of earthy material that is raised above a waterlogged area, usually to provide a growing medium for plants.

Neutral (soil): Describes the situation where a soil is neither acidic nor alkaline (pH value 6.5-7.5).

Nitrate: A form of nitrogen(NO3) capable of being dissolved and held in solution. Because it is soluble, nitrate is highly mobile and available for uptake by plants. Its mobility also means that it can be leached down the profile easily.

Nitrogen: A nutrient essential for plant growth. It can also play a major role in eutrophication.

Nitrogen level: See nutrient level.

Nitrogen load: See nutrient load.

Non-wetting (soil): Describes a soil material that is water repellent. Non-wetting soils typically have a sandy topsoil with organic compounds that form a wax like coating on the sand grains. Early in the season, infiltration into non-wetting soils will be very patchy, with many areas of topsoil remaining dry. As the season progresses the non-wetting character of the topsoil is usually overcome slowly.

Nutrient: A mineral substance absorbed by the roots of a plant to provide that plant with nourishment.

Nutrient cycle: The movement of nutrients from the air or soil, to soil-water, into plants and eventually returning to the soil. The cycle typically involves nutrients transforming from one form to another and back again.

Nutrient deficiencies: The lack of an adequate amount of a plant nutrient. This may result in a number of symptoms, including poor plant growth, yellowing or death.
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**Nutrient input:** Describes the process whereby nutrients are added to a soil, water body or ecosystem.

**Nutrient level:** A measure of the total amount of nutrients present in soils, plants or water at any given time. Typically expressed in terms of mass of nutrients present per given volume such as parts per million (ppm) or milligrams per litre (mg/L).

**Nutrient load:** A measure of the amount of nutrient transported by a river or stream. Typically expressed in terms of mass of nutrients over a given time period (e.g. tonnes per year).

**Nutrient loss:** The removal of nutrients (e.g. from applied fertilisers) from an ecological or agricultural system. Nutrient loss from agricultural systems occurs via the hydrological cycle (transported by water in solution or attached to sediments) or by removal of farm produce (e.g. sending milk, meat or grain to markets).

**Nutrient retention ability:** The ability of the soil to adsorb and retain added nutrients. The nutrients may be held in a form that is inaccessible to plants.

**Organic matter:** Material that includes the residual products of living organisms (remnants or plant and animal tissue, often decomposed). Organic matter can be an important component of topsoil, improving fertility, soil structure and water retention.

**Orogen:** A zone of weakness in the Earth’s crust along which movement and deformation has taken place during a period of tectonic plate movement. The rocks of an orogen may include deformed and reworked parts of older cratons as well as new volcanic and sedimentary rocks.

**Outcrop (geology):** Part of a geological formation or structure that appears as rocks on the ground surface.

**Palaeochannel:** The floor of an ancient drainage system containing old sedimentary deposits. Palaeochannels are often partly obscured or eroded by contemporary drainage systems and may cross existing drainage divides.

**Pallid zone:** Pale coloured white to pink kaolinitic clay (a stable with aluminosilicate minerals) clayforming a lower horizon of the *lateritic profile*. The horizon is pale in colour because the iron has been removed.

**Peak flow:** Describes the greatest volume of water that flows past a given point at any time. Can apply to flows in a river, stream or drain as well as to flood events and runoff.

**Perched aquifer:** A sub-surface material containing perched groundwater.

**Perched groundwater:** Groundwater in an unconfined aquifer (in a saturated condition) near the land surface and separated from deeper groundwater by unsaturated materials. Perched groundwater is typically shallow, thin and ephemeral (i.e. temporary or seasonal) and sits on top of materials of low permeability, such as clay and hardpans, which restrict the downwards flow of water.

**Perched water table:** The upper surface of perched groundwater.

**Percolation:** The downward movement of water through soil and regolith.

**Perennial (plant):** A plant whose life cycle continues for more than one season. Includes trees and shrubs and many species of grasses.

**Perennial pasture:** A pasture composed primarily of perennial plants.

**Perennial stream:** A stream or part of a stream that flows continuously throughout the year, the surface of which is generally lower than the adjacent water table.

