An examination of ecosystem dependence on shallow groundwater systems in the Western rivers region, Lake Eyre Basin, South Australia

Volume 1: Report

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Department of Environment, Water and Natural Resources

An examination of ecosystem dependence on shallow groundwater systems in the Western Rivers region, Lake Eyre Basin, South Australia

Volume 1: Report

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Summary

The project *Ecosystems Dependent on Shallow Groundwater Systems in the Western Rivers region, Lake Eyre Basin, South Australia* investigates a key knowledge gap concerning the natural environment of the Wintinna and Arckaringa Creeks region of the Western Rivers portion of the Lake Eyre Basin (LEB). This data gap is the distribution and characteristics of shallow groundwater in riparian landscapes and the degree to which ecosystems are dependent on that shallow groundwater. A further primary aim of this project was to undertake initial investigations into the degree of inter-connectedness of the shallow watertable and deeper groundwater, particularly groundwater within the Great Artesian Basin (GAB).

Ultimately, the outcomes of this study will enable the Department of Environment, Water and Natural Resources (DEWNR) and other state and Commonwealth agencies to better assess the impacts that might occur of any proposed major developments in the region that affect either surface water or groundwater resources. The knowledge will also inform both surface and groundwater resource management and planning in the region.

This study employed a multifaceted approach to addressing this data gap with field and desktop investigations including:

- Water chemistry sampling from groundwater and surface water
- Tree sapflow monitoring
- Tree and soil water potential
- Tree and water isotope sampling
- Remotely sensed imagery analysis.

In all cases, no riparian ecosystem investigated appeared to be singularly reliant on shallow groundwater, with most either providing evidence for a mixed source, or predominant reliance on soil water. Although this last interpretation is based on a lack of evidence for other sources rather than direct evidence from soil water analysis.

In all cases, xylem water from *E. camaldulensis*, *E. coolabah,* and *Acacia spp.* stems displayed some apparent stable isotope ($\delta^{18}O$ & $\delta^{2}H$) enrichment compared to nearby groundwater samples, suggesting that in no instance is groundwater the only water source for vegetation in these areas. *E. camaldulensis* near Wintinna Creek and *E. coolabah* near Algebullcullia Bore near Lora Creek appear to have the most comparable stable isotope results to groundwater. In contrast, acacias in general and E. *camaldulensis* and *E. coolabah* in the vicinity of Stewart Waterhole display the most enrichment, indicating that these trees are the least likely to be dependent on groundwater. Although it was not possible to adequately analyse the stable isotope values from soil water during this study, given that the vast majority of stable isotope results from xylem water occur somewhere between groundwater and surface water, it is highly likely that soil water is a predominant source of water for vegetation.

Despite the low pre-dawn leaf water potential (LWP) recorded, the trees measured were mostly in healthy and moderately healthy condition. For example, *E. camaldulensis* (variety *obtusa*) midday LWPs were recorded from -2.7 MPa to as low as -4.2 MPa, and the maximum and minimum pre-dawn LWP recorded for a *E. camaldulensis* was -3.93 MPa. Similarly, at Stewart Waterhole, where pre-dawn LWPs were highest, the midday LWPs were still considered low at between -2.45 and -3.17 MPa. A possible conclusion is that *E. camaldulensis* var. *obtusa* is able to extract water at lower soil water potentials than *E. camaldulensis* var. *camaldulensis* (more common in southeastern Australia), although further research would be required to confirm this. The very low pre-dawn LWPs recorded in trees at most sites supports the conclusions of the stable isotope analysis—that the riparian and floodplain vegetation is not relying on groundwater as a primary water source.

Riparian eucalypts (*E. coolabah, E. camaldulensis*) investigated as part of this study display low base level sapflow (transpiration) fluxes compared to other arid zone riparian eucalypts. They are also able to maintain a healthy condition despite very low soil water availability. This is in keeping with their location in the most arid and variable climate within Australia, with generally higher salinity of groundwater in the catchment.

Both *E. coolabah* and *E. camaldulensis* appear to act as facultative phreatophytes, in that they can take advantage of any shallow groundwater present, but can persist in its absence. There was either no definitive evidence for groundwater dependence stemming from LWP, sapflow and stable isotope data, or only circumstantial evidence, such as the location of tree

stands below bank tops. Further, *E. coolabah* appear to have root systems with the capacity to switch between shallow soil moisture stores (e.g. rainfall and streamflow infiltration) and deeper groundwater stores. There is also some evidence that the trees are capable of hydraulic redistribution – that is moving soil moisture from one part of the root system to another via the tree, thus optimising the distribution and use of soil moisture. In particular, *E. coolabah* show highly flexible patterns in utilising available water from shallow sources. These patterns, and the low baseline transpiration rates of the trees, emphasise the resistant nature of this riparian species to long drought periods, and uncertain access to suitable quality groundwater.

There are notable differences in hydrochemistry between groundwater from the shallow aquifers associated with riparian landforms, the Hamilton Sub-basin and the GAB. Redox and pH conditions inherent between the aquifers control differences in hydrochemistry, particularly with respect to trace elements, whereas differing aquifer mineralogy, or differing ages and associated hydrochemical evolution cause other differences. These data suggest that the various aquifers, from which groundwater was sampled during this investigation, are unlikely to be interconnected in such a way as to result in notable large-scale groundwater mixing or migration over relatively short timescales. Connection between aquifers allowing very slow groundwater migration and hydrochemical evolution may be possible.

This report also presents a remote sensing-based groundwater dependent ecosystems (GDE) index that could assist to upscale the results of field-survey methods to the entire study region. The GDE Index identifies and maps, on a pixel basis, areas that remain green into prolonged dry periods and therefore are most likely to be associated with groundwater availability. The index calculates how often the Normalised Difference Vegetation Index (NDVI) (derived from MODIS imagery from 2000 to present, at 16 day intervals) exceeds a threshold (indicative of actively growing vegetation); then periods likely to be influenced by significant rainfall events are excluded.

Examination of the daily rainfall data and temporal NDVI traces shows that during dry periods, the mean NDVI for the study area as a whole is generally about 0.15. There is an obvious increase in NDVI post 'significant' rainfall, which peaks at 0.2 to 0.25 generally, then tapers off over the following 6 months if there are no other significant rainfall events. Based on a comparison of sampling sites to the GDE index parameters, Wintinna Homestead has the highest potential of being a GDE, followed by an E. coolabah location on the bank at Francis Camp. The Ethel Well site recorded a GDE Index value of 67.6; while the majority of the locations at the EJ Bore, Cootanoorina Waterhole, and Francis Camp Waterhole sites ranged from 30 to 50. None of the locations at Stewart Waterhole was above 6.3, along with three locations at Cootanoorina Waterhole and one at Francis Camp.

A key data gap in this study is a regional scale assessment of potential ecosystem vulnerability to changed surface water and groundwater conditions. Classifying the landscape to better target future field studies and assist upscaling and transferability of results may achieve this. Such a classification scheme may employ the South Australian Lake Eyre Basin (SA LEB) aquatic ecosystems and GDE Index (Gotch et al. 2015) and incorporate other datasets such as surface geology, soil type, vegetation coverage, hydrology, and phreatic groundwater conditions. Additionally, a potentially important source of water for riparian ecosystems was unable to be sampled, being soil water. Consequently, conclusions concerning the reliance of riparian ecosystems on soil water are highly dependent on a lack of evidence for other water sources, rather than direct evidence from soil water. Therefore it is recommended that proponents of future water resource development proposal in the region undertake a more thorough investigation of sources of water used by trees in order that risks to riparian and floodplain vegetation can be confidently determined.

1 Introduction

1.1 Background

The Western Rivers of the Lake Eyre Basin (LEB) are located in the highly arid far north region of South Australia (McMahon et al., 2008). However, despite its aridity, heavily-water dependent ecosystems are a notable feature in the region. These include permanent springs fed by the Great Artesian Basin (GAB), permanent and semi-permanent riverine waterholes and extensive riparian and floodplain woodlands.

The project *Ecosystems Dependent on Shallow Groundwater Systems in the Western Rivers region, Lake Eyre Basin, South Australia* investigates a key knowledge gap in the region: the distribution and characteristics of shallow groundwater in riparian landscapes, and the degree to which ecosystems are dependent on that shallow groundwater. It follows on from DEWNR's *Coal Seam Gas and Coal Mining Water Knowledge Program*, which undertook preliminary desktop investigations that touched on this topic, most notably:

- *South Australian Lake Eyre Basin aquatic ecosystem mapping and classification* (Miles and Miles 2015) – developed a hierarchical classification of aquatic ecosystems consistent with the interim Australian national aquatic ecosystems classification framework (AETG 2012) and applied to GIS mapping of aquatic ecosystems (including attributes of groundwater dependency – water source, salinity, water regime) using existing spatial datasets.
- *Lake Eyre Basin (South Australia): mapping and conceptual models of shallow groundwater dependent ecosystems* (Miles and Costelloe 2015) – built on the work of Miles and Miles (2015) to refine the mapping of groundwater dependency based on recent investigations and develop preliminary conceptual models of ecosystems dependent on shallow groundwater.
- *Mapping groundwater dependent wetland and riparian vegetation with remote sensing* (White et al. 2014) – a feasibility study to determine the capability of remotely sensed techniques developed using satellite and airborne imagery for detecting vegetation permanency, extent and health associated with groundwater dependent ecosystems (GDEs) of the Arckaringa and Peake ephemeral creek systems.

This project progresses these preceding studies with on-ground research and a multiple lines of evidence approach to address knowledge gaps using:

- Analysis of groundwater and surface water chemistry
- Tree and water isotope analysis
- Tree sapflow monitoring
- Tree and soil water potential
- Remotely sensed imagery analysis.

A key factor limiting the understanding about shallow groundwater is a lack of shallow wells. The original intention was to install a number of shallow wells during this investigation; however, time constraints made this unachievable, and therefore the project relied on sampling the few existing shallow wells in the region.

The lack of shallow groundwater wells in the wider Far North region of South Australia stems largely from the fact that, with a few exceptions, economic abstraction of shallow groundwater is limited due to the presence of the more reliable and better quality GAB groundwater. However, connectivity with deeper (GAB) groundwater and surface water, or lateral and longitudinal connectivity, could lead to adverse, localised impacts on shallow groundwater resources if a major development were to occur in the region. This project provides baseline information on how lowering of the watertable (i.e. from pumping), or changes in streamflow patterns (i.e. from flow regulation or climate change), may affect a foundational part of the ecosystem – the riparian tree assemblage.

1.2 Aims and objectives

The primary aim of this project was to understand how important the shallow watertable is to the ecosystems of the floodplains and channels of the LEB Western Rivers catchments. Specifically, the project objectives were to:

- Clearly define and identify the ecosystems that are dependent on shallow groundwater (EDSG) (as distinct from those dependent on GAB groundwater or surface water only) and the ecological receptors of the ecosystems in question;
- Understand the significance of shallow groundwater to these ecosystems and their ecological receptors (e.g. degree of reliance on shallow groundwater systems vs other water sources)
- Improve knowledge about the basic hydrogeology of shallow groundwater (SG) systems in the Western Rivers region including commencing investigations into how connected the shallow watertable is to deeper groundwater, most notably that within the Great Artesian Basin (GAB).
- Gauge the likely susceptibility of these shallow groundwater systems to changes in hydrology and the likely response of ecological receptors
- Identify the information requirements that development proponents should address to identify and manage risks to EDSG.

Ultimately, the outcomes will inform both water resource management and planning in the region and enable DEWNR and other state and Australian Government agencies to assess any impacts to ecosystems dependent on shallow groundwater systems (EDSGS) for proposed developments affecting either the surface or groundwater resources.

1.3 Determining groundwater-dependence of ecosystems

For composing effective management strategies for GDEs, Eamus et al. (2006a) proposed four key questions to help guide development:

1. Which species or species assemblages, or habitats are reliant on a supply of groundwater for their persistence in the landscape?
2. What groundwater regime is required to ensure the persistence of a GDE?
3. What are the safe limits to change in a groundwater regime?
4. What measures of ecosystem function can be monitored to ensure that management is effective?

This project focused on addressing the first question and goes some way towards answering the remaining questions. Although Eamus et al. (2006a) strongly advocates the use of stable isotopes of water ($\delta^{18}O$ & $\delta^{2}H$) as a highly reliable method for determining groundwater dependency, this method is dependent on being able to sample soil and groundwater at locations where trees are sampled. As wells could not be drilled specifically for this project, other field methods (sapflow monitoring and leaf water potentials) were used to supplement isotope sampling. Additionally, remote sensing imagery analysis was used for the purposes of developing a GDE Index which could assist to upscale the results of the field survey methods to the entire study region.

1.4 Reporting structure

Given the size and multi-faceted nature of this investigation, the reporting will be presented in two parts. Relevant background information, the discussion of findings, the hydroecological conceptual models and conclusions and recommendations stemming from these investigations are provided in this report (Vol. 1). Detailed descriptions of methodology and results from the various field investigations, relevant literature review material and publically available data used to develop hypotheses are presented in the companion report entitled: "*An Examination of Ecosystem Dependence on Shallow Groundwater Systems in the Western Rivers region, Lake Eyre Basin, South Australia Volume 2: Supplementary report*".

2 Background information

2.1 Location and physiology

The project area is located in northern South Australia, approximately 750 km north-west of Adelaide. There are two overlapping study areas covered by this investigation. The first study area is the focus of field-based sampling works covers approximately 38 000 km^2 and extends from 20 km north of the Alberga River at the northern end to the Algebullcullia Creek at the southern end. The second study area which is the focus of the remote sensing Groundwater Dependent Ecosystem (GDE) index work, is approximately 105 000 km^2 and coincides with the Macumba River, Neales River and Warriner/Margaret Creek catchment areas. These two study areas are presented in Figure 2-1.

The climate of the region is generally arid, with weather patterns dominated by persistent high pressure systems. Rainfall predominantly comes from weak winter cold fronts originating from the Southern Indian Ocean or sporadic summer monsoon rainfall that originate in north-west Australia. Rainfall for the region averages 175 mm/y based on rainfall data obtained from Oodnadatta (BoM, 2016b), although this can vary significantly from year to year.

Given the arid climate, aeolian-driven erosion as described by Mabbutt (1977) is an important process in shaping the physiology of the region. Although the landscape is predominantly flat, desert-dominated, consisting of sand dunes and gibber plains, there are important landscape variations within the study area

The area is predominantly situated in the Stony Plains bioregion, which consists of tablelands and low gibber plains with crusty red duplex soils within some of the most arid areas in Australia. It also contains small areas of the Simpson–Strzelecki Dunefields bioregion (a gently sloping alluvial plain with extensive dunefields on calcareous earths) in the south and east and the Finke bioregion (an area of arid sand plains with dissected uplands and valley on sands or massive and structured earths) in the north-west.

The largest towns within the study area are Oodnadatta, with a population of approximately 300 and Marla, with a population of 72 (Figure 2-2). The area of investigation covers the traditional lands of the Arabana, Antakirinja Matu-Yankunytjtajara and Yankunytjtajara Antakirinja people.

The pastoral industry represents the predominant land use across the region, while mining and tourism are increasingly becoming important industries (Figure 2-2). The majority of water supplies for domestic, pastoral, commercial and industrial purposes in the region are derived from groundwater as surface water resources are small and unreliable. Most groundwater is sourced from the GAB, with some supplies derived from the underlying Arckaringa Basin in areas to the south-east of the study area (Figure 2-1).

2.2 Hydrology

A recent detailed summary about the hydrology of the area of investigation was provided in the report entitled "*Context statement for the Arckaringa subregion*" (Miles et al, 2015). The following is a brief synopsis of information provided in this report.

The field sampling area of investigation is almost entirely within the Neales River catchment, with the remainder located within the Macumba catchment to the north (Figure 2-1). As previously stated in Section 2-1, the remote sensing GDE Index study area coincides with the Macumba River, Neales River and Warriner/ Margaret Creek catchment areas. Of all the catchments covered by this investigation, the most is known about the Neales, albeit from incomplete data collected over only a 13 year time period (Miles et al. 2013).

The Neales River catchment is characterised by complex, multiple anastomosing channels, shallow channel definition, wide floodplains and waterholes, the intermittent watercourses of the Neales-Peake system typically flow in response to the more localised thunderstorm-derived rainfall (Miles et al. 2015). Most waterholes are small, between 5 and 90 ML and are fillable by small rainfall events. Larger rainfall events are therefore capable of recharging alluvial and floodplain groundwater stores (Miles et al, 2015).

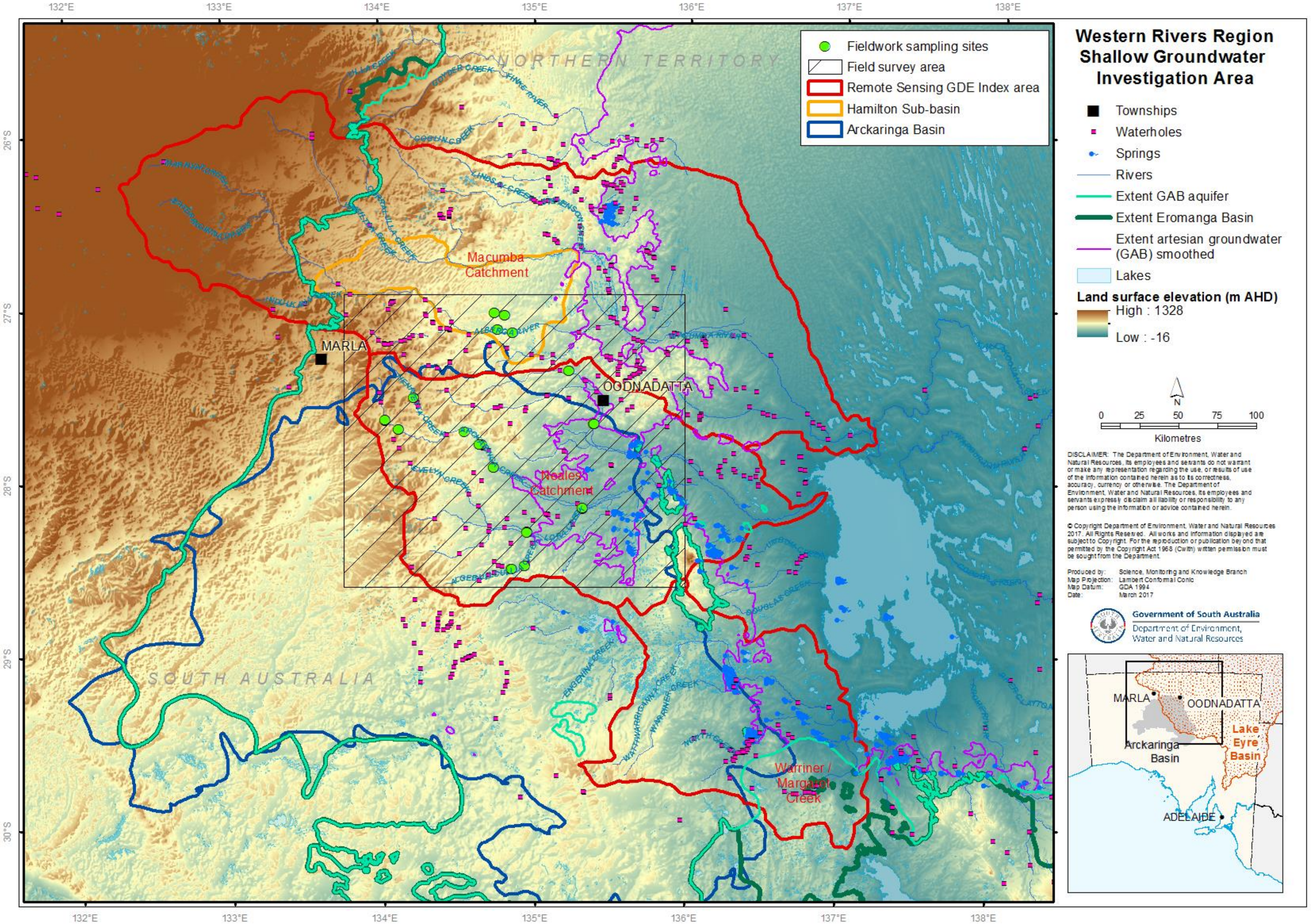

Figure 2-1: Physical geography of the study area

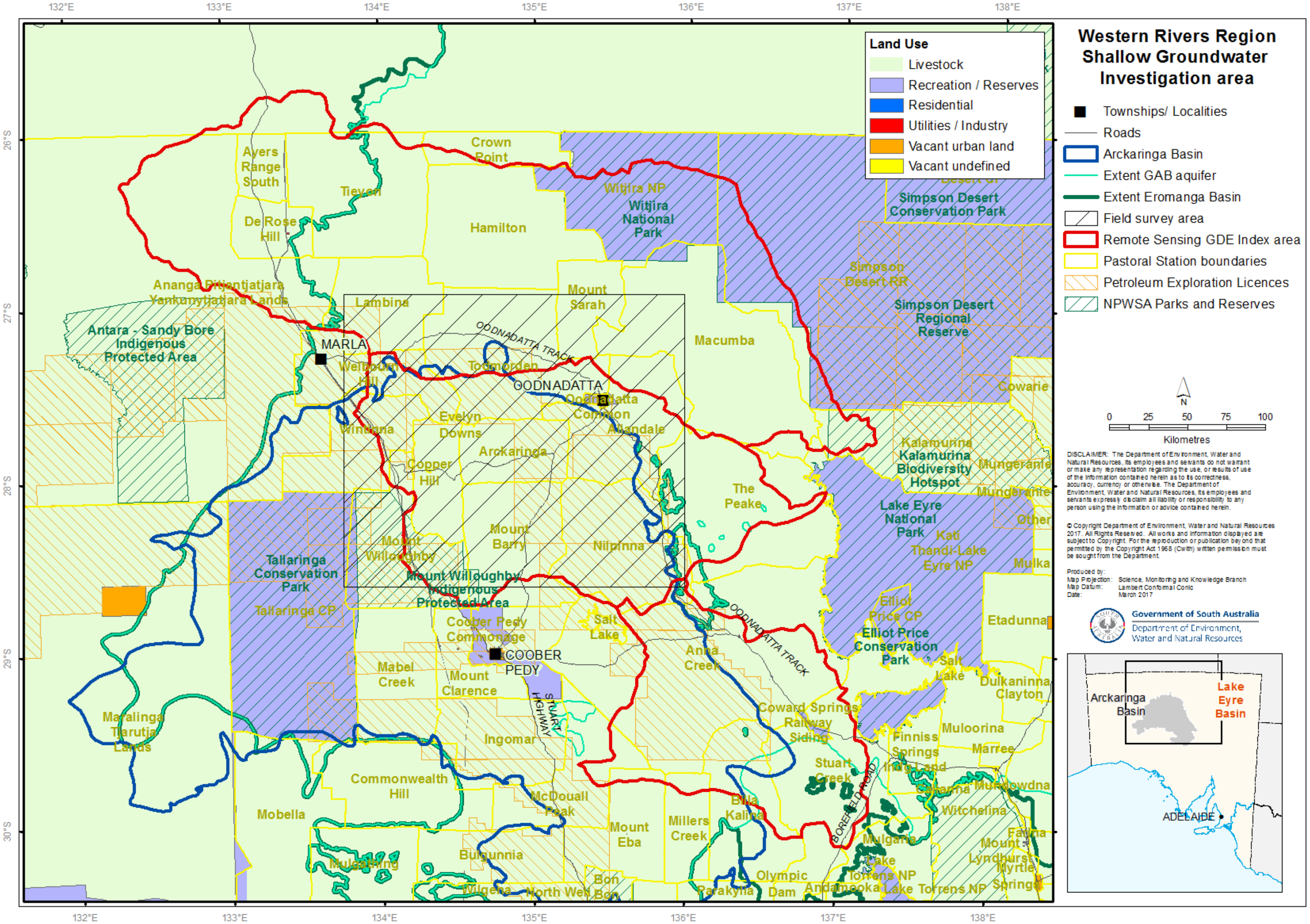

Figure 2-2: Human geography of the study area

Waterholes found within the Neales River catchment are either saline (20 000 to 250 000 mg/L) that are flushed only during flood events or those that are fresh (100–200 mg/L) that may increase in salinity slowly via evapotranspiration during no-flow periods. Fresh waterholes are typically found in the upper reaches of the catchment whereas saline waterholes are typically found in the middle and lower reaches of the catchment.