**Permeability:** The capacity of a material to transmit a fluid such as water. Permeability is a characteristic of the soil or rock only, and is not a measure of the rate at which water passes through the material (i.e. it is different from hydraulic conductivity). A material that is highly permeable will have
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few restrictions to the passage of water. A material with low permeability will provide major restrictions to the movement of water.

**Permeable**: The degree to which a solid material will allow fluids to pass.

A highly permeable material has a saturated hydraulic conductivity in excess of 2.5 m/day.
A moderately permeable material has a saturated hydraulic conductivity of about 0.5-2.5 m/day.
A material of low permeability has a saturated hydraulic conductivity of less than 0.02 m/day.

**pH**: A measure of how acidic or alkaline a solution or soil is. The pH scale, ranges from 0 to 14, with 0-6 being **acidic**, 7 **neutral** and 8-14 **alkaline**. In technical terms pH is the negative logarithm of the hydrogen ion concentration of a solution.

**Phosphate**: A form of phosphorus (PO₄³⁻) capable of being dissolved and held in solution. Because it is soluble, phosphate is highly mobile and available for uptake by plants. Its mobility also means that it can be leached down the profile easily.

**Phosphorus**: A nutrient essential for plant growth. It can also play a major role in eutrophication.

**Phosphorus retention index**: A measure of the ability of a soil to adsorb and hold phosphorus, commonly abbreviated to PRI.

**Piezometer**: Tubing (typically a PVC pipe) sunk into the ground to pass into a confined aquifer, usually to depths of 2-10 m. The lower 1-2 m of pipe is slotted to allow water to enter the pipe. The level of this water reflects the piezometric head of the aquifer at that depth. Piezometers are installed to monitor the level of water tables as well as salinity levels.

**Piezometric head**: The level to which the water rises in bores drilled into an aquifer. If recharge occurs high in the landscape, the piezometric head low in the landscape is likely to be above the top of the aquifer. It will also often be above the water table of overlying aquifers, or even the ground surface.

**Plain**: A general term referring to any flat area of land.

**Plateau**: A comparatively flat, upland area bounded by slopes to lower ground. The plural form of plateau is plateaux.

**Pliocene**: The last epoch of the Tertiary Period of geological time occurring approximately 2-5 million years ago.

**Point source**: Describes the discrete area or particular point from which nutrients that contribute to eutrophication are discharged. Examples of point sources include effluent disposal sites, dairies, piggeries and factories.

**Ponding**: A form of inundation whereby water collects on the soil surface in puddles.

**Pore**: A space in a soil material not filled by solid particles. Pores are holes filled with air or water.

**Precipitation**: Water falling to earth due to the force of gravity. Includes rain, hail, sleet or snow.

**Preferred pathway**: A channel or pore in a soil layer, which otherwise has low permeability, through which water flows preferentially. Old tree root channels are preferred pathways in many clayey subsoils in the South-west Hydrological Region.

**PRI**: See phosphorus retention index.

**Primary salinity**: Describes the situation where soils are inherently saline as a result of natural processes. As a general rule, areas affected by primary salinity do not get developed for agriculture.

**Profile**: See soil profile.

**Quartz**: Mineral composed of silicon dioxide (SiO₂).
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Quartz vein: A tabular of sheet-like body of quartz that has been intruded into a join or fissure in the surrounding rocks. On the surface, quartz veins appear as discontinuous lines of white rock (quartz) outcrops.

Quaternary: The period of geological time extending from the end of the Tertiary Period (about 2 million years ago) to the present.

Rainfall intensity: The amount of rain falling in a given time interval. Rainfall intensity is usually expressed in millimetres per hour (mm/hour).

Recharge: The water that moves into a groundwater body and therefore replenishes or increases subsurface storage. Recharge typically enters aquifers by rainfall infiltrating the soil surface and then percolating through the zone of aeration (unsaturated soil). Recharge can also come via irrigation, the leakage of surface water storage or leakage from other aquifers. The term recharge is also used to describe the process of water entering a groundwater body.

Recharge area: An area of land from which a significant amount of recharge occurs.

Recharge rate: The speed at which water moves into a groundwater body. Expressed in units of depth per time (e.g. mm/year).