Shallow, hypersaline groundwater within alluvial and floodplain aquifers in one reach of the Neales River catchment is thought to be a consequence of evaporative concentration. The extensive presence of the relatively impermeable layer of the Bulldog Shale between near surface alluvial sediments and aquifers at depth is interpreted to limit the potential for connectivity between surface water and regionally extensive groundwater (Miles et al. 2015). Beyond this, there is limited information regarding the interaction between groundwater and surface water environments.

There are no volumetric flow-data collected in the study area; however, stage height data of varying quality and length exist for all waterholes over the period 2000 to 2013 for the Neales River catchment. The most complete stage dataset from the Algebuckina Waterhole (Figure 2-4) describes major flood events as well as local flow events, including multiple small flow events associated with a particularly wet period between 2010 and 2011 (Figure 2-3).

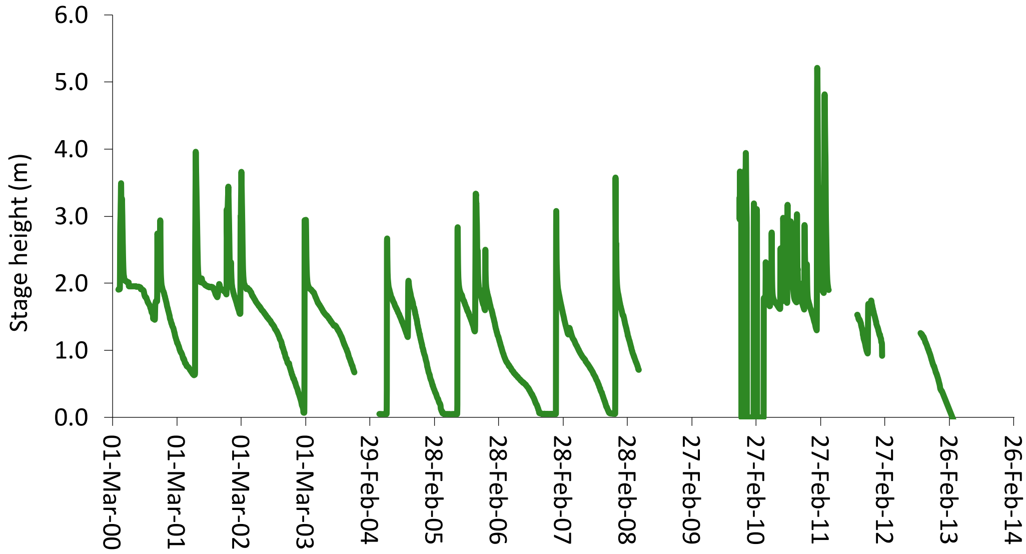

Figure 2-3: Stage height at Algebuckina Waterhole from March 2000 to March 2013 (from Miles et al. 2015)

2.3 Geology and hydrostratigraphy

A summary of the geology and hydrostratigraphy for the field-based sampling works area of investigation is provided in Appendix A. Of note for this study is the near surface geology that consists of Cenozoic (Quaternary, Neogene and Paleogene) fluvial sands, silts and clays associated with current day hydrology and the Hamilton Sub-basin and Mesozoic units including the Bulldog Shale, Cadna-owie Formation and Algebuckina Sandstone. Outcrop geology for the area of investigation is provided in Figure 2-4.

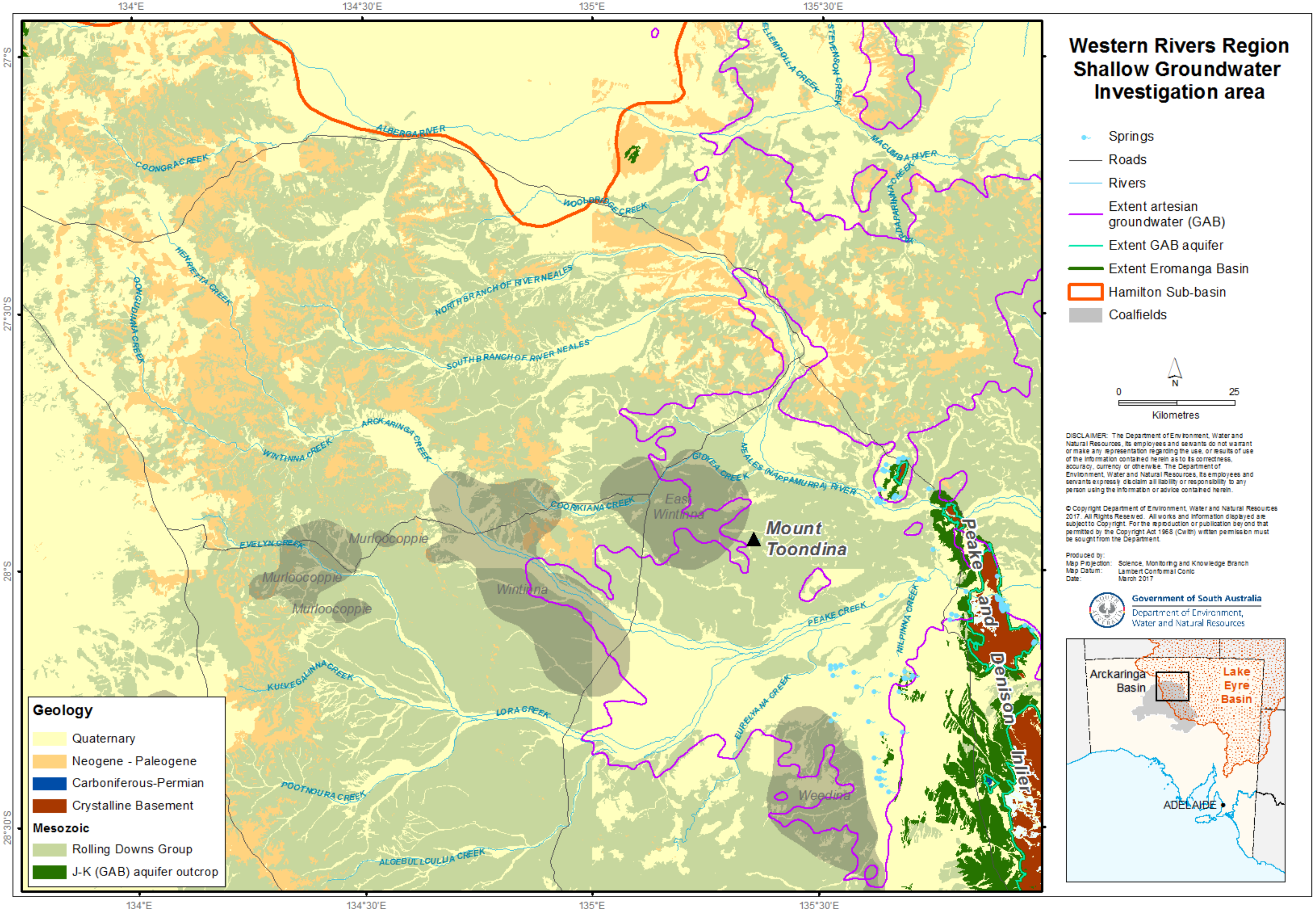

Figure 2-4: Surface geology of the study area

Table 2-1: Summary of hydrogeology of the area of investigation

Aquifer	Description	Parameters	Flow characteristics	Comment
Perched aquifers and bank storage	May exist in the upper catchments in soil or rock above underlying aquitards.	None available	Localised flow systems that respond to flow events in associated drainage systems	Because of their isolation from larger aquifers, the risks to ecosystems dependent on perched aquifers tend to be more localised in nature than risks to ecosystems reliant on more extensive groundwater systems.
Cenozoic alluvials (QTa aquifer)	Aeolian and alluvial sediments associated with current-day drainage lines	Typically low yielding (0.5 and 1 l/sec). Variable salinity (100 and 35 000 mg/l) (Dunster, 1984; Bowering, 1975)	Typically flows west to east in concordance with topography (Figure 2-5)	Aquifer is unlikely to be continuous across the study area.
Hamilton Sub-basin	A small sedimentary basin that is flanked by the Alberga River to the south, the Musgrave Ranges to the west and St Johns Anticline to the east.	Poorly understood but thought to be similar to groundwater found in the QTa aquifer	Typically flows west to east in concordance with topography (Figure 2-5).	Documentation of these sediments is poor. Sediments reach a thickness of 79 m in the vicinity of the western margin (Rogers 1995)
Bulldog Shale	Localised fractured rock aquifer developed in near surface claystone, siltstone, and shale near the Stuart Highway and Mt Willoughby Station. Note, regionally considered an aquitard	Low yielding (<0.5 l/sec. to 1.2 l/sec), but good quality (100–1000 mg/L TDS) Transmissivities varies between 1.7 and 79.1 m^2/day (Dunster, 1984; Smith, 1976; Herraman, 1976).	Speculated to flows west to east in concordance with topography based off limited data (Figure 2-5)	Groundwater supply interpreted as unreliable and potentially a function of discharge into underlying J-K aquifer (Smith, 1976). Such a mechanism would recharge to the J-K aquifer.
GAB (J-K aquifer)	Sandstone and siltstone of the Cadna-owie Formation and Algebuckina Sandstone	Yields vary between 0.025 l/sec and 44 l/sec, although most in study area < 4 l/sec. TDS varies between 150 mg/L and 26,500 mg/l, although most <7,200 mg/L. pH between 5.3 to 8.9 although most between 6.5 and 7.9	West to east with a gradient of approximately 0.001 (Figure 2-6)	For the most part, the J-K aquifer within the area of investigation is either unconfined or sub-artesian, with zones of unsaturated J-K aquifer occurring along the western margin.

2.4 Hydrogeology

A review of literature indicates that there are a number of aquifers of note within the area of investigations. Detailed descriptions of these aquifers are presented in Chapter 2 of the companion report entitled: "*An Examination of Ecosystem Dependence on Shallow Groundwater Systems in the Western Rivers region, Lake Eyre Basin, South Australia Volume 2: Supplementary Report*". Table 2-1 below provides a summary of pertinent information. Other aquifers, such as the Mount Toondina Formation and Boorthanna Formation are important aquifers in the region; however, a lack of appropriate infrastructure prevented during this study.

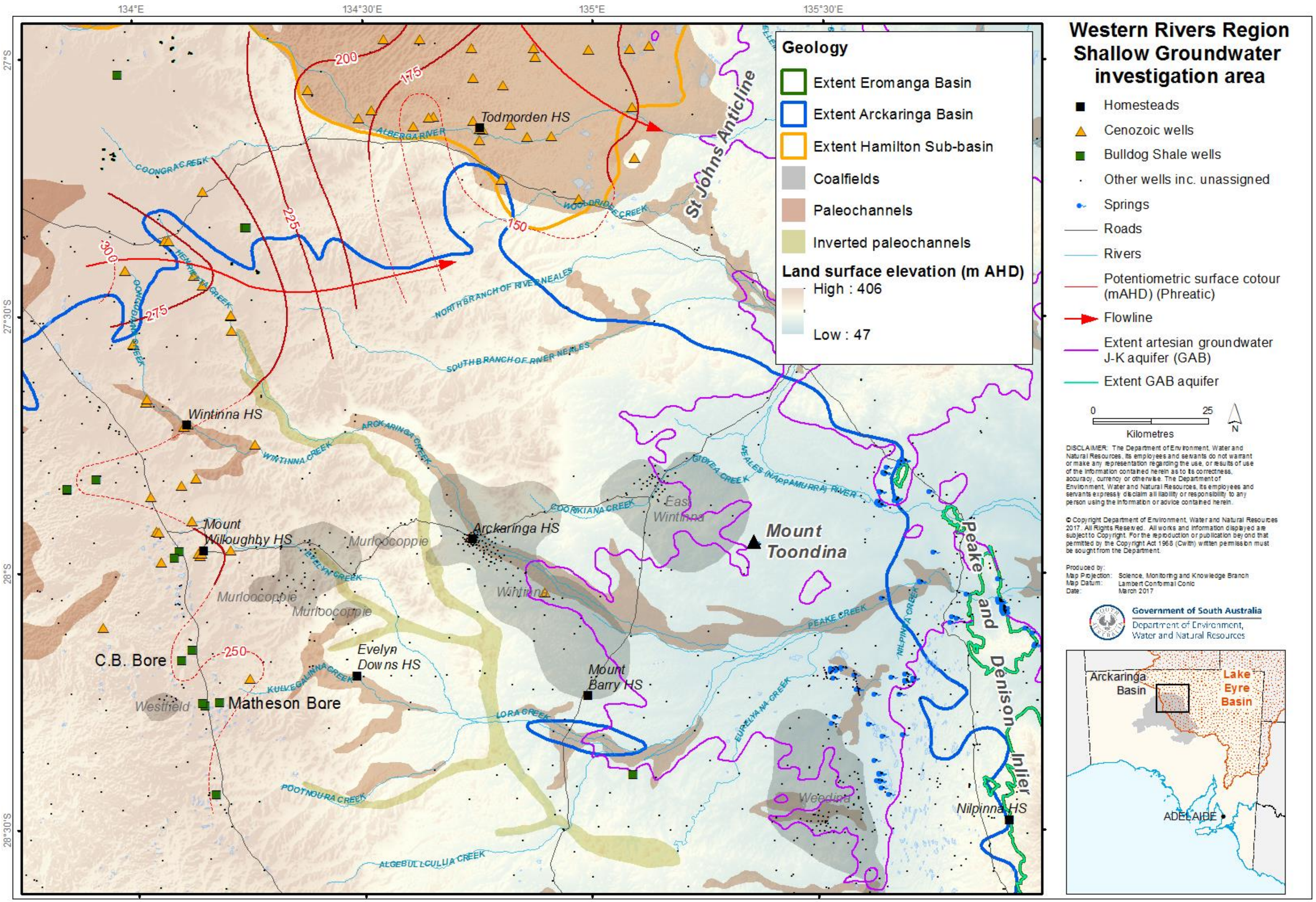

Figure 2-5: Potentiometric surface contour interpretation of phreatic groundwater based on reduced standing water level (RSWL) (m AHD) data

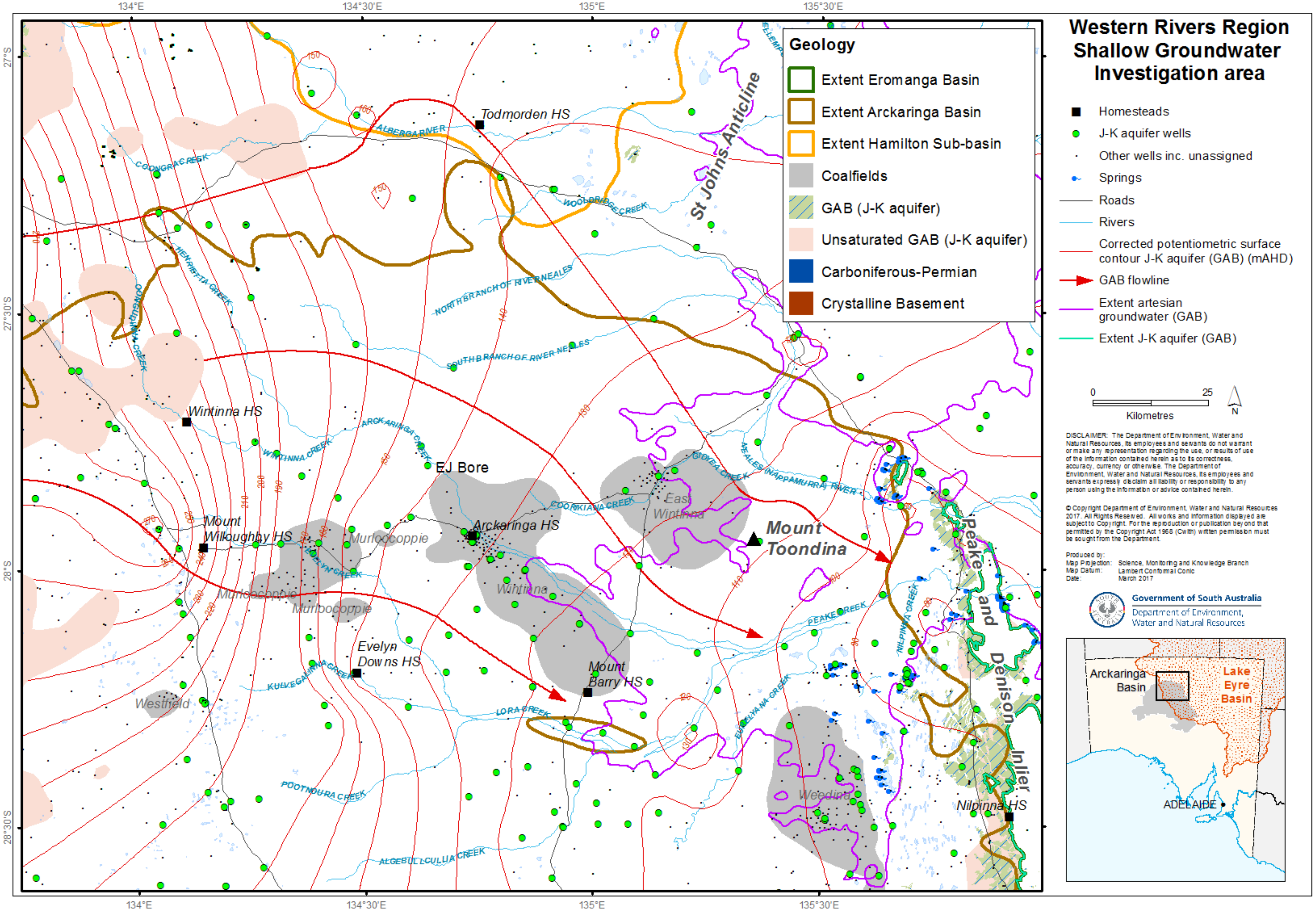

Figure 2-6: Corrected J-K aquifer (GAB) potentiometric surface contours (m AHD)

2.5 Ecosystems dependence on shallow groundwater

2.5.1 Known and potential groundwater dependent ecosystems in the study region

Groundwater dependent ecosystems (GDEs) are defined as 'ecosystems that require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements so as to maintain their communities of plants and animals, ecological processes and ecosystem services' (Richardson et al. 2011). The GDE Atlas (BoM 2015) presents the current knowledge of GDEs in Australia and maps the likelihood of their occurrence. Within the area of investigation, GDE classification excluding GAB spring wetlands relies on depth to phreatic groundwater mapping and distribution of vegetation communities. However, both these features are poorly mapped and previous work by Miles and Costelloe (2015) found that the GDE Atlas might have overestimated the likelihood of many ecosystems being GDEs. In particular, the GDE Atlas classified many watercourses in the Neales River catchment as having a moderate likelihood of being surface expression GDEs when surface water is in fact only present in most stretches during flow events. Miles and Costelloe (2015) undertook to update mapping of shallow groundwater dependent ecosystems in the western Lake Eyre Basin and developed conceptual models based on recent studies, expert knowledge and literature review. The outputs of Miles and Costelloe (2015) were used as a starting point for this study and the report provides a detailed description of the background knowledge about ecosystems dependent on shallow groundwater (EDSG).

Eucalyptus coolabah (Coolabah) and *E. camaldulensis* ssp. *obtusa* (River Red Gum) both occur in the study region, with the latter having a more restricted distribution. The Arckaringa Creek sites show a pattern of *E. camaldulensis* in the up-stream catchment areas (e.g. Wintinna) occurring at a relatively high density, becoming mixed *E. camaldulensis* and *E. coolabah* moving downstream (Francis Camp). In the middle reaches of Arckaringa Creek, (near EJ Bore, Figure 2-5 and Figure 3-2) the assemblage becomes *Acacia* spp. dominant with occasional *E. coolabah* on bank top positions but no *E. camaldulensis*. In the lower reaches where the tributaries join to become Peake Creek (near Cootanoorina Waterhole Figure 3-2), the assemblage becomes *E. coolabah* dominant with fewer acacias. Geomorphological field works by Wakelin-King (2015) show that these changes in tree assemblage coincide with a decrease in gradient and mean grain size of the channel sediments, however the role of the watertable to these environments has yet to be established. Previous studies have shown these species commonly use groundwater (e.g. Costelloe et al. 2008; Mensforth 1996; Mensforth et al. 1994; Kath et al. 2014) and so they have been assumed to be indicators of potential GDEs (e.g. GDE Atlases BoM, 2016a, BoM 2015). However, Costelloe et al. (2008), found that floodplain *E. coolabah* overlying hypersaline groundwater can also survive on soil water alone and it has also been proposed by Miles and Costelloe (2015) that *E. camaldulensis* in the upper catchments may survive on soil water periodically infiltrating during flow events.

With respect to other species, little is known regarding their dependence on groundwater and so a literature review was undertaken to determine the depth to phreatic groundwater under a selection of large woody perennial plant species to try and partly address this data gap. Although 'non GDE species' occurred over a greater range of depths to the watertable than 'GDE species' and 'unknown' species, there was little differentiation in depth to water between the GDE species and unknown species. Results were limited by sparse records for a number of species as well as lack of differentiation between other species, most notably *E. camaldulensis, Acacia spp*. and *E. coolabah*. Details of this study are presented in Chapter 3 of the companion report entitled: *"An Examination of Ecosystem Dependence on Shallow Groundwater Systems in the Western Rivers region, Lake Eyre Basin, South Australia Volume 2: Supplementary Report"*.

2.6 Key knowledge gaps to manage risks to GDEs

Two coinciding knowledge gaps hamper the assessment of how groundwater or streamflow changes affect riparian trees. Firstly, the water use requirements and groundwater dependency of many arid zone, riparian and floodplain tree species are not known, as most work in this area has focussed on largely semi-arid areas where regulation of perennial rivers has affected floodplain tree health (e.g. Doody et al 2009; Holland et al 2009). Secondly, there is insufficient monitoring of unconfined groundwater in many arid regions to properly define watertable depth, particularly where unconfined water yields are low or of poor quality (Tweed et al 2011; Costelloe et al 2012). Data collection that addresses these gaps in turn can identify areas within a catchment where hydrological changes will result in significant detrimental changes to the riparian tree communities. The development of conceptual models also assists to identify important knowledge gaps and to extrapolate learnings from field studies to regional scale.

Whilst there is evidence to support the existence of ecosystems dependent on shallow groundwater, an important knowledge gap is the type of aquifers in which the groundwater exists and the connectivity between these aquifers. As outlined in Section 2.3, knowledge concerning shallow groundwater hydrogeology is poor. In particular, there is little knowledge about the degree of connectivity between Cenozoic aquifers and the underlying GAB, hampering the ability of managers to determine risks to GDEs.

A summary of which ecosystems are likely to be dependent on shallow (non-artesian GAB) groundwater is presented in Table 2-2. GDE classification is based upon the two classification systems that have been developed nationally for this purpose: the interim Australian National Aquatic Ecosystems (ANAE) classification framework (AETG 2012) and the GDE Atlas (BoM 2016a; Richardson et al. 2011). A summary of these classification systems is provided in Chapter 3 in the companion volume to this report.

Of 22 waterholes in the Neales River catchment that have been the subject of hydrological monitoring, only four are considered likely to receive groundwater inputs (Costelloe 2011). Most other waterholes were found to be either discharging or effectively 'sealed' by clay 'lining' the banks (Costelloe 2011). Miles and Costelloe (2015) provide a comprehensive summary about the current state of knowledge about non-GAB GDEs in the study area.

Table 2-2 Overview of ecosystems likely to be dependent on shallow groundwater[1], in the riparian and floodplain environments in the study area

Ecosystems likely to be GDEs in the study area	Supporting evidence for groundwater dependency	ANAE[2] classification (Miles & Miles 2015)[3]	GDE Atlas classification and relevant attribution
Saline waterholes	Costelloe (2011) has shown that four waterholes in the middle and upper reaches of the Neales River catchment as being likely to receive groundwater inputs. There are saline semi-permanent and potentially permanent waterholes downstream of the junction of the Neales River and Peake Creek that are also highly likely to receive significant groundwater inputs (McNeil et al. 2011; Ryu et al. 2014).	System type: riverine Water source: combined (groundwater source: alluvial) Water regime: inflows: seasonal; persistence: permanent & mid-term	Surface GDE
Riparian *Eucalyptus coolabah* and *E. camaldulensis* woodlands[4]	Woodlands growing on the banks of some semi-permanent and permanent waterholes in channelised reaches where periodic high flow events result in bank storage and/or recharge and freshening of shallow groundwater (see text for discussion riparian groundwater vs soil water) (Costelloe et al. 2008)	System type: riverine Water source: combined (groundwater source: alluvial) Water regime: inflows: seasonal; persistence: annual to permanent	Terrestrial GDE
Floodplain *E. coolabah* and mixed *Acacia* spp. woodlands	Costelloe et al. (2008) found a floodplain *E. coolabah* growing over hypersaline groundwater was unlikely to be using groundwater, however White et al. (2014) show floodplain vegetation exhibits prolonged vigour and is therefore likely to be groundwater dependent	System type: floodplain water source: combined (groundwater source: alluvial) Water regime: inflows	Terrestrial GDE

[1]Excluding GAB springs and diffuse discharge

[2]ANAE Australian National Aquatic Ecosystem (AETG 2012)

[3]Most relevant attributes only shown here

[4]Note: in multi-channel parts of the study area, such as the Arckaringa study site, the traditional distinctions of floodplain and riparian zone is difficult to apply, Wakelin-King (2013) describe these as anastomosing channel reaches

3 Methodology and results overview

3.1 Field sampling methodology overview

As summarised in Section 1.1, various field methods were employed to meet project objectives. Field sampling sites were selected to cover a range of land systems and ecosystem types found in the study area and to build on earlier investigations, to encompass areas both up and downstream of the coal occurrences in the Arckaringa Basin. Not all methods were employed at each site; a summary of what sampling was undertaken and where it occurred is presented in Table 3-1. Groundwater (hydrochemistry) sampling sites are shown in Figure 3-1, and tree and soil sampling sites are shown in Figure 3-2. Most field sampling was undertaken between 17 and 20 November 2015 with additional sapflow monitoring using data loggers between March 2015 and November 2015. Due to the limited and opportunistic nature of water and soil sampling and in particular the lack of soil water analysis, only limited attempts were made to quantify water sources to the various riparian vegetation communities studied. There was no rainfall reported within the study area during the sampling period. Additionally BoM (2017) reports the average November point (area < 1 km^2) potential evapotranspiration (PET) for November for the study area is between 270 and 340 mm/month whereas the equivalent average areal (area >1 km^2) PET is between 150 and 170 mm/month.

A detailed description of methodologies used during this investigation are provided in Sections 4, 5 and 6 in the companion volume to this report.

3.2 GDE Index methodology overview

As mentioned in Section 1.1, White et al. (2014) undertook a feasibility study to determine if satellite and airborne imagery could be used to detect vegetation permanency, extent and health associated with groundwater dependent ecosystems (GDEs) of the Arckaringa and Peake ephemeral creek systems using remotely sensing methodologies. During this investigation, the experimental Groundwater Dependent Ecosystem (GDE) index as developed by White et al. (2014) for the Neales River catchment and to extend the area examined to include the entire western Lake Eyre Basin (LEB) was further refined. Refinement of the methodology developed by White et al. (2014) included:

- Updating the Moderate Resolution Imaging Spectroradiometer (MODIS) temporal imagery on which it is based to the present
- Using gridded (raster surface) rainfall data from the Bureau of Meteorology rather than individual rainfall station data
- Using daily rather than monthly rainfall data
- Creating a tool which allows the user to define the parameters used, i.e.:
    a. Normalised Difference Vegetation Index (NDVI) threshold
    b. significant rainfall events, defined by the cumulative rainfall total to be reached in a defined number of days
    c. length of the dry period in days
    d. root directory where the data is stored.

Further discussion of the GDE Index methodology developed and used during this investigation is provided in Section 7 of the companion volume to this report.

3.3 Results

A detailed presentation of results for all field-based and remote sensing works conducted as part of this investigation are provided in Sections 4, 5 6 and 7 in the companion volume to this report. Table 3-2 provides a summary of key results obtained during the investigation.

In the case of groundwater samples from the J-K aquifer, samples from shallow wells (screened <50 mbgs) were initially examined separately from samples collected from deeper wells. The reason for this was that groundwater collected from shallower wells is more likely to be directly accessible to riparian vegetation and is therefore of particular interest to this study.

Table 3-1: Summary of sampling sites and methods

River/ creek	Site	Sample no. (Figures 3-1, 3-2)	Sapflow	Leaf and soil water potential	Twig-derived stable isotopes	Groundwater hydrochemistry interpreted aquifer	Surface water hydrochemistry
Arckaringa Creek	**Ethel Well**	1		*E. camaldulensis*	*E. camaldulensis*	QTa aquifer	
	Wintinna HS No. 2 Bore	2	*E. camaldulensis*	*E. camaldulensis*	*E. camaldulensis*	QTa aquifer	
	Stan Well	3					
	Junction Well (Wintinna)	4			*E. camaldulensis*, *E. coolabah*	QTa aquifer	
	Francis Camp Waterhole	5	Riparian: *E. camaldulensis* & *E. coolabah* FP: *E. coolabah*	Riparian: *E. camaldulensis* & *E. coolabah* Floodplain: *E. coolabah*		No bore	
	EJ Bore	6	*E. coolabah* & *Acacia cambagei*	*E. coolabah* & *A. cambagei*		J-K aquifer	
	Cootanoorina Waterhole	7	FP: *E. coolabah*	Riparian: *E. coolabah* & *A. stenphylla* FP: *E. coolabah*	*E. coolabah* & surface water	No bore	Cootanoorina Waterhole
	McLeod Bore	8				J-K aquifer	
Lora Creek	**Ricky No. 2 Bore**	9				J-K aquifer	
	Algebullcullia Bore	10			*E. coolabah*	J-K aquifer	
	Junction Bore	11			*E. coolabah, Acacia spp.* & groundwater	J-K aquifer	
Neales River	**Stewart Waterhole**	12	*E. camaldulensis* & *E. coolabah*	*E. camaldulensis* & *E. coolabah*	*E. camaldulensis*, *E. coolabah* & surface water	No bore	Stewart Waterhole
	No. 1 Bore	13				J-K aquifer	
	Sanity Bore	14				J-K aquifer	
Alberga/Macumba River	**Sheila Bore**	15			*E. coolabah*	HSB aquifer	
	Homestead 4 Bore (Todmorden)	16			*E. coolabah, A. cambagei*	QTa aquifer	
	Homestead 2 Bore (Todmorden)	17					
	Perseverance Bore	18				HSB aquifer	
	Carneggie Bore No. 1	19				HSB aquifer	

Grey shading indicates sampling not undertaken. Aquifer codes: 1. J-K aquifer: Main GAB J-K aquifer. 2. HSB: Hamilton Sub-basin aquifer 3. QTa: Cenozoic alluvial (QTa) aquifers. Note: detailed descriptions of aquifers found in Section 2 of the companion volume to this report..

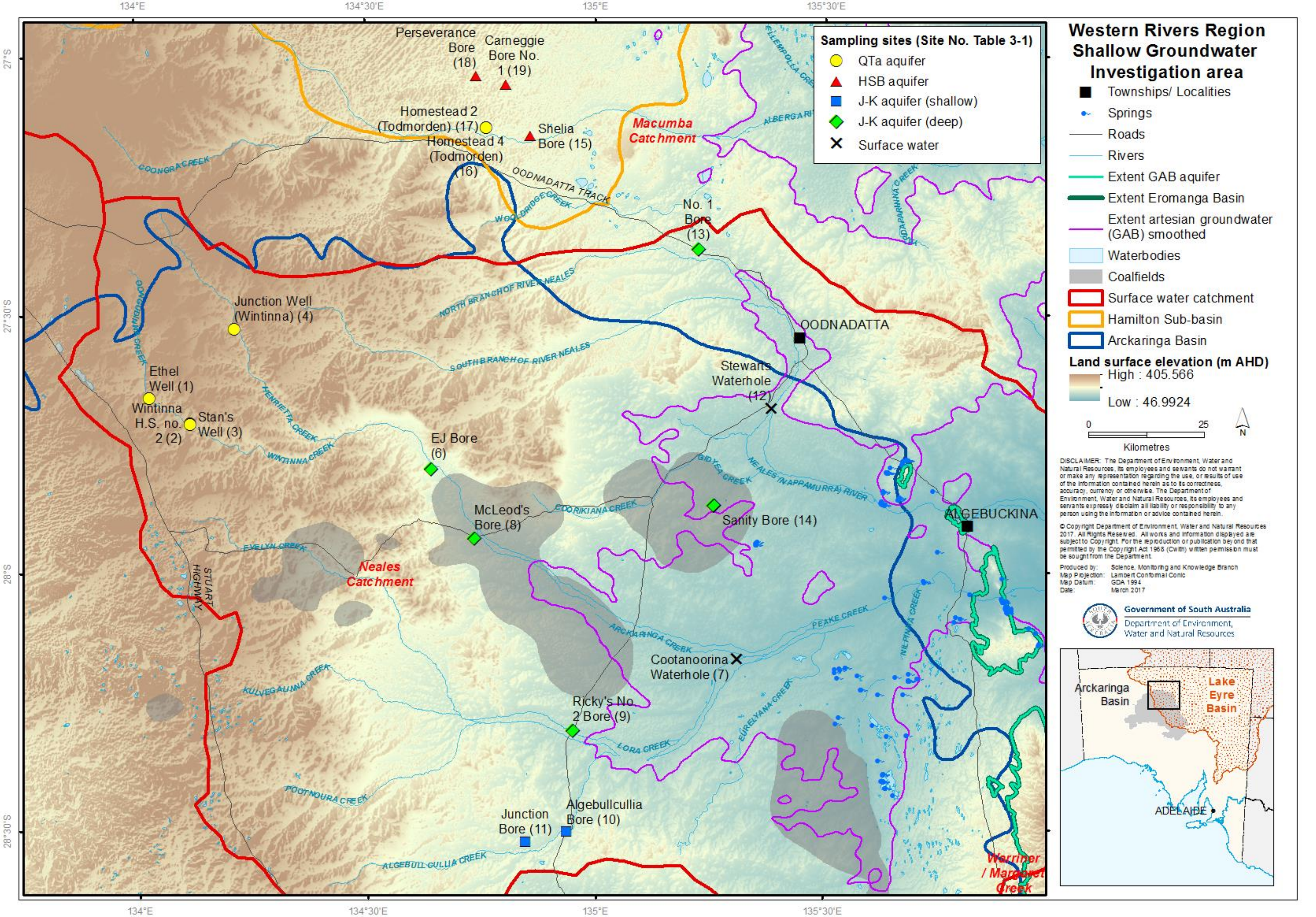

Figure 3-1: Hydrochemistry sampling sites

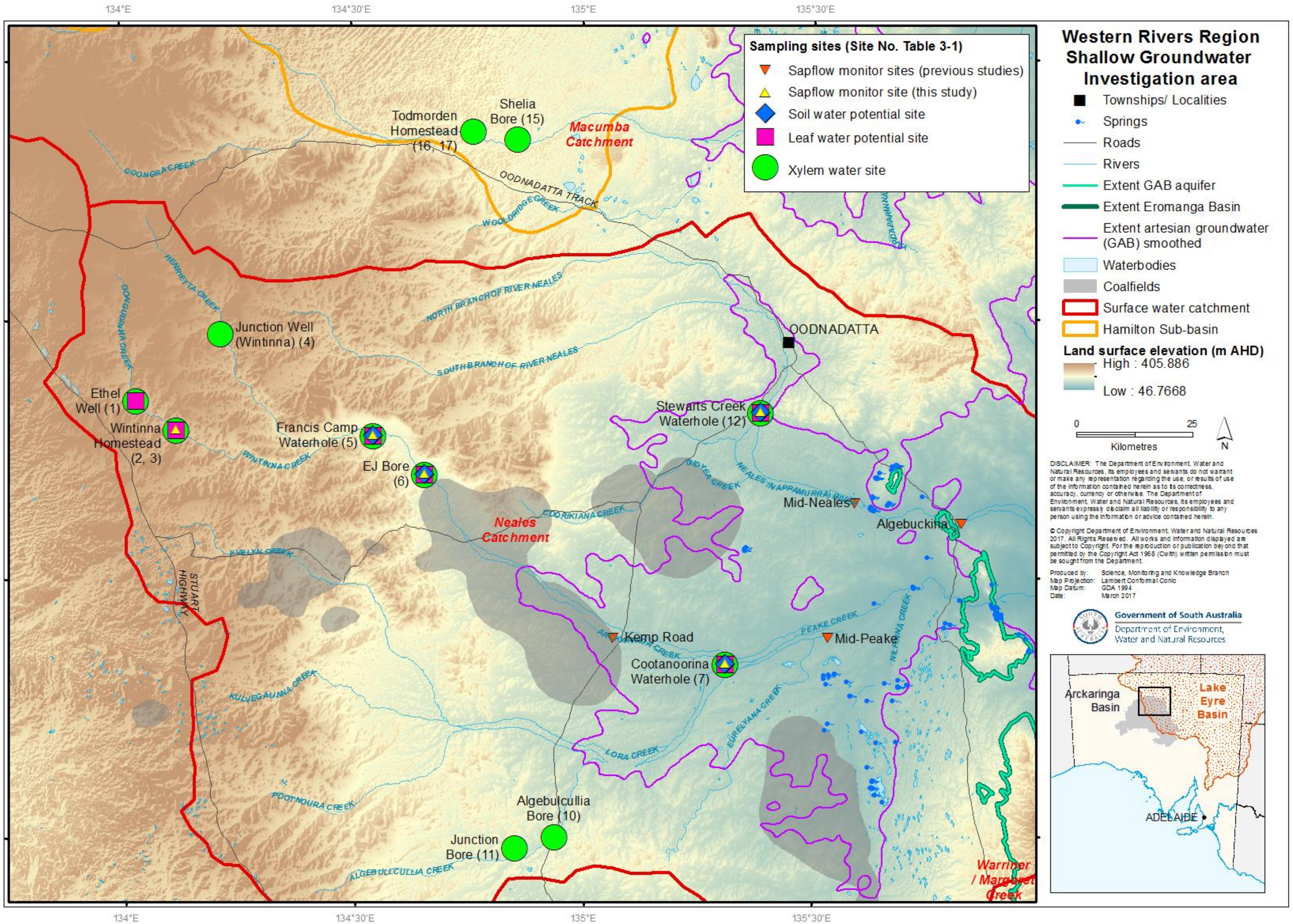

Figure 3-2: Tree and soil sampling sites

Table 3-2: Summary of key results from the various studies undertaken during this investigation

Study	Main characteristics
Groundwater Hydrochemistry	Major ion concentrations in groundwater samples from different aquifers varied notably when their proportional distribution relative to one another was examined using a Piper diagram and scatter plots. Additionally, isotopic strontium ($^{87}Sr/^{86}Sr$) and radiocarbon (^{14}C) also proved beneficial with respect to defining different groundwater groupings based on aquifer type. Groundwater could be organised into one of three hydrochemical classifications that are related to the source aquifer: 1. GAB (J-K) aquifer, 2) Hamilton Sub-basin (HSB) aquifer and 3) Cenozoic alluvial (QTa) aquifers. Salinity in the J-K and HSB aquifers is brackish, whereas it is fresher in the QTa aquifer. HSB and QTa groundwater is neutral to slightly alkaline and oxidising, in contrast to slightly acidic to neutral and reducing in the J-K aquifer. Dissolution and precipitation processes displayed in hydrochemistry results reflect these water quality conditions. $^{87}Sr/^{86}Sr$ is consistently elevated in groundwater samples from the HSB and QTa aquifer compared to J-K aquifer and the reciprocal of ionic strontium (1/Sr) is notably high from QTa groundwater compared to groundwater from other aquifers. Although there are variations in the stable isotope ratios of groundwater interpretable between various groundwater types, such variations are sufficiently small when compared to variations observed with surface water and xylem water samples that groundwater might be considered as a single grouping for the purposes of examining the source of xylem water. Typically, δ^2H and $\delta^{18}O$ groundwater results appear depleted compared to xylem and surface water.
Xylem water chemistry	In all cases, xylem water from *E. camaldulensis, E. coolabah,* and *Acacia spp.* stems displayed some apparent stable isotope enrichment compared to nearby groundwater samples, suggesting that in no instance is groundwater the only water source for vegetation in these areas. *E. camaldulensis* near Wintinna Creek and *E. coolabah* near Algebullcullia Bore near Lora Creek, appear to have the most comparable stable isotope results to groundwater. In contrast, acacias in general and *E. camaldulensis* and *E. coolabah* near Stewart Waterhole are the most enrichment, indicating that these trees are the least likely to be dependant on groundwater.
Leaf water potential	Although the trees measured were mostly in healthy and moderately healthy condition, there was little correlation with pre-dawn leaf water potential (LWP); all trees returned low pre-dawn LWP results. Pre-dawn mean LWP results varied between - 0.5 (*E. camaldulensis,* Stewart Waterhole) and -4.53 MPa (*A. cambagei*, EJ Bore). With respect to *E. camaldulensis*, this finding suggests that this species is able to extract water at lower soil water potentials than previously thought. Midday LWPs did not show clear trends between sites or species. Differences between pre-dawn and midday LWPs display the influence of water availability, with trees that had higher pre-dawn LWPs having larger differences between pre-dawn and midday LWP.
Soil water potential	Cootanoorina Waterhole was the only site where the tree pre-dawn LWP and soil matric potentials at the same location overlap, with soils between 0.5 m and 1 m having corresponding matric potentials. In all other cases, sampled soil matric potentials were less than the corresponding leaf water potential. However, soil sampling was equipment-limited and a full suite of samples between the surface and the watertable was not able to be collected at any of the sites.
Sapflow monitoring	Riparian eucalypts (*E. coolabah, E. camaldulensis*) investigated as part of this study display low base level sapflow (transpiration) fluxes compared to other arid zone riparian eucalypts, returning values between -799 and 801 $kg.m^{-2}d^{-1}$, although the majority of result were between -91 and 211 $kg.m^{-2}d^{-1}$. Negative results may be indicative of hydraulic lift (i.e. bringing soil water up from deeper levels and depositing it at shallower soil levels). An annual evapotranspiration rate of between 2 and 58 mm was calculated; this is significantly less than the median annual rainfall over the catchment (Oodnadatta 175 mm, Bureau of Meteorology).
Remote sensing GDE Index	Examination of the daily rainfall data and temporal NDVI traces shows that during dry periods the mean NDVI for the study area as a whole is generally about 0.15. There is an obvious increase in NDVI post 'significant' rainfall, which peaks at 0.2 to 0.25 generally, then tapers off over the following 6 months if there are no other significant rainfall events. Based on a comparison of sampling sites to the GDE index parameters, Wintinna Homestead has the highest potential of being a GDE, followed by an E. coolabah location on the bank at Francis Camp. The Ethel Well site recorded a GDE Index value of 67.6, whereas the majority of the locations at the EJ Bore, Cootanoorina Waterhole, and Francis Camp Waterhole sites ranged from 30 to 50. None of the locations at Stewart Waterhole was above 6.3, along with three locations at Cootanoorina Waterhole and one at Francis Camp. There are no obvious correlations or relationships between the GDE Index and either the pre-dawn or the midday leaf water potential reading, by either tree type or position (bank vs. floodplain). This is not surprising due to the 250 m resolution of the GDE Index data.

4 Discussion

4.1 Hydrogeological findings

4.1.1 Hydrochemical differences between groundwater of the J-K aquifer and the Hamilton Sub-basin/QTa aquifers

There are a number of notable differences in the concentrations of trace elements between groundwater within the J-K aquifer of the GAB and those from younger overlying aquifers. Such differences can be used to fingerprint groundwater from different aquifers, describe prevailing groundwater conditions and indicate the possible relationships between groundwater from different aquifers within the area of investigation. These differences are best represented in the distributions of NO_x-N (Figure 4-1A), Si (Figure 4-1B) and Li (Figure 4-1C), however are also notable in the trace elements of Mn, V, Fe and U (see Chapter 4 of the companion volume to this report. With the exceptions of NO_x-N and Si, it is thought that the differences are related to the differing redox and pH conditions that are potentially encountered within the aquifer systems. This is because the J-K aquifer is deeper and typically confined within the area of investigation, and that anoxic and slightly acidic conditions are likely to be a characteristic (Figure 4-1D). In contrast, groundwater from the shallower Hamilton Sub-basin (HSB) and Cenozoic alluvial (QTa) aquifers are typically unconfined and are therefore likely to present more oxidized and more alkaline conditions than the deeper aquifer (Figure 4-1D).

Therefore, elements that are more soluble in anoxic or acidic conditions, such as manganese and iron (Thornber, 1992), are elevated in the J-K aquifer, whereas elements that are more soluble in oxidized or alkaline groundwater such as vanadium (Wright and Belitz, 2010) and uranium (Bianconi and Kögler, 1992; Wanner and Forrest, 1992), are likely to be elevated in the shallower QTa and HSB aquifer groundwater.

Lithium (Li, Figure 4-1C) may have a source rock origin related to the GAB. Kszos and Stewart (2003) state that the primary sources of economic quantities of lithium in the USA are salts found in pegmatites or from arid-region brines, particularly those found in playa lake settings in volcanic terrain. With respect to the J-K aquifer, sediments deposited during the early Cretaceous included volcanolithic sediments from rhyolite volcanism from the eastern margin as well as quartz sand derived from cratonic regions such as the Gawler Craton (Veevers 2006). Keppel (2013) also noted dissolution features within quartz sand grains collected from mound springs south of Lake Eyre and interpreted them as being sourced from the supplying aquifer given the likely volcanolithic source of such features. However, further work determining the lithium content of aquifer material is required to confirm this hypothesis.

Elevated nitrate (NO_x-N, Figure 4-1A) and silica (Si, Figure 4-1B) concentrations in the shallower QTa and HSB aquifers are likely to have biological origins. In the case of nitrate, Barnes et al. (1992) discussed how groundwater from shallow aquifers in Australia's arid regions were naturally elevated, in some cases over recommended levels for human health (50mg/L, NHMRC, NRMMC, 2011). The sources included near surface biological-fixation by cyanobacteria in soil crusts, bacteria in termite mounds and a lack of denitrification activity in affected soils leading to nitrate accumulation in unconfined groundwater after rain-induced flushing of soils. Elevated silica concentrations in near-surface groundwater are thought to be related to the differences in solubility between biotic and abiotic derived silica minerals, with the solubility of biogenic silica being 17 times higher than that of quartz (Cornelis et al. 2011). Biogenic silica is typically amorphous and in terrestrial environments accumulate as phytoliths ("plant-rocks"), which are the remnants of silica used in plant and stem structures. Phytoliths are released into the soil profile as plant litter decomposes, where they become available for dissolution and recirculation back into plants. Ongoing contribution of dissolved silica from other mineral forms is thought to eventually lead to an elevated accumulation in groundwater connected with plant litter and the rhizosphere.