Regional aquifer: A material containing groundwater that is part of a regional flow system.

Regional discharge: Discharge emanating from a regional flow system.

Regional flooding: A form of flooding that affects large areas rather than just a small localised area. Usually initiated when major rivers break their streambanks.

Regional flow system: Groundwater flows that transport permanent groundwater long distances, up to 50 km or more, typically through confined or semi-confined aquifers in sedimentary deposits that can be several hundred metres thick.

Regional water table: The upper surface of groundwater in a regional aquifer.

Regolith: All the unconsolidated earth materials occurring above solid bedrock. Regolith includes soil, unconsolidated sediments and weathered bedrock. Soil scientists regard as “soil” as being only that part of the regolith that is modified by organisms and soil-forming processes. Most engineers describe the whole regolith, even to a great depth, as “soil.”

Revegetation: The process of returning perennial plants to land that was cleared. Land can be revegetated with native or introduced species.

Roaded catchment: An artificial catchment area for a dam or earthen tank constructed by compacting the soil in a similar manner to that used to form the surface of an earth road. Roaded catchment consist of many parallel ridges with smooth and impervious surfaces that minimise infiltration and maximise runoff. Roaded catchments are commonly used in areas receiving less than 420 mm rainfall.

Root zone: The portion of the soil profile where the majority of plant roots are found, typically within the top 30-50 cm.

Rooting depth: The depth to which plant roots can penetrate the soil without being restricted by a physical or chemical barrier.

Runoff: Water flowing downslope over the ground surface, also known as overland flow. Precipitation that does not infiltrate into the soil and is no stored in depressions becomes runoff.

Saline (soil): A soil containing sufficient soluble salts to reduce productivity.

Saline (water): A term used to describe that has high salinity levels (in excess of 5,000 mg/L) – these levels limit its suitability for many uses.

Saline seep: An area where saline groundwater is discharged.
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**Salinisation:** The process of accumulation of soluble salts in soil.

**Salinity:** An accumulation of soluble salts in the soil root zone, at levels where plant growth or land use if affected adversely. Also used to indicate the amounts of various types of salt present in soil or water.

**Salinity level:** The measured amount of salt contained in soil or water.

**Salt store:** Refers to the total amount of salt present within the regolith (both saturated an unsaturated) under a certain area of land. Usually expressed in terms of tonnes per hectare.

**Salt tolerant:** A term used to describe plants and animals that are capable of living in saline soil or water.

**Sand:** (a) Coarse soil particles that range in diameter from 0.05-2.0 mm; (b) Soil texture class dominated by sand sized particles (>75%) and containing few clay sized particles (<15%); (c) Soil profile with a sandy texture in the top 3 cm.

**Sandplain:** Extensive level to gently undulating landform with sandy soils, little topographic relief and few stream channels.

**Sandplain seep:** Seepage that occurs where groundwater is discharged from the base of sandy or gravelly deposits that are upslope.

**Sandstone:** Sedimentary rock containing predominantly sand-sized grains cemented together.

**Saprock:** Partially weathered bedrock that remains in situ and typically consists of a gritty material retaining the fabric (structure and orientation) of the underlying rock. Saprock is often called saprolite, which literally means “rotten rock”.

**Saturated:** The condition whereby effectively all of the pores and voids in a soil or aquifer are filled with water which has a pressure equal to, or greater than, atmospheric pressure.

**Saturated hydraulic conductivity:** See hydraulic conductivity.

**Saturation excess runoff:** Occurs when water that falls on (or is being applied to) the ground surface becomes runoff (overland water flow) because the soil is already saturated and cannot accept any more water.

**Scarp:** An escarpment, cliff or steep slope falling away from the margin of a plateau or other raised landform.

**Secondary salinity:** Describes the situation where salinity levels have increased as a result of human activities changing the water balance. Secondary salinity often occurs as a result of agricultural development and can be responsible for preventing large areas of agricultural land from being productive.

**Sediment:** An accumulation of soil and rock particles, chemical precipitates, and organic remains deposited by water or wind.