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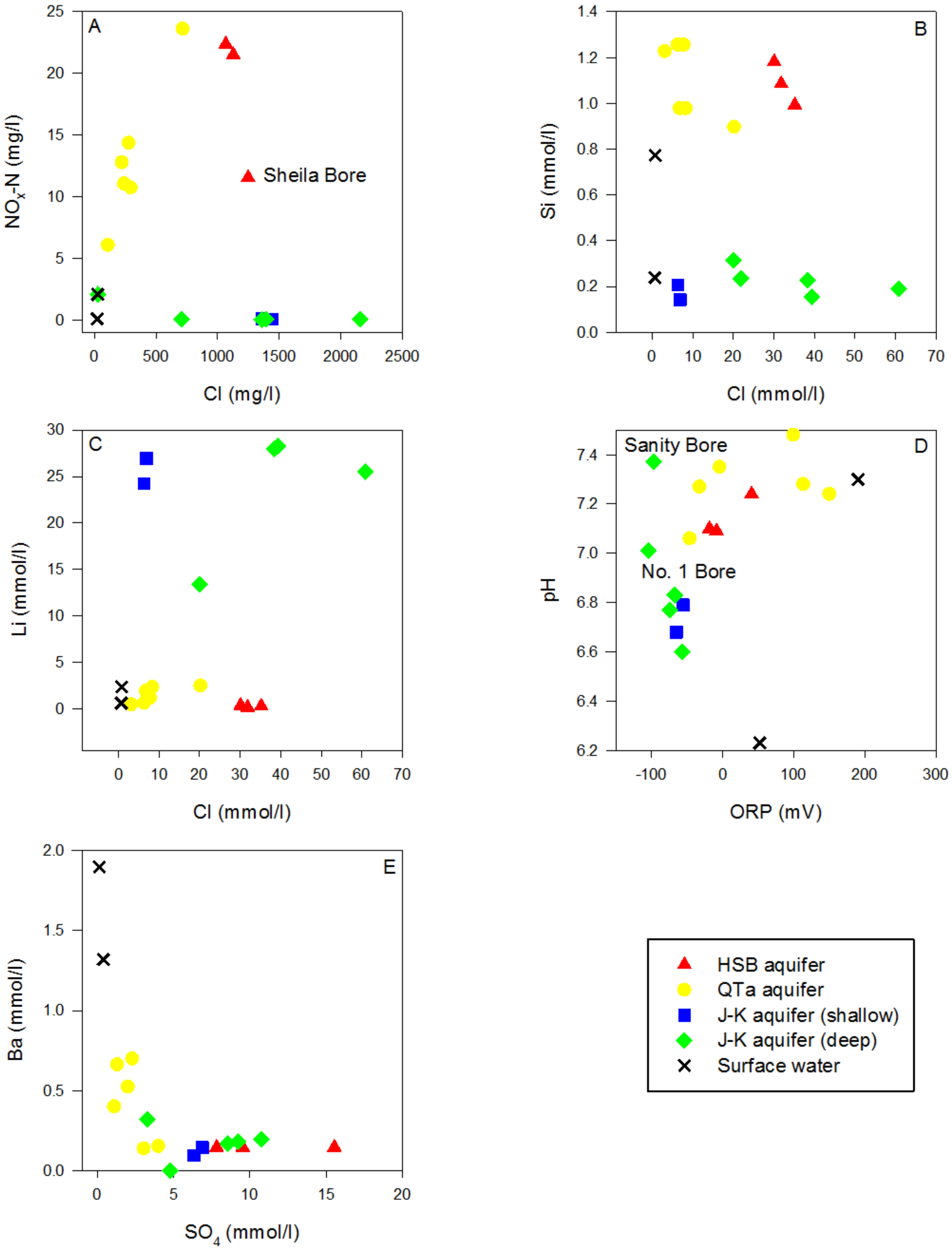


Figure 4-1: Scatter plots of A) Cl- (mg/l) vs NOx-N (mg/l), B) Si (mmol/l) vs Ci (mmol/l), C) Li (mmol/l)vs Cl (mmol/l) D) pH vs ORP (mV) and E) Ba (mmol/l) vs SO_4 (mmol/l)

Such notable differences in trace element concentrations between groundwater from different aquifers does not necessarily rule out aquifer interconnectivity, as hydrochemical evolution based on redox and pH conditions along a flow path might be expected if the flow path in question permits the migration of groundwater from oxidized unconfined conditions of a recharge area, to anoxic conditions of a deeper confined system. However such hydrochemical differences do indicate that if there is connectivity, such connectivity is not substantial or migration between aquifers is very slow under current hydrogeological conditions

Additionally, groundwater from the three aquifers sampled during this study generally all displayed notable differences in radiocarbon (^{14}C), which may be relatable to the age of groundwater (Figure 4-2). Consequently, groundwater from the deepest aquifer (J-K aquifer) returned the oldest uncorrected apparent groundwater age. Likewise, ^{14}C from the shallowest aquifer located closest to the modern drainage system, inferred the youngest uncorrected apparent groundwater age (QTa aquifer). These results support the notion that there is no substantial connectivity between aquifers within the study area. The one exception to this was the result from Sheila Bore (HSB aquifer, Table 3.1 and Figure 3.1), which was more comparable to results from the QTa aquifer than the HSB aquifer. That being said, the location of Sheila Bore near the Alberga River suggests that the ^{14}C result from this well may be influenced by localised recharge and interconnectivity between the HSB and QTa aquifers at this location.

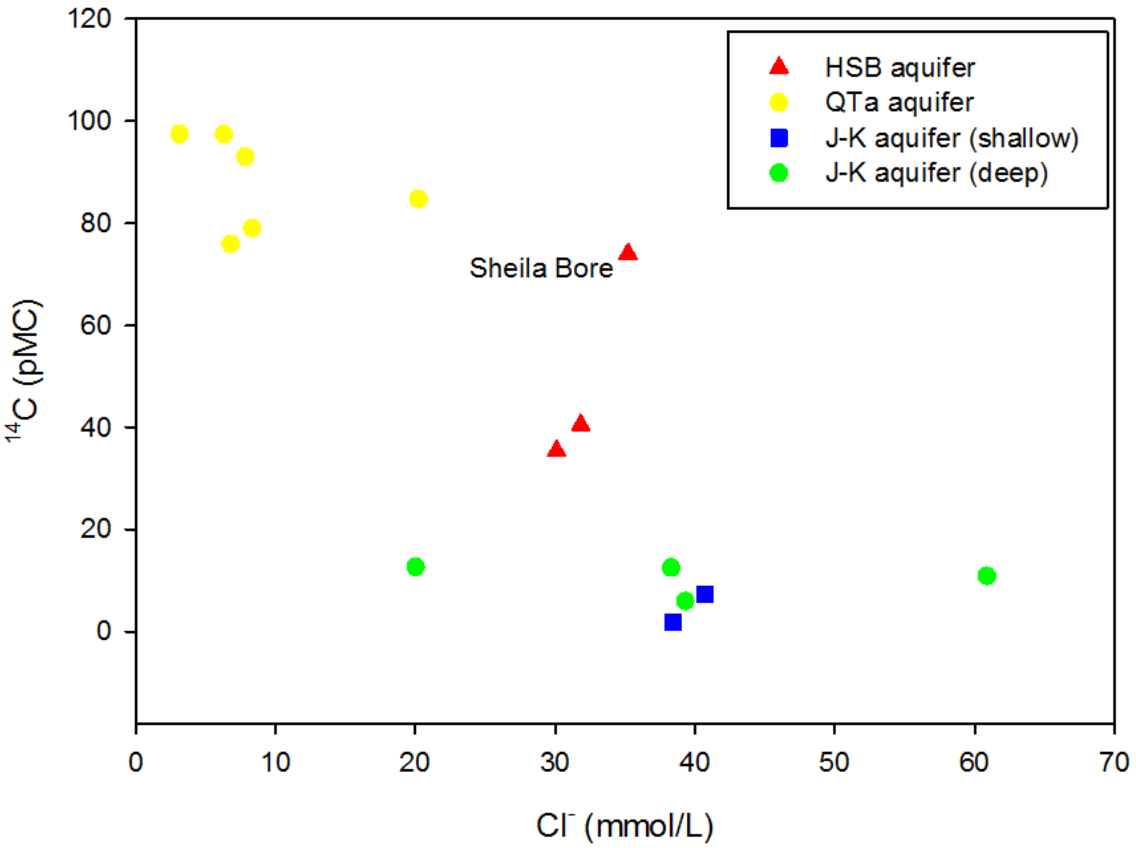


Figure 4-2: ^{14}C (pMC) vs Cl- (mmol/L)

4.1.2 Unique hydrochemistry of the Hamilton Sub-basin and QTa aquifers

In addition to the previously mentioned differences in hydrochemistry between the shallow HSB and QTa aquifers and the deeper J-K aquifer, there are also noteworthy differences in chromium, selenium and barium concentrations that are unique to HSB and QTa aquifer groundwater respectively, which further discriminate between groundwater types within the study area. (See Chapter 4 of the companion volume to this report).

Concentrations of chromium are notably higher in groundwater from the HSB aquifer, or the margins of the HSB aquifer, than those from elsewhere and this may be related the mineralogy of the HSB aquifer. For example, Robertson (1991) found elevated concentrations of chromium in the arid Cenozoic groundwater basins in south-western USA. There, as is interpreted for the HSB aquifer, Robertson (1991) found that groundwater conditions were typically oxidising and alkaline. However, further investigations of the aquifer material in the USA found that silicate hydrolysis of volcanic ash and tuffs in fine-grained alluvial deposits, combined with low concentrations of carbon dioxide, ferrous iron and organic matter, were the primary cause for and maintenance of oxidising, alkaline conditions that promoted the oxidation of immobile chromium (III) to chromium (IV). Although the average concentrations in southwestern USA were an order of magnitude higher than those found within the HSB aquifer, this example does suggest that further investigation of aquifer materials and mineralogy is required to ascertain whether this is the source of chromium in the HSB aquifer.

Similarly to chromium, selenium concentrations are notably higher in groundwater from the HSB aquifer, or the margins of the HSB aquifer, in addition to Ethel Well in the Wintinna Creek region of the QTa aquifer. Selenite SeO_3^{2-} and selenate SeO_4^{2-} which form under oxidising conditions, are the most soluble forms of selenium (Anderson, 1995) and these oxidising conditions are most likely to occur in shallow unconfined aquifers such as the HSB aquifer. However, the limited occurrence of detectable selenium to largely the HSB aquifer and one well in the Wintinna Creek region suggests that a limited source may also be important in addition to favourable water quality conditions for selenium dissolution. The likely source of selenium is from the unsaturated soil profile in this region; Engberg et al. (1998) state that selenium in groundwater is non-point source derived and that the principal source in near-surface water in the western USA was soil and subsoils beneath irrigated land. This is because selenium naturally accumulates in soil via evaporation and bioaccumulation processes. Consequently, it is speculated that connectivity with the unsaturated soil profile has led to elevated selenium concentrations in the HSB aquifer. Further, the HSB aquifer provides an environment where time and a lack of through flow compared to aquifers in the immediate vicinity of rivers and creeks allows elevated concentrations to accumulate.

Although minor concentrations occurs in all groundwater samples, barium was observed to be most concentrated in groundwater from the QTa aquifer near Wintinna Creek than other groundwater types within the study area. Mineral occurrences of barium notably barite, are typically insoluble.

Wunsch (1991) proposed three possible sources of elevated barium in shallow groundwater to overcome issues regarding insolubility:

- sulfate reducing bacteria that deplete dissolved sulfur, thus allowing more barium to occur in solution
- water-rock interaction with barium enriched rocks, including shale and clay units
- mixing of barium enriched deeper groundwater with shallow groundwater.

Of relevance to this study are the first two points; it is noted that like the Wunsch (1991) study in Kentucky USA, there is an inverse correlation between sulphate and barium concentrations in groundwater, potentially hinting at the role of sulphate reducing bacteria (Figure 4-1E). Secondly, shale and clay units are present within the study area; however, their barium content and their relationship to the QTa aquifer near Wintinna Creek are currently unknown. To further this investigation, it is suggested that analysis of the mineralogy and chemistry of QTa aquifer material and ^{34}S analysis of groundwater be carried out to determine bacteria-mediated fractionation.

4.1.3 Origins of recharge water

Generally most aquifers receive recharge following larger rainfall events (> 40 mm), however shallow aquifers with direct connection to watercourses may receive recharge following only small rainfall (and flow) events. Comparison of groundwater stable isotope results compared to monthly rainfall signatures using the method outlined in Leaney et al (2013) suggest the size of rainfall events required to induce recharge are between 80–100 mm/month using amount weighted-mean monthly rainfall volumes and > 40 mm/month using amount weighted-mean monthly rainfall thresholds. This generally fits the hypothesis that reasonably high rainfall events are responsible for most recharge (Figure 4-3). However, the two results from the wells located near the Wintinna Homestead (Wintinna Homestead No. 2 Bore and Stan Well) do not appear to be enriched by evaporation and also suggest recharge can occur at much lower thresholds (>0 mm/month using amount weighted-mean monthly rainfall thresholds). This suggests that recharge can occur at least locally at even very low flow events. Hancock et al (2015) at a location along the Finke River, Northern Territory (NT) made a similar finding.

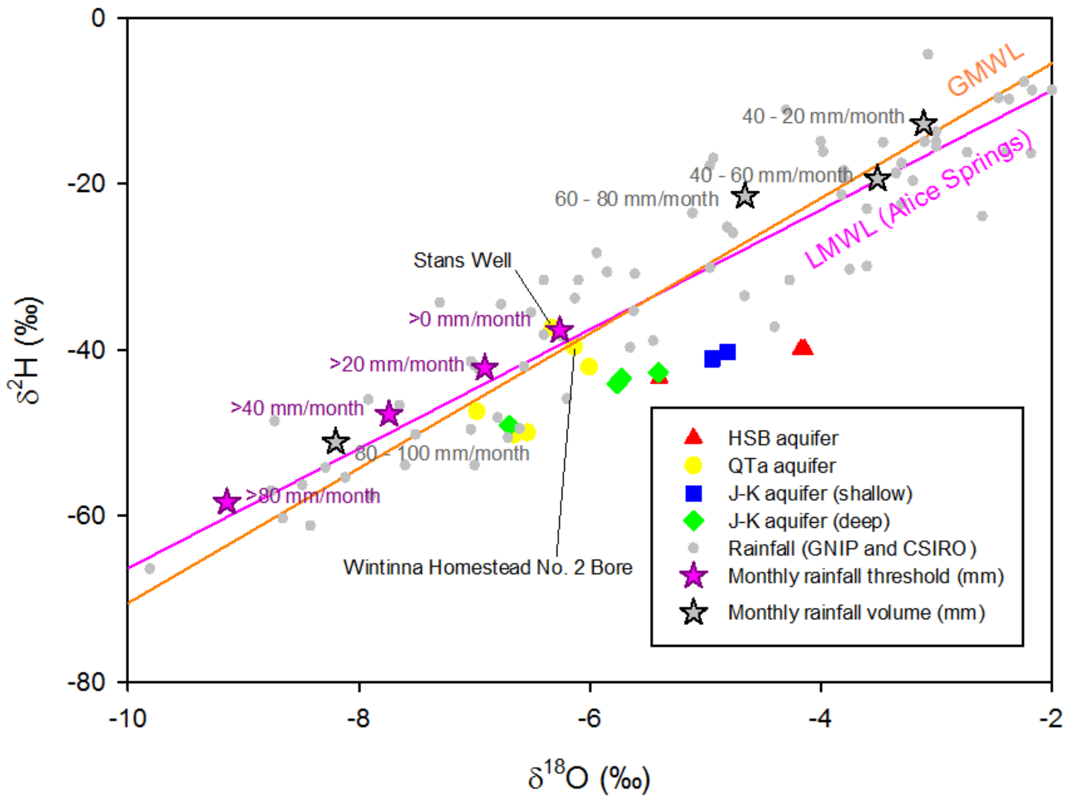


Figure 4-3: Groundwater stable isotope ratios from this investigation relative to amount weighted-mean monthly rainfall volume and amount weighted-mean monthly rainfall threshold categories. Rainfall data obtained from a compilation by Leaney et al. (2013). Mean rainfall trends - LMWL: Local Meteoric Water Line. GMWL: Global Meteoric Water Line.

4.2 Hydroecological findings

4.2.1 Comparison of stable isotopes of water between groundwater and xylem water

In all cases, xylem water from *E. camaldulensis*, *E. coolabah* and *Acacia spp*. stems appeared enriched compared to nearby groundwater samples, suggesting that in no instance is groundwater the only water source for vegetation in these areas based on these data alone. That being said, it is notable that the level of comparative enrichment varies between sites and between species. Consequently, vegetation in the vicinity of Wintinna Creek, particularly *E. camaldulensis,* as well as *E. coolabah* in the vicinity of Algebullcullia Bore near Lora Creek, appears to have the most comparable xylem water and groundwater stable isotope results. In contrast, acacias in general and *E. camaldulensis* and *E. coolabah* in the vicinity of Stewart Waterhole display the most enrichment compared to groundwater. Of note is that the shallow groundwater in the vicinity of Algebullcullia Bore is interpreted to be shallow (<50 mbgs) J-K aquifer (depth to water 15.3 mbgs), which would make this the only instance in this study where the results suggest the J-K aquifer to be at least partially providing a direct water supply to riparian vegetation.

In the majority of cases, xylem water from *E. camaldulensis*, *E. coolabah* and acacia stems are depleted compared to the surface water samples collected from the broad study area. Only *E. camaldulensis* and certain *E. coolabah* in the vicinity of Stewart Waterhole and to a lesser extent, acacia samples from the Hamilton Sub-basin appear to obtain the majority of water from surface water.

Given that the vast majority of stable isotope results from xylem water fall somewhere between groundwater and surface water, two possible interpretations as to where riparian vegetation obtains water within the study area can be made:

A) The predominant source of water for vegetation is soil water from the unsaturated zone, and/or

B) Vegetation obtains water from a variety of sources inclusive of but not limited to groundwater.

Given it was not possible to adequately sample or analyse the stable isotope values from soil water during this study, it is therefore difficult determine if soil water is a primary source based solely on the isotope data. However, other data from this study and comparison to other studies and data from the general vicinity (Costelloe et al. 2008), supports the hypothesis that soil water provides the predominant source of water for vegetation. Costelloe et al. (2008) found partly through the comparison of $\delta^{18}O$ values that xylem water from *E. coolabah* at a number of locations within the Neales River and Diamantina River catchments were either predominantly sourced from soil water from a depth greater than 0.5 mbgs, or that vegetation was accessing a combination of soil water and groundwater. Mean $\delta^{18}O$ values for xylem water study sites covered by Costelloe et al (2008) ranged from 4.1‰ (Diamantina River) to -0.4 ‰ (Diamantina River), in comparison to mean soil water results that ranged between -5.9‰ (Neales River) and 7.2‰ (Diamantina River) and mean groundwater results that ranged between -3.7‰ (Neales River) and 0.4‰ (Diamantina River).

With respect to the hypothesis that vegetation obtains water from a variety of sources, inclusive of but not limited to groundwater, this appears more reasonable in areas where the variation between stable isotope values from xylem and groundwater are relatively small. Like hypothesis A), evidence to support this hypothesis is limited by the lack of soil water results for comparison. That being said, this hypothesis could be used as the basis for estimating the maximum limit for groundwater use by vegetation. By using the groundwater and surface water results as end members, a mass balance calculation can be used to broadly approximate the maximum possible percentage contribution of groundwater to any xylem water value. Table 4-1 presents the results of mass balance calculations for xylem water collected near wells. For the purposes of this exercise, the Cootanoorina Waterhole result was used as the surface water end member for two reasons. The first reason is that as xylem water appears to have undergone fractionation at some point, using a surface water end member result with a comparative history is desirable with respect to matching likely water sources. Secondly, as this exercise is designed to find the maximum limit for possible groundwater utilization by vegetation, the Cootanoorina Waterhole result is preferred given the relatively large enrichment observed. For the groundwater end member, the nearest well to where the xylem sample was collected was used. It must be noted that these results are highly unlikely to represent the true percentage usage of groundwater by vegetation, as the important contribution of soil water cannot be quantified. The possible maximum utilization of groundwater by vegetation in the study area, excluding the waterhole sites, may vary from approximately 30% (*Acacia* spp., Hamilton Sub-basin) to approximately 90% (*E. camaldulensis*, Wintinna Creek). This confirms observations obtained by a simple reading of Figure 4-4 regarding the areas where groundwater is most likely to be at least partially contributing to water available for vegetation.

Diffuse discharge as a possible source of water to riparian vegetation communities within the study area is currently considered unlikely or difficult to determine. Diffuse discharge from the J-K aquifer into shallow aquifers is considered unlikely for the majority of the study area, as J-K aquifer groundwater is largely sub-artesian or at depths greater than 50 mbgs. Additionally Harrington et al. (2012) reported hydraulic conductivity for the overlying Bulldog Shale of between 3.5×10^{-9} to 8.6×10^{-9} m/day (K_h) and 3.5×10^{-9} to 8.6×10^{-9} m/s, (K_v). Such extremely low hydraulic conductivities render meaningful diffuse discharge from the J-K aquifer through non-deformed Bulldog Shale into the shallow sub-surface unlikely. The only location where this may be a factor is at Algebullcullia Bore, where the J-K aquifer is shallow enough to be potentially accessed by riparian vegetation. With respect to other aquifers, the HSB and QTa aquifers are largely unconfined within the study area, so there is insufficient upward hydraulic pressure for diffuse discharge to occur.

Table 4-1: Results of mass balance calculations between groundwater and surface water to determine maximum possible fraction* of groundwater input to xylem water. Surface water end member used in each case was Cootanoorina Waterhole.

Area	Well (GW end member)	Xylem sample name	Depth to groundwater (m)	Groundwater EC (μS/cm)	GW fraction δ^2H (%)	GW fraction $\delta^{18}O$ (%)
Lora Creek	Algebullcullia Bore	Algebullcullia Bore - *E. coolabah*	15.3	6456	90	75
	Junction Bore Mount Barry	Junction Bore - *E. coolabah*	27.1	6955	63	57
		Junction Bore – *Acacia spp*.			50	51
Wintinna/ Arckaringa Creek	Junction Well Wintinna	Junction Well (Wintinna) - *E. coolabah*	6.9	1588	72	73
		Junction Well (Wintinna) - *E. camaldulensis*			85	82
	Ethel Well	Ethel Well - *E. camaldulensis*	9	3105	60	62
	Wintinna H.S. No. 2 Bore	Homestead (Wintinna) - *E. camaldulensis*	?	955	90	84
Hamilton Sub-basin	Homestead No. 2 Bore Mount Todmorden	Homestead No. 4 Bore (Mt Todmorden) - *E. coolabah*	?	2098	56	58
		Homestead No. 2 Bore (Mt Todmorden) – *Acacia spp*.			28	37

* It must be noted that these results are highly unlikely to represent the true percentage usage of groundwater by vegetation, as the important contribution of soil water cannot be quantified.

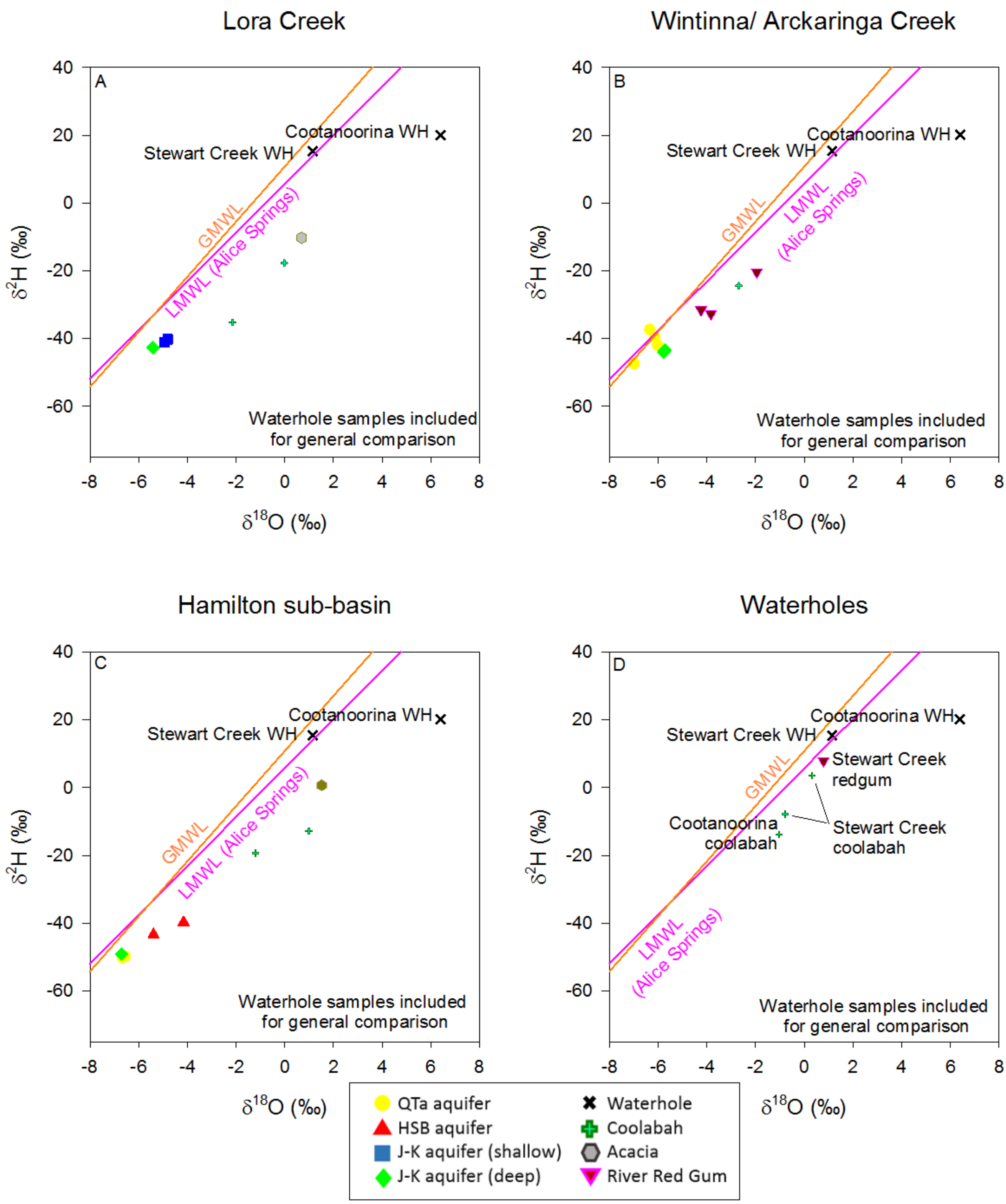


Figure 4-4: Stable isotope results for vegetation and groundwater samples from the A) Lora Creek B) Wintinna and Arckaringa Creeks C) Hamilton Sub-basin region and D) the Stewart Creek and Cootanoorina Waterholes

4.2.2 Sapflow and leaf water potential

The highest pre-dawn LWPs were recorded for *E. camaldulensis* and *E. coolabah* growing on the channel bank at Stewart Waterhole. These results indicate that these trees are accessing water from a highly saturated source, but this source could be either ‘bank storage’ or deeper groundwater as the soil coring indicated the soil is dry at 1 m below pool level some metres away from the water’s edge. Surface water monitoring at Stewart Waterhole has shown leakage (recharge) to groundwater, although Costelloe (2001) suggests that the waterhole may also receive some groundwater discharge when the water level is very low.

At Cootanoorina Waterhole, the channel bank *E. coolabah* had lower pre-dawn LWPs than Stewart Waterhole, indicating they are accessing water from soil with lower total water potential than the Stewart Waterhole trees. The waterhole was only partly full when the LWP measurements were taken with the sampled trees growing approximately 10 m from the water’s edge; therefore less of these tree roots may be able to access bank storage. There has been limited monitoring of water levels at Cootanoorina Waterhole, however interaction with groundwater is considered unlikely. As with Stewart Waterhole, the soil coring did not find saturated soil at the same elevation as the surface water level.

Floodplain *E. coolabah* at Cootanoorina Waterhole had much lower pre-dawn LWP (below -3 MPa) than the channel edge. This result, and the observation of Bulldog Shale at 1 m depth, indicates that these trees utilise soil water from soil with total water potential below -3 MPa at the time of sampling. These trees extract sufficient water to survive in healthy condition by existing at relatively low densities (compared with channel margins) in order to extract water over a large area. This strategy has been found to occur for floodplain *E. coolabah* downstream in the catchment, where the soil depth from which trees can extract water is instead restricted by a shallow, hypersaline watertable (Costelloe et al. 2008).

The *E. coolabah* and *Acacia cambagei* at EJ Bore (Arckaringa Creek) are also unlikely to be using groundwater, as the pre-dawn LWP were very low. Two E. coolabah where found to have pre-dawn LWP of -3.45 and -3.63 MPa (slightly lower than the Cootanoorina Waterhole floodplain *E. coolabah*) and the *A. cambagei* was even lower at -4.48 and -4.53 MPa. Previous sapflow monitoring of *E. coolabah* and *A. cambagei* downstream of this site near Arckaringa Homestead has also found that trees are not likely to be accessing groundwater and instead rely on soil moisture stores replenished by streamflow and some rainfall (Ryu et al. 2014).

Field-based groundwater salinities were measured at 955 µS/cm (EC) at Stan Well and 3105 µS/cm at Ethel Well. An accurate groundwater elevation in relation to the tree elevation could not be collected at either site as both wells were being pumped, but, as the wells are sited just above the floodplain, it is likely that there would be low salinity groundwater within the root zone of the *E. camaldulensis*. However, the pre-dawn LWPs indicated that the *E. camaldulensis* at these sites were accessing water from soil with a water potential of around -2 MPa, lower than the water potential of those at Stewart Waterhole. Therefore despite the presence of shallow, low salinity groundwater at these sites, the trees appear not to be able to access water from a saturated source. The courser grained sediments at this site compared with downstream sites may be an influencing factor. At Francis Camp Waterhole, *E. camaldulensis* had even lower pre-dawn LWPs than at the upstream sites (Wintinna Homestead), between -2.53 and -3.93 MPa, while the *E. coolabah* had pre-dawn LWPs within a similar range (-1.93 to -3.47 MPa). It is therefore unlikely that these trees have access to permanent groundwater either, relying on bank recharge during flow events and rain fed soil moisture. The *E. coolabah* on the floodplain had higher pre-dawn LWPs than the channel *E.* coolabah on the channel bank which may have been in response to a recent rainfall event. However, none of the trees showed any significant sapflow response to rainfall or possible streamflow events that pastoralists reported at Wintinna Homestead in June 2015 (Figure 4-5 and Figure 4-6). The waterhole was dry in November 2015 and so no streamflow occurred in this period. The soil profile data showed that the gravelly sediments in this area had very low water content with highly negative soil matric potential values (<-19 MPa, see Figure 4-7) in the bank top position (to 1.5 m) and in the channel base (to 0.7 m).

The leaf-water potential results for this site also showed very low pre-dawn values, -3.47 to -3.93 MPa for the bank top sites and -2.43 MPa for the floodplain *E. coolabah*. The differences between the bank top and floodplain data are consistent with the sapflow results. No data are available on the depth to groundwater at this site but the sapflow, leaf water potential and soil matric potential data are all consistent with relatively deep groundwater (if any). Therefore, it is likely that the trees utilise deep soil moisture at this site and the presence of E. camaldulensis on the bank top position may be because a perched aquifer or bank storage persists for some time following a flow event.

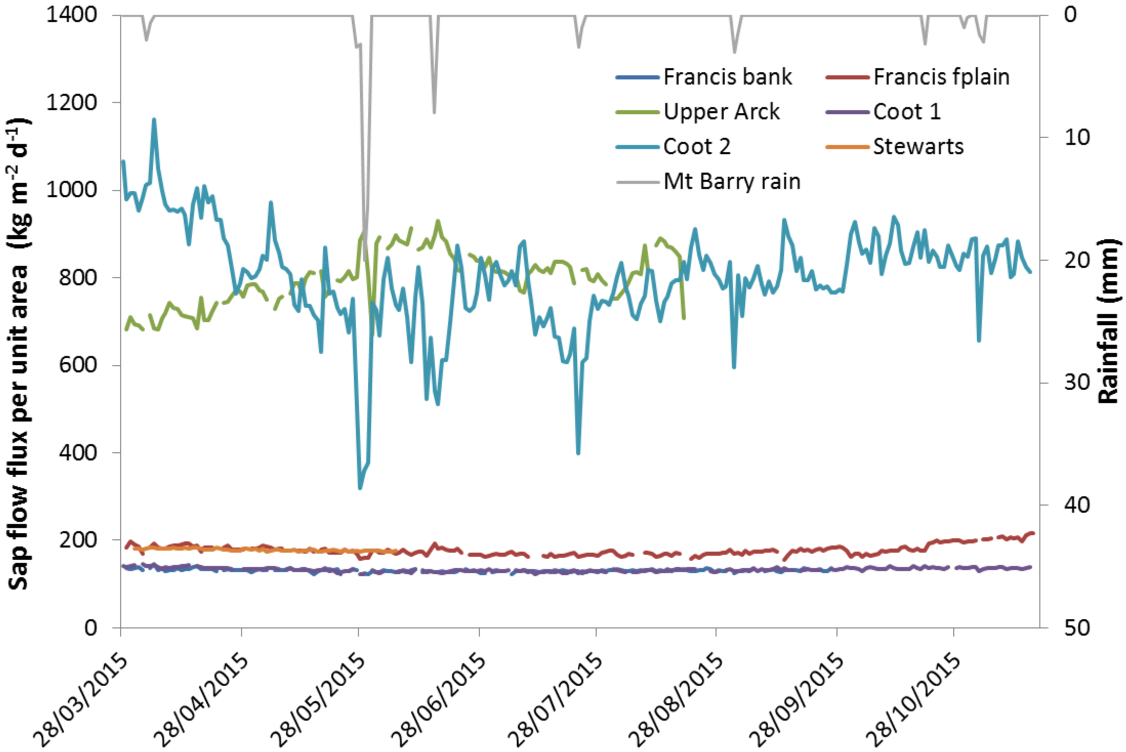


Figure 4-5: Mean per unit area sapflow fluxes for instrumented *E. coolabah* in the Neales catchment, 2015

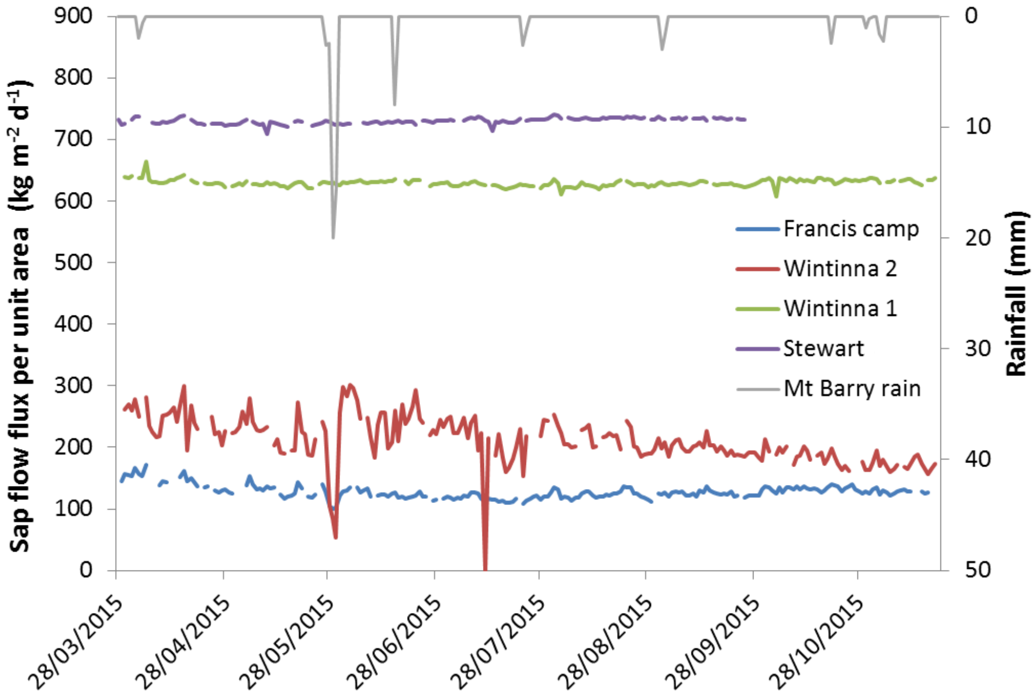


Figure 4-6: Sapflow results (per unit area of sapwood) for E. *camaldulensis* trees in the Neales River catchment.

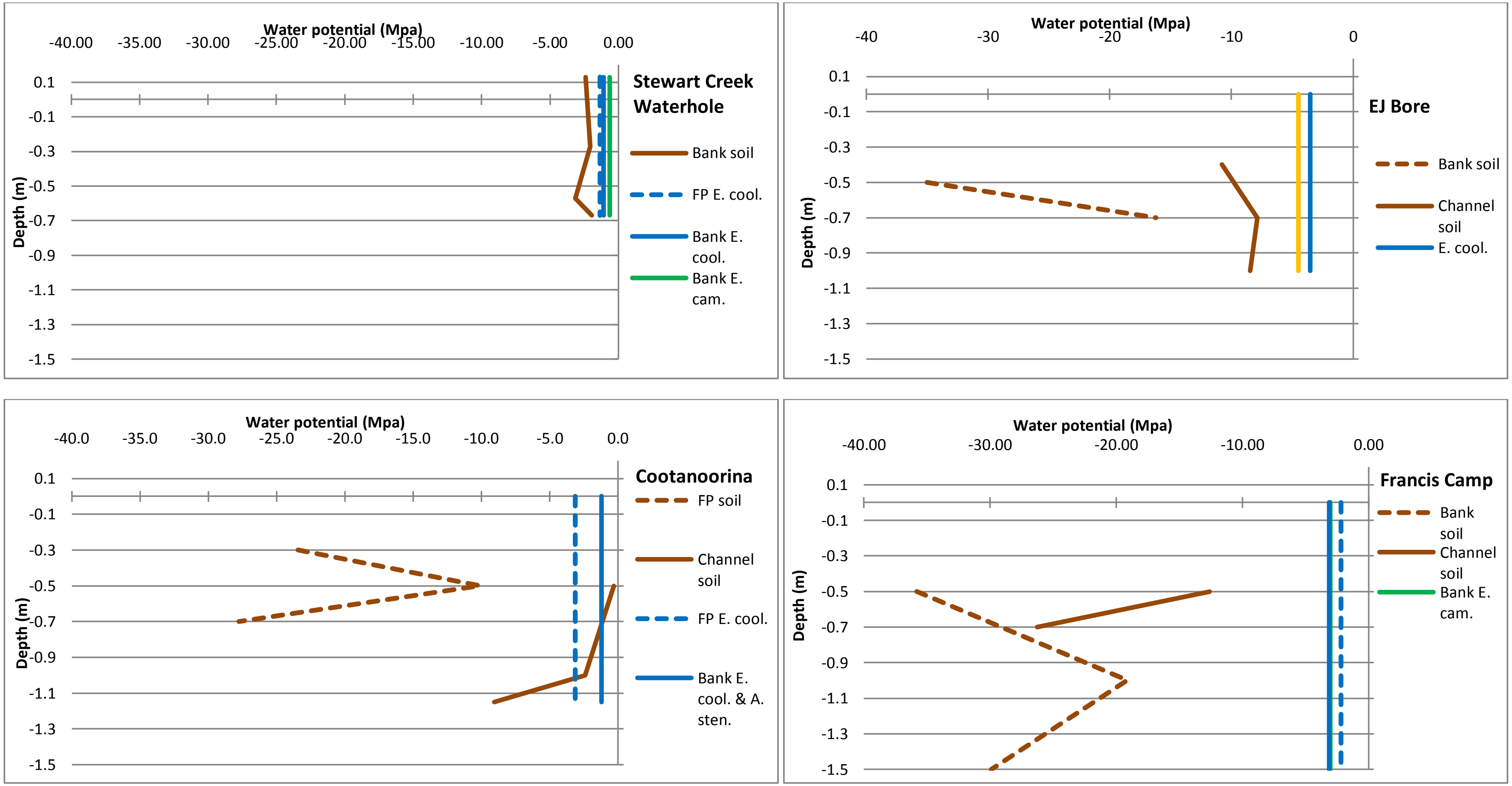


Figure 4-7: Soil matric potentials at measured depths and mean average pre-dawn leaf water potentials at four sites. Note: for sites Stewart Waterhole bank and Cootanoorina Waterhole, channel the soil depth is relative to the surface water level (where water level = 0) and at all other sites it is relative to the soil surface: FP = floodplain, E. cam = *E. camaldulensis,* E. cool. = *E. coolabah*; A. cam. = *A. cambagei*, A. sten = *A. stenophylla;* tree water potentials are the mean average for a given species and location, with the mean for each tree calculated from one to three leaf measurements

The small amount of soil water potential sampling undertaken for this project (Figure 4-7) assisted in the interpretation of the LWP results. It is likely that the riparian trees (E. coolabah and Acacia stenophylla) at Cootanoorina Waterhole channel are extracting water from a zone of high soil water availability (bank storage) around the waterhole. At Stewart Waterhole, the soil matric potential was 1 to 2 MPa lower than the tree pre-dawn LWPs, indicating the trees may be accessing water from either:

(i) a zone of higher water potential either closer to the bank–water interface;

(ii) below the depth of the soil sampled (more likely in the case of the floodplain E. coolabah); or

(iii) a combination of both (likely for the bank trees).

Previous hydrological studies at this site have shown that the Stewart Waterhole is leaky and discharges to groundwater below the depth of the channel bed (Costelloe 2011). Soil and leaf water potentials at EJ Bore and Francis Camp Waterhole indicate that, although trees grow preferentially on bank top positions and probably access bank storage during and soon after flow events, their roots need to extend to below the bed of the channel to access zones of higher moisture. At Francis Camp Waterhole, the trees growing below the elevation of the bank top (FCR2, FCR3, and FCC2) had higher pre-dawn LWPs than those growing on the bank top, indicating they may be able to more readily access zones of higher moisture in the channel sediments.

Of interest, there were no significant sapflow responses to the June 2015 streamflow event known to have occurred at Stewart Waterhole and (highly likely) at Wintinna Homestead. It may be the case that these sub-bank, full-flow events did not result in significant recharge to groundwater. There was also a notable lack of seasonality in the sapflow results indicating all trees are water limited (as opposed to light and warmth limited).

The tree health measurements indicated that the majority of trees were in good health despite some having low pre-dawn LWPs (see Chapter 4 of the companion volume to this report). These results are in contrast to those from areas affected by river regulation and salinity (e.g. River Murray) where low pre-dawn LWP are associated with poor tree health attributed to infrequent flooding and high salinity groundwater (e.g. Holland et al. 2009, Doody et al. 2009). This result indicates the trees measured in this study are likely to be growing in equilibrium with their environment. Field observations of the sites suggest a likely correlation between pre-dawn LWP and tree density rather than tree health; i.e. trees with higher pre-dawn LWPs occur in areas of higher tree density, typically channel bank positions where more frequent flooding is likely to occur. Confirmation of this theory requires further investigation and a different sampling design. Annual evapotranspiration (ET) is significantly less than the median annual rainfall, although the low density of trees in the quadrats almost certainly means this ET rate does not capture the total ET from the quadrats. However, these low ET rates do emphasise the relatively low water usage by the riparian and floodplain trees in this highly arid and variable environment.

There is some evidence that the trees are capable of hydraulic redistribution (Figure 4-8) with negative sapflow fluxes immediately following heavy rainfall indicating movement of water from shallow soil layers to deeper soil layers. As noted this could have been due to faulty installation, however this behaviour is consistent with previous results (e.g. Ryu et al 2014). This behaviour was less apparent in the Neales River data from 2015 but this may reflect the low rainfall and few streamflow events of this period. Most cases of hydraulic redistribution describe hydraulic lift, the movement of deeper soil water to shallow soil layers during dry periods (Burgess et al. 1998; Ludwig et al. 2003; Hultine et al. 2004) but the opposite direction of transport can occur in semi-arid riparian trees (Burgess et al. 1998; Hultine et al. 2004). The advantage of hydraulic redistribution of shallow soil moisture to deeper soil layers would be to optimise the availability of the water resource supplied by infrequent rainfall and streamflow events by reducing losses from soil evaporation and competition with shallow rooted plants.

4.2.2.1 Comparison between species

From the results of the study, it was not possible to draw any strong conclusions about the differences between LWPs of different species and the sample design did not support statistical comparison of the means between species. However, the results indicate that there is no consistent difference between the sapflow rates or leaf water potentials of *E. coolabah* and *E. camaldulensis*. The range of pre-dawn LWPs for all species overlapped except *A. cambagei* which had the lowest pre-dawn LWPs. Mean average pre-dawn LWP for *E. camaldulensis* was -1.97 MPa (standard deviation 1.02), slightly higher than the mean average for *E. coolabah* of -2.28 MPa (S.D. 1.01).