**Sedimentary deposits:** Materials that have been moved from their site of origin by the action of wind, water, gravity or ice and then deposited. When these materials become consolidated and hard they are known as sedimentary rocks.

**Sedimentary rock:** A rock consisting of consolidated sediments, including sandstone, siltstone, shale, conglomerate, limestone, dolomite and evaporites.

**Sedimentation:** The deposition of sediment, usually by water. Sedimentation is the result of water erosion and involves soil particles being washed downslope or downstream before being deposited.

**Seep:** See seepage.

**Seepage:** Occurs where the water table intersects the ground surface and water flows out. This is active discharge and is driven by the hydraulic gradient.
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Seepage interceptor drains: Sub-surface drains constructed in duplex soils on hillslopes to drain waterlogged areas as well as to intercept water moving towards waterlogged areas. A channel is dug through the topsoil into the clayey subsoil and collects water seeping through the highly permeable topsoil. In conventional seepage interceptor drains the spoil (earth removed from the channel) is mounded on the downslope side of the channel where both runoff and seepage are collected. In reverse seepage interceptor drains the spoil is placed upslope an acts as a grade bank intercepting runoff, while seepage enters the channel.

Semi-confined aquifer: An aquifer (geological formation containing water) overlain by a layer that partly restricts the upward movement of water.

Shear zone: A tabular geological zone (i.e. zone having two dimensions much greater than the third like an upturned table top) where rocks have been deformed due to shear stress (i.e. stress causing fracturing and compression along parallel planes).

Sheet erosion: The removal of a fairly uniform layer of soil by raindrop splash and/or runoff. No perceptible channels are formed and soil particles are either transported to rills, gullies and streams or moved downslope to temporary stores. Soil stored on the slope is liable to be displaced by subsequent erosion. Sheet erosion is often found in combination with rill erosion.

Silt: Medium sized soil particles that range in diameter from 0.002-0.05 mm.

Siltstone: A sedimentary rock composed of mostly silt sized particles.

Soak: A water supply structure constructed by excavation in an area receiving seepage or where the water table is close to the surface. Soaks are most common on the Coastal Plains and on poorly drained flats and valley floors in the Forested Hills. In some soaks the spoil is used to construct a dam wall to capture runoff in addition to the seepage.

Sodic (soil): A soil in which the subsoil has a high exchangeable sodium percentage (ESP >6 in sodic soils, >15 in highly sodic soils). Sodic soils can be structurally unstable and plant growth may be adversely affected. Clays in sodic soils disperse when exposed to water and are highly erodible. Low permeability is often a feature of sodic soils.

Soil: A natural medium for the growth of land plants. Soil consists of a mixture of unconsolidated mineral and organic material developed by physical, chemical and biological processes.

Soil amendment: See amendment.

Soil compaction: The process of increasing soil density caused by the soil particles becoming more closely packed resulting in air being removed. Soil compaction is often caused by the pressure exerted by the weight of machinery or livestock trampling. Topsoil compaction leads to reduced infiltration while subsoil compaction slows water percolation through the profile.

Soil profile: A vertical cross-section of soil, and/or regolith, extending downwards from the Earth's surface. The profile consists of all the soil horizons and regolith layers sitting on top of each other.

Soil structure: The size, shape, type and degree of development of natural aggregates (called peds or clods) found in soil. Well structured soils peds are well developed and this provides good soil/water/air relationships for the growth of plants. In well structured soils, there are few physical barriers to the movement of water or the growth of roots. Well structured soils are usually more stable and less prone to erosion than poorly structure soils.

Soil water: Commonly applied to sub-surface water occurring in the soil and regolith in an unsaturated condition (i.e. above the water table). This water is also sometimes referred to as soil water storage, soil moisture or sub-surface water.

Spoon drain: A form of surface drain that is 3-4 metres wide, approximately 30 cm deep and can be constructed with a grader. The spoil is spread on either side of the channel. Spoon drains are suitable for removing excess water from land that is cropped.
Storage capacity: The total amount of water that a soil, aquifer, dam or other form of water storage can hold.

Stream flow: The transportation of water across the ground surface concentrated into streams, creeks, rivers and drains.

Stream salinity: Refers to the situation where there is a concentration of dissolved salts in a watercourse (e.g. stream or river). Although most current examples of stream salinity are directly associated with secondary salinity in the catchment area, there were streams that were saline before clearing began.

Structure (soil): See soil structure.

Subsoil: The lower part of the soil profile. The lower layer/s are usually higher in clay and lower in organic matter than the upper layers (or topsoil). The subsoil is usually referred to as the B horizon/s and most typically begins at depths of 30-60 cm.

Sub-surface flow: The movement of water in saturated conditions below the ground surface. This term is typically used to describe temporary, lateral groundwater flows in the topsoil or subsoil and often involves perched groundwater.

Sub-surface storage: Water stored below the ground surface, either as groundwater in aquifers, in the capillary fringe or as unsaturated soil water.

Sub-surface water: All water occurring below the ground surface.

Surface drainage: Systems that are designed to intercept and remove excess surface water. Surface drainage works include spoon drains and W-drains.

Surface flow: A term used to describe the movement of water across the ground surface as runoff or stream flow.

Surface storage: A term used to describe the water that remains on the ground surface either as surface moisture or accumulated in depressions such as puddles, swamps or lakes.

Surficial: On or near the surface.

Surficial aquifer: An unconfined aquifer in a surface deposit. Water in a surficial aquifer is referred to as surficial groundwater and the water table is situated close to (or is sometimes on or above) the ground surface. Surficial aquifers typically contain perched groundwater.

Surficial deposit: Materials lying more or less loosely on the land surface, formed independently of the soil or rocks below and usually transported and deposited there by natural agencies such as wind or water. Often the exposed, upper layer of an unburied sedimentary deposit.

Suspension: Describes the situation where soil (or other solid) particles are held in water without being dissolved. Soil held in suspension can be transported long distances by water. Muddy water typically contains a large amount of soil in suspension.

Temporary perched groundwater: Perched groundwater that is seasonal or ephemeral. A typical example is the perched groundwater found during winter in the sandy topsoil of many duplex soils. Perched groundwater may only be present for a few hours or days following rain.

Tertiary: The period of geological time approximately 2-66 million years ago.

Texture (soil): A description of soil material based on field assessment that describes the relative abundance of sand, silt and clay particles. Soils with a light texture have a high proportion of coarse (sand) particles. Soils with a heavy texture have a high proportion of fine (clay) particles.

Throughflow: The lateral movement of sub-surface water in the soil. Throughflow usually involves the downslope movement of perched groundwater; the water flows through a moderately to highly permeable
soil material above an impeding layer and usually follows the slope of the ground surface. Throughflow can also occur in unsaturated conditions.

**Topography:** The relative positions and elevations of the natural or man-made features of an area that describe the shape of its surface.

**Topsoil:** The upper part of the soil profile. These surface layer/s are usually higher in organic matter (at lease at the surface) and lower in clay than the lower layers (or **subsoil**). The topsoil is usually referred to as the A horizon/s and is most typically 15-60 cm deep.

**Transmissivity:** The rate at which water is transmitted through a one metre wide slide across the entire depth of an aquifer. Transmissivity is recorded in units of square metres per day (m$^2$/day). It provides a better comparison of the possible yield of an aquifer than saturated hydraulic conductivity because it takes into account the thickness of the aquifer.

**Transpiration:** The process by which water is absorbed from the soil by plant roots, is transported through the plant and is removed from the leaf surfaces by evaporation.

**Tributary:** A stream or river that flows into a larger stream or river.

**Truncated (laterite):** A lateritic profile from which the upper layers have been removed by erosion. Soils found on truncated lateritic profiles have often formed from mottled or pallid zone materials.

**Unconfined aquifer:** An aquifer (geological formation containing water) over which there is no aquitard (layer that restricts the upward movement of water). This means there is no barrier to movement of water between the ground surface and the aquifer. The water table may rise or fall freely as water enters and leaves the aquifer.

**Unconsolidated:** Describes sediments and deposits that are loose and not hardened.

**Undulating (landscape):** Describes landscapes with slopes of about 3-10%.

**Unsaturated:** The condition whereby the pores and voids of a soil or aquifer are filled with a mixture of water and air. The pressure of the water is less than atmospheric pressure.