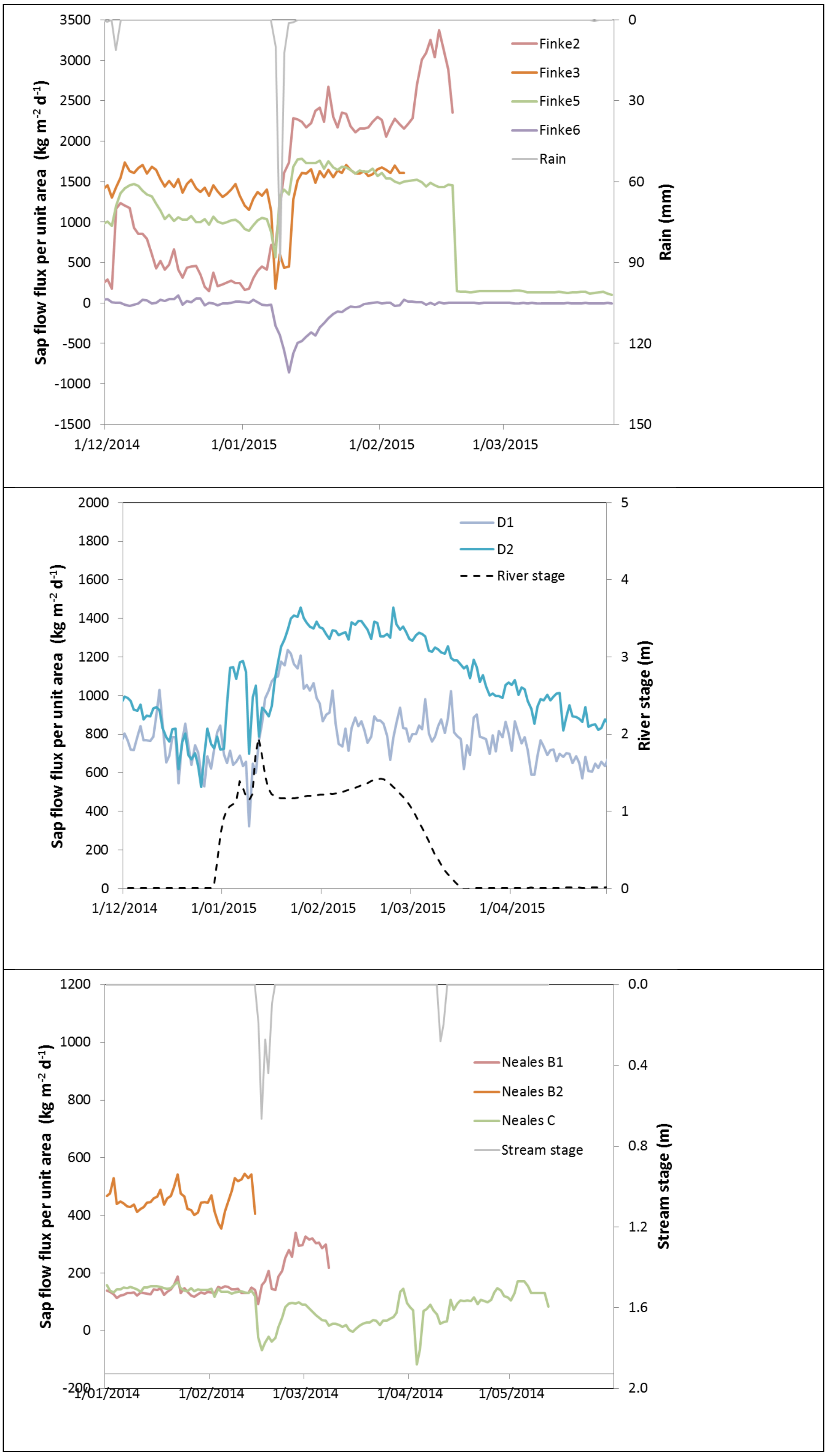


Figure 4-8: Daily sapflow flux per unit area for four E. coolabah trees from previous studies in the Finke River flood out (top), Diamantina River catchment (middle) and Neales River catchment (bottom)

E. camaldulensis with higher sapflow rates and lower leaf water potentials were associated with sites with probable access to groundwater (Wintinna Homestead, Stewart Waterhole). The *E. camaldulensis* at Stewart Waterhole had slightly higher pre-dawn LWPs than *E. coolabah* growing on the channel banks, although to determine if this difference is true in all cases may require more sampling. At this site the *E. camaldulensis* grew at a slightly lower elevation that the *E. coolabah*, being level with the surface water. This is consistent with previous observations that *E. camaldulensis* grow just above waterhole cease-to-flow level while *E. coolabah* grow at bank full elevations (Costelloe et al., 2004). In comparison, the *E. camaldulensis* and *E. coolabah* at Francis Camp Waterhole, where access to groundwater was less likely, had very similar, low sapflow rates.

The monitored *E. coolabah* showed two distinctive differences in sapflow behaviour. Four trees (Cootanoorina, Francis Camp, and Stewart Waterholes) showed very low and steady sapflow per unit area fluxes with no response to streamflow events and little seasonality. Two trees (Cootanoorina Waterhole and EJ Bore) showed higher and more variable sapflow fluxes. Surprisingly, the *E. coolabah* did not show a significant positive correlation between mean per unit area sapflow flux and leaf water potential (pre-dawn or midday, R^2 values of 0.19-0.28). The two trees with the highest sapflow fluxes also had among the lowest pre-dawn leaf water potentials of the *E. coolabah* (-3.12 to -3.63 Mpa). The reasons for this are unclear. It is possible that the trees have high circumferential variability in water use due to differing access to soil moisture in different parts of the root system (e.g. at Cootanoorina Waterhole) or possible equipment malfunction (e.g. high negative flux rates at EJ Bore). Any circumferential variability could result in mismatches between the leaf water potential and sapflow flux measurements.

Distribution of *E. camaldulensis* in the Neales River catchment is somewhat irregularly distributed, occurring in the upper Arckaringa Creek sub catchment (Francis Camp Waterhole to the upper reaches) and patchily in the mid-upper reach of the Neales River (approximately Angle Pole Waterhole to Cramps Camp Waterhole). We installed sapflow loggers in *E. camaldulensis* at three locations, including Wintinna Homestead (Arckaringa), Francis Camp Waterhole (Arckaringa), and Stewart Waterhole (Neales).

Similar to the *E. coolabah* data, two large *E. camaldulensis* trees (Wintinna Homestead and Stewart Waterhole) showed significantly higher sapflow fluxes to the other two trees (smaller tree at Wintinna Homestead and Francis Camp Waterhole) but the *E. camaldulensis* results generally were less variable than the *E. coolabah* showing high sapflow fluxes. The *E. camaldulensis* mean daily unit area sapflow rates showed a non-significant positive correlation with tree circumference (n=4 only) but this may suggest that the very mature trees have more extensive or deeper root systems with improved access to groundwater than for smaller trees, and this is particularly suggested by the differences observed between the Wintinna Homestead pair. The availability of bank storage water is likely to be driving the difference between sapflow rates in the two trees in bank top positions. The Stewart Waterhole tree occurred below bank top in a frequently inundated waterhole while the Francis Camp Waterhole tree occurred at bank top in a less frequently inundated waterhole that was likely dry over the study period. The *E. camaldulensis* sapflow rates also displayed a significant positive correlation with leaf water potential (both pre-dawn and midday, R^2 values of 0.72–0.83) and this was in contrast to *E. coolabah* (see above). Such a correlation is expected and potentially indicates that circumferential variation is not a significant factor for *E. camaldulensis*. However, the limited data demonstrates considerable differences in sapflow rates between nearby trees.

While the study focussed on the two dominant eucalypt species, some measurements from *Acacia* species were also collected. *A. stenophylla* recorded the lowest average LWP (-1.22 MPa, S. D. 0.55), but only two trees of this species were sampled at one location (Cootanoorina Waterhole bank) and the results were similar for *E. coolabah* growing at the same location. Differences between pre-dawn leaf water potentials were observed between *E. coolabah* and *A. cambagei* at the EJ Bore site, with the latter being lower, therefore in very low water availability sites the larger *E. coolabah* are likely able to draw water from deeper sources than the smaller *A. cambagei*.

4.2.2.2 Comparison to previous sapflow results

On a per unit area of sapwood basis, the results of the Neales River sites in 2015 were consistent with previous sapflow data collected in the Neales, Finke and Diamantina catchments. (See Section 6.2.3 of the companion volume to this report). However these results are significantly lower than data from riparian/floodplain eucalypts reported by O'Grady et al. (2009) from the Ti-Tree Basin (200 km north of Alice Springs). The comparison of results from all studies suggests that *E. coolabah* and *E. camaldulensis* of the South Australian LEB respond to the most arid and variable rainfall and streamflow environments in Australia by requiring only low levels of transpiration during dry periods.

The response of the Neales River catchment trees to rainfall and possible streamflow (Figure 4-5 and Figure 4-6) was more subdued than shown by E. coolabah in the Finke and Diamantina catchments (Figure 4-8). The Finke River catchment trees typically showed a substantial response to the large flood event of January 2015 (inferred from rainfall data) that resulted in widespread inundation in the study site (Finke Flood out). The Diamantina *E. coolabah* sites were located between Birdsville and Goyder Lagoon and showed significant responses to sub-bank full flows in 2015. The timing of the responses was somewhat delayed relative to the onset of streamflow and suggests that the peak tree response was coincident to shallow groundwater recharge from the channel flow. In contrast, none of the monitored trees in the Neales catchment in 2015 displayed a clear response to streamflow events. The different Neales sites monitored in 2014 also only showed very modest responses to small sub-bank full flows. For instance, rainfall and sporadic streamflow events in February 2014 and a modest increase in *E. coolabah* sapflow from the hypersaline zone in the mid-Neales (Costelloe 2011) appeared to correlate. The Arckaringa Creek site did not experience streamflow in February 2014 but the *E. coolabah* displayed a short-term decrease in sapflow following rainfall in February and April 2014. This response may be due to activation of shallower parts of the root system utilising the increases in near surface moisture following rainfall.

4.3 Evaluation of the GDE Index Tool

The aim of building a GIS-based tool to calculate a GDE Index which identifies, on a pixel basis, areas that are most likely to be associated with groundwater availability was achieved through the development of a python script which allows the user to input a variety of parameters to explore the gridded daily rainfall data and MODIS 16 day composite NDVI data from 2000 to present. The index tool calculates how often NDVI exceeds the user-defined threshold (indicative of actively growing vegetation) during dry periods (the parameters of which are also defined by the user). One particular scenario was presented in detail, with other possibilities included in the appendices of the companion volume to this report. Unfortunately, this study was not able to collect sufficient on-ground data that to select the most appropriate thresholds for the different parameters to enable upscaling of the results.

The parameters used for the detailed scenario are based on the pattern and values of NDVI and daily rainfall. These values were calculated as the means for the entire study area. The results appear to be credible for the Stony Plains Interim Biogeographic Regionalisation for Australia (IBRA) Version 7, as defined by the GDE Atlas of Australia (the majority of the study area), and the Simpson Strzelecki Dunefields IBRA. The major differences between the results of the GDE Index and the GDE Atlas of Australia for these areas are in some low potential areas identified by one or the other method. The majority of the Simpson Strzelecki Dunefields IBRA was classified as low potential for groundwater potential using both methods, while the GDE Atlas of Australia classified some areas of the Stony Plains IBRA as low potential where the GDE Index did not (Figure 4-9).

The average NDVI values in the Finke IBRA (in the north-west of the study area) are above those of the rest of the study area, as also reported and observed in other studies in the region (Lawley et al. 2011 and Clarke et.al. 2014). This leads to an overestimation of the GDE potential for this IBRA using the parameters for this scenario. This is supported by the comparison with the GDE Atlas of Australia, where little has been mapped as a GDE in the Finke area. Further application of the GDE index method should treat the IBRA regions separately and select the most appropriate thresholds for each IBRA region; an NDVI threshold closer to 0.3 instead of 0.2 for the Finke region.

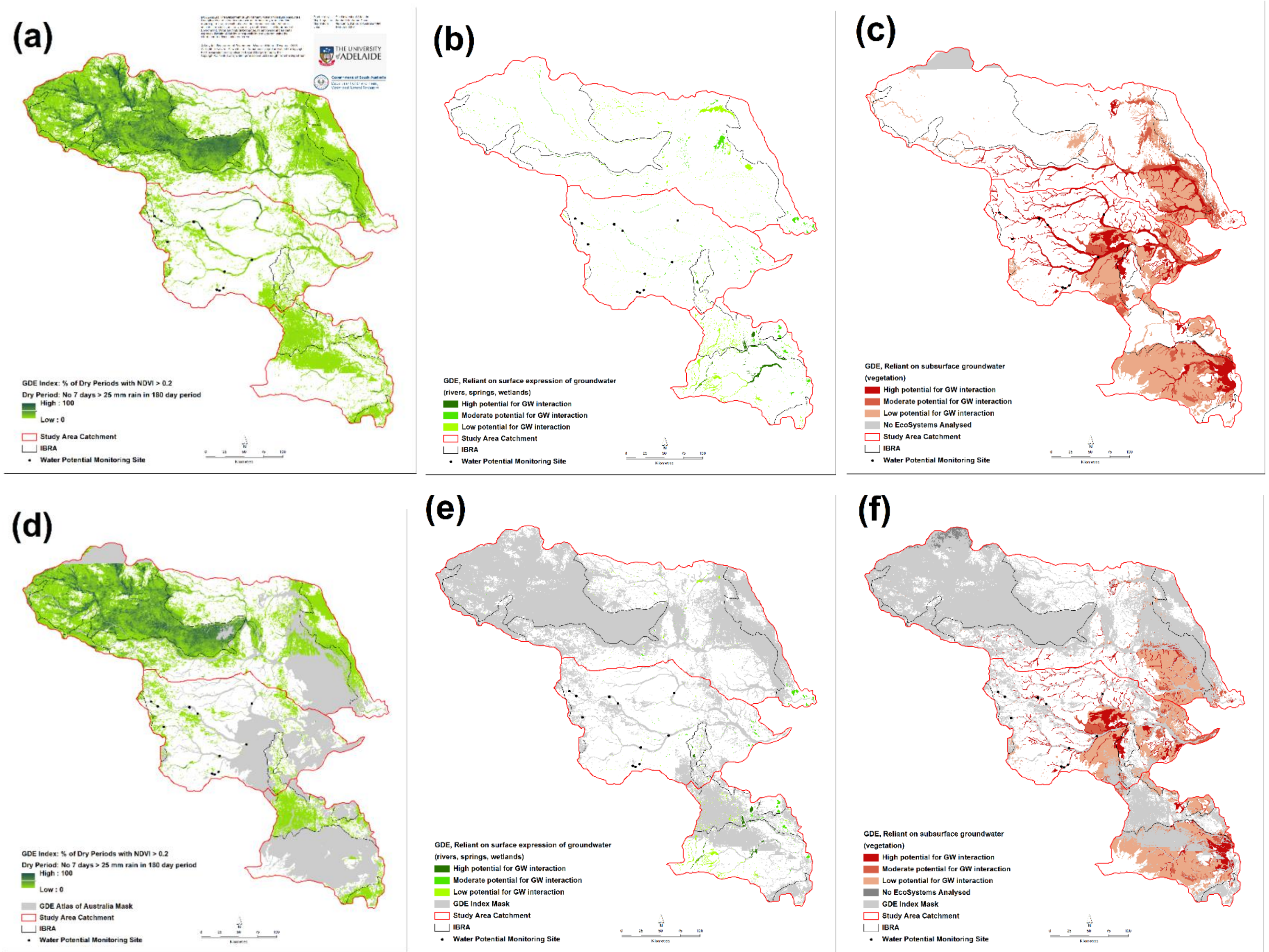
As the AWAP daily rainfall data are interpolated from the relatively few rainfall stations around the study area, it is likely that isolated rain falling between stations is missed (in which case the area is falsely recorded as being dry) or an isolated rainfall at a station means nearby areas are falsely recorded as having had rainfall when they did not. However, the fact that the results show areas with the highest GDE likelihood being more or less where expected for the majority of the region (i.e. rivers/floodplains), suggests that this potential for error is not having a great effect.

Performing a separate analysis by IBRA, of rainfall and NDVI patterns, would improve the understanding of the best rainfall and NDVI thresholds to use for each IBRA. The sandy soils present in the Finke IBRA region result in a greater proportion of the rainfall being available for plant uptake during small rainfall events, whereas in more clay soils elsewhere in the study area a greater proportion of small rainfall becomes too tightly held by the soil for plants to be able to access it (Eamus et al. 2006a; Eamus et al. 2006b). It is worth noting again that the Finke area was classified as Work Package 8 in the GDE Atlas of Australia, with different rules to Work Package 2 which covers the majority of our study area (SKM, 2012).

It is obvious from the qualitative comparison of this GDE Index (which can include many scenarios) and the GDE Atlas of Australia that different remote sensing methods present different results for detecting the likelihood of GDEs. The GDE Atlas is the current national definitive mapping of GDEs. But there are some gaps in the GDE Atlas of Australia due to lack of data (SKM, 2012). The methodology presented here could help fill these gaps. The GDE Index also provides a greater level of detail, with values ranging from 0 to 100 for each 250 m resolution pixel, as opposed to the three classes (low, moderate or high potential) used in the GDE Atlas.

Further investigation of the GDE Index parameters is required, as well as verification in the field, to determine if the GDE Atlas of Australia methodology or the methodology presented in this report produces a more confident identification of GDEs for the study area.

An analysis of the GDE Index values for the field leaf water potential monitoring sites showed that they were all identified as potential GDEs for the scenario presented here. The lowest potential was at Stewart Waterhole and a number of locations at Cootanoorina Waterhole. Low values can be caused by regular water within a pixel location which will lower the NDVI value, as water bodies have NDVI values close to 0 or negative. The Water Observations from Space (WOfS) data indicates that at the Stewart Waterhole and Cootanoorina Waterhole monitoring site pixels the highest inundation rates (% of times a pixel is classified as inundated from clear Landsat observations) are only 6.5% and 8% respectively. It should be noted however that WOfS tends to underestimate the percentage of inundation due to the pixel mixing effects of narrow channels surrounded by vegetation, as evidenced by water level data from Stewart Waterhole.



(a) GDE Index (b) The GDE Atlas of Australia: Ecosystems that rely on the surface expression of groundwater (rivers, wetlands, springs) (c) The GDE Atlas of Australia: Ecosystems that rely on the subsurface presence of groundwater (vegetation) (d) GDE Index masked by the GDE Atlas of Australia (surface and subsurface) (e) The GDE Atlas of Australia (surface) masked by the GDE Index (f) The GDE Atlas of Australia

Figure 4-9: Comparison of outputs from the GDE Index Tool and the GDE Atlas of Australia

The areas identified as high potential GDEs do in fact follow the river and stream banks. However, it is not wise or meaningful to analyse the comparison between the GDE Index and any breakdown by tree type or position (bank vs floodplain) with the current field data. One 250 m resolution pixel may contain a variety of tree types and/or both bank and floodplain areas (these are often only separated by 10 to 100 m). The GDE index shows large variations in these general locations (Figure 4-10), but the close clustering of the monitoring sites means these variations have not been sampled. The localized variations in GDE Index could guide future sampling of water potential or other field-based indicators of GDEs.

In conclusion, the GDE Index Tool has shown great potential to be able to identify shallow groundwater ecosystems in the western Lake Eyre Basin. However, further analysis and field validation is necessary to determine the ideal parameters for individual IBRAs.

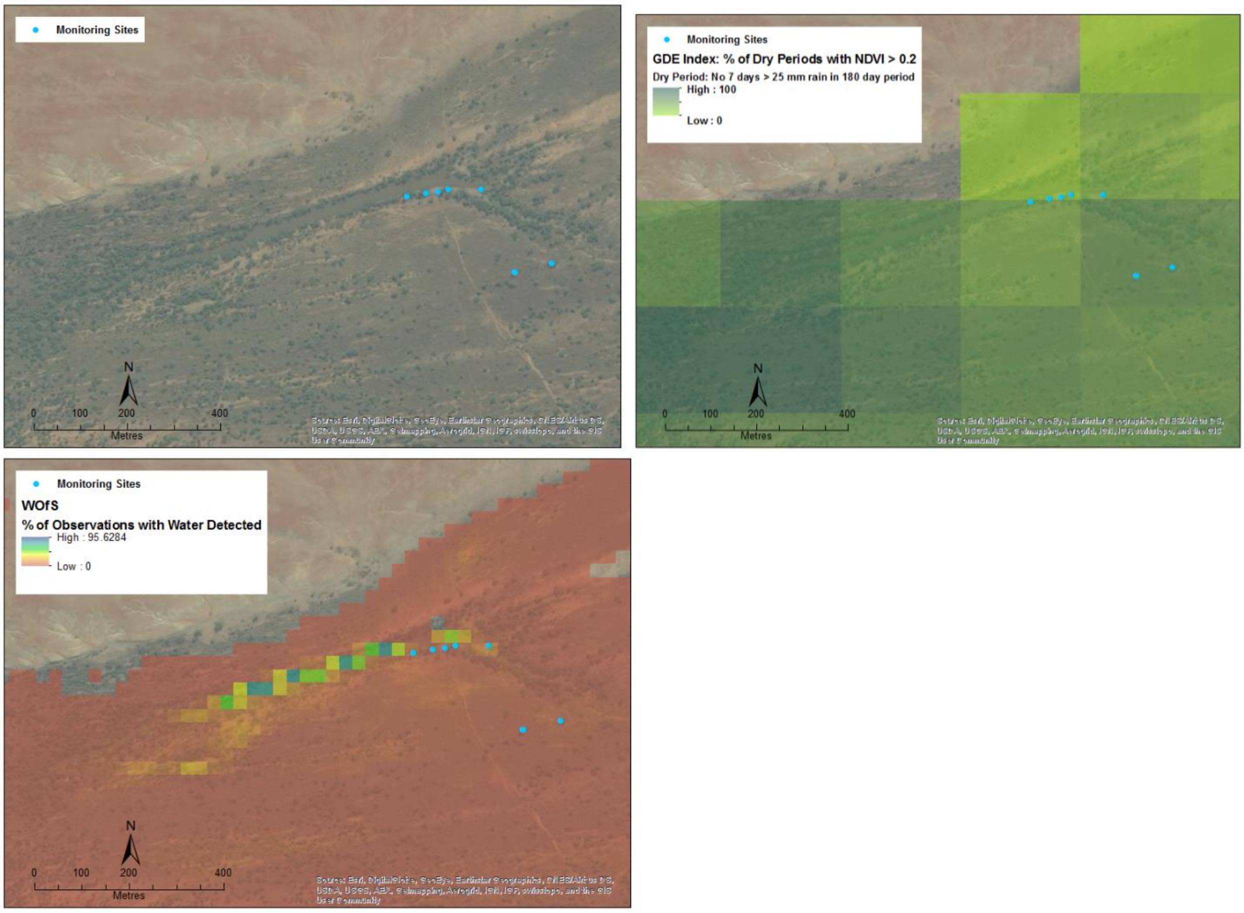


Figure 4-10: GDE Index and WOfS inundation Cootanoorina Waterhole (a) Leaf water potential monitoring sites, (b) GDE_Index, (c) WOfS inundation

5 Hydroecological conceptual models

5.1 Vulnerability of ecosystems to groundwater development

Based on the understanding of water sources used by riparian and floodplain trees gained through this study, the vulnerability of these ecosystems to groundwater development activities is summarised in Table 5-1 below. The water resource development activities are a subset of those presented in Wilson et al. (2014). It is important to note that this assessment does not consider the impacts to GAB springs, which have been investigated through the LEB Springs Assessment Project (Keppel et al. 2015, Keppel et al. 2016 and Gotch et al. 2016) or to aquatic riverine ecosystems, which have been investigated through the LEB Rivers Monitoring project (Hooper and Miles 2015).

Whilst this project has improved the knowledge about shallow groundwater systems and ecosystem reliance on shallow groundwater, there remain significant knowledge gaps. Any proposal for water resource development (including activities associated with mining and other resource extraction) would require a thorough investigation of the hydrogeology of the local area and role of shallow groundwater in supporting riparian and floodplain ecosystems. In some circumstances impacts occurring in other catchments may provide some insights, such as the discharge of bore drains into river channels (e.g. in the Diamantina catchment).