**Unsaturated flow:** The movement of water in the soil at water contents less than saturation.

**Upland:** A general term for the higher part of the landscape.

**Valley:** An elongated, relatively large, externally drained depression of the Earth’s surface that is primarily developed by stream erosion.

**Valley floor:** A general term for the nearly level, lower part of a valley.

**Vegetative cover:** Plants that cover the ground surface. Includes grasses, herbs, trees, shrubs and crops. Vegetative cover usually protects the soil from erosion and increases evapotranspiration rates.

**Velocity:** The speed of movement of water flowing past a point in a specific direction. A high velocity flow involves fast moving water.

**Water balance:** The relationship between input, storage and output within a hydrological system. If the amount of water entering the system is the same as the amount leaving, then storage remains constant and the system can be considered to be in equilibrium. Where input exceeds output, the water balance becomes altered and the amount of water stored in the system increases. Conversely, the balance can be altered as storage decreases in response to output exceeding input.

**Water erosion:** The detachment and transport of soil particles by water leading to the wearing away of the land surface.

**Water storage:** A broad term referring to any situation where water is temporarily or permanently held, including in aquifers, soil water, lakes, farm dams and reservoirs.
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**Water table:** The upper surface of a body of groundwater occurring in an unconfined aquifer. At the water table, pore water pressure equals the atmospheric pressure.

**Water use (plant):** Describes the uptake of water from the soil by a plant. Most of this water is then transpired into the atmosphere.

**Waterlogging:** The condition whereby soil becomes saturated with excess water to the extent that most or all of the soil air is replaced.

**Waterway:** Usually describes a natural or constructed drainage line used for water disposal. Waterways run up and down a slope (not on a surveyed gradient). Artificial waterways are installed to safely transport excess water from grade banks, grade furrows and interceptor drains. They should be designed so that they can handle peaks flows, the channel should have a broad, flat or slightly dished floor. The term waterway is also applied broadly to all the surface water bodies (including creeks, rivers, lakes and estuaries) that are connected by stream flow.

**Weathered:** Describes the state of a material (e.g. rock, bedrock, sediment or colluvium) once it has been subjected to physical disintegration, chemical decomposition or biologically induced changes at or near the Earth’s surface. The process of weathering involves essentially no transport of the altered material.

**Weathered profile:** See deeply weathered profile.

**Weathering:** The process leading to the formation of a weathered material.

**Weathering in situ:** Describing the genesis of regolith that has formed directly as a result of weathering of the underlying bedrock without any major movement of the materials.

**Wheatbelt:** The hydrological zone that encompasses the upper Blackwood Catchment east of Katanning and Wagin. Towns include Harrismith, Kukerin, Dumbleyung and Nyabing. The Wheatbelt is characterised by low rainfall, subdued landscape and a relatively deep weathering profile.

**Wind erosion:** A process in which the soil is detached and transported from the land surface by the action of the wind.

**Zone of aeration:** An area below the ground surface which is above the zone of saturation. This zone is characterised by unsaturated conditions, but saturation may occur temporarily in some areas (e.g. saturation following heavy rainfall as water moves down towards the water table). The zone of aeration is also known as the vadose zone of the unsaturated zone.

**Zone of saturation:** An area below the ground surface which is permanently saturated. This zone is usually relatively deep below the surface and is thick, containing large volumes of water. The zone of saturation lies below the water table in unconfined aquifers, and below the aquitard in confined aquifers.
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Limitations

URS Australia Pty Ltd (URS) has prepared this report in accordance with the usual care and thoroughness of the consulting profession for the use of Department of Environment and Conservation and only those third parties who have been authorised in writing by URS to rely on the report. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report. It is prepared in accordance with the scope of work and for the purpose outlined in the proposal dated 3 May 2006.

The methodology adopted and sources of information used by URS are outlined in this report. URS has made no independent verification of this information beyond the agreed scope of works and URS assumes no responsibility for any inaccuracies or omissions. No indications were found during our investigations that information contained in this report as provided to URS was false.

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