Table 5-1: Potential impacts of groundwater development activities on riparian and floodplain ecosystems

Water resource development activities (Pressure)	**Potential pathways for impacts to occur** (Stressor)	**Vulnerability of riparian and floodplain ecosystems (other than GAB springs)** (Response)	**Key knowledge gaps**
Groundwater dewatering and extraction	Reduced groundwater (GW) pressure (artesian GAB) Reduced GW level (non-artesian GAB and unconfined GW) Change in GW flow direction	Dewatering of the GAB likely to have low level impacts Dewatering of shallow aquifers – the extent of the impact would depend on the extent and connectivity of shallow groundwater, which remains an unknown. However, given that this study has established that it is unlikely that shallow groundwater sources are a significant source of water to trees in most areas, we assume that adverse risks of dewatering shallow groundwater is low. Ecosystems reliant on perched aquifers would have a low level of vulnerability from impacts outside the aquifer but would be very vulnerable to impacts on the aquifer	Degree to which vegetation on the outer floodplain is reliant on the GAB where the water level is within the root zone. Lateral and longitudinal extent of shallow aquifers Existence and extent of perched aquifers Locations where vegetation is reliant on shallow groundwater sources and degree of reliance
Discharge to surface water	Increased bank storage Increased fluvial recharge Groundwater quality changes	Increased water available to vegetation along channel banks could result in changes in vegetation composition or density, this would be a change in the ecological character of the riparian woodlands (see Hooper and Miles 2015); the vegetation growing as a result of discharge to surface water would be vulnerable when discharge ceases Potential for impacts on the level and salinity of groundwater which would have deleterious impacts on the overlying vegetation	Potential for fluvial recharge to groundwater Extent of shallow saline groundwater Areas where bank storage is important for vegetation compared with perched aquifers

Water resource development activities (Pressure)	Potential pathways for impacts to occur (Stressor)	Vulnerability of riparian and floodplain ecosystems (other than GAB springs) (Response)	Key knowledge gaps
Managed aquifer recharge (MAR)	Increased GW pressure (artesian GAB) Increased GW level (non-artesian GAB and unconfined GW) Change in GW flow direction	The effects would be dependent on what aquifer water was being discharged to, and it is considered unlikely that it would be discharged to the shallow aquifer, however, if it were to be, the overlying vegetation would be vulnerable if the groundwater were saline Current regulations prevent MAR if it will have a negative impact, and prevent water discharge if it is of different quality to the receiving waters.	Groundwater flow direction Hydrogeology of shallow groundwater systems, particularly the depth to the watertable and lateral and longitudinal connectivity
Surface water extraction	Reduced bank storage Reduced fluvial recharge Groundwater quality changes	Vegetation growing around longer-term waterholes could be at risk, but vegetation around shorter-term waterholes and ephemeral channels would be unlikely to be impacted as shorter term waterholes would likely be less useful water sources for extraction	Extent of fluvial recharge to shallow groundwater resources Areas where bank storage is important for vegetation compared with perched aquifers
Surface water diversion and capture	Change in flow regime Change in extent of flooding	Impacts likely to be most severe at the location where surface water is diverted/captured and the reach around which the water is diverted If the same volume and flow regime was delivered downstream (i.e. diversion only), then downstream ecosystems should be unaffected. Reduced soil water/groundwater recharge from reduction in large floods Impacts from small scale diversions (e.g. roads) are able to be overcome provided the infrastructure is designed not to interrupt natural flooding (e.g. sufficient culverts)	How flow regime would be maintained during large flood events

5.2 Conceptual models

5.2.1 Box-line conceptual models

A generic summary box-line conceptual model of riparian and floodplain eucalypt woodlands is shown in Figure 5-1. This illustrates the key drivers for arid zone riparian and floodplain woodland processes and the agents of change acting on them. These conceptual models were developed to be used to illustrate what drivers and processes are important for potential riparian and floodplain GDEs and the pathways for impacts to occur.

More detailed box-line conceptual models were developed for the two dominant woodland types considered most likely to utilise shallow groundwater, *Eucalyptus camaldulensis* (Figure 5-2)and *E. coolabah* (Figure 5-3). Fauna trait groups presented are based on the analysis in Section 3.2 of the companion report entitled "*An Examination of Ecosystem Dependence on Shallow Groundwater Systems in the Western Rivers region, Lake Eyre Basin, South Australia: Supplementary Materials*". The conceptual models for the two woodland types were based on the supporting references given in Chapter 8. A box-line model for *Acacia cambagei* was not developed due to insufficient available information and the outcomes of this study indicating *A. cambagei* has a low potential for groundwater reliance. The results of the indicator fauna trait group analysis are shown in Figure 5-4.

The detailed conceptual models illustrate the potential flow-on effects of mining, CSG and other surface and groundwater developments on ecosystem functions and food webs with supporting references. Key hydrological drivers of both Eucalyptus woodland types are vulnerable to mining and CSG-related agents of change as well as other surface and groundwater-related agents of change and climatic drivers. Water quality and tree physiology may be affected by the hydrological drivers, with feedback loops between tree water use and soil and groundwater availability. Tree physiology drivers and processes impact ecosystem function and food webs, but these may also be affected directly by hydrological drivers. While the drivers and agents of change of these woodland types are similar, the presence of shallow alluvial groundwater is considered to be a stronger driver for *E. camaldulensis* than *E. coolabah*.

5.2.2 Pictorial conceptual model

Figure 5-5 provides a pictorial conceptual model of *E. coolabah, E. camaldulensis,* and *A. cambagei* water use. We have based this model on information obtained from a literature review that we modified to reflect the outcomes of the field investigation for this project. The diagram shows that these key woodland tree species occur across a spectrum of surface-water, groundwater, and soil water situations and have opportunistic water use strategies to utilise water when and where it is available.

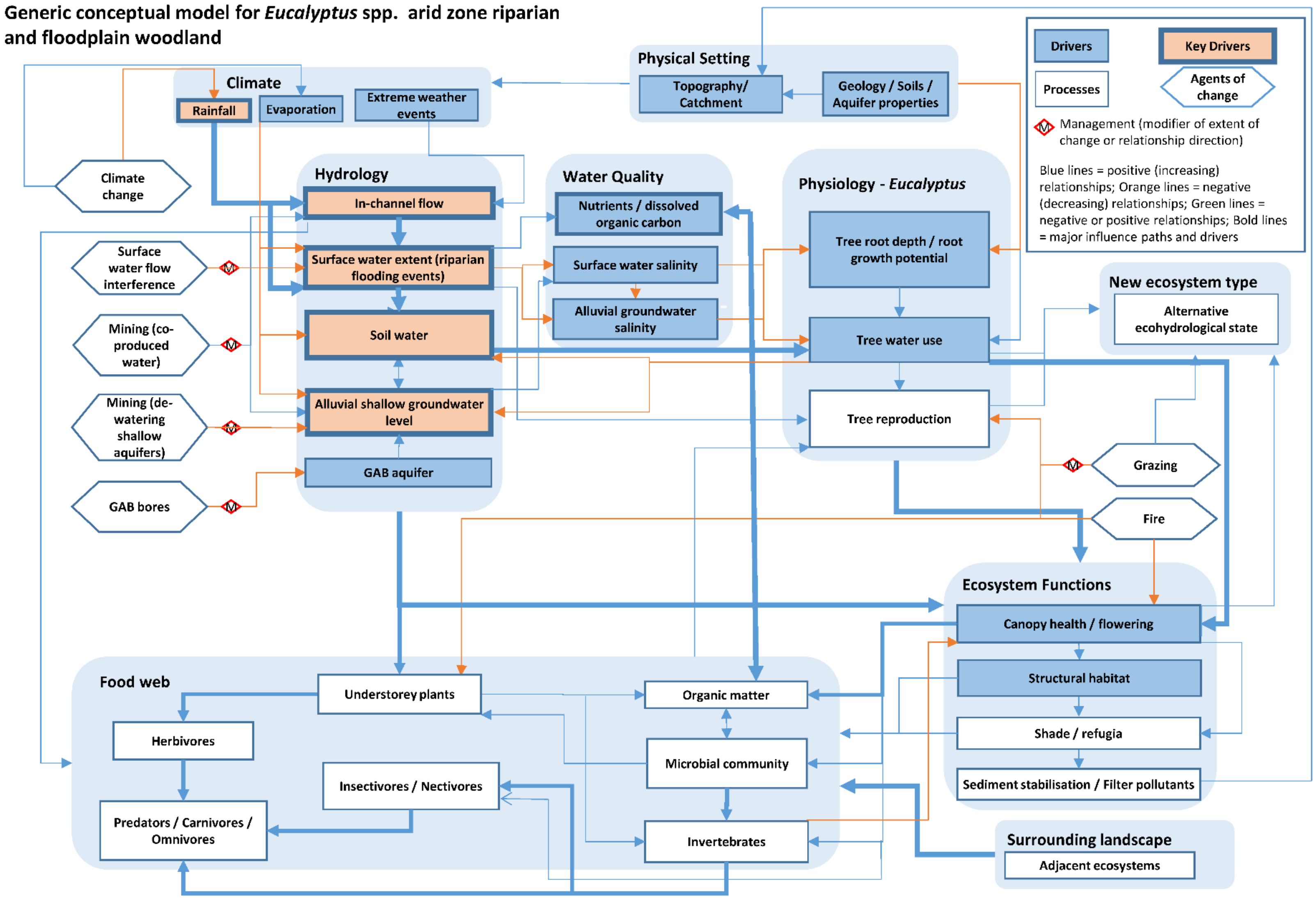
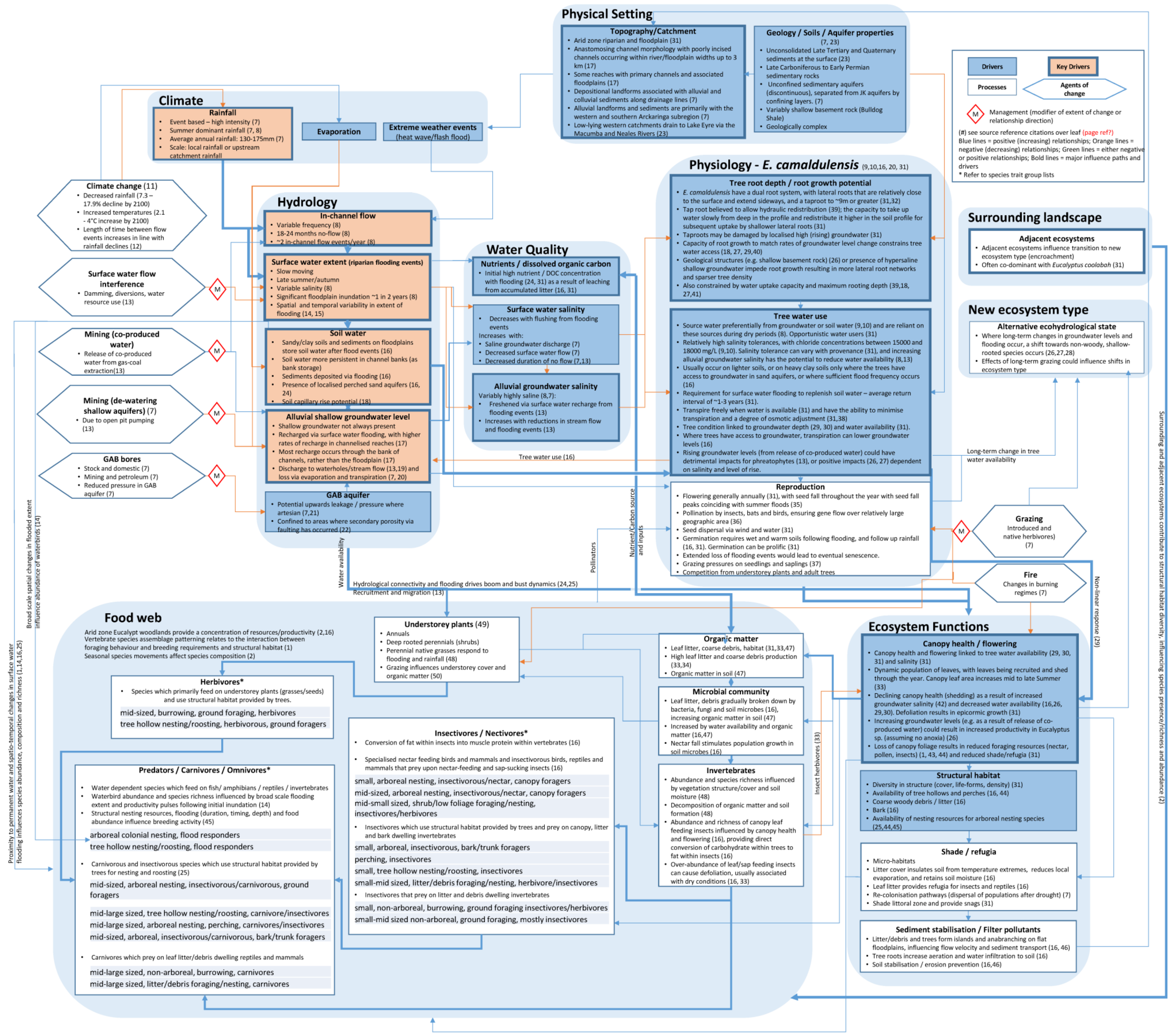


Figure 5-1: Generic conceptual model for Eucalyptus spp. arid zone riparian and floodplain woodland

Conceptual model for *Eucalyptus camaldulensis* arid zone riparian woodland



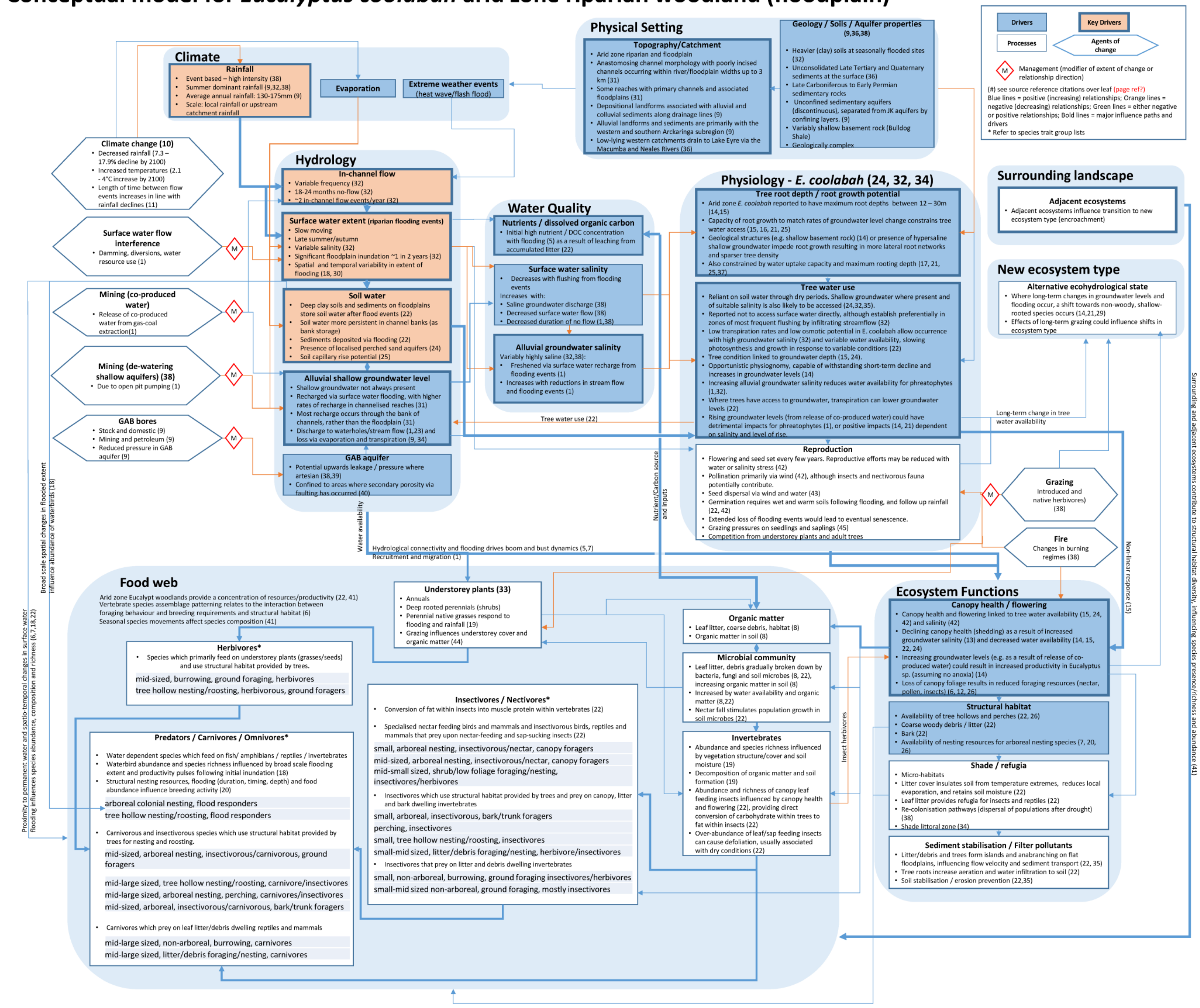
Indicator species trait groups – *Eucalyptus camaldulensis* woodland community

Insectivores / Nectivores									Herbivores		Predators / Carnivores / Insectivores							
small, arboreal nesting, insectivorous/nectar, canopy foragers	mid-sized, arboreal nesting, insectivorous/nectar, canopy foragers	mid-small sized, shrub/low foliage foraging/nesting, insectivores/ herbivores	small, arboreal, insectivorous, bark/trunk foragers	perching, insectivores	small, tree hollow nesting/roosting, insectivores	small-mid sized, litter/debris foraging/nesting, herbivore/ insectivores	small,non-arboreal, burrowing, ground foraging insectivores/ herbivores	small-mid sized non-arboreal, ground foraging, mostly insectivores	mid-sized, burrowing, ground foraging, herbivores	tree hollow nesting/roosting, herbivorous, ground foragers	arboreal colonial nesting, flood responders	tree hollow nesting/roosting, herbivorous, flood responders	mid-sized, arboreal nesting, insectivorous/ carnivorous, ground foragers	mid-large sized, tree hollow nesting/roosting, carnivore/ insectivores	mid-large sized, arboreal nesting, perching, carnivores/ insectivores	mid-sized, arboreal, insectivorous/carnivorous, bark/trunk foragers	mid-large sized, non-arboreal, burrowing, carnivores	mid-large sized, litter/debris foraging/nesting, carnivores
Slender-billed Thornbill (ssp)		Brown Honeyeater (r)	Purple Dtella	Rainbow Bee-eater	Chocolate Wattled Bat	Black-headed Scaly-foot		Brown Ctenotus		**Australian Ringneck** (2)	Little Black Cormorant		Grey Shrikethrush	Australian Owlet-Nightjar	Black-breasted Buzzard (r)	Long-nosed Dragon	Perentie	Patch-nosed Brown Snake
Weebill (4)		Grey-crowned Babbler (ssp)	**Tree Dtella** (3)	White-breasted Woodswallow	Gould's Wattled Bat	Black-necked Snake-lizard		Centralian Coppertail		Major Mitchell's Cockatoo (r)	Yellow-billed Spoonbill		Pied Butcherbird	Southern Boobook	Collared Sparrowhawk	Pygmy Mulga Goanna		
White-plumed Honeyeater (1)		Western Bowerbird		Masked Woodswallow	**Striated Pardalote** (4)	**Bynoe's Gecko** (3)		Spencer's Burrowing Frog		**Brushtail Possum** (5)	White-necked Heron			Spotted Nightjar	Little Eagle			
Yellow-rumped Thornbill (5)		Eastern Desert Ctenotus			Tree Martin	**Common Snake-eye** (3)		**Slater's Skink** (e) (6)			Australasian Darter (r)				Australian Raven			
Rufous Whistler		Common Bronzewing				Eastern Two-toed Slider												
Mistletoebird (3)						Fire-tailed Skink												
Chestnut-rumped Thornbill																		
Grey-fronted Honeyeater																		

Indicator species lists identified from BDBSA (records where >10% of all species locations are within 100m of *Eucalyptus camaldulensis* locations) for the Arckaringa basin.
Indicator species lists should not be considered complete, and composition of trait groups indicate general habitat/nesting/foraging/diet preferences.
Species in bold are identified as indicator species for *Eucalyptus camaldulensis* woodlands as identified by Pavey & Nano (2009) (1); Reid & Gillen (2); Brandle et al. (2003) (3); Herring et al. (2003) (4)
r = State rare (NPW Act); e = State endangered (NPW Act)

Figure 5-2: Box-line model and indicator species trait groups for *Eucalyptus camaldulensis* arid zone riparian and floodplain woodland

Conceptual model for *Eucalyptus coolabah* arid zone riparian woodland (floodplain)



Indicator species trait groups – *Eucalyptus coolabah* woodland community

Insectivores / Nectivores									Herbivores		Predators / Carnivores / Insectivores							
small, arboreal nesting, insectivorous/nectar, canopy foragers	mid-sized, arboreal nesting, insectivorous/nectar, canopy foragers	mid-small sized, shrub/low foliage foraging/nesting, insectivores/ herbivores	small, arboreal, insectivorous, bark/trunk foragers	perching, insectivores	small, tree hollow nesting/roosting, insectivores	small-mid sized, litter/debris foraging/nesting, herbivore/ insectivores	small,non-arboreal, burrowing, ground foraging insectivores/ herbivores	small-mid sized non-arboreal, ground foraging, mostly insectivores	mid-sized, burrowing, ground foraging, herbivores	tree hollow nesting/roosting, herbivorous, ground foragers	arboreal colonial nesting, flood responders	tree hollow nesting/roosting, herbivorous, flood responders	mid-sized, arboreal nesting, insectivorous/ carnivorous, ground foragers	mid-large sized, tree hollow nesting/roosting, carnivore/ insectivores	mid-large sized, arboreal nesting, perching, carnivores/ insectivores	mid-sized, arboreal, insectivorous/carnivorous, bark/trunk foragers	mid-large sized, non-arboreal, burrowing, carnivores	mid-large sized, litter/debris foraging/nesting, carnivores
Chestnut-rumped Thornbill	**Black-faced Cuckooshrike** (6,27)	Brown Honeyeater (r)	**Desert Tree Frog** (27)	**Black-faced Woodswallow** (27)	Chocolate Wattled Bat	Adelaide Snake-eye	Eastern Striped Skink	**Beaked Gecko** (28)	**Long-haired Rat (Plague Rat)** (27)	**Australian Ringneck** (6, 28)	Great Cormorant	Australian Shelduck	**Grey Shrikethrush** (28)	Australian Owlet-nightjar	Australian Hobby	Long-nosed Dragon	Perentie	Curl Snake
Grey Fantail	**Ground Cuckooshrike** (6)	Common Bronzewing	Desert Wall skink	**Masked Woodswallow** (27)	**Gould's Wattled Bat** (28)	Barred Snake-lizard	Main's Frog	Brown Ctenotus	Western Netted Dragon	**Bourke's Parrot** (28)	Little Black Cormorant		**Magpielark** (27)	Southern Boobook	**Australian Magpie** (6,27)	Pygmy Mulga Goanna		Desert Whipsnake
Grey-fronted Honeyeater	**Spiny-cheeked Honeyeater** (27,28)	**Crested Pigeon** (6,17)	Eyrean Wall Skink	White-breasted Woodswallow	Inland Broad-nosed Bat	Black-headed Scaly-foot	**Tessellated Gecko** (28)	Centralian Coppertail	Western Bluetongue	**Budgerigar** (6,27)	Little Pied Cormorant		**Pied Butcherbird** (6)	Spotted Nightjar	**Australian Raven** (27)			Five-ringed Snake
Grey-headed Honeyeater	**Yellow-throated Miner** (6, 27)	Eastern Desert Ctenotus	Purple Dtella	Pacific Swift (Fork-tailed Swift)	Inland Forest Bat	Black-necked Snake-lizard	Water-holding Frog	**Dwarf Skink** (27)		**Galah** (6, 27)	Nankeen Night Heron				Black Falcon			Western Brown Snake
Mistletoebird (28)		Grey-crowned Babbler (ssp)	**Tree Dtella** (27,28)	**Rainbow Bee-eater** (27)	Lesser Long-eared Bat	**Bynoe's Gecko** (27,28)		Gibber Ctenotus		**Little Corella** (6,27)	Royal Spoonbill				**Black Kite** (27)			
Red-capped Robin (28)		Inland Thornbill		Red-backed Kingfisher	Little Broad-nosed Bat	Canegrass Dragon		Saltbush Slender Bluetongue		Major Mitchell's Cockatoo (r)	White-necked Heron				Black-breasted Buzzard (r)			
Restless Flycatcher (r)		Painted Dragon		**White-backed Swallow** (27)	Red-browed Pardalote	**Common Snake-eye** (27,28)		Sandplain Ctenotus		Maned (Australian Wood Duck)	Yellow-billed Spoonbill				Central Bearded Dragon			
Rufous Whistler (28)		**Singing Honeyeater** (27)			**Striated Pardalote** (6)	**Dwarf Three-toed Slider** (28)		**Slater's Skink** (e) (2)		**Mulga Parrot** (6,28)					Collared Sparrowhawk			
Weebill		Southern Whiteface			**Tree Martin** (27)	**Eastern Two-toed Slider** (27)				**Zebra Finch** (27)					Letter-winged Kite (r)			
White-plumed Honeyeater (6,27)		Splendid Fairywren			White-striped Free-tailed Bat	Fire-tailed Skink				**Brushtail Possum** (3)					Little Crow			
White-winged Triller		**Variegated Fairywren** (27)				Gidgee Skink									Little Eagle			
Willie Wagtail (6,27,28)		**White-browed Babbler** (28)				Narrow-nosed Planigale									Swamp Harrier			
Yellow-rumped Thornbill		**White-winged Fairywren** (27)				Ooldea Dunnart									Tawny Frogmouth			
						Sudell's Frog									**Wedge-tailed Eagle** (27)			
															Whistling Kite (27)			

Indicator species lists identified from BDBSA (records where >10% of all species locations are within 100m of *Eucalyptus coolabah* locations) for the Arckaringa basin .
Indicator species lists should not be considered complete, and composition of trait groups indicate general habitat/nesting/foraging/diet preferences.
Species in bold are identified as indicator species for *Eucalyptus coolabah* woodlands as identified by Pavey & Nano (2009) (6); Brandle (1998) (27); Brandle et al. (2003) (28).
r = State rare (NPW Act); e = State endangered (NPW Act)

Figure 5-3: Box-line model and indicator species trait groups for *Eucalyptus coolabah* arid zone riparian and floodplain woodland

Acacia cambagei trait groups

Insectivores / Nectivores									Herbivores		Predators / Carnivores / Insectivores							
small, arboreal nesting, insectivorous/nectar, canopy foragers	mid-sized, arboreal nesting, insectivorous/nectar, canopy foragers	mid-small sized, shrub/low foliage foraging/nesting, insectivores/ herbivores	small, arboreal, insectivorous, bark/trunk foragers	perching, insectivores	small, tree hollow nesting/roosting, insectivores	small-mid sized, litter/debris foraging/nesting, herbivore/ insectivores	small,non-arboreal, burrowing, ground foraging insectivores/ herbivores	small-mid sized non-arboreal, ground foraging, mostly insectivores	mid-sized, burrowing, ground foraging, herbivores	tree hollow nesting/roosting, herbivorous, ground foragers	arboreal colonial nesting, flood responders	tree hollow nesting/roosting, herbivorous, flood responders	mid-sized, arboreal nesting, insectivorous/ carnivorous, ground foragers	mid-large sized, tree hollow nesting/roosting, carnivore/ insectivores	mid-large sized, arboreal nesting, perching, carnivores/ insectivores	mid-sized, arboreal, insectivorous/carnivorous, bark/trunk foragers	mid-large sized, non-arboreal, burrowing, carnivores	mid-large sized, litter/debris foraging/nesting, carnivores
Grey-headed Honeyeater	Ground Cuckooshrike	Inland Thornbill	Eyrean Wall Skink	Red-backed Kingfisher	Chocolate Wattled Bat	Black-necked Snake-lizard	Main's Frog	Gibber Ctenotus	Western Netted Dragon	Bourke's Parrot			Grey Shrikethrush	Australian Owlet-nightjar	Grey Falcon (r)	Pygmy Mulga Goanna	Mulga Snake	Desert Whipsnake
Grey-fronted Honeyeater	Spiny-cheeked Honeyeater	Grey-crowned Babbler (ssp)	Desert Wall skink	Rainbow Bee-eater	Lesser Long-eared Bat	**Gidgee Skink** (1)	Water-holding Frog	Saltbush Slender Bluetongue		Mulga Parrot			Pied Butcherbird		Black Falcon	Long-nosed Dragon		Curl Snake
Rufous Whistler	**Black-faced Cuckooshrike** (1)	Variegated Fairywren	**Tree Dtella** (1)		Gould's Wattled Bat	Dwarf Three-toed Slider	**Tessellated Gecko** (1)	**Dwarf Skink** (1)		Australian Ringneck			Grey Butcherbird		Letter-winged Kite (r)			Burton's Legless Lizard
Chestnut-rumped Thornbill		White-winged Fairywren	Desert Tree Frog		Inland Forest Bat	Sudell's Frog	Ghost Skink	Brown Ctenotus		**Galah** (1)					Collared Sparrowhawk			
Weebill		Southern Whiteface			Striated Pardalote	Barred Snake-lizard		Beaked Gecko							Little Raven			
Hooded Robin (ssp)		Eastern Desert Ctenotus			Tree Martin	**Common Snake-eye** (1)		Saltbush Ctenotus							**Black-faced Woodswallow** (1)			
Red-capped Robin		Common Bronzewing				**Bynoe's Gecko** (1)		Short-legged Ctenotus							Central Bearded Dragon			
Mistletoebird		**Crested Pigeon** (1)				Narrow-nosed Planigale									Australian Raven			
White-plumed Honeyeater		Splendid Fairywren				Ooldea Dunnart									Black-breasted Buzzard (r)			
Willie Wagtail (1)		Singing Honeyeater				Stick-nest Rats									Masked Woodswallow			
White-winged Triller						**Fat-tailed Dunnart** (1)									White-breasted Woodswallow			
Yellow-rumped Thornbill						**Bronzeback Legless Lizard** (VU,r) (2)									Whistling Kite			
															Little Crow			
															Tawny Frogmouth			
															Australasian Darter (r)			
															Australian Magpie			
															Wedge-tailed Eagle (1)			

Indicator species lists identified from BDBSA (records where >10% of all species locations are within 100m of *Acacia cambagei* locations) for the Arckaringa basin
Indicator species lists should not be considered complete, and composition of trait groups indicate general habitat/nesting/foraging/diet preferences.
Species in bold are identified as indicator species for *Acacia cambagei* shrublands as identified by Brandle (1998) (1); McDonald & Fyfe (2008) (2).
r = State rare (NPW Act); e = State endangered (NPW Act); VU = National vulnerable (EPBC Act)

1) Brandle, R. (1998). A Biological Survey of the Stony Deserts, South Australia, 1994-1997. Heritage and Biodiversity Section, Department for Environment, Heritage and Aboriginal Affairs, South Australia.

2) McDonald, P. & Fyfe, G. (2008). A survey for the bronzeback snake-lizard (Ophidiocephalus taeniatus). Department of Natural Resources, Environment, the Arts and Sport, Alice Springs.

Figure 5-4: Indicator trait groups for *Acacia cambagei*

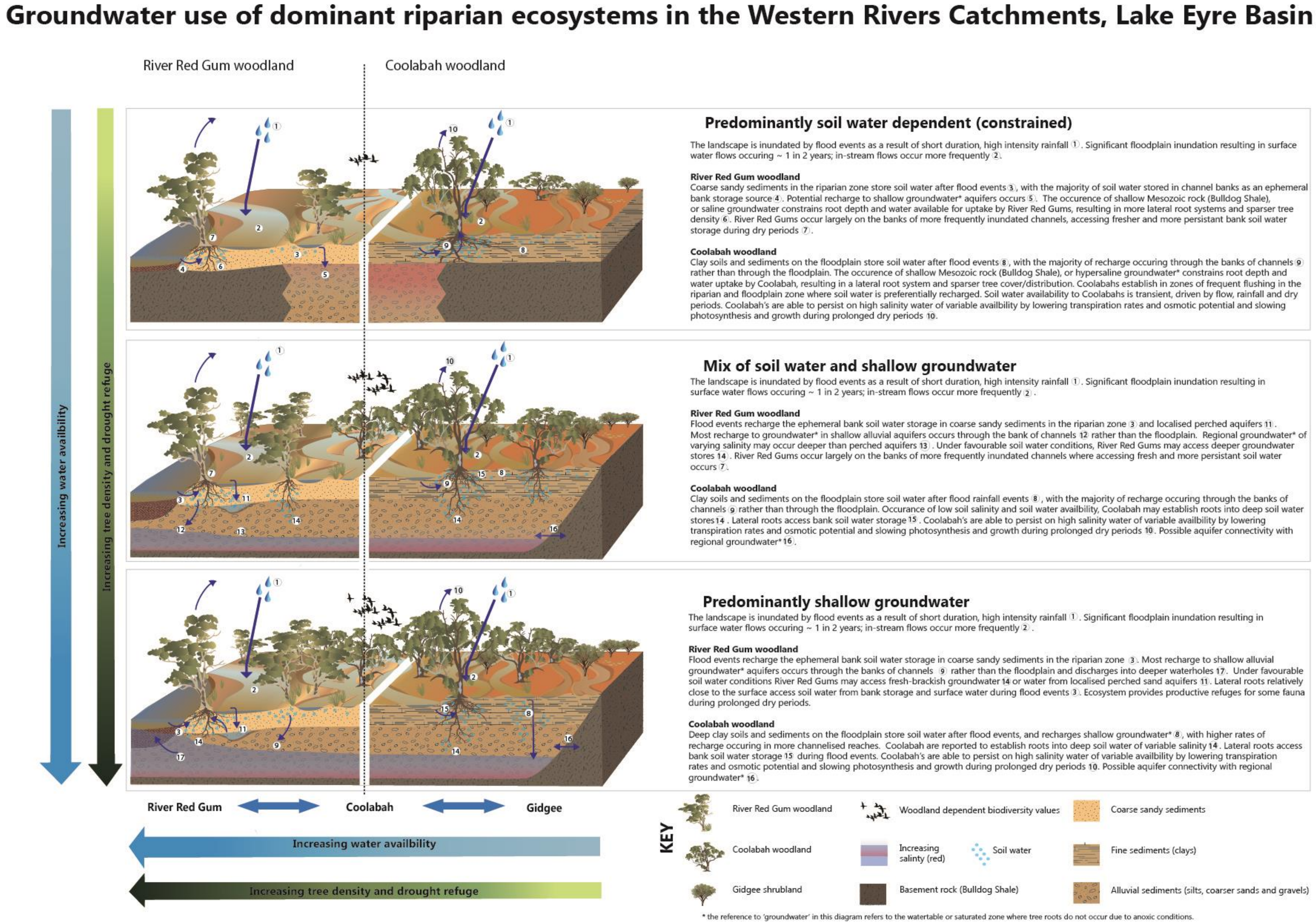


Figure 5-5: Conceptual model diagram of riparian and floodplain woodlands illustrating water sources used by dominant tree species

6 Conclusions and recommendations

This investigation has greatly progressed the understanding of the role of groundwater in maintaining riparian ecosystems in the Neales River catchment. Additionally, the understanding of the hydrogeology of the shallow aquifer system has been greatly improved. The key findings in relation to the specific objectives of the project are:

Objective 1: Clearly define and identify the ecosystems that are dependent on shallow groundwater (EDSG) (as distinct from those dependent on GAB groundwater or surface water only) and the ecological receptors of the ecosystems in question

In all cases, no riparian ecosystem investigated appeared to be entirely reliant on shallow groundwater, with most either providing evidence for a mixed source, or predominant reliance on soil water, although this last interpretation is based on a lack of evidence for other sources rather than direct evidence from soil water analysis.

E. camaldulensis stands near Wintinna Creek and *E. coolabah* near Algebullcullia Bore appear to have the most reliance on shallow groundwater based on comparable stable isotope results, whereas acacias in general and *E. camaldulensis* and *E. coolabah* near Stewart Waterhole display the least apparent reliance. The only instance where groundwater from the J-K aquifer appears to at least be partially providing a water supply to riparian vegetation is near Algebullcullia Bore. On the other hand, most of the *E. coolabah* monitored in 2015 did not show any definitive evidence of access to groundwater, with the Stewart Waterhole *E. coolabah* being a possible exception. Earlier isotope sampling from the Algebuckina site in 2013 indicates that riparian *E. coolabah* there have access to bank storage groundwater and data from the Finke River and Diamantina River supports *E. coolabah* using groundwater from depths of <10 m.

The GDE Index Tool showed strong potential for identifying GDE likelihood at a broad scale, but the number of sites able to be included in the field investigation were insufficient to calibrate the index. Any location with raster rainfall and NDVI can use this tool. The GDE Index Tool showed strong differences between IBRA regions, and therefore further applications of the tool would need to use different parameters for each IBRA based on further examination of rainfall and NDVI patterns. Localised variations in the outputs of the GDE Index Tool could guide the locations of future on-ground investigations that would in turn enable selection of parameter and thresholds for GDE likelihood.

Objective 2: Understand the significance of shallow groundwater to these ecosystems and their ecological receptors (e.g. degree of reliance on shallow groundwater systems vs other water sources)

As alluded to above, no riparian ecosystem investigated appeared to have a sole reliance on groundwater for sustenance, although some appeared at the time to be potentially more reliant than others did. Additionally, there appeared to be evidence that the riparian vegetation investigated is able to change and adapt their reliance on particular source waters dependent on availability.

For example, Both *E. coolabah* and *E. camaldulensis* appear to act as facultative phreatophytes, in that they take advantage of the presence of shallow groundwater but can persist in its absence. The Francis Camp Waterhole *E. camaldulensis* may not have had access to groundwater during the 2015 period but its location below bank top suggests that *E. camaldulensis* may need the presence of a saturated zone (i.e. bank storage) for at least some periods for their persistence in the landscape. Further, *E. coolabah* appear to have root systems with the capacity to switch between shallow soil moisture stores (e.g. rainfall and streamflow infiltration) and deeper groundwater stores. There is also some evidence that the trees are capable of hydraulic redistribution – that is moving soil moisture from one part of the root system to another via the tree, thus optimising the distribution and use of soil moisture.

Objective 3: Improve knowledge about the basic hydrogeology of shallow groundwater (SG) systems in the Western Rivers region. Inclusive to the objective is to commence investigations into how connected the shallow watertable is to deeper groundwater, most notably that within the GAB.

Three distinct groundwater sources could be identified that correlate to the three identified aquifers within the study area, being the J-K aquifer of the GAB, the shallow QTa aquifer, which is associated with current day drainage system and the shallow HSB aquifer associated with the Hamilton Sub-basin. Redox and pH conditions inherent between the aquifers cause many of these differences, particularly with respect to trace elements. Other differences relate to differing aquifer mineralogy, or differing groundwater ages.

These data suggest that the various aquifers from which groundwater was sampled during this investigation are unlikely to be interconnected in such a way as to result in notable large-scale groundwater mixing or migration over relatively short timescales. Connection between aquifers that allows very slow groundwater migration and hydrochemical evolution may be possible, particularly when one considers the importance of redox and pH conditions. Additionally, localised connectivity such as between the HSB and QTa aquifers near Sheila Bore may also occur.

Objective 4: Gauge the likely susceptibility of these shallow groundwater systems to changes in hydrology and the likely response of ecological receptors

In particular, *E. coolabah* show highly flexible patterns in utilising available water from shallow sources (i.e. infiltrated rainfall and streamflow) and/or shallow groundwater (i.e. approximately <10 m deep). These patterns and the low baseline transpiration rates of the trees emphasise the resistant nature of this riparian species to long drought periods and uncertain access to suitable quality groundwater. Similarly, E. *camaldulensis* also appear to be highly adaptable with respect to obtain water from a variety of sources. This ability of riparian vegetation to adapt and adjust their ability to obtain water from a variety of water sources and the fine adaption to life in such an arid environment may provide some buffer to hydrological change. However, lowering of the watertable or decreases in the frequency of flow events is likely to have detrimental effects on the health of these vitally important ecosystems.

Based on stable isotope data, groundwater recharge to the shallow QTa aquifer near Wintinna Homestead can occur at very low levels of streamflow. In other areas, reasonably rainfall events between 20 mm and 40 mm a month, using amount weighted-mean monthly rainfall thresholds, are required. Consequently, changes to hydrology that reduce the occurrence of flow events based on these relatively high rainfall events are likely to impact shallow groundwater resources and consequently any ecosystems at least partly dependent on these.

Objective 5: Identify the information requirements that development proponents must address to identify and manage risks to EDSG

Whilst the methods employed in this project have provided strong evidence for the objectives outlined above, a number of data gaps persist. Most pertinently, there is a requirement for a regional scale assessment of potential ecosystem vulnerability to changed surface water and groundwater conditions, potentially by classifying the landscape to better target future field studies and assist upscaling and transferability of results. Such a classification scheme may employ the South Australian Lake Eyre Basin (SA LEB) aquatic ecosystems and GDE Index (Gotch et al. 2015) and could incorporate other datasets such as surface geology, soil type, vegetation coverage, hydrology, and phreatic groundwater conditions.

A key data gap in this study was the absence of soil water sampling. Consequently, conclusions concerning the reliance of riparian ecosystems on soil water are highly dependent on a lack of evidence for other water sources, rather than direct evidence from soil water. Without drilling additional wells at the study sites and the collection of soil and concomitant groundwater samples, these conclusions remain somewhat uncertain. Therefore it is recommended that proponents of future water resource development proposal in the region undertake a more thorough investigation of sources of water used by trees in order that risks to riparian and floodplain vegetation can be confidently determined. Isotope comparison between groundwater, soil water, and tree water would be an essential component of such an investigation. Additional shallow wells would also enable greater understanding concerning the degree of connectivity between aquifers.

Future studies could also incorporate more trees at each site along transects traversing the channel and floodplain environments. Pre-dawn LWP measurements provide a lower cost measure to supplement isotope sampling. Daytime leaf water potential measurements were of limited value in this study and future studies could benefit from only collecting pre-dawn measurements, which would have the added benefit of conserving gas used in the measurement (a limitation for using this method in remote locations). Sapflow monitoring is a useful method for understanding water balances (Eamus et al. 2006a, Eamus et al. 2006b) however the high variability in the results for this study suggest that future studies may need to invest in at least two loggers per tree and more trees being monitored per site.

Another recommendation arising from this study is to undertake further spatially targeted on-ground GDE investigations to enable the GDE Index Tool parameters to be refined for each IBRA region. This would enable more confident identification of GDE likelihood at the broad scale, which could replace the mapping of ecosystems dependent on subsurface groundwater (terrestrial GDEs) in the GDE Atlas of Australia.

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9 Appendices

A. Summary of hydrostratigraphy

Table 9-1: Summary of hydrostratigraphy of Pre Mesozoic units

Period	Basin	Formation	Lithology description	Depositional environment	Hydrogeological characteristics	Outcrop
Pre-Cambrian	Crystalline Basement		Limestone, sandstone, shale, quartzite, dolomite, tillite, conglomerate and volcanic rocks	Largely marine deposition within a pelagic and continental shelf environment respectively	Fractured rock aquifer in part	Extensive outcrop within the Peake and Denison Inlier to the southeast of investigation area.
Cambrian to Devonian	Warburton Basin		Five separate depositional sequences occur—simplistically, these sequences include a basal suite of shallow marine sedimentary rocks, followed by a marine prograding sequence through to deep marine organic-rich lime mud and shale. A marine regression sequence then followed into a shallow marine sequence. Minor volcanolithic units	Shallow to deep marine	Unknown	No outcrop known in the area of investigation
Carboniferous-Permian	Arckaringa Basin	Boorthanna	Boorthanna Formation	Upper unit: inter-bedded marine clastic rock, with grain sizes ranging from silt to boulders. Lower unit: glaciogene sandy to bouldery claystone diamictite, intercalated with shale and carbonate layers	Fluvial, alluvial and glaciogene. Evidence for density-driven deposition in a marine environment in deeper parts of the basin	Groundwater from sandstone and conglomerate units are good aquifers with high yield
Permian	Arckaringa Basin	Stuart Range	Grey mudstone, siltstone and shale	Low energy marine	Main confining bed in the Permian sequence	No outcrop in the area of investigation
Permian	Arckaringa Basin	Mount Toondina	Upper unit: inter-bedded marine clastic rocks, with grain sizes ranging from silt to boulders. Coal seams. Lower unit: shale, siltstone and sandstone	Fluvial, alluvial and glaciogene. Evidence for density-driven deposition in a marine environment in deeper parts of the basin	Groundwater from sandstone and conglomerate units are good aquifers with high yield	Type section found at the Mount Toondina Piercement Structure

Table 9-2: Summary of hydrostratigraphy of Great Artesian Basin

Period	Basin name	Formation name	Lithology description	Depositional environment	Hydrogeological characteristics	Outcrop
Jurassic	Great Artesian Basin	Algebuckina Sandstone	Fine to coarse-grained sandstone, with granule and pebble conglomerates	Low gradient fluvial including rivers, floodplain. Both arid and wet climates	Major GAB aquifer, high yielding bores	Outcrop found near the margin of the Peake and Denison Inlier
Cretaceous Jurassic		Cadna-owie Formation	Heterogeneous, mainly fine-grained sandstone and pale grey siltstone. Coarser sandstone lenses occur in the upper part of the formation	Transitional from terrestrial freshwater to marine	Upper part is a good aquifer, high yields and good water quality	Outcrop found near the margin of the Peake and Denison Inlier
Cretaceous		Bulldog Shale (Rolling Downs Group)	Grey marine shaly mudstone, micaceous silt, and pyrite are also present, with minor silty sands. Occasional lodestones	Low energy, marine, cool climate	Main confining bed for the Jurassic-Cretaceous aquifers	Extensive outcrop in western and central portions of the investigation area
		Coorikiana Sandstone (Rolling Downs Group)	Predominately carbonaceous, clayey, fine-grained sandstone and siltstone	High energy, marine, shore face and gravel bars	Minor aquifer	Outcrop within the north-eastern portion of the study area, particularly between the Arckaringa Creek and Alberga River
		Oodnadatta (Rolling Downs Group)	Laminated, claystone and siltstone, with inter-beds of fine-grained sandstone and limestone	Low energy, shallow marine	Confining layer with minor aquifers	Extensive outcrop within the north-eastern portion of the study area, particularly between the Arckaringa Creek and Alberga River

Table 9-3: Summary of hydrostratigraphy of Cenozoic units

Period	Basin	Formation	Lithology description	Depositional environment	Hydrogeological characteristics	Outcrop
Late-Palaeocene to mid-Eocene		Eyre	Quartzose sandstone, minor pebbly sandstone and conglomerate, silcrete	Fluvial and locally lacustrine	Aquifer	No outcrop mapped in the region
Mid-Oligocene to Pliocene		Doonbara	Clastics, commonly silicified or ferruginised. Quartzose sandstone and granule conglomerate with maghemite pisolites.	Alluvial and colluvial	Aquifer	Outcrop north-west of the Peake and Denison Inlier and in the headwaters of the Kulvegalinna and Evelyn Creeks
Mid-Oligocene to Pliocene	Pliocene to Quaternary	Miracking Conglomerate	Cross-bedded fluvial conglomerate with silcrete clasts and medium-grained sandstone	Fluvial and alluvial	Aquifer	Outcrop in Wintinna, Henrietta and Evelyn Creeks; also in vicinity of break-aways south of Arckaringa Creek
		Mount Willoughby Limestone	Cream, pale brown and pink calcareous rock with iron stained clay and detrital quartz	Fluvio-lacustrine	Aquifer	Outcrop in Wintinna, Henrietta, Evelyn, Kulvegalinna and Oongudinna Creeks
		Etadunna inc. Alberga Limestone	Dolomite and limestone with Mg-rich claystone and fine-grained sand.	Fluvio-lacustrine	Aquifer	Outcrop near the Peake and Denison Inlier and the eastern Hamilton Basin region.
		Cordillo Silcrete	Silica-indurated sandstone and some conglomerate, chalcedony and opaline rocks	Regolith processes overprinting Eyre Formation	Unknown	No outcrop mapped in the region
Pliocene to Quaternary		Simpson Sand	Dunal sand	Aeolian and alluvial	Aquifer	Outcrop in Hamilton Basin and areas north
		Woodgate Gravel	Light to medium red-brown, consolidated polymict gravel (or pebbly sand); small to medium scale, low-angle, planar cross-bedding; minor carbonate veining in base of unit.	Alluvial and fluvial	Aquifer	No outcrop mapped in the region
		Pedirka	Dark red-brown, very fine to medium, poorly sorted, stiff clayey under red-brown, somewhat friable, fine sand with minor red clay, moderately sorted. Dark red-brown clayey sand at top.	Fluvial?	Aquifer	Outcrop in areas east of the Hamilton Basin

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